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QUALITY ASSURANCE IN MIXED-MODEL ASSEMBLY LINES THROUGH VISION-BASED DEEP LEARNING

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ABSTRACT
Quality assurance (QA) is a vital part of assuring efficiency and dependability in mixed-model assembly (MMA) lines, which produce a range of items simultaneously. Vision-based deep learning (DL) has become a successful technique for automatic fault detection with unmatched accuracy and scalability. This approach applies strong neural networks (NNs) to the visual input, which enables the real-time detection of defects over a range of product model types. Although a tremendous amount of progress has been made, problems like adaptability to dynamic contexts, real-time input integration, and model explainability persist. Recent advances in multi-task learning, hybrid architectures, and transformer-based models look promising to overcome these constraints. This article presents an exhaustive overview of the methodologies in place, significant gaps in research, and analyses of how vision-based DL might be transformative for quality assurance systems. For this systematic literature review, a total of 80 existing studies were selected from the year 2017-2024 respectively. Among that, the number of reviewed articles has also gradually increased year by year. In 2017, only one article was reviewed, while in 2018 it increased to two, then to eight in 2019. The same pattern went on in 2020 at 6 papers, 7 in 2021 and 2022, 11 in 2023, and finally exploded to 38 publications in 2024, signifying that research interest has been on the increase. The future approach will be focused on scalable, interpretable, and efficient solutions in line with the requirements of current production systems.
Keywords:Quality Assurance, Mixed-Model Assembly Lines, Vision-Based Deep Learning, Defect Detection, Manufacturing Automation, Explainable Artificial Intelligence (XAI), Real-Time Feedback Systems

INTRODUCTION :
Modern manufacturing has progressed significantly from a single-model assembly line to a highly flexible MMA line (Piero & Schmitt, 2017). These systems allow for the production of numerous product versions on one line, thereby satisfying diverse client needs and market trends. However, this has made it difficult to maintain uniform quality across all models, which has increased the need for better quality assurance systems. QA is a part of the manufacturing process; it ensures that products meet specifications and have no defects. The MMA lines usually fail the traditional quality assurance procedures because of the higher variability in the product designs and processes (Bauters, 2019). Manual inspection may be tedious and prone to errors, while traditional automated solutions may lack agility in such dynamic scenarios. Vision-based solutions changed quality assurance by using cameras and sensors to capture more detailed visual data of an item during assembly.
Flaws can be detected, dimensions measured, and assemblies done with higher precision and accuracy than manual techniques. Operating in real-time and the ease of integration into lines of production have made such solutions indispensable in today's industry. Deep Learning (DL) has opened up the doors for vision-based systems as powerful algorithms capable of learning complex patterns and making exact conclusions (Zamora-Hernandez et al. 2021). Convolutional Neural Networks (CNNs) and Generative Adversarial Networks (GANs) are two techniques that allow systems to detect flaws, classify parts, and adapt to new product models with minimal human intervention. Together, vision-based systems and DL hold unparalleled potential for quality assurance in mixed models (Riedel et al. 2021). This research discusses vision-based DL applications

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for quality inspection in MMA lines. An overview of issues associated with the application is made, the technology and approach considered are reviewed, and the performance is evaluated. Moreover, it deals with the present limitations and options for further research on increased application and effectiveness of the technology.

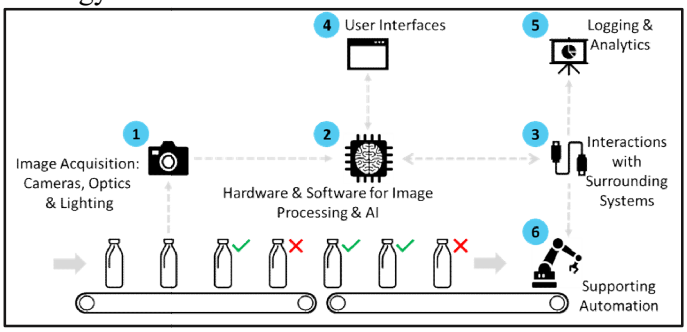

Figure 1: QA with AI vision (Mokuwe et al. 2022)

Importance of QA in MMA: QA is a very essential part of production, which ensures that all products meet set performance, reliability, and safety standards. MMA lines require high importance for QA since several product versions are manufactured simultaneously (Mokuwe et al. 2022). To maintain uniformity among all models, design, component, and assembly processes have to be monitored strictly since they have variability built into them. Defects can easily spread if proper QA is not followed, and it may lead to consumer dissatisfaction and reputational damage. QA processes are important in the discovery of faults early, minimization of rework, and reduction of waste, which is particularly relevant in MMA lines. Faulty products are costly and disrupt production schedules, thereby reducing operational efficiency. Effective QA systems make the process easier as they can detect anomalies in real-time, prevent faults from being propagated further downstream, and eventually save both time and resources (de Souza Silva & Paladini, 2024). Increasingly strict industry rules and greater customer expectations have created the need for solid quality assurance systems in place for compliance and market competitiveness. Quality assurance in MMA lines ensures that each product variant meets not only the regulatory requirements but also the expectations of customers. By sustaining high-quality output, manufacturers can secure a competitive advantage in this dynamic industrial scene. Role of Vision-Based DL in QA: These tools have emerged as great in automating quality assurance processes: vision-based systems enable a non-invasive manner, by which flaws can be detected in real-time as minute visual data is acquired from cameras and sensors (Zhou & Wen, 2024). This improves the systems and involves algorithms that can make their way through complicated patterns such that they are capable and much more efficient as compared to standard QA practices. DL techniques are particularly effective in dealing with complex visual input, especially convolutional neural networks (Ugo-Njoku & Opara, 2024). In MMA lines, this system adapts to wide-ranging shapes, sizes, and assembly configurations because product variation is extreme. In addition to diagnosing problems with precision, vision-based DL works in real time, so manufacturers may correct issues without disrupting the production line.

Scalability is a large advantage of vision-based DL. Once trained, these systems can be executed to perform a wide array of functions across several lines of products, including defective part identification and component checks (Sikora & Tiacci, 2024). Moreover, they tend to improve continuously since their learning is based on fresher data, which is great for dynamic mixed model scenarios. Manufacturers may reduce downtime, increase accuracy levels, and improve efficiency overall in quality assurance with the integration of DL systems into vision systems (Alfaiz et al. 2024).

PROBLEM STATEMENT:

MMA lines introduce unique quality assurance challenges as they manufacture many product variations simultaneously, each with a different configuration and standards. Maintaining consistent quality in all products is challenging due to the inherent variability in design, assembly processes, and parts. Traditional solutions for quality assurance, including manual inspections and strict rule-based automation, have been unable to effectively address the dynamic nature of mixed-model systems. These methods often involve high inspection costs, longer processing times, and more errors that lead to inefficiency and possibly undetected defects in products during the production process. Although vision-based technologies have significantly enhanced defect detection and process monitoring in manufacturing, several of these have limitations when applied to MMA lines. Traditional vision systems would often fail to cope with the complexities of model differences, lighting differences, or changing product mixes. Often, these systems require adjustments or retraining for each new version of a product. To overcome these limitations, there is an acute need for novel DL methods that can automatically learn to adapt to different manufacturing conditions, recognize complex patterns, and make accurate error detections with speed. This research aims to address such gaps by exploring the capability of vision-based DL for quality assurance in MMA lines, with its ability to make the process more flexible, scalable, and dependable.

MOTIVATION :

Increasing complexity and demand for customization in modern manufacturing, especially in MMA lines, emphasize the great need for more efficient and scalable quality assurance systems. Traditional quality assurance methods such as manual inspection and rule-based automation have been proven ineffective in dealing with the dynamic unpredictability of product variants; the defect rate is high, the operational cost is higher, and production is delayed. The advantage presented by vision-based systems means a great deal, though limits persist in adjusting constantly shifting production conditions and diversified designs. AL assimilation with vision-based QA therefore represents a disruptive technology - to wit: one wherein real-time fault detection might become possible automatically, adaptatively set within new models and under any kind of production. This breakthrough promises to enhance not only the accuracy and efficiency of quality control processes but also improve the general competitiveness and sustainability of manufacturing operations through the reduction of waste, downtime, and other operational inefficiencies. Thus, the exploration of vision-based DL for QA in MMA lines is critical for meeting modern industry's expansive demands.

OBJECTIVES:

- To install high-resolution cameras and sensors in key areas of the assembly line, capturing real-time visual data for automated defect detection and replacing manual inspection tasks.
- To preprocess and augment the visual data captured by vision systems, ensuring consistency in image quality and improving the effectiveness of DL models in detecting defects.
- To train DL models, such as CNNs, using labeled datasets that enable the system to recognize defects across a variety of product variants.
- To deploy DL models in the production environment, enabling real-time defect detection and classification, and automating the identification of defective products for immediate action.
- To continuously monitor system performance and refine DL models by retraining them with new data, ensuring sustained accuracy and adaptability to evolving production conditions and product designs.

RESEARCH METHODOLOGY

Method for SLR on QA in MMA Lines Through Vision-Based DL

Search Strategy

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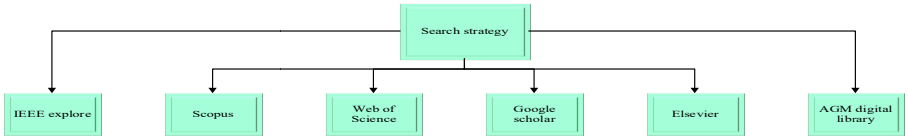

Figure 2: Search strategy

INCLUSION CRITERIA:

- Articles on QA & DL in manufacturing or assembly line environments.
- Research on computer vision-based strategies for quality inspection in mixed-model lines of production.
- DL industrial applications, especially in production line environments, are being explored.
- DL is applied in research to detect defects, automate processes, and improve assembly lines.

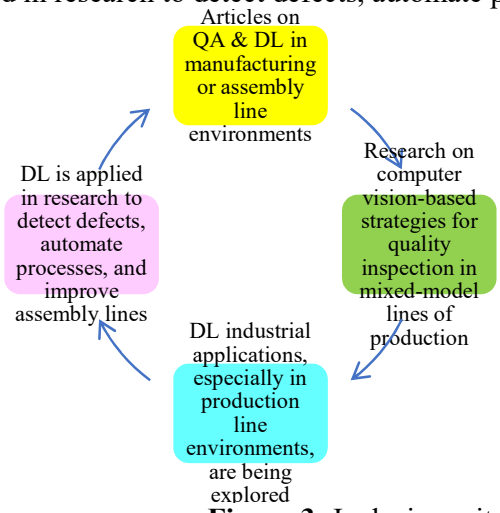

Figure 3: Inclusion criteria

EXCLUSION CRITERIA :

- Papers that do not relate to manufacturing or MMA lines.
- Research focusing on non-vision-based QA methods.
- Non-peer-reviewed publications or abstracts without sufficient technical detail.

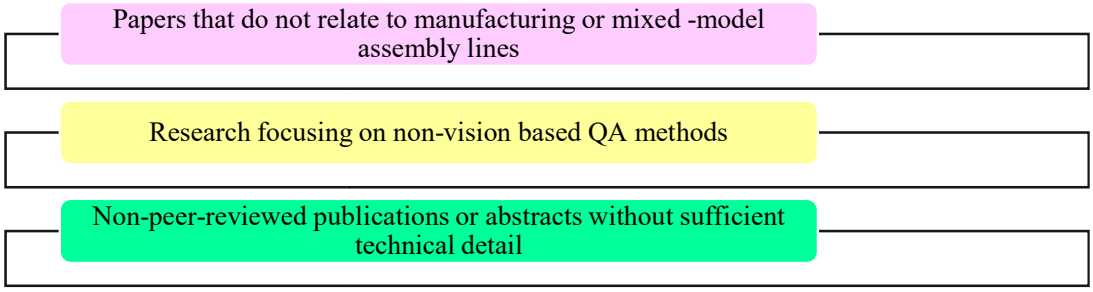

Figure 4: Exclusion criteria

KEYWORDS & BOOLEAN EXPRESSIONS :

"Quality Assurance" OR "Mixed-Model Assembly Lines" OR "Mixed-Model Manufacturing" OR "Computer Vision" OR "Deep Learning" OR "CNN" OR "Manufacturing" OR "Industrial Process" AND "Assembly line quality control" AND "Production line QA" AND "Machine learning" AND "Neural Networks" AND "AI in Manufacturing" AND "Vision-based quality inspection" AND "Vision-based defect detection" AND "Smart manufacturing" AND "Industry 4.0" AND "Object detection" AND "Image classification" AND "Deep neural networks". The search strategy is

illustrated in Figure 2, figure 3 shows the Inclusion criteria and the following figure 4 is the Exclusion criteria. Moreover, the Figure 5 shows the Prisma chart.

DATA EXTRACTION :

Article Information: Title, authors, journal, publication year.

Study Focus: The DL model outperformed traditional methods in defect detection and Significant productivity gains were realized within the assembly line.

Methodology: Qualitative or quantitative approach, data sources, analysis techniques.

Findings and Conclusions: Main findings related to the QA in MMA Lines through Vision-Based DL models

Quality assessment

Each study was evaluated for quality and relevance using criteria suchas,

- Clarity of research questions and objectives.
- Suitability of the methodology.
- Strength of data analysis and clarification.
- Relevance to the QA in MMA Lines through Vision-Based DL models
- Contribution to the field.

PRISMA chart

- **Identification**

Records identified through database searching (n = 200)
Additional records identified through other sources (n = 10)
Total records identified (n = 210)

- **Screening**

Records after duplicates removed (n = 180)
Records screened (n = 150)
Records excluded (n = 30)

- **Eligibility**

Full-text articles assessed for eligibility (n = 100)
Full-text articles excluded (n = 20)

- **Included**

Studies included in qualitative synthesis (n = 80)

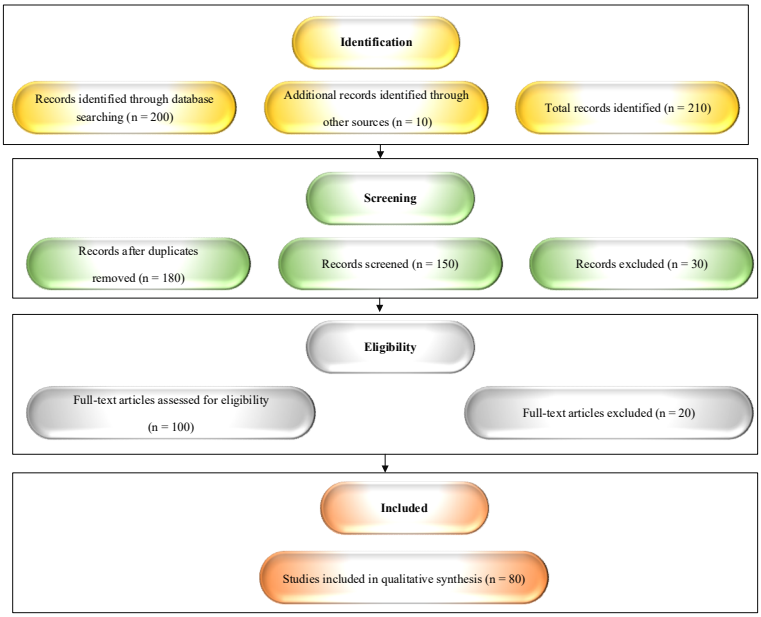

Figure 5: Prisma chart

CHARACTERISTICS AND COMPLEXITIES OF MMALINES :

In 2019, Jiahua et al. presented an integrated approach for the balancing and sequencing of un-paced buffered mixed-model manufacturing lines. Applying a combined precedence diagram transforms the balancing problem into a single-model problem, and by applying the NEH method for sequencing, the makespan is minimized. Three cases illustrate its usefulness. In 2022, Lakhdar Belkharroubi & Khadidja Yahyaoui, aimed to reduce the cycle duration in MMA lines by resolving the MiMALBP-II problem by the hybrid method of Reactive GRASP with RPW heuristic. It compares the results of the proposed algorithm with basic GRASP and tests it on three problems. In 2018, Zhang et al. suggested a new service model to reduce damage and transportation costs by incorporating the concept of an Assembly Distribution Centre (ADC).

Flexsim is used for simulating the effectiveness of the proposed model, which addresses all the challenges faced in China regarding final vehicle logistics using the new MMA line method. In 2021, Mohseni-Darabi et al. presenteda bi-objective mathematical design for mixed-model sequencing on assembly lines for reducing operator displacement and idle time, using GAMS and CPLEX with an improved ε-constraint approach to support decision-makers in choosing the best methods. In 2020, Yuwei et al. presented a Two-sided MMA line balancing modeled through a multi-objective scientific model. The model will optimize paired stations, the balancing rate of the assembly line, and the smoothness index with zoning and cooperative constraints under an updated genetic method for better efficiency. In 2019, Tong et al. addressed scheduling problems in MMA lines for urban rail cars using a model with optimization objectives including part set minimization, blocking, and reduction of hungry time. To prove its efficiency, the paper uses a genetic algorithm-based scheduling method on the Plant Simulation platform. In 2020, Nazari et al. focused on balancing and sequencing assembly lines in a competitive market by considering sequence-dependent setup times. It gives a simulated annealing approach to solving huge problems more efficiently compared to mixed integer programming models and ant colony optimization in terms of time. In 2020, Wang et al. developed a multi-objective cuckoo search approach utilized for resolving the car-sequencing issue in MMA lines. The program optimizes different aspects of this problem, like part usage rates, workstation workload, idle time, and switching costs, thus being useful for practical applications. In 2023, Huo & Lee presented a mixed-integer linear programming approach to balance and sequence multi-manned MMA lines. It utilizes Benders' decomposition method with valid inequalities to minimize workers, stations, and utility work. Using numerical data, the paper shows how well the model performs. In 2023, Zhang et al. used a resilient optimization model for balancing the mixed-model multi-manned assembly lines under uncertain demand conditions. A reinforcement learning-based MOEA is proposed to achieve the reduction of production costs with penalty costs that outperform competitor MOEAs in experiments. In 2023, Nourmohammadi et al. used digital human modeling and posture assessment (REBA) to include ergonomic variables in MMA line balancing. It defines the problem as a MILP model with three objectives: cycle time, ergonomic risk, and total risks. The E-NSGA-II algorithm outperforms previous methods for generating optimal balanced workstation solutions. In 2021, Capela et al. presented a machine vision prototype for quality inspection of an automotive assembly line and focused on the use of Faster-RCNN and YOLOv3 to identify engine labels. With proprietary data from an automotive facility, the models performed extremely well with accuracy going as high as 100% with data augmentation; Faster-RCNN did outperform YOLOv3. In 2029, Mazzetto et al. suggested a deep learning-based system to recognize and classify different objects in car assembling without the need for specific interventions on the production lines. The system achieves quite acceptable accuracy and cycle length, showing that it behaves well in a real assembly line. In 2024, Karaklasa et al. developed a framework for object detection using 3D vision sensors, template matching, and CNN algorithms. It was implemented in the real world with an automotive scenario and had better efficiency, accuracy, and flexibility, with

applications in several industrial scenarios. In 2019, Busogi et al. introduced an information entropy approach to reduce complexity in mixed model assembly lines by sequencing products. Simulations are run to demonstrate how sequencing allows for increased predictability for the system and minimizes complexity, thus increasing productive output without increasing workload
In 2023, Li et al. developed anMMA line balancing issue that incorporates learning effects as well as the uncertainty of demand besides optimizing two conflicting objectives, namely, cost and cycle time by proposing a mixed integer-related heuristic & variable district searching technique, offering efficient solutions under different system response times. In 2020, Addy explored 'transition complexity' at the Nissan Smyrna plant, which can impact defect rates when shifting among different models of vehicles produced. It suggests several areas for simplification: simplifying kitting procedures and layouts and also changes in manufacturing schedules. In 2022, Belkharroubi & Yahyaoui presented a Hybrid Reactive Greedy Randomized Adaptive Search Procedure (HRGRASP) for the MiMALBP-I problem that maximizes workstation numbers based on cycle times. The HRGRASP algorithm is performing better compared to other algorithms against a wide range of problems of sizes. In 2021, Mönch et al. propose the use of variable takt times against fixed takt times as an approach to improve productivity on MMA lines. It highlights the critical nature of balancing time against quality, using a customization-adaptive mixed-integer programming approach that outperforms set takt times. In 2022, Meng et al. discuss MMA line balancing with defensive maintenance (MALB_PMs) and introduce a mixed-integer formulation and a cooperative co-evolutionary method. The proposed method optimizes cycle times and task distribution, which is more efficient and provides more Pareto solutions than other algorithms.

Table 1: Summary of Studies on MMA Line Balancing and Optimization Techniques in Automotive Manufacturing

Author(s)	Proposed Technique	Performance	Research Aim	Problem Statement	Limitations
Jiahua et al. 2019	An integrated methodcombining combined precedence diagram, combined priority rule, and NEH algorithm	Effectiveness verified by three cases.	To solve the balancing and sequencing problem of unpackedbuffered MMA line	Balancing and sequencing of assemblylines with buffers to ensure efficient operation	Limited to three cases for validation
Lakhdar Belkharroubi & Khadidja Yahyaoui, 2022	A hybrid algorithmcombining Reactive GRASP and RPW heuristic	Compared with basic GRASP for better results	To solve MiMALBP-II and minimize cycle time	Need to minimize average cycle time in MMA lines	Limited problem scope for testing
Zhang et al. 2018	Goal chasing method, Flexsim simulation	Shows better time performance compared to other methods	To optimize final vehicle assembly and logistics with a new service mode	High damage rate and costs in final vehicle transportation	Limited to on eillustrative example without a simulation experiment

Mohseni-Darabi et al. 2021	A bi-objective mathematical model with augmented ε-constraint method	Provides Pareto optimal solutions	To minimize displacement and idle time of operators in MMA lines	Sequencing problem in MMA line	No experimental validation for large-scale instances
Yuwei et al. 2020	Multi-objective genetic algorithm (GA)	Improved efficiency with the modified GA	To minimize the number of paired stations, balance rate, and smoothness index	Balancing and sequencing in a two-sided MMA line	Limited problem application (automobile company example)
Tong et al. 2019	Genetic algorithm-based scheduling, embedded in Plant Simulation	Effective in simulation	To solve the scheduling of urban rail vehicle MMA line	Minimizing part set, blocking time, and hunger time in scheduling	Limited to simulation environment without real-world validation
Nazari et al. 2020	Simulated annealing with α-sampling and efficient assignment heuristic	Outperformed MIP and ant colony optimization	To solve MMA line problems with sequence-dependent setup times	MMA line balancing with sequence-dependent setup times	Lack of broader application and validation
Wang et al. 2020	Multi-objective cuckoo search algorithm with record matrix	Good results in real case	To resolve the car-sequencing issue in MMA lines	Variation in parts usage, workload, and modelswitching costs	Requires more verification for larger cases
Huo & Lee, 2023	Mixed-integer linear programming (MILP) model with Benders' decomposition algorithm (BDA)	Demonstrated effectiveness through numerical results	To balance and sequence MMALs while minimizing workers and stations	MMALs with diverse products and optional features	Limited to numerical testing and small-scale examples
Zhang et al. 2023	Multi-objective evolutionary algorithm (MOEA) with Q-learning-based crossover and mutation	Outperforms 11 competitive MOEAs in experiments	To balance mixed-model multimanned assembly linesunder uncertain demand	Uncertain demand requiring robust assembly line configuration	Limited to benchmark instances and lacks real-world validation
Norma Hammadi et al. 2023	Enhanced Non-Dominated Sorting Genetic Algorithm (E-NSGA-II)	Dominates other methods in terms of performance metrics	Addressing MMALBP with ergonomic factors and worker posture	MMA line balancing problem (MMALBP) considering workerposture, cycle time, and ergonomic risks	May not fully account for all environmental factors or changes in real-world production scenarios

Capela et al. 2021	Faster-RCNN and YOLOv3 object detection algorithms	Faster-RCNN: 92.5% (without data augmentation), 100% (with data augmentation)	Smart quality inspection in automotive assembly	Engine label detection for Citroën and Peugeot models in an automotive assembly line	May require extensive data augmentation and manual data preparation
Mazzetto et al. 2019	Deep learning-based object detection	Acceptable accuracy without interventions on the production line	Automating workpiece detection and classification in automotive assembly	Detecting and classifying multiple objects in MMA lines	Accuracy may depend on real-time environmental conditions and lighting
Karaklasa et al. 2024	3D Vision Sensors, Template Matching, Deep Convolutional Neural Network (CNN)	Demonstrated in pre-industrial setup, flexible for various manufacturing contexts	Optimizing object detection for automotive assembly operations	Addressing vehicle motor and gearbox assembly using advanced sensors and CNN	Performance may vary based on real-world complexities outside of pre-industrial testing
Busogi et al. 2019	Information entropy-based methodology for product sequencing	Demonstrates the impact of sequencing on complexity control	Minimizing complexity in MMA lines	Addressing complexity in assembly systems as product variety increases	Limited by assumptions in product sequencing models and complexity quantification
Li et al. 2023	Mixed-integer-related heuristic, Modified variable district search approach	Efficient under varying system response times	Optimizing MMA line balancing along with learning effect & uncertain demand	Balancing the overall expected cost &average cycle duration in mixed-model schemes	May not handle extremely dynamic, real-time system responses effectively
Addy, 2020	Not specified	Not specified	Reducing transition complexity in MMA lines	Addressing defect rate variationsdue to transitions between vehicle models	Requires system specific adjustments and interventions for effective results

Belkharroubi & Yahyaoui, 2022	HRGRASP	Comparison with GRASP, heuristics-based approach, and Lingo solver	Solving MMA line balancing problem (MiMALBP-I)	Optimizing the number of workstations for fixed cycle time	Not tested across a variety of assembly line settings, limited scope
Mönch et al. 2021	Mixed-Integer Programming (MIP) model	Reduces labor inefficiencies and complexity	Introducing variable takt times in MMA lines	Balancing takt time with product variety in mixed-model production systems	May face challenges in applying to industries outside of the agriculture sector
Meng et al. 2022	Cooperative Co-evolutionary Algorithm with mixed-model variable step-size decoding	Outperforms other algorithms, closer to true Pareto front	MMA line balancing with preventive maintenance	Optimizing cycle time and task alteration considering PM scenarios	Limited to small-scale instances and may require further validation for large-scale applications

VISION-BASED DL APPROACHES FOR QA IN MMA LINES :

In 2022, Stauder & Kühl discussed the challenges of sequence scrambling. Customers want customized products at mass-produced prices, leading to sequence scrambling. Induced by operational and product-related problems, sequence scrambling is still a problem. A supervised classification model uses product attributes such as body shape and color to predict sequence deviations with 50% prediction accuracy. Process-related aspects such as the condition of the machines have been excluded from the focus of this study on product attributes. In 2024, Yao et al. provided a method for predicting the completion status of aircraft MMA lines based on a Dynamic Bayesian Network (DBN). It solves problems like data scarcity and time-varying situations. The model uses expert knowledge and particle filtering to enhance the precision of the forecast. The experimental results indicate that the AMMALs have higher prediction capability, which would help aircraft industries plan. In 2024, Hoffman provided a system efficiency model for the Nissan Smyrna Vehicle Assembly Plant that introduces product and process data to the model. It relates assembly jobs to car attributes so bottlenecks and improvements in production can be identified easily. It gives a much more efficient method of deciding system efficiency, optimizing production sequences, and enhancing plant performance. In 2024, Alhomaidhi addressed the MMA Line Balancing Problem (MALBPLW) by integrating the learning effects of workers and the dependency of tasks. It delivers a new mathematical model with a solution approach to optimize assembly line task assignment. This cost-reducing and increasing production efficiency strategy develops an overall framework for optimizing industrial resources. In 2022, Zhou & Zhao focused of optimizing the scheduling of part feeding in automotive MMA lines using a hybrid fuzzy-neural-based dynamic scheduling approach. It illustrates through some computational experiments that the suggested method outperforms benchmark algorithms in scheduling decisions and performance.

In 2019, Qattawi & Chalil Madathil suggested the optimization and Redesign of Automotive Assembly Lines Using the Clustering Technique and the Task Mutuality Index. The solution reduces modeling effort and time taken to achieve a practical redesign and improves line balancing and takt time. In 2018, Biele & Mönch discussed the low Volume Aeroplane Assembly Lines Planning

Mixed Model Assembly Lines. The article presents research on production planning for low-volume assembly lines of aeroplanes. It focuses on labor and inventory holding costs. The paper proposes two mathematical models of worker allocations and processing times. Heuristics are used to optimize the models, which demonstrate outstanding performance in computational studies and real-world circumstances. In 2020, Mazzetto et al. recommended the use of deep learning-based techniques to support visual inspection tasks within car manufacturing lines. The intent is to increase the precision and speed of computer vision systems while reducing their involvement in the factory's business cycle. The approach is illustrated with models for object detection, semantic segmentation, and anomaly detection. In 2022, Lv et al. presented a multi-agent optimization approach is presented in this work as an attempt to balance and sequence MMA lines, leveraging deep reinforcement learning. It employs balancing agents and sequencing agents to optimize the whole system as the workload overload and idle time reduction are implemented. Experiments involving comparative analyses with heuristic algorithms and genetic algorithms show how the strategy performs better with this strategy. In 2021, Zhou & Zhu contributed to the active development of the part-feeding process in MMA lines using a knowledge base and an enhanced version of the fruit fly optimization algorithm. The material delivery distance and throughput in the system are improved using a proposed mathematical methodology. Results of some computational experiments reveal that a proposed scheduling scheme increases productivity and system efficiency during dynamic conditions.

Table 2: Summary of Research on Optimization and Efficiency Techniques in MMA Lines

Author(s)	Technique Proposed	Research Aim	Model Efficiency	Performance	Research Gap
Stauder & Kühl, 2022	Supervised classification model based on product features	Predicting sequence deviations in automotive MMA lines based on product-related features	Predicts up to 50% of major sequence deviations in advance	Effective in predicting deviations, but does not consider process-related factors	Does not address machine conditions, shift plans, or other process-related factors in the prediction
Yao et al. 2024	Dynamic Bayesian Networks (DBNs) and agent model	Predict completion states in aerospace MMA lines with limited data.	Solves small-sample problems using DBN parameter learning and expert knowledge	Improved predictive ability with enhanced reasoning speed and prediction accuracy	Limited data accumulation, the dynamic nature of the assembly line, and difficulty with new models
Hoffman, 2024	An integrated model linking production sequence with assembly jobs	Enhance system efficiency by combining product and process data for the Nissan Smyrna Vehicle Assembly Plant	Measures system efficiency by integrating product and process data	Identifies bottlenecks and optimizes production sequences	No combined data system for both product and process data in previous approaches

Alhomaidhi, 2024	A mathematical model with learning effect and worker prerequisites	Optimize assembly line task assignments while considering learning effects and worker classifications	Achieves enhanced cost-effectiveness and resource utilization	Demonstrated cost reduction and improved production efficiency	Lack of comprehensive framework integrating learning effects with real-time worker performance
Zhou & Zhao, 2022	Hybrid fuzzy-neural dynamic scheduling method (SOM + FCM + KB)	Optimize productivity and cost in part feeding scheduling under a Kanban system	Efficient scheduling based on real-time status and production requirements	Superior to benchmark algorithms in terms of scheduling performance	Limited focus on integrating product-related factors in dynamic part feeding scheduling
Qattawi & Chalil Madathil, 2019	Clustering algorithm with task mutuality index	Redesign and rebalance assembly lines considering product demand variability and new product models.	Reduces optimization time and simplifies redesign efforts	Effective in balancing labor costs, optimizing assembly lines	No consideration of how task mutuality affects new product introduction and assembly line design
Biele & Mönch, 2018	Time-indexed linear and non-linear mathematical formulations	Balance labor and inventory costs in MMA lines with a fixed job sequence	Flexible allocation of workers while considering cost and processing time	High performance in balancing labor and inventory costs using heuristics	The challenge of applying linear/non-linear formulations in real-world scenarios with fixed assignments
Mazzetto et al. 2020	Deep learning for computer vision in visual inspection tasks	Assist in automotive assembly line visual inspection tasks using deep learning-based methodologies	Enhances computer vision systems with minimal disruption to assembly line time	Success in object detection, segmentation, and anomaly detection in a real setting	Environmental settings affecting the performance and accuracy of CVSs in real-time assembly environments
Lv et al. 2022	Multi-agent optimization with deep reinforcement learning	Optimize balancing and sequencing problems in MMA lines using deep reinforcement learning	Coordination of agent outputs to achieve global optimization	Superior to traditional heuristic rules and genetic algorithms in large-scale tests	Insufficient focus on large-scale MMA lines and scalability of methods

Zhou & Zhu, 2021	VSCFOA-enhanced GRNN for dynamic scheduling	Solve real-time part feeding scheduling in dynamic automotive MMA lines	Coping with dynamic environments for higher productivity	Demonstrates higher productivity and system performance in dynamic environments	Lack of research into dynamic scheduling's impact on overall production quality in mixed-model systems

ENHANCING QUALITY CONTROL IN MMALINES THROUGH DL AND COMPUTER VISION :

In 2022, Rio-Torto et al. developed a hybrid inspection system that reduces worker fatigue and increases adaptability by incorporating both automated detection and human input. It uses 3D vehicle generators and applies domain adaption techniques to fill the gap between labelled and real-world data. Results indicate better performance in the detection of non-conforming car parts, suggesting a symbiotic machine-human assembly line that would enhance efficiency. In 2019, Munoz et al. designed a mixed reality-based user interface to enhance worker ergonomics in automotive quality control. It aims at the reduction of worker stress while increasing productivity through an improved intuitive manner for the presentation of fault information. A usability evaluation that compares the new interface with Mercedes-Benz's current system demonstrates important improvements in worker performance. In 2024, Zhang et al. developed a mixed-integer linear programming model is designed for energy and cost savings in multi-skilled worker MMA lines. A new co-evolutionary algorithm is developed to optimize a trade-off between energy and cost and significantly outperforms other state-of-the-art algorithms for several instances. Experiments validate the effectiveness of the algorithm in optimizing assembly line operations. In 2019, Zhang et al. considered the Type-II MMAline balancing problem with uncertain task time. To develop and solve a robust optimization model, the paper employs a hybrid genetic algorithm (HGA) that combines heuristic approaches with adaptive local search. Experimental results indicate that the HGA is useful in enhancing production efficiency in the presence of uncertainty. In 2023, Paprocka & Krenczyk discussed mixed-model, multi-version assembly line sequencing for energy efficiency. The optimization of vehicle sequencing is carried out by the Grey Wolf Optimiser (GWO) which surpasses greedy heuristics and Simulated Annealing. The contributions will ensure long-term assembly line solutions with reduced energy consumption.

In 2024, Cheng et al. examined MMA line scheduling with lot streaming and batch transfer. An innovative mathematical formulation decreases the completion time, manufacturing cost, setup cost, transportation cost, and inventory costs. The proposed multi-objective co-evolutionary simulated annealing approach outperforms traditional algorithms and so enhances the performance of manufacturing systems. In 2021, Zhang et al. discusses a dynamic takt time (dTT) approach toward assembly line balance and sequencing, which incorporates real-time worker and product statuses into the decision-making process. To optimize both characteristics, an improved artificial bee colony algorithm has been designed. Case studies show that dTT improves line efficiency by minimizing idle time, better than any other optimization techniques. In 2023, Dalle Mura & Dini introduces a genetic algorithm solution to MMA line balance that includes job rotation along with collaborating robots to ensure improvements in ergonomics. The tool optimizes both cost and worker ergonomics, reducing noise exposure as well as energy consumption. An industrial case study finds that it enhances workers' well-being and productivity. In 2024, Tiacci suggested an asynchronous Assembly Line Control Matching as well as sequencing difficulties are addressed in asynchronous MMA lines. The optimization of task assignment, buffer allocation, and model sequencing reduces blocking and hunger. A strategy combining both techniques is developed using a genetic algorithm, leading to greater line efficiency through focused optimization. In 2023, Peng et al. addresses the challenges of assembly line balancing and sequencing under different precedence relations. It

presents a comparison of MILP and CP models, while an iterative decomposition method is proposed. The results showed that CP outperformed MILP, while decomposition was superior in terms of solution quality and economy in time.

Table 3: Summary of Studies on Assembly Line Optimization: Techniques, Performance, and Research Insights

Author Name	Proposed Technique	Performance Score	Research Aim	Research Gap	Limitations	Motivation	Dataset Used
Rio-Torto et al. 2022	Hybrid quality inspection system (automated detection + human feedback)	F1 score: 0.565 (unconstrained), 0.601 (fixed camera setup)	Improve worker performance by reducing fatigue and improving adaptability	Lack of real-time, manual data annotation in factory settings	Limited to specific factory floor setups	Improve accuracy and efficiency in automotive quality control	Simulated data, Real factory floor data
Munoz et al. 2019	Mixed reality-based user interface for quality control inspection	No explicit performance score	Improve ergonomics, reduce stress, improve productivity	Existing interfaces lead to worker stress and fatigue	Usability test limited to Mercedes-Benz factory	Enhance ergonomics and reduce stress for workers	Mercedes-Benz factory data
Zhang et al. 2024	Multi-objective co-evolutionary algorithm for assembly line balancing	Superiority to seven multi-objective evolutionary algorithms	Minimize energy and cost requirements in multi-manned assembly lines	Lack of solutions considering energy and cost trade-offs in balancing	Algorithm effectiveness limited by real-world constraints	Improve energy efficiency and cost reduction	269 instances of assembly line data
Zhang et al. 2019	Hybrid genetic algorithm (HGA) for type-II MMA line balancing	Benchmark instances tested; effectiveness proven	Optimize production efficiency under uncertain task times	Difficulty in managing uncertainty in task durations	Uncertainty in tasktimes might still affect performance	Improve production efficiency in uncertain conditions	Benchmark instances, simulated data

Paprocka & Krenczyk, 2023	GWO for sequencing in MMA lines	GWO outperforms other algorithms (Simulated Annealing, Greedy heuristics)	Optimize sequencing for MMA lines with environmental considerations	Limited research on multi-objective optimization considering environmental factors	Limited to sequencing problems in MMA lines	Improve sequencing to reduce environmental impact and energy consumption	Real mixed-vehicle assembly line data
Cheng et al. 2024	Multi-objective coevolutionarysimulated annealing algorithm for assembly job shop scheduling	Outperforms seven competitive multi-objective algorithms	Optimize job shop scheduling with lot streaming and batch transfer	Lack of integrated scheduling techniques in mixed-model assembly	Algorithms may not generalize well in diverse settings	Improve competitiveness and reduce production costs	Benchmark data, simulated data
Zhang et al. 2021	Dynamic takt time (dTT) method using an improved artificial bee colony (iABC) algorithm	Evaluated with performance indexes (e.g., inverted generational distance, spacing metric)	Optimize balancing and sequencing by adapting to real-time production conditions	Fixed takt time ignores real-time assembly line status	Limited to pacing and sequencing problems	Optimize resource use by considering dynamic assembly line status	Case study data from different scales
Dalle Mura & Dini, 2023	Genetic algorithm for MMA line balancing with job rotation and collaborative robots	Industrial case study discussed	Improve ergonomics and energy expenditure in assembly lines	Lack of ergonomics consideration in assembly line balancing	Algorithm performance may be context-dependent	Enhance worker well-being and productivity	Industrial case study data
Tiacci, 2024	Genetic algorithm with discrete event simulation for balancing, buffer allocation, and sequencing	Evaluated on benchmark instances	Solve MALBP, BAP, and SP simultaneously to increase line efficiency	Buffer allocation and sequencing techniques not well integrated	Limitations in scalability and generalization	Improve overall line efficiency by optimizing workload distribution	Benchmark instances, simulated data

Peng et al. 2023	MILP and CP models for flexible MMA lines with alternative precedence relations	Better performance of CP over MILP, iterative decomposition method superior	Address balancing and sequencing problems with alternative precedence relations	Limited understanding of alternative precedence relations in assembly lines	CP performance is limited by problem complexity	Improve flexibility and efficiency in assembly lines	Computational experiments, simulated data

TECHNIQUES FOR ENSURING QUALITY IN MMALINE PRODUCTION:

In 2024, Varyani et al. uses a new approach, where the sequence-dependent setup times are classified as workpiece-independent or workpiece-dependent. A mathematical model minimizes the launch intervals of the workpieces, reducing the downtime and energy consumption. The NP-hard problem is solved by a genetic algorithm that outperforms the classic branch-and-bound approaches. Computational investigations prove that the GA enhances the quality of solutions, reduces energy consumption, and makes it cost-effective. In 2023, Hashemi-Petroodi et al. develops a dynamic task assignment problem using an MDP within a mixed-integer linear program model. The reduction rules improve the tractability of both the stochastic and robust models. This is a challenging problem of reducing costs by all, or the worst, manufacturing takts. Computational experiments have demonstrated dynamic assignments perform better than static models. In 2023, Ebrahimi et al. modelled the dynamic mixed model-assembly line with walking workers through the application of the scenario from the Fiat Powertrain. Using a hyper-heuristic along with a simulation-optimization approach allows for time saving during actual manufacturing moments in dynamic environments. Managerial implications highlighted that indeed the simulation would handle reality constraints in terms of solution generation, proving the application of the presented dynamic sequencing method. In 2023, Huchzermeier & Mönch suggested the adoption of product customization and innovation, MMA lines are being taken up. A variable rate launching (VRL) method removes idle intervals and utility work, and hence 100% production is achieved under optimal conditions. A mixed-integer model computes the cost of closed/open workstations for given fixed and variable takt times. Heuristic solutions address various station lengths and process times. Industrial applications have demonstrated that VRL methods significantly reduce labor costs, queue length, and throughput time. In 2024, Mezghani et al. establishes a resilient Mixed-Integer Linear Programming (MILP) model, thereby minimizing upfront design and reconfiguration costs. It accounts for the worst-case production needs so that future reconfiguration will be easier. Adversarial technique works effectively to solve the huge instance. Benchmark trials validate that the model could decrease design and reconfiguration cost when compared to traditional approaches.

In 2023, Edouard et al. discusses ICARRE, a method of discovering assembly interfaces in available products through Assembly Process Planning (APP). A rule-based algorithm parses APPs and checks against restriction lists and visual inspections. It has been successfully tested within the helicopter industry and applied as an integrator of previously discarded parts, although it still finds itself plagued by the lack of knowledge concerning some of the interfaces and disparate operations that arise. The technique provides practical insights for new product development by emphasizing its applicability in a variety of contexts. In 2024, Fani et al. discusses the sequencing of jobs in a dynamic environment, applying evolutionary algorithms and simulation. A framework was

optimized for sequences under stochastic conditions and has been tested by case studies of real-world situations. The results illustrate managerial benefits and ease of upgradability by iteratively following data-driven strategies. This novel solution effectively combines simulation with evolutionary optimization. In 2024, Anh & Van Hop formulates task times as fuzzy stochastic variables (FRVs) to solve the model assembly line balancing challenges (MALBP) under uncertainty. GA-MIP beats other approaches in terms of targets and computation time according to a comparative investigation. This method effectively manages uncertainty in manufacturing contexts. In 2024, Elyasi et al. suggested the process duration variability causes MMAL instability; this work uses an MDP/MILP approach to model a dynamic change in workforce during processes. The scalability problem has been solved by the decomposition of Benders. Managerial insights with cost-reduction, resilience, and MMAL robustness ideas have been gained from validation on real Stellantis data.

Table 4: Summary of Techniques, Datasets, Performance, and Limitations MMA Line Optimization Research

Author(s)	Proposed Technique	Dataset Used	Performance	Research Aim	Limitations
Varyani et al. 2024	Genetic Algorithm (GA) for MMAL optimization	Computational experiments	GA outperforms traditional methods in solution quality and speed	Optimize MMA lines to reduce energy consumption	Does not address all possible production scenarios
Hashemi-Petroodi et al. 2023	Markov Decision Process (MDP) and Linear Program (LP)	Benchmark and generated instances	Effective in dynamic task assignments for reconfigurable assembly lines	Study task assignment and worker movement in reconfigurable MMALs	Limited by stochastic parameters and complexity
Ebrahimi et al. 2023	Hyper-heuristic and simulation-optimization	Fiat Powertrain Technologies case	Simulation approach is effective in real-world dynamic environments	Solve sequencing problem with walking workers in MMALs	Simulation complexity in real-world scenarios
Huchzermeier & Mönch, 2023	Mixed-Integer Linear Programming (MILP) model	Numerical industrial benchmark	Variable rate launching reduces labor costs and idle time	Analyze variable rate launching for MMA lines	Assumes ideal production conditions for VRL
Mezghani et al. 2024	Robust Optimization approach for line design	Computational experiments	Robust model reduces design and reconfiguration costs	Account for product evolution during assembly line life	Focus on worst-case scenarios may limit broader applicability

Edouard et al. 2023	Rule-based algorithm for assembly interface identification	Helicopter industry case study	Effective in identifying interfaces for component reuse	Identify assembly interfaces for reused components in product design	May miss interfaces due to absence in assembly operations
Fani et al. 2024	Evolutionary algorithm and simulation-based optimization	Leather goods company case study	Framework supports dynamic, real-time decision making	Optimize production sequence in MMA lines	May not be fully adaptable to all production environments
Anh & Van Hop, 2024	Red Fox Optimization (RFO) and metaheuristic algorithms	No specific dataset mentioned	GA-MIP combination performs best in solution quality and time	Minimize workstations in MMA lines under uncertainty	Focus on task time uncertainty may limit broader applications
Elyasi et al. 2024	Markov Decision Process (MDP) for workforce assignment	Stellantis data	MDP improves line resilience against process time uncertainty	Manage workforce and task assignments in automotive MMALs	Requires Benders decomposition for large instances

APPLICATIONS OF DL IN QA: A FOCUS ON MMA LINES :

In 2024, Shao et al. suggested the MILP model is applied to handle Distributed Heterogeneous Hybrid Flow Shop Scheduling Problem (DHHFSP-MMAL) during the manufacturing and assembly stages. It proposes a parallel deep adaptive large neighborhood search that applies constructive heuristics for initial solutions and destroy-repair operators for optimisation. The experiments demonstrate the efficiency and effectiveness of PDALNS. In 2024, Akpinar developed an ant colony optimization hyper heuristic approaches the question of heuristic search spaces which seeks to find optimal balance across the MMA lines concerning the setup arrangements with specific dependences in their sequences by benchmark datasets against performance measures for testing their validity. In 2024, Sun adopted the application of selectivity banks that combine physical and virtual resequencing into automobile production lines. The nine techniques of resequencing are developed in pursuit of a minimum number of sequencing violations.

The results indicate marked improvements with virtual resequencing, specifically the IR9 technique. In 2024, Zhou & Zhao proposed Automatic Monorail Shuttle System (AMSS) enhances the efficiency of material input in automobile MMA lines. The shuttle and crossover scheduling problem is addressed by a shuffling frog leaping-based hyper-heuristic algorithm, which is shown to be better than other approaches regarding cost minimisation and convergence time. Utilizing a shuffling frog leaping-based hyperheuristic algorithm to schedule shuttles and crossovers outperforms previous methods both in cost minimization and convergence speed. In 2024, Alhomaidi & Askin developed a new approach to balancing MMA lines takes into consideration parallel line systems, tooling, and demand fulfillment. It develops optimization algorithms and has been assessed on a set of various test datasets which have shown an excellent performance level and practicality.

In 2024, Huang et al. suggested a study which takes a mixed-integer programming strategy to explore how Robotic Mixed-Model Two-Sided Assembly Lines (RMTAL) balancing can be achieved with set-up times and several constraints. Benchmarks are outperformed based on cycle duration and energy usage by an optimising entropy-based two-mode simulated annealing technique. In 2024, Liu et al. proposed a quality Prediction in Machine Tool Spindle Assembly. A stacking ensemble model that uses inspection data and feature selection is able to predict variance in the quality of spindle assembly. The ensemble approach improves the quality control process by giving practitioners accurate predictions and significant insights. In 2024, Li & Wang suggested Human-Robot Collaboration in Assembly Lines. HRC assembly lines will use a mixed-integer programming methodology to balance the productivity of the assembly lines with carbon emissions. It combines particle swarm with improvement rules improving performance, outperforming simulated annealing and hill-climbing heuristics. In 2024, Fathi et al. developed Robot Based Example of Assembly Line Balancing. A comprehensive review classifies research on robot-assisted assembly line balancing. Meta-heuristic methods dominate solutions, and the emphasis is on cycle time minimization. Industry 4.0 has sparked recent studies on collaborative robot-based assembly lines. In 2024, Katsigiannis et al. developed Hybrid simulation models to analyze the transition from mass manufacturing toward the Lean Manufacturing assembly lines model of JIT and Heijunka will decrease the lead time by 47.37%, increase throughput 5.99%, minimize the work-in-process level of 56.73% on adopting Lean Manufacturing (LM).

Table 5: Summary of DL Applications in MMA Line Optimization

Author Name	Proposed Model	Dataset Used	Performance Attained	Research Aim	Limitations	Application of Deep Learning
Shao et al. 2024	Distributed Heterogeneous Hybrid Flow Shop Scheduling Problem (DHHFSP-MMAL), PDALNS Algorithm	Synthetic dataset (manufacturing & assembly stages)	Efficient and effective scheduling algorithm; constructive heuristic enhances efficiency	Optimize scheduling in MMA lines combining manufacturing and assembly stages	High computational cost due to the complexity of heuristics and deep destroy-repair operators	Potential for incorporating deep learning for predictive maintenance and scheduling optimization
Akpinar, 2024	Ant Colony Optimization Based Hyper-Heuristic	Benchmark instances from literature	Effective balancing of sequence-dependent setups in MMA lines	Solve hierarchical assembly line balancingproblemsinvolving setupdependent task sequencing	Requires additional computational resources for large datasets	Limited; could use deep reinforcement learning for hyper-heuristic improvemnt

Sun, 2024	Integrated Resequencing with Selectivity Banks	Car assembly data	Virtual resequencing outperforms physical resequencing; IR9 algorithm performs best	Minimize sequencing rule violations in car assembly processes	Limited application to specific use cases such as car assembly	Deep learning models for predicting violations and optimizing sequence selection
Zhou & Zhao, 2024	Automatic Monorail Shuttle System (AMSS), SBHH Algorithm	Synthetic problem instances	Superior solution quality and convergence speed compared to benchmark algorithms	Enhance material feeding efficiency in MMALs while minimizing costs	Validation limited to simulations, lacks real-world application data	Deep learning could improve shuttle scheduling and anomaly detection
Alhomaidi & Askin, 2024	Comprehensive Assembly Line Balancing Models	Literature datasets (various structures)	Efficient line balancing with extended realistic characteristics	Develop comprehensive models for parallel lines, task-dependent tooling, and demand fulfillment	High complexity in adapting models to dynamic and uncertain production environments	Neural networks could enhance adaptive balancing under dynamic production conditions
Huang et al. 2024	Robotic Mixed-Model Two-Sided Assembly Line, Pareto Simulated Annealing	Benchmark instances	Outperforms state-of-the-art algorithms in over 93% of cases for hypervolume and IGD metrics	Optimize cycle time and energy consumption in robotic two-sided assembly lines	Scalability issues with increasing problem size	Use of deep reinforcement learning for robotic task optimization
Liu et al. 2024	Stacking Ensemble Model for Spindle Assembly Quality Variation	Spindle inspection dataset (925 samples)	Improved quality prediction accuracy and identification of key features	Predict spindle assembly quality variations using ensemble learning	Limited generalizability to other spindle assembly or related manufacturing processes	Deep learning models like CNNs can refine feature extraction for quality variation prediction

Li & Wang, 2024	Human-Robot Collaboration Assembly Line Model, PSO Algorithm	Benchmark datasets (10 datasets)	Improved cycle time and reduced carbon emissions compared to SA and LAHC heuristics	Address HRC assembly line balancing with carbon emission as a secondary objective	Focused on predefined datasets; real-time application of the proposed model is not explored	Deep learning could improve real-time robothuman interaction modeling and performance prediction
Fathi et al. 2024	Systematic Literature Review of Collaborative Assembly Lines	Literature review data	Identified gaps, trends, and meta-heuristic algorithms as dominant solutions	Review assembly line balancing studies in robotic and human-robot collaborative contexts	Descriptive analysis lacks numerical validation	Opportunities for deep learning to identify trends, automate insights extraction, and simulate future scenarios
Katsigiannis et al. 2024	Hybrid Simulation for Lean Manufacturing Transition	LEGO car assembly line simulation data	Significant reductions in lead time (47.37%) and WIP (56.73%), increased throughput (5.99%)	Evaluate lean manufacturing transition using hybrid simulation techniques	Application scope limited to educational or experimental assembly lines; scalability to real-world production is unclear	Reinforcement learning models could optimize lean manufacturing strategies in real-time scenarios

AUTOMATED QA IN MMA LINES: VISION-BASED DL SOLUTIONS :

In 2024, Timmerman presented a heuristic for the delinquent of inefficiencies in MMA lines due to long trucks exceeding workstation lengths by grouping long trucks with shorter ones to reduce idle time and stoppages. In 2024, Feng et al. suggested a novel resource-constrained assembly line balancing model, TRCLBP is proposed to reduce workstations and assembly cost using an enhanced genetic algorithm for improvement of convergence and performance. Cost reductions of 18% in case studies are recorded. In 2024, Claeys et al. developed a approach that is the design methodology for the automatic evaluation of assembly instruction quality using behavioral coding schemes and classifier algorithm, with an accuracy range of 64% which possibly identifies the quality issues along the assembly instruction monitoring. In 2024, Kulaç & Kiraz developed a study in Ergonomics in Assembly Line Balancing. An ergonomics-integrated assembly line balancing is suggested as a three-stage approach by making use of fuzzy logic and mathematical modeling in reducing the cycle time, increasing line efficiency, and minimizing the risk associated with ergonomic conditions and significant case studies showing considerable improvement. In 2024, Yilmazlar et al. suggested a bi-objective two-stage stochastic model is developed to address sequencing problems in automobile

assembly due to product failures. Hybrid optimization is used to decrease work overload by 20% and enhance reinsertion efficiency.

In 2024, Zacharia et al. addresses the challenges faced by collaborative robots in an assembly line setting with regards to workload allocation between humans and robots as well as production rates and workload smoothing, simulated experiments of robot integration show the benefits. In 2024, Jung et al. suggested an optimization simulator based on real-time production data and genetic algorithms is designed to increase productivity in garment production. A case study is given that shows a 34.8% increase in productivity in an Indonesian garment factory. In 2024, Zhang et al. presented a hybrid modeling approach to DT creation for production activities proposes the integration of human and robot DTs to improve system efficiency and provide insights for training workers, using a study on a washing machine assembly line as an example. In 2024, Mutale et al. proposed a hybrid PASP-TCQ model is presented to optimize the assembly process in wind turbine gearboxes, using a PSBFO algorithm to minimize assembly time, cost, and quality, achieving a 17% time saving and 10% cost saving. In 2024, Ramli et al. developed a Substituted Tiki-Taka Algorithm for Improvement over Existing Algorithms in Terms of efficiency and Energy Savings in Assembly Line Balancing with Respect to Energy Consumption: Case Study of an Industrial Unit. In 2024, Hou & Zhang developed study presents assembly line balancing and multi-AGV scheduling in flexible manufacturing systems and a multi-objective whale optimization algorithm and neural network-based scheduling method for increasing the efficiency and resilience of the production process.

Table 6: Summary of Assembly Line Balancing and Optimization Techniques in Manufacturing Research

Author(s)	Dataset Used	Proposed Technique	Performance Score Attained	Research Aim	Problem Statement	Quality Assurance	Limitations
Timmerman, 2024	Not provided	Heuristic approach for balancing truck lengths	Not provided	Mitigate inefficiencies in assembly line due to varying truck lengths	Idle time at affected workstations, line stoppages	Not provided	Not provided
Feng et al. 2024	Arithmetic case studies, enterprise engineering examples	Improved genetic algorithm (I-GA) with a three-layer chromosome initialization	18% reduction in total assembly cost	Solve resource-constrained assembly line balancing	Low productivity and high resource costs in two-sided assembly lines	Validated through case studies	Not provided

Claeys et al. 2024	Assembly experiments with intentionally flawed instructions	Behavioral Observation Theory-based automatic evaluation of assembly instructions	64% accuracy in identifying low-quality instructions	Improve the quality of assembly instructions	High labor intensity, complexity in creating instructions for high-variety, low-volume production	Accuracy could be improved	Limited accuracy in identifying all types of quality issues
Kulaç & Kiraz, 2024	Case study in wire harness factory	Fuzzy logic model integrated with ergonomic risk assessment	10-11% improvement in line efficiency, 12-25% improvement in ergonomic risk balancing	Address ergonomic factors in assembly line balancing	Lack of attention to ergonomic risks, inefficiency in balancing risk and productivity	Validated in a case study	Not provided
Yilmazlar et al. 2024	Not provided	Bi-objective two-stage stochastic program with local search algorithm and hybrid approach	20% reduction in work overload, reduced waiting time for failed vehicles	Integrate reinsertion process for failed vehicles in mixed-model sequencing	Work overload due to vehicle failure and reinsertion	Numerical experiments and dynamic reinsertion simulations	Waiting times may still be high in some cases
Zacharia et al. 2024	Not provided	Metaheuristic approach for collaborative robot assembly	Not provided	Improve assembly line balancing using collaborative robots	Variance and uncertainty in processing times for manual work	Heuristic approach for NP-hard problems	Limited application to real-world scenarios
Jung et al. 2024	Data from garment production line	Genetic algorithm-based optimization simulator	34.8% improvement in productivity	Optimize productivity in garment manufacturing	Difficulty in integrating real-time information for optimization	Real-world application in garment production	Limited to labor-intensive industries

Zhang et al. 2024	Real-world washing machine assembly line data	Hybrid model combining mechanism and time-series forecasting models	Not provided	Model human operators for enhanced system efficiency	Lack of attention to human operators in existing models	Hybrid modeling approach	Not applicable to all types of production systems
Mutale et al. 2024	Simulations on wind turbine gearbox data	PSBFO algorithm for time-cost-quality PASP optimization	17% reduction in assembly time, 10% cost reduction, quality index improvement to 0.93	Enhance efficiency, reduce costs, and improve quality in assembly	Complexity in optimizing assembly processes	Validated via simulations and statistical tests	Limited to wind turbine gearboxes
Ramli et al. 2024	Not provided	Substituted Tiki-Taka Algorithm for assembly line balancing with energy consumption	Improved line efficiency, reduced energy consumption	Optimize assembly line balancing with energy consumption	Lack of focus on energy efficiency in traditional methods	Validated in industrial case study	Not provided
Hou & Zhang, 2024	Simulation analysis of assembly workshop data	Multi-objective whale optimization algorithm, scheduling rules selection method with neural network and knowledge base	Improved manufacturing efficiency and workshop resilience	Solve multi-objective assembly line balancing and AGV scheduling	Complexity, uncertainty, and multi-constraints in flexible manufacturing	Verified through simulation analysis	Limited to assembly workshop settings

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RESULT ANALYSIS:

Under this section, the commonly used datasets as well as the performance scores attained by the existing models were discussed. A total of 80 existing studies were selected for this review between the years 2017-2024 respectively.

Chronological Review:

During the early phases of integrating vision-based deep learning for quality assurance in MMA lines, exploratory research was performed toward automating the defect detection processes. From 2017 to 2018, researchers focused on the traditional machine learning approaches, utilizing features derived from 2D images to detect surface defects and assembly issues. However, such systems were often required to involve extensive human feature engineering, which limited their scalability and accuracy in dynamic manufacturing scenarios. By 2019, CNNs have transformed this domain. Researchers began using CNNs for end-to-end defect identification with studies underlined by the ability to accommodate diverse product models and complex visual patterns. In 2020, further improvements were made by incorporating pre-trained deep learning models like ResNet and VGGNet, which enhanced the accuracy of defect classification while reducing the computational cost of training models from scratch.

Advanced DL architectures for MMA lines have seen huge deployments from 2021. At the beginning of 2022, the multi-task learning framework emerged such that hundreds of different error kinds may be detected and categorized concurrently over many models of the product leading to far greater throughput. A hybrid model by 2023 investigated researchers integrating vision-based DL into reinforcement learning about optimizing real-time decision-making. In 2024, a paradigm shift took place with the combination of transformer-based models with GANs to enhance the detection of faults in complex, multi-component products. In addition, academics have emphasized explainability and real-time applicability of these models, which answers industry concerns about trust and latency. Overall, the timeline emphasizes the transformative role that vision-based deep learning plays in increasing the efficiency, accuracy, and scalability of quality assurance in MMA lines.

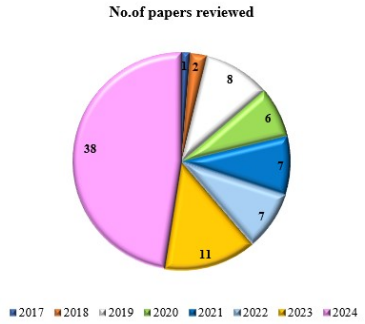

Figure 6: Total number of papers reviewed based on year

A review of papers over the period indicates a gradual growth of research contributions with more remarkable increases in recent years. Starting from 2017, only 1 paper was reviewed, with an increment to 2 in 2018. A major leap occurred in 2019 with 8 papers showing an increased interest in the topic. This trend continued, with 6 papers analyzed in 2020 and 7 in both 2021 and 2022, indicating steady research interest. The number increased sharply in 2023 to 11 papers analyzed, and in 2024, a surprising 38 papers, suggesting a huge rise in scholarly and research interest on the subject. This trend reveals the increasing importance and sense of urgency in academic and professional circles. Subsequently, figure 6 shows the pie chart for a total number of papers reviewed based on the corresponding year.

PERFORMANCE ANALYSIS:

Several authors reported significant improvements in performance metrics. Rio-Torto et al. (2022) achieved F1 scores of 0.565 and 0.601 under different scenarios, showing the power of their hybrid inspection methodology. Paprocka and Krenczyk (2023) reported that GWO was superior to simulated annealing and greedy heuristics in MMA line sequence optimization. Cheng et al. (2024) &Tiacci (2024) presented results that their algorithms were better than seven other competing multi-objective strategies. Zhang et al. (2019, 2024) proved the efficiency of their hybrid genetic and co-evolutionary algorithms for balancing and sequencing. Peng et al. (2023) demonstrated that CP models are better than MILP. Munoz et al. (2019) and Dalle Mura and Dini (2023) focused on qualitative benefits, such as better ergonomics and worker productivity, underlining the various features of different methods.

The studied approaches had performance gains to a significant degree. Varyani et al. (2024) report that their GA outperformed state-of-the-art methods both in terms of quality of solutions and execution time. Hashemi-Petroodi et al. (2023) exploited an MDP and LP strategy to effectively cope with dynamic task assignments; on the other hand, Ebrahimi et al. (2023) verified the feasibility of their proposed hyper-heuristic and simulation-optimization framework in real applications. Huchzermeier and Mönch (2023) presented the results of reduction of labor cost and idle time with the use of Mixed-Integer Linear Programming. Mezghani et al. (2024) reported cost minimization via the robust optimization approach they propose, and Fani et al. (2024) showed evolutionary algorithm-based dynamic decisions. Anh and Van Hop (2024) managed to win at fewer workstations, whereas Elyasi et al. (2024) showcased increased resilience of lines with their use of MDP-based assignments. Edouard et al. (2023) demonstrated the successful reuse of components with rule-based algorithms, highlighting the practice for the framework.

The outcomes of these studies varied based on the strategy applied. Shao et al. (2024) showed that their scheduling approach is efficient and effective, but the high computational cost of heuristics caused problems. Akpinar (2024) successfully balanced sequence-dependent settings, but the computational requirement increased with larger datasets. Sun (2024) showed that virtual resequencing is better than physical resequencing, but this is only applicable to car assembly cases. Zhou & Zhao (2024) outperform benchmark algorithms using solution quality and convergence time, although the lack of real data limits their deployment. Alhomaidi and Askin (2024) showed efficient line-balancing approaches, but their complexity while responding to variable production situations limited its effectiveness. Huang et al. (2024) showed better performance regarding cycle time and energy consumptions by outperforming previous algorithms, but its scalability issue remains as an open point. Liu et al. (2024) improved quality prediction accuracy for spindle assembly, but their model was restricted in generalizability. Li and Wang (2024) reduced cycle time and reduced carbon emissions in the assembly lines, but they did not study real-time applications. Fathi et al. (2024) presented trends and gaps in collaborative assembly line research, but their results were not supported by numbers. Katsigiannis et al. (2024) achieved some notable lead-time and work-in-progress reductions; however, their validity towards real-world scenarios is in doubt.

The findings of these studies are very interesting. Feng et al. (2024) demonstrated that their GA approach improved total assembly costs to 18%. Claeys et al. used an automatic evaluation method based on fuzzy logic models; it reached 64% of low-quality instructions. Kulaç and Kiraz worked on increasing the line efficiency with a fuzzy logic approach to the 10-11 percentage range, as well as balancing ergonomic risks to reach the 12-25 percentages range. Yilmazlar et al. (2024) applied a bi-objective stochastic program using a hybrid technique to lessen the work overload and the wait times for failed vehicles by 20%. Jung et al. (2024) showed an increase of production by 34.8% through the use of a genetic algorithm-based optimization simulator. Using their PSBFO algorithm, Mutale et al. (2024) improved the quality index to 0.93, reduced assembly time by 17%, and cost reduction by 10%. Ramli et al. (2024) employed the replaced Tiki-Taka Algorithm to boost line efficiency and reduce energy consumption. Hou and Zhang (2024) utilized a multi-objective whale optimization

algorithm along with neural network scheduling rules to improve the manufacturing efficiency and resilience of workshops, though the strategy was applicable only for the assembly workshops.

DATABASE ANALYSIS :

The studied research demonstrated their proposed methodologies on a variety of datasets. Rio-Torto et al. (2022) demonstrated a hybrid quality inspection system with automatic detection and human input using both simulated and real factory floor data. Munoz et al. (2019) used data from the Mercedes-Benz factory to enhance the ergonomics of quality control inspections with a mixed reality-based user interface. Zhang et al. (2019) and Zhang et al. (2024) utilised benchmark instances and simulated data to improve the production efficiency of an assembly line while cutting energy expenses. Paprocka and Krenczyk (2023) employed real mixed-vehicle assembly line data for assessing the suitability of GWO for sequencing. Cheng et al. (2024) and Tiacci (2024) tested their multi-objective optimization algorithms on benchmark and simulated datasets, discussing problems of job shop scheduling and assembly line balancing. Finally, Dalle Mura and Dini (2023) analyzed industrial case study data about job rotation and collaborative robots, whereas Peng et al. (2023) tested their models using computational experiments and simulation data.

The studies employed several datasets to validate their suggested strategies for optimizing MMA lines. Varyani et al. (2024) used computational experiments to demonstrate the effectiveness of their Genetic Algorithm. Hashemi-Petroodi et al. (2023) utilized Markov Decision Process (MDP) and Linear Programming (LP) for benchmarking and instance generation, whereas Ebrahimi et al. (2023) worked on real-world data from Fiat Powertrain Technologies. To analyze variable rate launching, Huchzermeier and Mönch used a numerical industrial benchmark (2023). Mezghani et al. in 2024 and Anh & Van Hop in 2024 conducted computational experiments, the latter combining RFO with metaheuristics. Fani et al. (2024) used a dataset from a leather goods company, whereas Edouard et al. (2023) applied a helicopter industry case study. Elyasi et al. (2024) have used Stellantis's data to examine workforce allocation with uncertain process times.

Shao et al. (2024) utilized the synthetic datasets that merged both manufacturing and assembly stages for resolving the MMA line scheduling issues. Akpinar (2024) applied the standard illustrations among the literatures to optimize the task sequencing in hierarchical assembly lines with sequence-dependent setups. Sun (2024) applied automobile assembly data for the study of resequencing approaches and their efficiencies in reducing sequencing rule breaches during the assembly process. Zhou and Zhao (2024) utilized artificial problem cases for enhancing the material feed effectiveness in MMA lines. Alhomaidi and Askin (2024) applied numerous structure sets from the literature to generate entire models of assembly line balancing, that solved different types of manufacturing problems. Huang et al. (2024) employed benchmark cases for optimizing the robotic two-sided assembly lines. Liu et al. (2024) proposed a quality change prediction method for spindle inspection using 925 samples of a spindle inspection dataset. Li and Wang (2024) investigated ten benchmark datasets for a human-robot collaboration (HRC) manufacturing line, emphasizing cycle time and carbon emissions. Fathi et al. (2024) performed an in-depth literature review on collaborative assembly lines. Katsigiannis et al. (2024) used data from LEGO's vehicle assembly line to simulate the transitions in lean manufacturing.

Feng et al. (2024) utilized I-GA, using a three-layer chromosome initialization to analyze mathematical case studies and examples in enterprise engineering. Claeys et al. (2024) performed assembly tests incorporating deliberately incorrect instructions in efforts to enhance the quality of assembly instructions using automated reviews based on Behavioural Observation Theory. Kulaç and Kiraz (2024) applied a fuzzy logic model with ergonomic risk assessment to a wire harness plant for line efficiency and ergonomic risk balancing. Yilmazlar et al. (2024) used a bi-objective two-stage stochastic program and a hybrid approach for the integration of failed vehicle reinsertion processes into mixed-model sequencing and carried out numerical tests as well as dynamic reinsertion

simulations. Zacharia et al. (2024) designed a metaheuristic approach for collaborative robot assembly to improve assembly line balancing using collaborative robots. Jung et al. (2024) maximized productivity using data from a garment production line and an optimisation simulator based on a genetic algorithm. Zhang et al. (2024) employed a hybrid model that integrates mechanism and time-series forecasting models to describe human operators in a real-world washing machine assembly line, thereby improving the efficiency of the system. Mutale et al. (2024) optimized assembly time, cost, and quality using the PSBFO method on simulations based on wind turbine gearbox data. Ramli et al. (2024) applied the Tiki-Taka Algorithm to balance output of an assembly line with energy consumption in an industrial case study. Hou and Zhang (2024) analyzed data of an assembly workshop by using a multi-objective whale optimization approach along with scheduling algorithms and neural networks.

RESEARCH GAP:

Despite significant progress in vision-based deep learning for quality assurance, state-of-the-art models have failed to adapt to the dynamic and diverse character of MMA lines. These variations in illumination conditions, product orientations, and the diversity of components provide obstacles thatmost deep learning algorithms can't generalize to. Current systems rely heavily on pre-defined information and fail to account for real-time environmental unpredictability, limiting their applicability in industrial environments. Another gap in the research is that there is a lack of effective multi-model frameworks that can handle simultaneous defect detection across many product lines. Another critical requirement is the incorporation of real-time feedback mechanisms. Although several studies have reported very high accuracy in fault detection under laboratory conditions, few have explored models that could offer immediate remedial feedback during production. In the absence of such systems, faults cannot be averted in advance and lead to inefficiencies and extended periods of downtime. In addition, most of the current methods favor accuracy over latency, making them unsuitable for high-speed assembly lines that require quick decision-making. Vision-based quality assurance system scalability for deep learning remains an unexplored avenue. Most proposed models would require enormous computational resources for processing and fail to scale across other manufacturing configurations. Another severe issue relates to the model's explainability; in most DL algorithms, the models themselves are just black boxes, rendering only a little understanding of its decision-making procedure. Therefore, questions regarding trust and responsibility would arise in these industrial areas. To address these problems and make such a system available for widespread deployment on real-world assembly lines, research in interpretable DL frameworks and lightweight, scalable systems is needed.

CONCLUSION :

Vision-based DL has become a solution for quality assurance in MMA lines, enabling the detection of faults at a higher accuracy and efficiency compared to the earlier methods used. It is capable of handling complex visual data with high adaptability to a wide range of product models. Still, there remain problems like low adaptability to dynamic contexts, poor availability of real-time feedback systems, scalability, and explainability. Closure of those gaps requires the development of strong, interpretable, and lightweight models that can handle real-time execution on high-speed assembly lines. There should be a focus for future research on integrating modern architectures like transformers, multi-task learning frameworks, as well as hybrid techniques towards better performance and adaptability. Moreover, the bridge between academia and industry is what may speed up their implementation. By solving these problems, vision-based deep learning has the potential to become a vital tool for modern industrial quality assurance that is efficient, reliable, and scalable. Apart from these, this systematic literature review has been reviewed based on 80 existing works of literature from the year 2017-2024 respectively.

FUTURE SCOPE:

The future of quality assurance in vision-based deep learning for MMA lines is to realize adaptive real-time systems that effortlessly handle dynamic production situations. Advanced architectures, including transformers and lightweight models, should become integral research priorities to boost scalability and efficiency. Industrial applications will require explainable AI frameworks to build trust and transparency. Further, bringing together deep learning with future concepts like edge computing and Industry 4.0 will introduce decentralized real-time defect recognition. All these advancements are capable enough to change the manufacturing world regarding quality assurance as better dependability, efficiency, and scalability will be addressed in it.

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