Enhancing Robotic Path Planning in Industrialized Construction: A Novel Benchmarking Approach

Amirpooya Shirazi[1] and Aladdin Alwisy[2]

[1,2] M.E. Rinker, Sr. School of Construction Management, University of Florida, United States
a.shirazi@ufl.edu, aalwisy@ufl.edu

Abstract –

Over the past decade, Industrialized Construction (IC) has experienced increasing attention, with numerous studies examining the integration of various technologies to boost productivity and efficiency through manufacturing-oriented strategies. Among these, robotic arms have emerged as a dominant solution. However, further research is required, as the interactions between robotic arms and the surrounding environment often remain suboptimal or even hazardous. This challenge is primarily attributed to the absence of a practical benchmarking tool for selecting appropriate path-planning pipelines under different scenarios. Moreover, existing benchmarking frameworks often disregard the complexity inherent in IC robotic stations, producing path-planning rankings that are not feasible for the required assembly strategies. To address these gaps, this study proposes a novel framework for generating a benchmarking tool that accounts for both the specific robotic arm task and user-defined criteria, enabling a ranking system for evaluating multiple path-planning pipelines. The proposed framework was validated in a simulated robotic station designed for manufacturing structural wooden assemblies. Findings highlight the framework's robustness by demonstrating how a criteria-driven evaluation metric can effectively compare diverse path-planning pipelines during a wooden stud pick-and-place task featuring complex geometric dimensions.

Keywords –

Industrialized Construction; Prefabrication; Robotics; Automation; Modular Construction

1 Introduction

Industrialized construction (IC) and prefabrication have gained significant traction over the past few decades primarily involving the off-site assembly of structural components, which are subsequently transported and installed at the construction site [1]. However, several persistent challenges continue to hinder the widespread adoption of IC, including issues related to design and quality, as well as limitations in technology adoption and the readiness of current practices [2]. In response, numerous studies have attempted to integrate advanced technologies into this sector. Among these advancements, the introduction of robotics into the IC is particularly promising, as it can substantially reduce both construction costs and time, in addition to enhancing labor productivity by alleviating or even eliminating labor-intensive tasks [3].

In this context, laying the groundwork for the incorporation of robotics into industrialized construction, thereby advancing it toward industrialized methods, has been acknowledged as a feasible outcome. Several robotic stations have been developed and assessed to facilitate the sector's transition toward industrialization and manufacturing [4]. Additionally, research has explored the use of robotic arms as components within mass production (or manufacturing line) stations [5]. Despite the recognized enhancements in productivity achieved through the integration of robotic arms within these sectors, substantial barriers continue to impede the broader implementation of robotic stations in IC practice.

These impediments are rooted in the unique attributes of raw construction materials (e.g., wooden studs), which display characteristics—particularly dimensional asymmetries in their geometries—that diverge significantly from the standardized components commonly utilized in robotic manufacturing lines [6]. Such discrepancies frequently often lead to unpredictable, and potentially hazardous, robotic movements within the manufacturing environment when performing collision-free path planning while carrying construction elements.

In response to these challenges, various studies have introduced new and innovative path-planning algorithms [7] or have developed robotic stations adapted from commercial solutions [5], [8]. Such planning pipelines, commonly referred to as inverse kinematic path planning pipelines, are designed to compute and generate collision-free trajectories for a robotic arm, transitioning from its initial configuration to a specified goal state while avoiding contact with environmental obstacles.

However, these newly proposed algorithms generally lack robust evaluation metrics, often relying solely on binary success-failure criteria, which stand in contrast to the algorithms widely tested using the existing simulation packages and software like MoveIt [9] and Isaac Sim [10]. These simulation platforms are designed to visualize the collision-free trajectories of robotic arms using diverse path-planning algorithms, thereby ensuring that the real robotic arm can replicate these validated movements efficiently once deployed. Moreover, the commercial path planning solutions—such as the ABB path planner integrated into RobotStudio®—have not demonstrated sufficient practicality when handling construction components. This shortcoming arises because these proprietary solutions typically do not support online predictive planning or widely tested adaptation.

To overcome these limitations, this research aims to establish a standardized validation framework capable of evaluating a variety of robotic arm path planning algorithms within IC strategies. By selecting validation metrics that align with key performance criteria (e.g., safety, efficiency, and real-time responsiveness), this framework can systematically prioritize each metric in relation to specific testing scenarios (e.g., performing pick-and-place operations on construction components) by comparing nominated path planning algorithms. As a result, these ranked metrics serve as a reliable benchmarking tool, enabling informed selection of appropriate path planning algorithms for each IC task—an essential step in effectively integrating robotic technologies into the IC sector.

2 Literature Review

Previous investigations into path planning algorithms for robotic applications have typically utilized a range of benchmark scenarios, varying in complexity and evaluation metrics. In some of the earliest works, for instance, Zhao et al. [11] presented a straightforward scenario in which a robot moves from a start to a goal configuration without incorporating either environmental complexity or object manipulation tasks. Subsequent other studies introduced simple geometric obstacles (e.g., spheres and cubes) to evaluate path planning performance [12], [13], while others extended this approach by incorporating more complex obstacles, such as shelves [14], or by progressively increasing scene complexity from cuboidal obstacles to shelves [15]. Despite these advancements, two significant limitations are apparent in the existing literature. First, although dimensional asymmetry and shape complexity are critical factors when considering objects to be manipulated, most studies have not fully integrated picking and placing tasks into their test scenarios. As a result, the reported evaluation metrics—often limited to basic measures—may not reliably represent conditions encountered in robotic IC environments. Second, although some research has examined more intricate obstacle arrangements, these scenarios still fail to approximate the full complexity of manufacturing lines associated with IC strategies [5]. Accurately reflecting the intricacies of such environments is essential for ensuring that path planning algorithms are not only collision-free but also contextually suitable for real-world assembly tasks.

Several studies have begun to acknowledge these issues by introducing pick-and-place tasks into their experimental setups, although the objects remained relatively simple and symmetrical [6], [16]. To bridge this gap, [7] proposed a series of case studies involving pick-and-place operations with progressively more complex scenes, approaching the richness found in IC environments. Nonetheless, their evaluation remained restricted to fundamental metrics such as planning time and success rate, leaving room for more comprehensive assessments. Another noteworthy contribution is found in Metvaei et al.'s work [5], which presented a robotic station capable of automatically performing component pick-and-place tasks for manufacturing structural wall panels. However, this framework relied on RobotStudio® and an offline conversion of paths into RAPID code, limiting adaptability and responsiveness. In IC workflows, the ability to dynamically adjust paths is crucial due to component tolerances and variations that arise on the production floor. Offline programming and proprietary software constrain real-time adaptability, potentially leading to misalignments and decreased product quality. These findings underscore the necessity of employing open-source path planning algorithms that offer greater flexibility and integrative evaluation. By doing so, researchers can more thoroughly assess a range of metrics—beyond mere planning time and collision avoidance—ensuring that the proposed solutions are well-suited to the demanding conditions of robotic IC tasks.

3 Objectives

This study aims to address the existing limitations in evaluating path planning algorithms within robotic IC tasks by developing a standardized evaluation framework. By integrating this framework, researchers can systematically assess the robustness and effectiveness of various path planning algorithms across construction tasks with differing complexity levels. To achieve this, the proposed framework will be applied to a simulated robotic station equipped with an ABB IRB6620 robotic arm featuring a custom multifunctional end effector. A representative pick-and-place operation involving wooden studs is employed as a case study to illustrate the framework's utility, enabling the comparative analysis of path planning algorithms by informing the refinement of validation criteria.

4 Methodology

4.1 Overview

The proposed framework is structured into three consecutive phases, each designed to collectively yield a robust benchmarking tool for assessing path planning algorithms in IC tasks. As illustrated in Figure 1.A, the first step focuses on deriving a comprehensive set of evaluation metrics. These metrics are obtained by synthesizing those previously employed across various studies, each of which has assessed one or multiple path planning algorithms. The selection of metrics is guided by predetermined qualitative criteria, prioritizing those that best align with the requirements and constraints of the designated robotic testing environment. The second step (Figure 1.B) entails the systematic identification and selection of experimental procedures to serve as evaluation case studies. This involves deconstructing the overall strategy for producing construction assemblies into a series of discrete tasks that highlight critical points of interaction between robotic systems and construction components. Among these identified tasks, those that expose the limitations of previously studied scenarios are chosen to evaluate the candidate path planning algorithms. Finally, in the third step (Figure 1.C), each selected path planning algorithm is assessed through direct observation of its generated motions. By comparing these observed trajectories against the established qualitative criteria from the first step, it becomes possible to assign appropriate weights to the extracted metrics. These weighted metrics thus enable a nuanced evaluation of path planning algorithms, ensuring that their performance can be rigorously compared and optimized for diverse qualitative requirements across a range of IC tasks.

4.2 Evaluation Metrics Selection

Although no standardized benchmarking tool currently exists for evaluating the efficiency of various path planning algorithms, numerous studies have employed diverse metrics to compare newly proposed algorithms with existing methods or to benchmark different planning pipelines against each other. To establish a more consistent framework, this section not only introduces a metric selection pipeline to be used as the evaluation metrics in testing scenarios, but also compiles a reference of metrics commonly found in the literature (Table 1). By providing researchers with a streamlined approach for selecting appropriate evaluation measures, this work facilitates more meaningful comparisons of path planning pipelines within various case studies involving the implementation of robotics in the IC sector.

The fundamental evaluation metric employed in many path planning studies is the binary assessment of whether a given pipeline succeeds or fails in solving a case study scenario. For instance, You et al. [17] introduced a GPT-based robotic task solver that uses ChatGPT4.0 to interpret provided 2D and 3D data—such as the initial state of a Hanoi Tower Puzzle—and

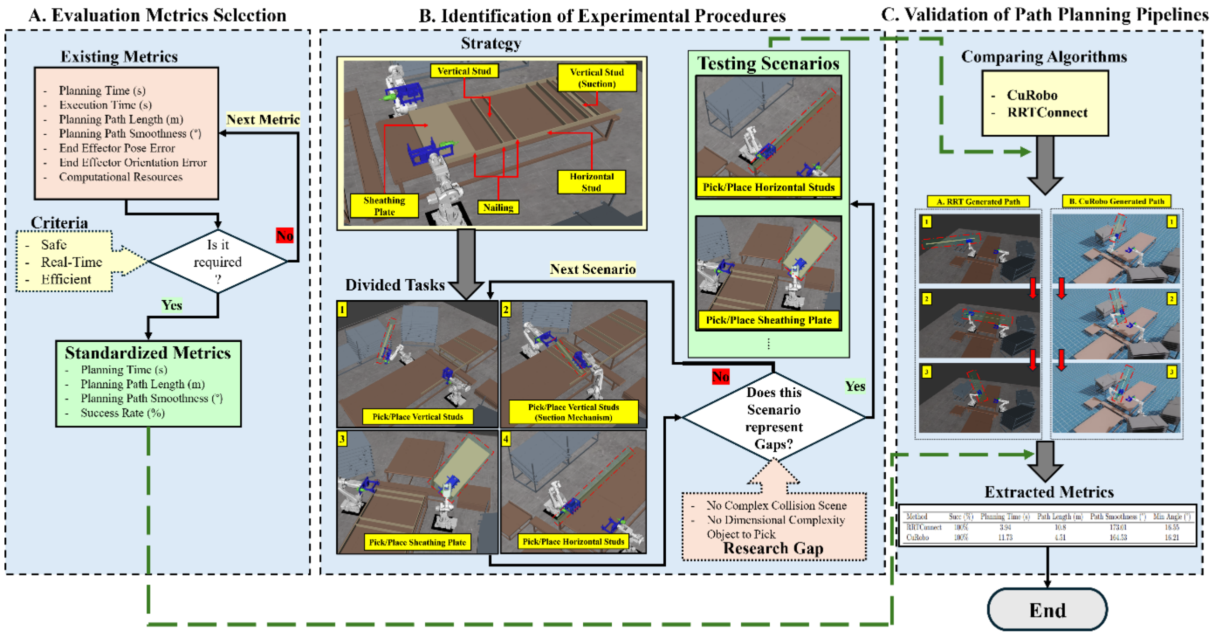

Figure 1. Methodology Overview.

generate a sequence of movements. These movements are then integrated into a ROS-based path planning framework to execute the robot's tasks. Although their work offers an initial exploration of employing Large Language Models (LLMs) for identifying task sequences in IC robotic assembly, it does not validate the path planning algorithm itself. Beyond the fundamental success/failure metric, other measures—including the accuracy of pick-and-place operations—would be valuable for such construction-oriented applications. In a more comprehensive comparative study, Ying et al. [6] developed a deep learning–based path planner optimizer and evaluated its impact on several path-planning pipelines using two principal metrics of planning time and the travel distance of the robotic tool. Similarly, Yi et al. [13] examined these metrics—planning time and path length—when proposing an enhanced P_RRT* [18] path planner. They utilized the average number of sampling nodes as a metric, reflecting computational resource demands [12]. However, within robotic IC tasks, where computational resources are less constrained, this measure is less relevant. Other studies have also considered cost function optimality, particularly in reinforcement learning–based planners [16], [19]. While cost optimality is crucial for path-planning algorithmic evaluations, it does not substantially impact IC tasks, where metrics affecting path characteristics are more informative.

In addition to these established metrics, Liu and Zuo [14] introduced path smoothness as another critical evaluation criterion. This concept involves assessing the continuity of directional changes along the generated trajectory. While they did not formally quantify smoothness for direct algorithmic comparison, their visualization underscored its importance, indicating that smoother directional changes can enhance both safety and efficiency. Building upon this notion, Zhou et al. [16] proposed a quantifiable smoothness metric derived from three consecutive path points and the angle formed between them; values approaching zero indicate trajectories closer to a straight line, thus denoting a smoother path. Furthermore, they introduced "path clearance" as an additional metric, defined as the average distance between each path point and the nearest obstacle or invalid state. Larger clearance values correlate with safer and more reliable paths.

Moreover, some studies have considered additional metrics, such as evaluating the end effector position and orientation error relative to the desired coordinates [11] or measuring the energy consumption of the robotic arm under different planning algorithms [20]. While these metrics offer insights into precision and efficiency in certain contexts, they are less directly applicable to the nuanced demands of IC tasks.

In conclusion, while certain metrics employed in previous studies may have been limited to specific robotic tasks within IC strategies, the key metrics for effectively selecting an appropriate path planning pipeline include success rate, planning time, path length (which can also reflect execution time), path smoothness, path clearance, and end effector coordination error (applicable only to real-world contexts). Accordingly, when utilizing the proposed framework to identify a suitable path planning pipeline for robotic IC applications, it is essential to select relevant metrics from the compiled reference set (Table 1)—encompassing those drawn from prior evaluation studies—based on the predetermined criteria established for comparing planning pipelines.

Table 1. Existing Metrics.

Metric	Parameter	Source
Success Rate	(%)	[6], [13], [16], [17], [19]
Planning Time	(s)	[6], [13]
Path Length	(m)	[6], [13]
Path Smoothness	(°)	[14], [16]
Path Clearance	(m)	[16]
End Effector Error	(mm)/(°)	[11]

4.3 Identification of Experimental Procedures

The overarching objective of this framework is to develop a benchmarking tool that prioritizes relevant metrics for assessing diverse path planning pipelines within different IC tasks. To achieve this, it is necessary to identify and incorporate those scenarios where the limitations of existing metrics become evident, thereby revealing gaps in current benchmarking approaches. This entails deconstructing and categorizing assembly strategies into more elementary operational tasks performed by the robotic arm. By focusing on tasks that address these identified research gaps, the testing scenarios can be enriched to more accurately reflect real-world demands. As a result, the framework can generate a metric prioritization scheme that evaluates the performance of path planning pipelines within the corresponding tasks.

4.4 Validation of Path Planning Pipelines

In the final step, the standardized metrics selected should be used to evaluate the chosen path planning pipelines. These pipelines, identified for validation, must showcase the defining characteristics of either optimal or nonoptimal solutions according to the criteria outlined by the standardized metrics. To facilitate this assessment, the trajectories generated by each selected algorithm should be visualized within a simulated environment, allowing a comparison of the outcomes against the established criteria and the subsequent designation of each pipeline as either optimal or nonoptimal.

Moving forward, the standardized metrics identified in the literature should be calculated for each nominated path planning pipeline after generating the corresponding robotic arm trajectory in the chosen experimental scenario. By comparing the resulting metrics and ordering them according to the specified satisfaction criteria, a comprehensive benchmarking system can be established. This system will enable researchers to systematically compare any path planning pipeline within the defined testing context.

4.5 Case Study

Among the various approaches to robotic IC, the production of wooden structural assemblies has gained traction due to the relative ease of manufacturing and assembly compared to systems relying on steel or concrete components. In this study, the selected manufacturing strategy focuses on the fabrication of wooden structural panels, encompassing tasks such as the precise picking and placement of wooden studs with varying dimensions and functions, the positioning of wooden sheathing plates, and the nailing of these components. The simulated robotic workstation employs a multifunctional end effector—incorporating a gripper, suction system, and nail gun—in conjunction with conveyor belts that enhance the reachability of materials. This integrated setup enables the efficient production of wooden structural assemblies that may differ in length, include openings, and exhibit other variable design features. Figure 2.A illustrates the overall configuration of the robotic workstation, which comprises two ABB IRB6620 robots, two conveyor belts, and multiple material tables, thereby allowing the robots to access wooden studs of various lengths and thicknesses as required.

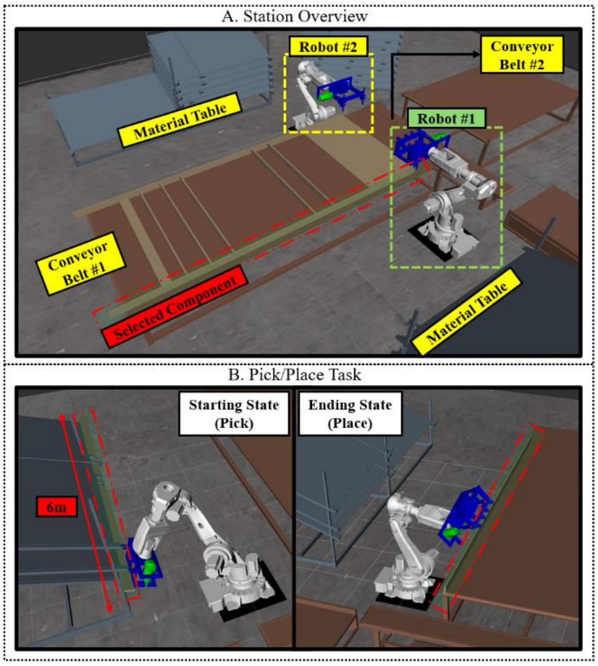

Figure 2. A) Robotic station overview. B) Selected pick/place task

4.5.1 Metrics Selection

In this study, the primary objective is to ensure the safe and reliable handling of components by simultaneously achieving the desired final configuration and minimizing potential hazards associated with both motion trajectories and tool–component interactions. To achieve this end, the most critical metrics for evaluating the effectiveness of path planning are considered success/failure, planning time, path length, and path smoothness. These metrics reflect the practical priorities of safety and efficiency more accurately than alternatives such as end effector positioning error, energy consumption, or computational optimality, which are more relevant in other domains or under different operational constraints. Furthermore, while path clearance is a common metric in standard pick-and-place tasks, it becomes less informative in scenarios involving dimensionally asymmetric construction components—such as wooden studs or sheathing plates—since the tool center point often fails to align symmetrically with the component's volume.

4.5.2 Identification of Experimental Procedures

The manufacturing of a wooden structural panel can be divided into three primary tasks, each informing the selection of path planning algorithms. The first task involves picking and placing wooden studs—both vertical and horizontal—using a robotic gripper. These studs vary in length, resulting in pronounced dimensional asymmetries that must be accommodated by the path planning strategy. The second task entails the handling of both wooden studs and sheathing plates through suction mechanisms. Although these components also exhibit dimensional asymmetries, their centers of volume are comparatively closer due to the more uniform distribution of their length and width, thereby posing a simplified set of path planning challenges compared to picking and placing wooden studs utilizing gripper. The third task centers on nailing the wooden components and involves two robots working in parallel: while one robot stabilizes the studs, the other applies the nails. Notably, this task does not include pick-and-place operations and thus does not address the dimensional asymmetry issues present in the first two tasks.

To specifically address the limitations identified in previous studies the chosen testing scenario focuses on placing the top plate stud. The top plate represents the component with the greatest length, thereby maximizing the offset between its center of volume and the robot's tool center point. By incorporating the top plate placement task into the experimental setup, this scenario directly confronts the challenges associated with handling asymmetrical components (Figure 2.B). Furthermore, the simulated environment depicted in Figure 2.A introduces more complex spatial constraints, thereby rectifying the shortcomings of earlier studies that relied on overly simplistic obstacle configurations.

4.5.3 Validation of Path Planning Pipelines

While initially deploying open-source path planning algorithms from the MoveIt framework (OMPL library [21]), we confirmed their ability to generate collision-free trajectories. However, despite demonstrating acceptable validation metrics in previous studies, these algorithms did not consistently produce movement plans that could be characterized as safe and efficient (Evaluation Metrics Criteria). As shown in Figure 3.A, the RRTConnect-based [22] solution yielded abrupt rotational motions of the wooden stud, potentially increasing the risk of collisions in a dynamically changing environment. In contrast, the CuRobo [23] path planning algorithm—recently introduced and benchmarked favorably against other approaches—produced more stable, contextually appropriate trajectories (Figure 3.B). Based on this comparative assessment, we selected CuRobo to represent an effectively functioning path planning algorithm and RRTConnect as a pipeline for suboptimal performance within our robotic IC station. Although these two algorithms operate on different computational platforms (RRTConnect using the CPU and CuRobo leveraging GPU capabilities), planning time remains an essential performance metric. The implications of these differences in computational resources and their influence on algorithmic efficiency and suitability will be analyzed further in the Results and Discussion section.

5 Results and Discussion

In this study, 4 performance metrics were extracted to determine an appropriate path for robotic arms engaged in a pick-and-place scenario involving a 6-meter wooden stud. These metrics—Success Rate (%), Planning Time (s), Path Length (m), Path Smoothness (°), and the Minimum Angle (°) as derived from the average path smoothness—were assessed for two distinct path planning algorithms: RRTConnect (integrated with MoveIt and Rviz), serving as a motion generator misaligned with the desired criteria, and CuRobo (utilizing Isaac Sim), serving as a motion generator aligned with the desired criteria. As indicated by multiple studies evaluating path planner pipelines [15], RRTConnect is widely regarded as one of the most efficient planners in complex environments. Because offsite modular construction work zones often exhibit such complexity—particularly due to the presence of materials, components, and human workers—we selected RRTConnect as the representative graph-based planner and then compared it to a state-of-the-art planner announced by NVIDIA in 2024 to demonstrate our proposed benchmarking framework. Notably, the STOMP [24] planner was also tested but failed to compute a solution within the 60-second timeout period and was therefore excluded from our results.

Therefore, Each scenario was repeated ten times for both planners, and the results—summarized in Table 2—show that while both algorithms achieved a 100% success rate, CuRobo required, on average, more than 7.5 seconds longer to plan than RRTConnect.. Nonetheless, this additional time does not substantially impact the suitability of the generated paths for real-world pick-and-place operations, particularly given the possibility of reducing planning time by employing more powerful computational resources (e.g., GPU-based training seeds). Meanwhile, CuRobo generated significantly shorter paths, with a length of approximately 4.51 meters, less than half that achieved by RRTConnect, thus meeting the initial criteria favoring reduced path length. However, path length alone is insufficient for full

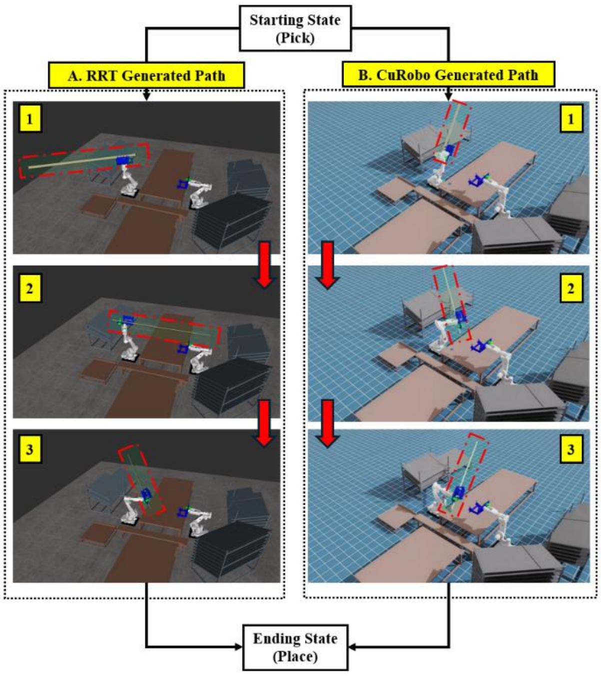

Figure 3. Representing the generated path utilizing RRT (A) and CuRobo (B) algorithms.

evaluation, and consideration must also be given to path smoothness to avoid unsafe abrupt directional changes. Although both algorithms demonstrated negligible differences in path smoothness (less than 10° variation) and produced minimum angles of around 16°, the CuRobo algorithm ultimately proved more effective in this scenario. Accordingly, the metrics can be ranked in descending order of importance—beginning with Success Rate, followed by Path Length, then Path Smoothness, and subsequently Minimum Angle—while Planning Time emerges as comparatively less critical for the tested scenario.

Table 2. Experiment Results

Methods	Success Rate (%)	Planning Time (s)	Path Length (m)	Path Smoothness (°)	Min Angle (°)
RRTConnect [22]	100	3.94	10.8	173.01	16.55
CuRobo [23]	100	11.73	4.51	164.54	16.21

6 Conclusion

In conclusion, this study successfully identified, defined, and applied a set of weighted validation metrics to compare distinct path planning algorithms under conditions of dimensional asymmetry, which, although demonstrated here with a single robotic workstation, could be extended to various workstations and manufacturing strategies within the IC sector. Future efforts could involve categorizing these manufacturing strategies to form a comprehensive dataset of tasks for robotic stations, ultimately enabling the creation of a standardized, rule-based methodology for robotic operations in industrialized construction sector.

7 References

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