



TWO-STAGE TASK SCHEDULING METHODS FOR HRC CONSTRUCTION TASKS

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Abstract

Scheduling is critical in human-robot collaboration (HRC) in construction, including work-rest scheduling and task sequencing. However, previous research often examines the two scheduling components as distinct optimization problems, neglecting their interdependence. This oversight can lead to ineffective collaboration, resulting in human fatigue and underutilized robotic capabilities. This study presents two-stage methods utilizing a modified genetic algorithm (GA) to optimize HRC scheduling. By addressing the complexities inherent in HRC environments, proposed methods aim to balance safety and productivity in construction tasks. The study also discusses the effects of the order in which scheduling components are optimized on HRC performance.

Introduction

The construction industry is inherently labor-intensive and has historically lagged in the adoption of digital and automated technologies. This has resulted in significant challenges, including a high incidence of musculoskeletal disorders among workers and a decline in overall productivity (Zhang et al., 2023). Additionally, the situation of straining labor resources is exacerbated by an aging workforce and a diminishing interest in construction careers among younger demographics (Melenbrink et al., 2020). While construction robots have the potential to enhance productivity and improve safety conditions, their adoption has been limited due to the complex and unpredictable environments that define construction sites (Wu et al., 2022). Consequently, HRC presents a viable solution, integrating the advantageous attributes of robots, including strength, precision, and consistency, with human capabilities such as intuition, critical judgment, and adaptability (Wang et al., 2019).

Scheduling is a vital issue in HRC, which refers to the systematic allocation of tasks and resources to both human workers and robotic systems within a work environment (Lewandowski & Olszewska, 2022). This process involves defining the timing, duration, and sequence of activities performed by each participant. Effective HRC scheduling can optimize resource utilization, ensuring that human and robotic capabilities

are employed efficiently to achieve maximum productivity while minimizing idle time and enhancing workflow continuity (Mammadzada, 2023). A well-structured schedule can also account for the physical and cognitive limitations of human workers, reducing the risk of fatigue and occupational hazards. Overall, scheduling in HRC is a strategic component that significantly influences productivity and safety, laying the foundation for successful interactions between human and robot agents and enhancing the effectiveness of the collaborative system (Pupa and Secchi, 2021).

There are two primary components in the scheduling problem: work-rest scheduling and task sequencing. Work-rest scheduling is essential for managing the workload and rest periods of human workers, effectively mitigating fatigue caused by the physically demanding nature of construction tasks. By optimizing work-rest schedules, organizations can enhance worker productivity and safety, ensuring that human agents remain efficient throughout their shifts. Existing literature (Tao et al., 2024; Yi and Wang, 2017; Yi and Wang, 2016) has predominantly employed linear programming techniques to determine optimal work-rest schedules with coarser time granularity specifically in environments that involve only human labor. Task sequencing, which determines the order of task execution, is critical for reducing downtime and maximizing workplace output. Current research predominantly emphasizes task sequencing for long-term scheduling of construction projects (Abuwarda et al., 2024) or for simple tasks that require several sequential steps (Ye et al., 2024).

In summary of research gap, the current state of scheduling research in the construction industry remains largely confined to manual construction tasks, with limited attention devoted to the HRC scenarios (Wu et al., 2022). In addition, work-rest scheduling and task sequencing have been examined in isolation, despite their inherent interdependence, particularly in the context of HRC. The sequence of tasks significantly affects the timing and duration of required rest periods. For example, when workers undertake physically intensive activities, they generally necessitate longer recovery times to alleviate fatigue and maintain productivity (Xu and Hall, 2021). On the contrary, the scheduling of rest periods can

influence task sequencing, necessitating the rearrangement of tasks to ensure that critical activities are completed prior to human agents taking breaks. This strategic rearrangement is vital for preserving workflow continuity and optimizing the utilization of robot systems. In conclusion, task scheduling in HRC involves the intricate interplay among task sequencing, work-rest scheduling, and the dynamic interactions between human and robot agents (Steidel, 2019). Failure to coordinate these elements may disrupt the workflow, leading to increased downtime for robots, reduced productivity, and worker fatigue.

The scheduling problem is recognized as NP-hard, especially within the realm of large-scale construction projects. Heuristic methods, such as GA, have shown considerable effectiveness in navigating the solution space and achieving either near optimal or optimal solutions (Zhu et al., 2021). This study utilizes a multi-objective GA optimization framework with two stages aimed at maximizing workplace output and robot utilization, while concurrently minimizing human fatigue. To model the coordination interactions in HRC, we employ discrete event simulation at each time point, which offers a detailed representation of task execution and the dynamics of resource allocation, including materials and agents. Furthermore, this study introduces and compares two-stage methods that prioritize the resolution of work-rest scheduling and task sequencing, respectively. In the first approach, we refine the broad category of work into specific tasks, enabling a more precise sequencing of these tasks. In the second approach, we strategically integrate rest periods into the established task sequence at appropriate intervals. Ultimately, this research aims to enhance the effectiveness of scheduling in HRC environments, contributing to improved productivity and worker well-being.

The article is organized as follows. Section 2 reviews previous studies related to scheduling problems. Section 3 introduces the two-stage methods utilizing modified GA. Section 4 includes a case study to illustrate the application of two-stage methods. Section 5 discusses the results of the analysis while Section 6 summarizes the study, discusses the limitations and future developments of this research.

Related Work

Work-rest scheduling

Ensuring the physical and mental well-being of human workers is paramount, as it directly impacts their safety, job satisfaction, and the overall productivity of construction projects. Excessive workloads can lead to fatigue, diminished cognitive functioning, and heightened accident risks. Thus, optimizing work-rest schedules becomes a valuable strategy to allow workers to recuperate effectively, promoting occupational health and enhancing job satisfaction (Hsie et al., 2009).

Research on work-rest schedules in construction can broadly be divided into two primary categories based on the methodologies employed and the objectives pursued.

The first focuses on simulation-based approaches that analyze various work-rest schedules' effects on productivity and performance. Studies (Seo et al., 2016; Zhang and Lin, 2023a) have demonstrated the positive impacts of rest breaks on fatigue reduction, although they often lack comprehensive optimization of work-rest schedules, typically examining a limited number of fixed work-rest schedules.

The second category emphasizes the development and optimization of work-rest schedules through mathematical methodologies. Hsie et al. (2009) utilized a GA to minimize job completion time and energy expenditure, while some studies (Yi and Wang, 2017; Yi and Wang, 2016; Tao et al., 2024) applied mixed-integer linear programming (MILP) to maximize productive time. Despite their contributions, these studies often employ broader time granularity (e.g., 5 minutes or 10 minutes), potentially overlooking the advantages of shorter, more flexible rest intervals crucial for dynamic construction environments. Implementing finer time granularity, such as one-minute intervals (Zhang et al., 2022), could enhance adaptability to evolving task demands. It may necessitate heuristic algorithms to manage the increased computational complexity that results from expanded search space.

Task sequencing

The sequence in which tasks are performed can profoundly influence the efficiency and synergy of interactions between human workers and robotic systems. By refining the order of tasks, one can enhance the flow of materials, optimize resource utilization, and ultimately boost the productivity of the entire operational framework. This intricate decision-making process necessitates a careful examination of multiple interrelated factors, often marked by inherent conflicts and trade-offs. These include time constraints, prioritization of tasks, and the technological dependencies that exist among various construction activities (Ujazdowski and Piotrowski, 2022).

Research in the construction sector has largely focused on optimizing entire projects or processes using building information modeling in a four-dimensional context. For example, Abuwarda et al. (2024) analyzed worker reassignment and task sequences based on physiological data over a 40-day project. However, there exists a relatively limited body of research that focuses on the granular optimization of specific tasks, which is particularly pertinent in the context of HRC, where intricate coordination is essential. For example, Ye et al. (2024) utilized GA to ascertain the optimal sequence of construction tasks for multi-robot systems engaged in steel structure fabrication. Such fine-grained optimization is crucial in HRC scenarios, where the efficient synchronization of tasks and resources can significantly impact overall project success.

In industrial applications, similar challenges have been explored more extensively, particularly in the context of the classic disassembly line balancing problem. Liao et al. (2023) applied linear programming to establish optimal

disassembly sequences for desktop computers in HRC environments. However, this approach faces limitations with complex constraints, making meta-heuristic algorithms a more suitable solution. Jiao et al. (2021) emphasized their effectiveness in addressing intricate optimization problems, while Li et al. (2019) compared various meta-heuristic techniques, including GA and the Bees Algorithm, demonstrating their adaptability in enhancing efficiency within HRC environments.

Methodology

Existing literature on task scheduling has predominantly focused on scenarios involving only human workers, with limited exploration of HRC dynamics. Additionally, prior studies have examined work-rest scheduling and task sequencing in isolation, neglecting their interdependence in HRC contexts. To address the gaps, this study will convert the real-time and dynamic interactions of HRC into discrete events at each time point and focus on exploring the impact of the scheduling problem on the HRC construction work. The integrated optimization model for the HRC scheduling problem presents several key characteristics: 1) The model encompasses strategies for allocating tasks between human workers and robots, along with detailed scheduling information for each agent; 2) Coordination requirements among humans and robots are crucial, focusing on the need for seamless collaboration to achieve task objectives, prevent potential bottlenecks, and ensure that each participant adheres to reach their full potential; 3) Resource requirements, including agent availability and material constraints, are considered, where resource allocation is intricately linked with both task assignment and scheduling processes. This comprehensive approach ensures that the interplay between human fatigue management and robotic efficiency is effectively addressed, leading to optimized resource management that accommodates the dynamic nature of HRC environments.

The dynamic characteristics inherent in HRC result in a non-linear relationship and necessitate a fine time granularity in scheduling. This requirement introduces a substantial number of decision variables, complicating the optimization landscape. Such complexity can present significant challenges for linear programming optimization algorithms, which may struggle to maintain the reliability and accuracy of task scheduling. In response to these characteristics, a modified GA is proposed, featuring a two-stage process. In the encoding phase, each chromosome integrates essential information regarding task features, time dimension and agent characteristics. During the selection phase, chromosomes are evaluated based on their fitness values, which are specifically calculated by considering the efficiency of the HRC scheduling, the material constraints required for task execution, and the dynamic nature of HRC construction. The crossover and mutation phase introduces variability by adjusting the order of tasks or reallocating rest periods, enhancing the robustness of the GA's search capabilities. We propose two distinct two-stage GA methods, one with fixed work-rest scheduling and one with fixed task

sequencing, as shown in Figure 1. By employing these two methods, we aim to effectively address the complexities inherent in HRC scheduling, optimizing both operational efficiency and worker well-being.

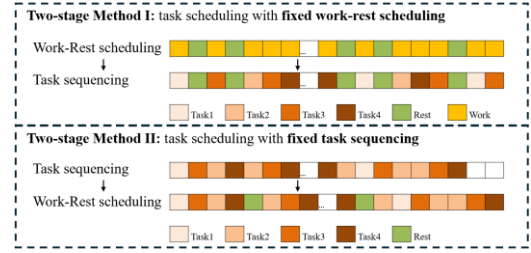


Figure 1: Framework of two-stage methods

Two-stage Method I: task scheduling with fixed work-rest scheduling

The encoding process is crucial, as it creates a framework that reflects the unique characteristics of human-robot collaboration. By incorporating the specific time units and differentiated work/rest schedules for both humans and robots, the GA can effectively model the interplay between these agents. Firstly, each chromosome is represented as a matrix consisting of three row vectors that encapsulate time units t_j ($j \in \{0, 1, \dots, n\}$), human work/rest periods H_φ ($\varphi \in \{0, 1\}$), and robot work/rest periods R_φ ($\varphi \in \{0, 1\}$). Each column in this matrix corresponds to a gene that defines the allocation strategy for tasks in specific time unit, indicating the assignment of work and rest periods on human or robot agent.

The chromosome initialization operator will randomly assign work and rest periods for both human and robot agents for each time unit. This random assignment ensures a diverse combination of scheduling, allowing the algorithm to explore various potential solutions. Following this initialization, a rigorous fitness calculation process is conducted to assess the quality of each chromosome. As the work-rest scheduling aims at relieving human fatigue, the evaluation focuses on two primary objectives: maximizing productivity time and minimizing the accumulated fatigue experienced by human workers, with the weight of 0.7 and 0.3 correspondingly. To achieve this, we will employ an improved fatigue-recovery model proposed by Zhang and Lin (2023a), shown in Equation (1) and (2). The model integrates the energy expenditure theory and proposes the productivity ratio in Equation (3) that corresponds to varying levels of fatigue. It recognizes that increased fatigue can have a detrimental effect on performance, leading to reduced efficiency and effectiveness in task execution. By incorporating these elements, our method allows for a nuanced analysis of dynamic nature in HRC environment. The next step involves selecting parental chromosomes to produce offspring. This selection process employs the roulette wheel method, a probabilistic technique that favors chromosomes with higher fitness values. During the fitness evaluation for all chromosomes

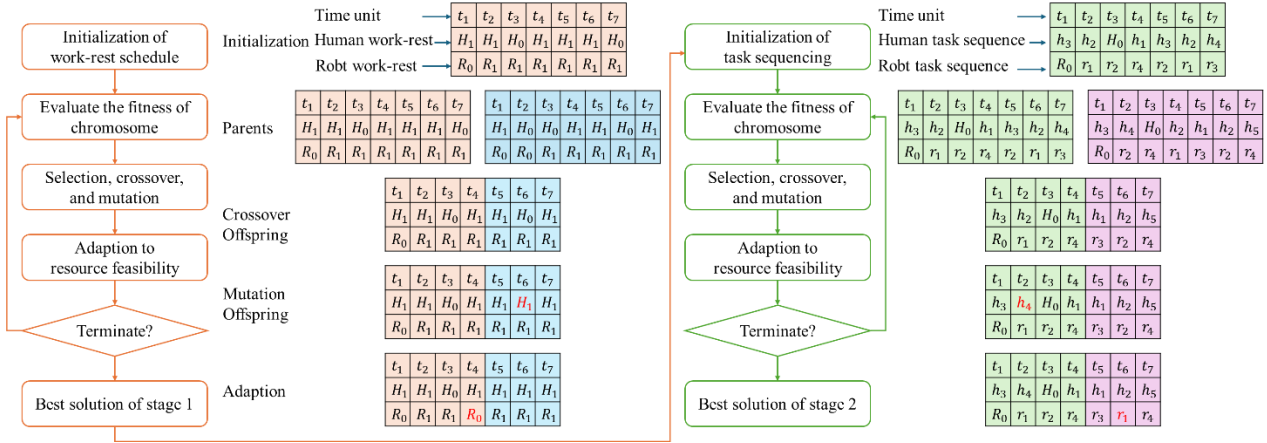


Figure 2: GA diagram of Two-stage Method I task scheduling with fixed work-rest scheduling

within a given generation, fitness values are normalized to ensure a balanced representation across the population. Normalization adjusts the raw fitness scores, allowing for a clearer comparison by transforming them into a common scale.

$$F(t) = R(\tau) + (1 - R(\tau))(1 - e^{-EER/200 \times t}) \quad (1)$$

$$R(\tau) = F(t) \times e^{-MEER/200 \times \tau} \quad (2)$$

$$P = \begin{cases} 100\%; & \text{if } 0.00 < F(t) \leq 0.50 \\ 90\%; & \text{if } 0.50 < F(t) \leq 0.56 \\ 80\%; & \text{if } 0.56 < F(t) \leq 0.62 \\ 65\%; & \text{if } 0.62 < F(t) \leq 0.70 \\ 50\%; & \text{else} \end{cases} \quad (3)$$

The crossover operator serves as a vital mechanism within the genetic algorithm, enabling the generation of offspring chromosomes through the exchange of genetic information between parent chromosomes at specific gene positions. During this procedure, two parent chromosomes combine their genetic material, resulting in two offspring chromosomes that inherit characteristics from both progenitors. This genetic exchange is designed to preserve advantageous traits while promoting diversity within the population. Generally, offspring chromosomes tend to exhibit enhanced fitness levels compared to their parents, as they are likely to inherit superior genes that contribute positively to the optimization objectives. In addition to crossover, mutation plays a crucial role in the functioning of the genetic algorithm. This process involves making alterations to one or more genes within a chromosome, thereby introducing new genetic variations into the population. Such modifications are essential for fostering genetic diversity, which helps prevent chromosomes from becoming stagnant and getting trapped in local optima. By facilitating the exploration of a broader solution space, mutation enhances the algorithm's ability to discover novel and potentially superior scheduling configurations. The resource feasibility will be subsequently verified to ensure operational efficiency and effectiveness. If resources are inadequate, robot agents may need to adjust their work states accordingly to accommodate the limitations of material supplement or requirements of the task. Through a series of generations characterized by these operators,

the genetic algorithm iteratively refines the population, ultimately converging on an optimal work-rest schedule.

In the second stage, within the framework of a fixed work-rest schedule, specific time periods designated for work are replaced with concrete tasks to facilitate better management and deployment. Human tasks are denoted as h_δ ($\delta \in \{1, 2, \dots, n\}$) while robot tasks are represented as r_δ ($\delta \in \{1, 2, \dots, n\}$). The fitness value of chromosomes will be calculated based on multiple objectives, including work output, robot utilization, and accumulated fatigue, with the weight of 0.6, 0.1 and 0.3 respectively. Focusing on work output ensures that the productivity of HRC system is maximized, leading to the successful and efficient completion of construction projects. Robot utilization is critical in optimizing the performance of robotic agents by utilizing robot capability of continuous working. Incorporating accumulated fatigue as a key objective addresses the well-being of human workers, recognizing that fatigue can adversely affect performance and increase the risk of accidents. By balancing these three objectives, the method can improve workplace performance while maintaining a sustainable work environment. Moreover, the crossover and mutation operators within the genetic algorithm are carefully designed to preserve the integrity of rest periods, ensuring that their positions remain fixed throughout these genetic operations.

Two-stage Method II: task scheduling with fixed task sequencing

The first stage of this approach is dedicated to optimizing the task sequence, whereby each chromosome is represented as a matrix comprising three distinct row vectors. These vectors encapsulate the time units t_j ($j \in \{0, 1, \dots, n\}$), human task sequence h_δ ($\delta \in \{1, 2, \dots, n\}$), and robot task sequence r_δ ($\delta \in \{1, 2, \dots, n\}$). The primary objective of this task sequencing is to enhance performance through an optimized arrangement of tasks, thereby maximizing efficiency and productivity within the work environment. Consequently, the objective of GA will focus on work output and robot utilization, with the

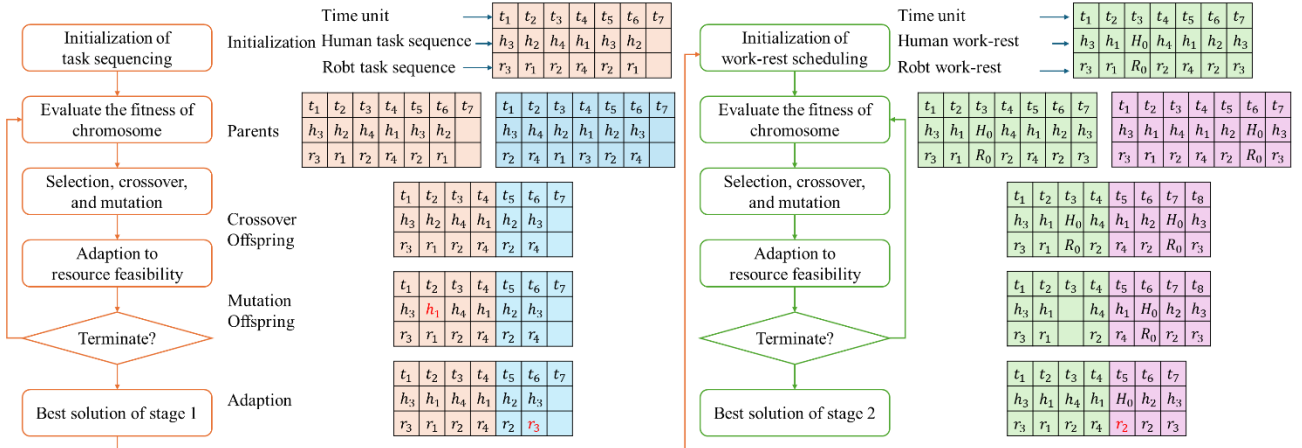


Figure 3: GA diagram of Two-stage Method II task scheduling with fixed task sequencing

weight of 0.7 and 0.3 correspondingly. This strategic emphasis on robotic capabilities is designed to leverage the inherent strengths of robotic systems, thereby facilitating the creation of a highly efficient task sequence. We can create a workflow that not only enhances the overall productivity of the project but also ensures that robotic capabilities are fully utilized.

Following the optimization of the task sequence, the second stage will involve generating the initial chromosomes, during which rest periods will be randomly inserted into the task sequence. Tao et al. (2024) established a precedent in which a total of 30 time slots were used, with 3 of those slots dedicated to rest periods. Following this model, we have opted to maintain a similar ratio of work to rest time slots in our two-stage method II, specifically implementing a 9:1 ratio. This decision implies that in the initial step of the sequence optimization process, 90% of the available time slots, or $0.9n$, will be allocated for work tasks. In the subsequent step, the remaining 10% of the time slots, or $0.1n$, will be reserved for the insertion of rest periods. In the crossover operator, particular care will be taken to preserve the optimal task sequence obtained in the first stage, ensuring that the integrity is not compromised. During the mutation operation, modifications will be implemented to guarantee that the total number of designated rest time slots consistently remain at $0.1n$ throughout the process. This strict adherence to the established quota for rest periods is essential for maintaining the integrity of the scheduling framework, thereby ensuring a balanced distribution between work tasks and necessary rest intervals. Additionally, the operational actions of robotic agents will be meticulously calibrated in accordance with various constraints, ensuring alignment with the overarching objectives of the project. In the second stage, the GA will employ the multi-objective of work output, robot utilization, and accumulated fatigue, with the weight of 0.6, 0.1 and 0.3 respectively, in determining when and how to integrate these rest periods. This careful consideration of rest breaks not only supports high output levels but also prioritizes the health and safety of workers. By striking this balance, we can enhance the overall outcomes in HRC environments, leading to a more sustainable work model.

Experiment

Considering the expansive nature of the construction industry and the longstanding tradition of bricklaying, this study applies two-stage methodologies to the HRC involved in the bricklaying process. This process exemplifies the critical interaction between human workers and robotic systems, particularly given the labor-intensive demands of bricklaying, which pose significant risks to workers and necessitate robotic assistance to enhance safety and operational efficiency. Recent advancements in bricklaying robotics, such as the SAM100 and Harian X, are increasingly integrated into construction projects (Wu et al., 2022). The operational procedures followed by bricklaying robots in both industrial applications and academic research typically adhere to similar methodologies for laying bricks. Consequently, this study utilizes SAM100 as a representative model to illustrate the brick laying process.

For the purposes of this analysis, we adopt a simplifying assumption of infinite raw material availability from the stockpile to isolate and evaluate the core algorithmic logic. However, human workers are still essential in replenishing the brick supplies and mortar supplies for the SAM100. Once the necessary materials are sufficiently stocked, the SAM100 robot can autonomously initiate the brick-laying process. The completion of each brick is marked by the removal of excess mortar by the human worker, making this task central to the work output. Given the premise that a worker can fully recuperate their energy levels during a designated lunch break (Tao et al., 2024), this analysis will concentrate on a half-day work schedule. The 1-minute interval granularity was adopted to address robots' unique dynamic coordination requirements in HRC. This temporal resolution enables precise modeling of adaptive task allocation and fatigue mitigation, with 240 half-day slots providing fidelity to capture interaction-critical microvariations.

Das (2014) conducted physiological assessments of brickfield workers, collecting heart rate data associated with three distinct tasks performed by human workers. A pivotal field study conducted by Ismaila et al. (2012) assessed the physiological responses of bricklayers at

various construction sites, revealing that their average working heart rate was recorded at 120.8 beats per minute. Saha et al. (1979) established a relationship between heart rate and energy expenditure, which provides a framework for understanding the physical demands placed on workers. Using Equations (4), we can derive the energy expenditure rate (EER) in kilocalories for the human tasks outlined in Table 1. Additionally, in the framework of two-stage method I, we employ a standardized EER based on Ismaila et al. (2012)’s study to optimize the work-rest schedule. Furthermore, Zhang and Lin (2023a) employed a metabolic energy recovery rate (MERR) of 3.50 kcal per minute to analyze fatigue recovery process. Operational requirements dictate that each brick laid requires 0.5 kg of mortar. The SAM100 robot can lay six bricks per minute, while the working speed of human laborers can be estimated based on video recordings.

$$EER(\text{kJ} \cdot \text{min}^{-1}) = \frac{\text{Heart Rate}(\text{beats} \cdot \text{min}^{-1}) - 66.0}{2.40} \quad (4)$$

Table 1: Relevant parameters for calculating the fatigue level and working output

Task Name	Brick Supplement	Mortar Supplement	Mortar Removing
Heart Rate	132.8	148.6	100.3
EER	6.65	8.22	3.41
Work Speed	12 bricks	15 kg mortar	30 bricks

Results and Discussion

The results derived from the application of two stage methods within the context of HRC in bricklaying tasks provide significant insights into the optimization of work output, robot utilization, and accumulated fatigue, as shown in Table. Each stage of the method operates under a generation limit of 100, and the methodology is applied across 100 separate executions. This structured approach ensures that the optimization framework undergoes extensive testing and validation, allowing for a thorough assessment of its effectiveness and reliability. By maintaining a consistent generation limit, each stage can explore a wide range of potential solutions, thereby enhancing the robustness of the outcomes produced. The repeated application of the method contributes to the statistical significance of the results, facilitating a more nuanced understanding of the optimization dynamics involved. The comparative analysis reveals noteworthy differences in the performance metrics associated with each method, thereby facilitating a more nuanced understanding of how the sequencing of optimization processes influences overall outcomes, shown in Table 2.

The mean work output for two-stage method I is recorded at 733 units, while two-stage method II demonstrates a notably higher mean output of 820 units. This disparity highlights the effectiveness of prioritizing the optimization of task sequencing. The focus on a fixed work-rest schedule of method I may inadvertently restrict the flexibility needed to maximize output during peak operational times. The structured nature of the work-rest intervals could lead to periods of inactivity when optimal

task execution could occur, thereby limiting the overall productivity of the system. The standard deviation in work output also supports this conclusion, with method I exhibiting a higher standard deviation of 31.02 compared to method II’s 8.61. This greater variability in method I suggests that the fixed work-rest scheduling may lead to inconsistent performance levels. In contrast, the more flexible and adaptive nature of method II results in a more uniform output, indicating that task sequencing plays a critical role in stabilizing productivity.

Table 2: Objective results of two-stage methods

	Two-stage Method I	Two-stage Method II
Work Output		
Mean	733	820
Std Dev	31.02	8.61
Robot Utilization		
Mean	82	103
Std Dev	111.07	8.21
Accumulated Fatigue		
Mean	133.24	203.20
Std Dev	18.83	1.44

Robot utilization metrics further corroborate the findings related to work output. Method I records a mean robot utilization of 82, while method II achieves a significantly higher mean of 103. The lower utilization in method I can be attributed to the constraints imposed by the fixed work-rest schedule, which may not align optimally with the operational needs of the robotic systems. When human workers are resting, the robots may be underutilized, leading to inefficiencies in the overall construction process. In contrast, method II’s focus on task sequencing enables a more effective integration of robotic capabilities into the workflow. The higher mean utilization of 103 suggests that robots are being deployed more strategically in conjunction with human labor, thereby maximizing the efficiency of HRC. Moreover, the high standard deviation observed in method I of 111.07 highlights inconsistencies in robot utilization, suggesting that the lack of a structured work-rest schedule may lead to fluctuations in human performance that, in turn, affect the efficiency of robotic operations. The low standard deviation of 8.21 in method II also indicates that robot utilization is more consistent, reflecting a well-coordinated effort between human workers and robotic systems, which is crucial for maximizing the efficiency of HRC systems.

Accumulated fatigue presents a critical measure of the physiological toll on workers engaged in labor-intensive tasks such as bricklaying. The results show that the mean accumulated fatigue for method I was 133.24, significantly lower than the 203.20 recorded for method II. Method II’s remarkably low standard deviation of 1.44 also indicates a consistent high level of physical demand. In method I, the optimization of work-rest schedules prior to task sequencing likely leads to improved energy management and reduced fatigue levels during work periods. Conversely, the higher accumulated fatigue in

method II suggests that while the work output is increased, the intensity of work during active periods may place greater demands on workers. This may result from the optimization of task sequences that prioritize efficiency and output over fatigue management. It is important to recognize that while higher productivity levels are beneficial, they must not come at the expense of workers' health and safety. Accumulated fatigue can lead to diminished cognitive function, increased risk of accidents, and ultimately lower productivity in the long term. Therefore, while method II demonstrates enhanced performance metrics, the implications for worker well-being must be carefully considered.

In summary, two-stage methods effectively consider both work-rest scheduling and task sequencing, making it highly applicable to HRC scheduling challenges. Their result divergence aligns with broader debates in construction automation literature: whether to prioritize human-centric wellness for Method I or task-centric efficiency for Method II as the foundational scheduling principle. The results suggest that neither purely sequential approach fully resolves the tension between ergonomic sustainability and operational rigor. Future frameworks may require iterative or integrated optimization mechanisms, where task sequencing and rest allocation are dynamically co-optimized.

Conclusions

This study employed two-stage methods to address the interdependence between work-rest scheduling and task sequencing. We effectively modeled the complexities inherent in HRC scheduling with a multi-objective GA. Our analysis compared the impact of the two-stage method with a fixed work-rest schedule against the two-stage method with fixed task sequencing on key performance objectives, including work output, robot utilization, and human fatigue. The results indicated that the two-stage method with a fixed work-rest schedule improved human fatigue management but resulted in lower overall work output and robot utilization. Conversely, the two-stage method with fixed task sequencing prioritized task efficiency and maximized robot utilization, although it led to increased levels of human fatigue. This comparison highlights the trade-offs inherent in HRC scheduling and emphasizes the need for a balanced approach to optimize both productivity and worker well-being, providing valuable insights into future studies aimed at refining HRC methodologies in complex construction settings.

A limitation of this study is the absence of real-world experimental settings. Current analysis was conducted primarily through simulations, which may not adequately reflect the dynamic and unpredictable characteristics of actual construction environments. Future research could also explore the possibility of considering work-rest scheduling and task sequencing simultaneously within HRC frameworks. Moreover, incorporating real-time fatigue monitoring mechanisms may advance adaptive rescheduling capabilities, enabling dynamic adjustments based on human cognitive and physical states. Such

advancements would strengthen the robustness of HRC scheduling systems.

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Declaration of AI-generated text

During the preparation of this work the author(s) used AI tools to paraphrase the content. After using this tool, the authors reviewed and edited the content as needed and took full responsibility for the content of the publication.

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