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A Study of Human-Robot Collaborative Construction Task Allocation Problem Considering the Level of Task Danger

Yilin Wang[1]*, Chao Mao[1]†, and Tingpeng Wang[1]
[1] Chongqing University, Chongqing, China
nicole_wyl@stu.cqu.edu.cn, maochao1201@cqu.edu.cn, and wangtingpeng@stu.cqu.edu.cn

Abstract

In recent years, the construction industry has been expanding its production scale, however the industry is facing problems such as low productivity and frequent safety accidents. With the potential to improve construction quality and safety, construction robots have become an important means of solving the industry's problems. However, given that construction robots are built for specific operating environments, they are not yet able to fully replace manual labor, and thus human-robot collaboration is bound to be the mainstay of construction for quite some time to come. Therefore, this paper focuses on the problem of human-robot collaboration on construction sites, and innovatively proposes a task allocation framework based on the degree of danger. Taking concrete floor slab construction as an example, this paper firstly identifies the dangers in traditional construction scenarios and robotic construction scenarios, and then quantitatively evaluates each danger using the likelihood, exposure, and consequence level evaluation method. Further, this paper designs a task assignment framework that aims to minimize the degree of danger while taking into account the cost-effectiveness. The framework is intended to assist the construction team in making scientific decisions to accurately select the appropriate robot type for introduction and ensure that the overall cost is maintained within an economically feasible interval.

* Created the first draft of this document
† Corresponding author

1 Introduction

The construction industry, as an important contributor to the global economy, has been expanding its production scale in recent years, and the global construction market is expected to grow to $13.9 trillion by 2037 from $9.7 trillion in 2022 (Oxford Economics, 2023). However, the industry is currently facing problems such as low productivity, frequent safety accidents, serious energy consumption, and low levels of information technology and industrialization (Zeng et al., 2003). Due to the aging of the construction workforce, the high exit rate from the industry, and the slowing down of the upgrading of workers' skill levels (Kumarage et al., 2023), surveys have already indicated that by 2035, the labor shortage in China's construction industry will reach 10.97 million (Wang et al., 2021), and the problem of imbalance in the supply and demand of labor will become increasingly serious. In addition, the construction industry has been recognized as the most dangerous industry in the world after mining and quarrying (International Labour Organization, 2023), and nearly 3 million workers worldwide die from workplace accidents or occupational diseases every year, of which 1 in 6 die in the construction industry (Cheng et al., 2020). Therefore, there is an urgent need to address the safety and labor dilemma in the construction industry. Construction robots, which can assist and replace “dangerous, laborious, dirty, and heavy” construction work, have the potential to improve construction efficiency and ensure construction safety and quality, and have become a mainstream solution to address these challenges facing the industry (Cai et al., 2019; Gharbia et al., 2020).

Various construction robots have been developed and applied (Zhang et al., 2022). Examples include measuring robots (Oshio et al., 2022), bricklaying robots (Melenbrink et al., 2020), and others. However, most of these robots are designed for specific environments, and it is difficult to quickly adapt to highly unstructured construction environments with only one type of robot (Liang et al., 2021). Therefore, humans are needed to utilize their strengths in responsiveness and intuitive decision making to assist construction robots in accomplishing construction tasks effectively. In the field of architecture, engineering and construction, human-robot collaboration is defined as workers and construction robots working together to accomplish a specific construction task, and each role must be able to contribute to the overall system (Zhang et al., 2023). Workers can play a variety of roles during their collaboration with construction robots, including supervisors, operators, teammates, programmers, and in some cases, as bystanders. In contrast, operator and teammate, which require deep interaction, are the most researched human-robot collaboration problems. In this context, operator refers to a construction worker who uses an operating device to control a robot to complete a construction task (Lee et al., 2011), and teammate refers to a worker who works with a robot to complete a construction task (Xiang et al., 2021). This study also focuses on these two types of roles in human-robot collaboration. Compared to traditional construction methods, human-robot collaboration avoids the problems faced when performing tasks with separate humans or robots and can achieve significantly better human-robot team performance than separate human or robot operations through complementary human-robot strengths (Seeber et al., 2020). However, the division of labor between construction workers and robots is not clear in human-robot collaborative systems. How workers and robots should cooperate to improve the safety and efficiency of the system has also become one of the challenging issues in the new on-site construction human-robot collaboration management model (Wang et al., 2024). This is exactly the human-robot collaboration task allocation problem discussed in this study.

The problem of task allocation for human-robot collaboration has become an increasingly popular research area (Tsarouchi et al., 2016), and reasonable task allocation between humans and robots can improve the productivity and stability of construction. However, the problem of human-robot collaborative task allocation is mainly focused on product assembly (Chen et al., 2014), and is rarely mentioned in the construction field. Although methods for task allocation among multiple construction robots have been proposed (Ye et al., 2024), it did not include workers at the construction site in the task allocation, and was proposed based on the assumptions of the capabilities of construction robots, which were not applicable to existing construction robots in the market. Meanwhile, while previous task allocation problems for humans and robots have focused on dimensions such as efficiency (Bogner et al., 2018), operational comfort (Kim et al., 2018), and resource utilization (Malik & Bilberg, 2019), this study focuses on the inherently hazardous nature of the construction industry and aims to use the task danger level as the main measure to rationalize the division of work tasks and provide a basis for human-robot collaboration in the construction industry.

2 Literature Review

Research related to human-robot collaboration in the construction field focuses on human-robot interaction and safety of human-robot collaboration. As a realization of human-robot collaboration, human-robot interaction is mainly used for the execution and scheduling of collaborative tasks to improve construction efficiency (Wilcox & Shah, 2012). Wang & Zhu (2021) proposed a vision-based framework to capture and interpret workers' gestures aimed at controlling construction machinery, which has significant advantages in the noisy context of building construction. Fang et al. (2018) developed a computer vision-based approach that utilizes two convolutional neural network models to determine whether a worker is wearing a seatbelt while working at height, enabling automated detection of workers who are not wearing a seatbelt.

As a guarantee for human-robot collaboration, safety is a key factor to consider for human-robot collaboration systems. ISO 10218-1/2 has specified safety requirements for industrial robot collaboration with four control modes including safety monitoring stationary, hand-held guidance, speed and distance monitoring, and power and force limitation (Kim et al., 2019; Yan et al., 2020). However, it focuses mainly on industrial robotic systems, and it cannot be fully generalized to the construction industry's robots and work environments. You et al. (2018) proposed a robot acceptance safety model to explore different approaches to overcome the challenges of human-robot collaborative workspace and to enhance safety perception. Kim et al. (2019) proposed a drone-based visual monitoring approach to detect impact hazards around workers in advance and achieve timely intervention to improve the safety of construction workers' work environment. However, the above studies mainly focus on the development of systems that can monitor the status of construction sites in real time from a technological perspective to improve construction safety, and do not consider the impact of the task allocation situation on construction safety from the perspective adopted by the industry, and the design of the human-robot model to reduce construction hazards is still subject to further research. You et al. (2018) showed that during the human-robot collaboration process, human mental stress and health condition are in need of special attention, and that a separated workspace is more likely to increase humans' trust in the robot, thus improving their perceived safety and reducing their worries and fears.

3 Methodology

The purpose of this paper is to establish a set of danger level metrics applicable to human-robot collaborative construction, and then propose a human-robot task allocation framework based on this danger level, and apply corresponding algorithms to solve the task allocation model. Eventually, we will apply this danger level-based human-robot collaborative construction task allocation method to real-world scenarios to verify its effectiveness and practicality.

The construction task allocation framework is shown in Figure 1. Firstly, by systematically sorting out relevant documents such as the Building Construction Manual and combining the actual situation of the on-site research, we carried out a comprehensive and detailed division of the construction process. This step is the basis for ensuring the accuracy of the subsequent task allocation. For the segmented processes, we comprehensively considered the technical capabilities and application status of the existing construction robots in the market, and judged whether the process is suitable to be completed by construction robots. For those construction processes that can be performed by robots, we adopt a permutation and combination approach to form multiple task allocation schemes. In order to determine the optimal task allocation plan under the premise of economic rationality, we made full use of the cost data obtained from the research, such as workers' salaries and robot rental prices, and evaluated the cost-effectiveness of each plan one by one. This step not only helped us to identify economically viable options, but also provided strong data support for subsequent optimisation.

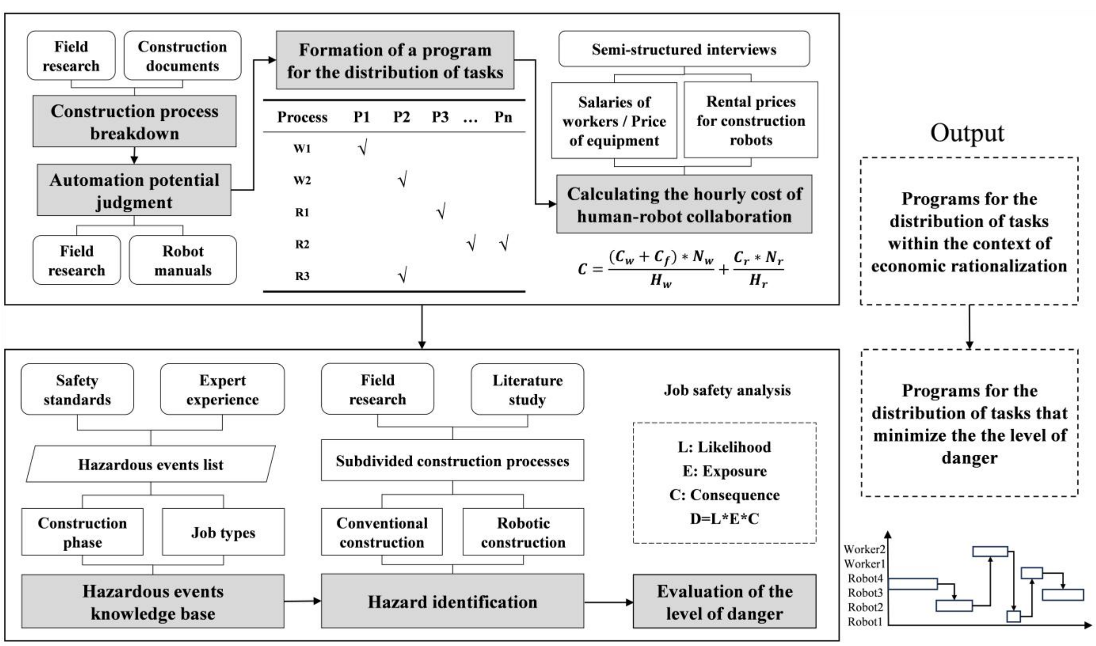

Figure 1: Methodology

However, cost was not the only factor we considered. While ensuring economic rationality, we also conducted an in-depth analysis and calculation of the danger level of each tasking option. In order to comprehensively and accurately assess the degree of danger, we have extensively collected valuable information such as accident cases, safety standards and expert experience. Through comprehensive analysis and generalisation, we came up with a list of hazardous events that each construction stage and each construction work type may face. Based on this, we further identified potential danger sources for each construction process in both traditional construction scenarios and robotic construction scenarios. The identification of these hazardous sources provides an important basis for our subsequent evaluation of the degree of danger. In order to arrive at a scientific and accurate evaluation result, we used the likelihood, exposure, and consequence level evaluation method to evaluate each danger source one by one. Through this step, we ultimately identified the task assignment programme with the lowest level of task danger.

4 Construction Task Allocation Model

Human-robot collaborative construction task allocation is the process of decomposing a complex construction task into sub-tasks of appropriate granularity and assigning the task to a construction worker or a construction robot to achieve the global optimum under consideration of specific constraints and objectives. In this paper, we have evaluated the scheme of assigning construction tasks based on two indicators: the cost and the degree of danger of the task.

4.1 The Cost of Human-Robot Collaboration

In the construction industry, human-robot collaborative automation is emerging as a key tool for improving construction safety and productivity. In order to ensure that this automation modification is economically viable, we can assess the cost-effectiveness of a human-robot collaboration system by developing a mathematical model. This model will help us to compare the costs of traditional construction methods with those of human-robot collaborative methods to ensure that the costs are kept within reasonable limits. The cost of working with human-robot collaboration system depends on the cost of equipment and labour (Sun et al., 2024). We focus on analysing equipment and labour costs to provide data support to construction project managers so that they can determine the optimal number of workers and construction robots required for a given project, thus achieving the optimal balance of cost-effectiveness and productivity. In short, this model is designed to help us find cost-effective configurations of human-robot collaboration to improve the overall economics of construction projects. Table 1 shows the parameters involved in the model.

Here, the parameters that affect the cost are the price of the construction robot, the price of the equipment used by the workers, and the salary of the workers. Therefore, the following equation (1) should be used to calculate the cost per hour of work for the human-robot collaboration system, where each parameter is defined as shown in Table 1.

Symbol	Definition
C	The hourly cost of human-robot collaboration
C_w	Salaries of workers
C_f	Price of facilities
C_r	Rental prices for construction robots
N_w	Number of workers
N_r	Number of robots
H_w	Working hours of workers
H_r	Working hours of construction robots

Table 1: Parameters in the cost model

$$C = \frac{(C_w + C_f) * N_w}{H_w} + \frac{C_r * N_r}{H_r} \tag{1}$$

4.2 The Danger of Human-Robot Collaboration

In the environment where workers and construction robots work together, with the application of construction robots, some of the construction tasks originally undertaken by workers are transferred to the robots. At this time, the task dangers faced by workers in the human-robot collaboration system contain two main aspects: the dangers in the traditional construction environment, and the dangers arising from working together with construction robots, as shown in Figure 2.

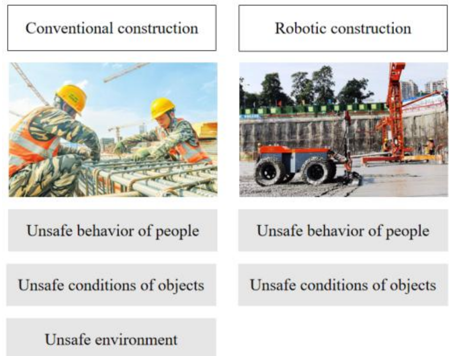

Figure 2: Components of danger for human-robot collaborative systems

Construction process	Hazardous events list
Fabric pouring	(1) The support surface of the fabric machine is not flat and solid enough, and more than 4 wire ropes are not used to tie diagonally, which may cause overturning phenomenon. (2) When installing, dismantling, or shifting the manual fabricator, there are unrelated people staying within the operation range. (3) When the pump pipe is clogged and needs to be flushed, the pump pipe port is not equipped with a reliable protective cover, and the operator stays at the front end of the pump pipe and within the rotating radius. (4) People stay under the overhang and around the discharge hose during operation of the fabricator. (5) Fabric machine operator violates rules during operation. (6) Failure to stop the construction operation of the fabricator in inclement weather, such as gusts of wind of grade 5 or above, thunderstorms, heavy snow, fog, etc., and the possibility of tipping over.
Vibration	(1) Failure of the operator of the concrete vibrator to wear insulated shoes and gloves. (2) Workers' hands or other parts may be pinched or hit by the moving parts of the vibrator. (3) Concrete vibration during work at height or at the edge of the work, if the safety protection measures are not in place, collapse or worker fall accidents may occur.
Paving	(1) During concrete paving, the ground can become very slippery and workers may slip or fall due to loss of footing.
Aluminum ruler scraping	(1) Prolonged bending, squatting, or repeating the same movement may lead to damage to a worker's musculoskeletal system and chronic pain or injury. (2) May slip and fall due to slippery floors, resulting in a fall or other bodily injury.
Compacting, grinding	(1) The use of machinery and equipment, such as compactors and mills, can lead to worker injuries if they are not operated properly or if the equipment is poorly maintained.

Table 2: List of hazardous events in concrete floor slab construction

In human-robot collaboration systems, construction workers are still required to perform part of the work. Danger assessment for this part of the task mainly focuses on unsafe human behavior, unsafe state of objects and unsafe environment in traditional construction scenarios. This study thoroughly considered the specific characteristics of construction sites and synthesized information from relevant technical specifications of construction projects, past accident cases, and other information to conduct a detailed job safety analysis of each specific construction process segment. Through in-depth communication with a number of relevant personnel, including safety officers, production managers, project managers, etc., we have compiled a list of hazardous events in concrete floor slab construction as follows, as shown in Table 2.

Type of construction robots	Hazardous events list
Intelligent follower fabricator	(1) Loss of control of fabric robot system poses risks to workers, including bumps and bruises.
Ground leveling robot	(1) During the operation of the robot, staying, playing or fooling around within 3m in the forward direction, 1m on both sides and the turning radius of the robot may pose a risk of being hit. (2) Operation of this product by untrained or inexperienced persons. (3) Failure to wear the required labor protection equipment before operating the equipment: helmet, reflective clothing, labor protection shoes, noise-reducing earplugs, and protective masks.
Crawler trowel robot	(1) When the robot is operating, there is a person within 1m of the operating range. (2) Operation of this product by untrained or inexperienced persons.
Polishing robot	(1) During the operation of the robot, staying, playing or fooling around within 3m in the forward direction, 1m on both sides and the turning radius of the robot may pose a risk of being hit. (2) Operation of this product by untrained or inexperienced persons. (3) Failure to wear the required labor protection equipment before operating the equipment: helmet, reflective clothing, labor protection shoes, noise-reducing earplugs, and protective masks.

Table 3: List of hazardous events for robots in the concrete engineering category

In addition, construction robots still need the assistance of workers in performing their tasks, and construction robots themselves, as a newly introduced work environment, bring new safety risks to workers. For the danger assessment of this part of the task, we focus on the unsafe behaviors of people and the unsafe state of objects in the construction robot operating scenario. This study follows the ISO 10218 standard and combines the specific situation of the actual application of construction robots to list the list of hazardous events that may be involved in various construction robots for each construction robot in the concrete engineering category, as shown in Table 3.

While the introduction of construction robots has eased the burden of risky labor on workers to some extent, the change has not been without its pitfalls. It is also accompanied by new challenges and risks, such as accidents that may be caused by robot mishandling or poor maintenance.

In view of this, this study considers the level of danger to workers in completing tasks as a core assessment indicator, aiming to minimize this level of danger through in-depth research. This study draws on the traditional method of danger assessment of operating conditions-the likelihood, exposure, and consequence level evaluation method to quantitatively analyze the overall safety condition of the construction site. In calculating the degree of danger for workers to complete tasks in the human-robot collaboration system, we use the following equation (2).

$$D = D_w + D_r \tag{2}$$

Where, D represents the level of danger to the worker in the human-robot collaboration system to accomplish the task; D_w represents the level of danger faced by the worker from the traditional construction environment; and D_r represents the level of danger faced by the worker from the construction robot.

4.3 Mathematical Model

The mathematical model for task allocation is as follows. By equation (3), we can make the danger level minimized. By equation (4), we can ensure that the cost of the human-robot collaboration system is less than the traditional construction.

$$minD = \sum_{i=1}^{n} (D_{wi} + D_{ri}) \tag{3}$$

$$s.t. \sum_{i=1}^{n} \left(\frac{(C_w + C_{fi}) * N_{wi}}{H_w} + \frac{C_{ri} * N_{ri}}{H_r} \right) \leq C_\alpha \tag{4}$$

Where, the definition of each parameter is the same as Eq. (1)(2), i represents the i^{th} process (i=1, 2, 3, ..., n), C_α represents the cost of the work of the human-robot collaboration system when the construction task is traditionally done manually only.

4.4 Solution Algorithm

For the above mathematical model, we set up a specific encoding method for the task allocation solution of human-robot collaborative construction, and realized the task scheduling of human-robot collaborative construction by using the violent search algorithm. Among the optimization objectives are that the cost of the human-robot collaboration system is less than the cost of conventional construction, i.e., the cost of doing it all manually, and that the optimal solution is the least hazardous.

The following is the design of the key computational process, as shown in Table 4.

Algorithm for Optimal Subtask Allocation

```
Input: process data, robot data, cost, and danger
Output: optimal allocation solution, allocation cost, allocation danger
Generate all possible allocation solutions:
    For each process, generate allocations (0 for manual, 1 for robot)
Define function to calculate total cost and total danger:
    Function: calculate_cost_and_danger(allocation)
      Initialize total_cost = 0, total_danger = 0
      For each process in the allocation:
          If manual (0):
            Add manual cost to total_cost
            Add manual danger to total_danger
          If robot (1):
            Add robot cost to total_cost
            Add robot danger to total_danger
            Record robot usage
      Return total_cost, total_danger
Find optimal allocation solution:
    Initialize best_index = None, min_danger = ∞
    For each allocation:
      Get its cost and danger
      If cost < manual cost and danger < min_danger, update optimal solution
Output optimal solution:
    If optimal allocation is found, output allocation, cost, and danger
    Otherwise, output "No optimal solution found"
```

Table 4: The key computational process

5 Case Study

In this paper, the concrete floor slab construction process is chosen as a case background to verify the feasibility of the proposed method. The concrete floor slab construction process includes pre-construction preparation, concrete mixing, fabric pouring, vibration and trimming. This paper focuses on the concrete construction robots of Bright Dream Robotics, a leading company in China's construction robotics industry, which produces a wide range of construction robots, among which the concrete construction robots include intelligent follower fabricators, ground leveling robots, crawler trowel robots, and polishing robots. These advanced robots have been practically applied in several construction projects. Given the scarcity and confidentiality of data on construction robots, cost data on construction robots in this study were collected from interviews and publicly shared cases. As a preliminary exploration, a hospital project in Chongqing is planned to carry out a robot trial on a 1000m2 site at a manageable cost, so only one of each type of construction robot will be introduced for the trial. The correspondence between the concrete floor construction process and the construction robot is shown in Figure 3 below.

In this case, 4 front-line personnel in construction and safety, 4 managers such as technical leaders and production managers are invited, and a total of 8 people score the hazardous events of each construction process and each construction robot. According to the 8 scoring results, the danger coefficient of each dangerous event can be derived in accordance with the formula for calculating the danger of each type of dangerous event.

To establish a model for solving the task allocation problem based on the violent search algorithm, this paper uses the python platform to write the algorithmic program to derive the optimal task allocation scheme with the minimum degree of danger and the cost within a reasonable range, as shown in Figure 4 below.In the distribution scheme, preliminary preparation is assigned to worker1, concrete transportation is assigned to worker2, concrete pouring and concrete vibrating is assigned to intelligent follower fabricators, paving is assigned to worker3, AI ruler scraping is assigned to crawler trowel robot, grinding is assigned to worker4. Ground leveling robot and polishing robot are not used in this case.

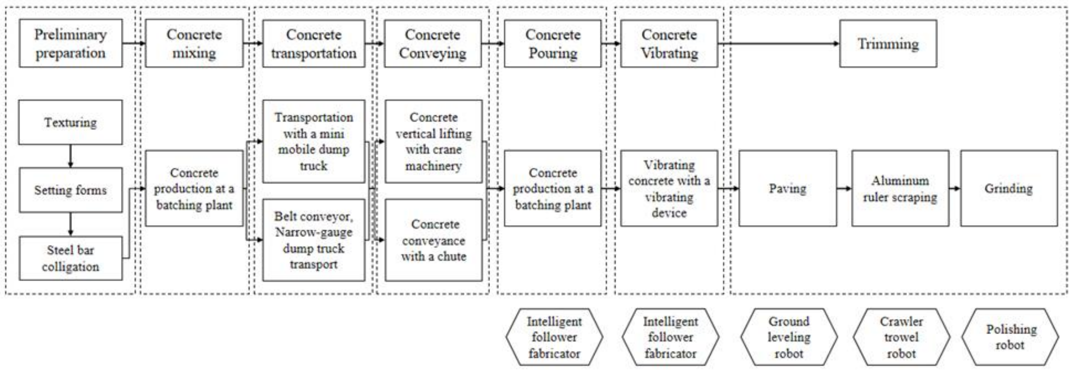

Figure 3: Construction process of concrete floor slabs

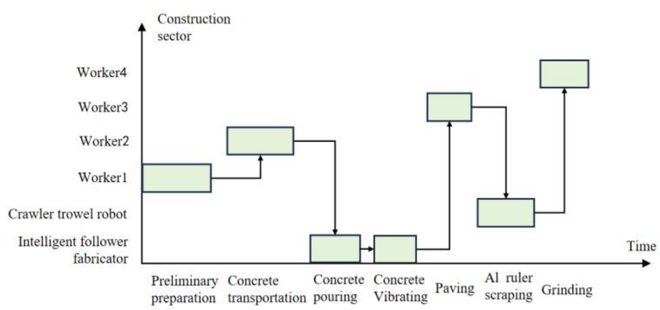

Figure 4: Optimal distribution of tasks program

6 Conclusions

Efficient cooperation between man and robot can improve construction productivity and safety. Appropriate human-robot collaboration task allocation is the premise and foundation for realizing good results of human-robot cooperative work. Meanwhile, the presentation of human-robot task assignment results can be considered as a strong motivation for construction teams to introduce construction robots, i.e., to reduce the level of danger and to keep the cost within reasonable limits. In addition, the design of construction robots for adapting to diversified and variable construction needs provides strong theoretical and technical support for the government to accelerate the construction of digital talent echelon, optimize the existing workforce structure, and reduce the low labor fitness caused by technological friction.

However, human-robot collaborative construction task assignment is a very complex process. This study establishes a human-robot collaborative construction task allocation model to solve this problem by taking the task danger level as the goal and taking into account the cost, and the case study results show that the human-robot collaborative task allocation method proposed in this study can effectively find the optimal solution. However, the worker and robot task allocation problem still needs further research. An effective human-robot collaborative system should consider the strategy of human-robot collaborative task allocation from multiple dimensions, not only considering the economic efficiency and safety, but also considering the time efficiency and completion quality of the workers and robots when they work together.

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