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Design and Evaluation of the Internal Space Layout of High-Speed Health Trains Based on Improved Systematic Layout Planning

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Abstract: High-speed health trains have the advantages of large rescue volume, strong continuous operation capability, and medical treatment on the way. It is the best transport platform for large-scale medical transfer tasks. To solve the problem of space limitations and the vehicle formation of high-speed health trains, a new method of space layout design and evaluation of high-speed health trains based on improved systematic layout planning (SLP) was proposed. First, SLP was improved, and the relationship between functional carriages was reasonably marshaled using the improved SLP. Then, according to the space constraints of high-speed trains and the requirements of the man–machine environment, the space layout of the vehicles was designed, and 3ds MAX software was used to visualize the designed layout structure. Finally, the static and dynamic simulation effects and adaptability of the design scheme were evaluated using the digital virtual simulation software JACK. The design scheme can meet the requirements of human–computer interaction efficiency. Compared with previous studies, the results of this study reflect the superiority and rationality of the design in functional configuration, space utilization, medical treatment, and injury-carrying capacity. The results of this study can provide theoretical support for the formation of high-speed health trains, and provide a reference for the research and development of such trains. It has certain practical application value.

Keywords: high-speed health train; marshaling of carriage; layout design; SLP

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1. Introduction

China, with its vast territory, large population, and frequent public health incidents, is among the countries with a high incidence of natural disasters [1]. Efficient and safe medical transportation is a key challenge in disaster medical rescue. Common methods of medical transportation include air transshipment and land transshipment. Aviation is a modern rescue method suitable for small-scale rescue operations that require a timely response. On the other hand, land transportation can better meet the needs of large-scale rescue operations, as it provides strong continuous operation capabilities and the ability to provide medical treatment en route. Moreover, it highlights the advantages of long-distance train transportation [2].

The railway train is a crucial transportation tool for transferring injured soldiers during wartime. It serves as the primary mode of transportation for long-distance medical evacuation both in combat and in the strategic rear. It also has the medical support capacity to treat and transport wounded soldiers, making it an essential component of medical rescue efforts in both peacetime and wartime [3,4]. However, compared with general-speed trains, high-speed trains have the advantages of big space, low noise, smooth operation, fast speed, strong space, airtight electromagnetic shielding ability, and so on, which have gradually become the frontier direction of health train research and development [5–7].

Through a literature search and research on the current situation, it was found that the health trains currently in operation include the China Health Express (Charity Ophthalmology Hospital), the Chinese People's Liberation Army Military Medical University (formerly the Third Military Medical University), a surgical emergency train developed by a locomotive factory in China, the "Peace Train" for China and Laos, the Lifeline Express from India, and the Sovereign Military Order of Malta (SMOM) health trains. The above-mentioned sanitary trains are all developed based on regular trains. The latest concept for the construction of a health train platform is the development of a health train based on standard multiple units. Based on literature research and the development of high-speed railways in various countries around the world, China's high-speed railway network and high-speed multiple units both belong to the world's most advanced level in the research of high-speed health trains based on high-speed multiple units. Relevant scholars have also carried out a lot of work in the development of high-speed health trains. For example, Wu Fan et al. [8] proposed a health train formation method based on standard EMUs based on the grouping and treatment process of health train services, proposed eight functional modules of health trains, and refined their functions. Li Yunming et al. [9] conducted a comprehensive study on the current application status of health trains and the development prospects of high-speed trains, and looked forward to the development of high-speed rail health trains. They pointed out that using high-speed trains as a platform for research on functional modules such as command, communication, medical care, and logistics support is necessary to provide technical support for the construction of high-speed health trains. Zhao Yi et al. [10] used the HTA theory to analyze the various functional modules of high-speed health trains and obtained a module-merging scheme under the condition of eight-carriage marshaling. As of now, the development of high-speed health trains is still in the conceptual stage, and it is necessary to conduct an integrated analysis of the entire vehicle from aspects such as vehicle selection, speed situation, and formation sequence, and propose an improved system layout planning method suitable for the formation and layout of high-speed health trains.

In order to achieve effective medical security, problems such as tools, personnel, and business process need to be considered [11]. It is necessary to improve the current locomotive structure and layout for the high-speed health trains with similar ideas to the general-speed health trains. This idea meets the needs of health trains, which can ensure the safety and speed of boarding and alighting the injured, reasonable medical equipment placement, complete medical rescue functions, and special medical processes for mild and severe injuries so as to fully and reasonably use the internal space of high-speed trains to scientifically treat the wounded in batches. Therefore, this paper uses the improved SLP to marshal the functional train carriage reasonably based on the functional train carriage units. Then, according to the space limitation and man–machine environment demands of high-speed trains, the interior space layout is designed. Finally, a set of scientific and reasonable reconstruction schemes of high-speed health trains is obtained by simulation verification by visual means.

2. Theoretical Foundation and Methods

2.1. SLP Improvement and Carriage Marshaling

The primary objective of designing a layout is to ensure the safe, efficient, and logical flow of logistics, people, and information. Numerous researchers have focused on optimizing factory workshop layouts, enhancing hospital medical service processes, and analyzing demand-driven layouts to support relevant designs [12–15]. However, designing layouts for high-speed health trains presents distinct challenges compared to configuring regular hospitals, primarily due to differences in application scenarios and target groups. Particularly in military settings, prioritizing the treatment of injured individuals and arranging carriages based on the required level of medical care becomes crucial [16].

The Systematic Layout Planning (SLP) methodology comprises procedural layout methods, with its five elements and their interrelationships guiding the layout principles.

Nonetheless, these principles cannot be directly applied to non-factory scenarios. Furthermore, the traditional SLP approach often neglects analyzing the interrelationships among operating units during facility planning, such as personnel activities and goods transportation. This oversight can result in the crossing of operation routes, leading to decreased efficiency and potential accidents [1]. Consequently, the direct application of SLP in high-speed train carriage layouts is not feasible. It is necessary to enhance SLP to align with the characteristics of a specific context and incorporate dynamic factors into the analysis and organization of interrelationships.

To improve efficiency in the flexible marshaling approach of high-speed health trains, individual modules are placed in a single carriage. In order to adapt to the application of future large-scale high-speed health trains, it is necessary to redefine the concept of basic elements, use modules as the basic elements for layout, and consider the minimum optimization of human crossing carriages in Section 2.3 in the vertical logistics and non-logistics relationship. Based on the improved SLP, this paper plans the vertical arrangement of the functional modules of the eight-marshal high-speed health train. The functional modules mainly include four categories: the medical module, living module, reserve module, and management module. The plan mainly involves (1) three groups of people: doctors, nurses, and the injured and sick; (2) the information flow of medical supply delivery, diagnosis and treatment services, a summary of injuries and illnesses, and diagnosis and treatment plans; (3) medical supply storage, preparation, and use; (4) auxiliary facilities such as medical equipment and toilets; and (5) time for each streamline and task. Accordingly, this paper redefines the five elements of SLP according to the characteristics of high-speed health trains: P (medical, nursing, and sick), Q (number of people), R (logistics, flow of people, information flow), S (guarantee materials, security services, auxiliary facilities), and T (time). Based on the improved SLP method, a planning model for the marshaling and layout of the high-speed health train carriage is developed, as shown in Figure 1.

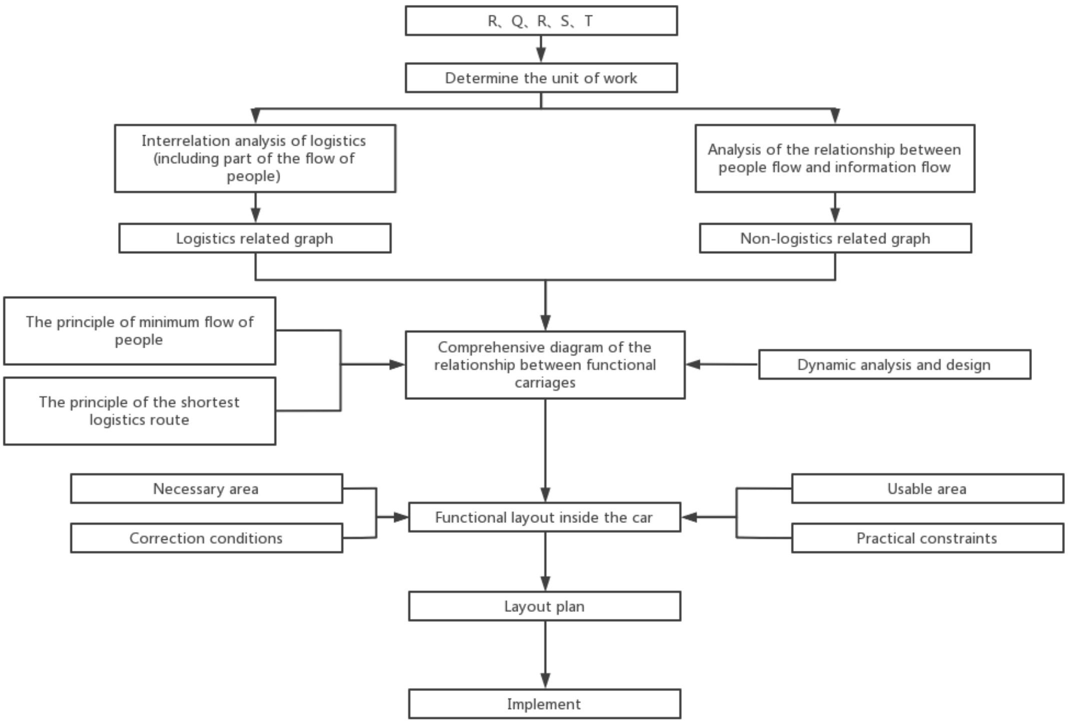


Figure 1. Planning model of carriage composition and interior layout of the high-speed sanitary train based on improved SLP method.

In the above planning model, the redefined P, Q, R, S, and T are used as information input, and the Chinese standard Electric Multiple Units (EMU) carriage is used as the operating unit to analyze the relationship between logistics and non-logistics. All logistics activities include personnel activities that control logistics, and non-logistics mainly include personnel flow and information flow. Based on the correlation diagram of logistics and non-logistics, according to the principle of the shortest logistics route and the principle of the minimum flow of people, the logistics and non-logistics are interspersed and integrated, and combined with the organizational model of linear movement [17,18], the relationship between functional carriages is formed. The comprehensive picture is taken as the arrangement plan of eight-marshal high-speed health train carriages. Based on the marshaling plan, according to the available area in the carriage and the necessary area of the functional layout, we fully consider the actual constraints and correction conditions to lay out the functions in the carriage, and finally obtain a layout plan that meets the requirements of the task and the adaptation of the human–machine environment.

2.2. Analysis of the Relationship between Logistics and Non-Logistics

2.2.1. Logistics Relationship Analysis

In order to realize the relevant functional modules and tasks of high-speed health trains, there are three groups of logistics relationships, as shown in Figure 2. In the first group, the storage and preparation carriages need to carry the storage tasks of equipment, medicines, etc., as well as the functions of distribution and pharmaceutical preparation, and the nurses carry out the transportation of medicines and consumables. In the second group, in order to avoid the congestion and conflict of moving lines caused by the concentration of injured and sick patients in the inspection carriage, the collection of blood and urine samples will be conducted on the beds of each functional carriage according to a certain priority, and the nurse will complete the inspection. In the third group, meals are prepared in the dining carriage and delivered to the relevant functional car by the nursing staff. The three groups of logistics relationships all contain people–flow relationships. In the logistics relationship shown in Figure 2a, the material supply activity is the most frequent logistics relationship; in Figure 2b, the sample inspection activity is usually performed once per medical transfer; in Figure 2c, the food delivery logistics activity is performed, at most, three times a day.

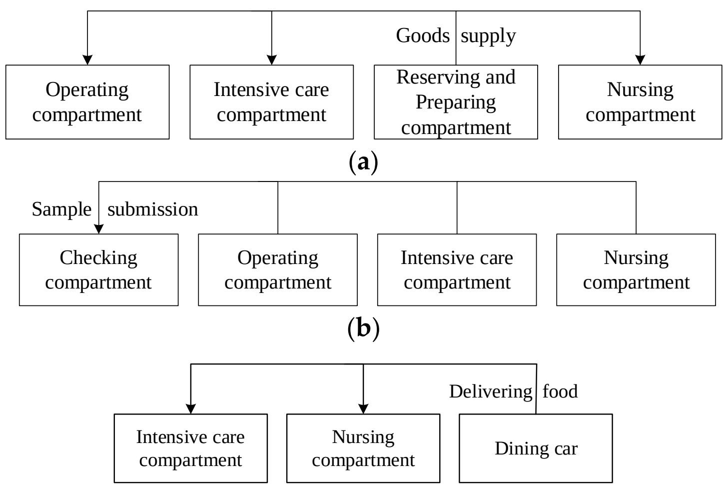


Figure 2. Logistics relationship of high-speed sanitary trains. (**a**) Logistics relationship between reserve and preparation carriages, intensive care carriages, and nursing carriages (**b**) Logistics relationship between surgical carriages, intensive care carriages, nursing carriages, and inspection carriages (**c**) The logistics relationship between dining carriages, intensive care carriages, and nursing carriages.

2.2.2. Non-Logistics-Related Graphs

Based on the task flow of the high-speed health train, three groups of non-logistic relationships are proposed, including the flow of the wounded and sick, the flow of medical staff (except for the flow of materials), and the flow of information, as shown in Figure 3.

In the flow line of the wounded and the sick, they enter the relevant functional carriages for corresponding medical treatment based on their injuries and transfer to other carriages as needed. The flow of medical staff is mainly from various functional carriages to and from the dining carriage and sleeping carriage for meals and sleep. The information flow line is that the command room dispatches tasks to each medical carriage according to the inspection results and formulates a plan based on the feedback of each carriage.

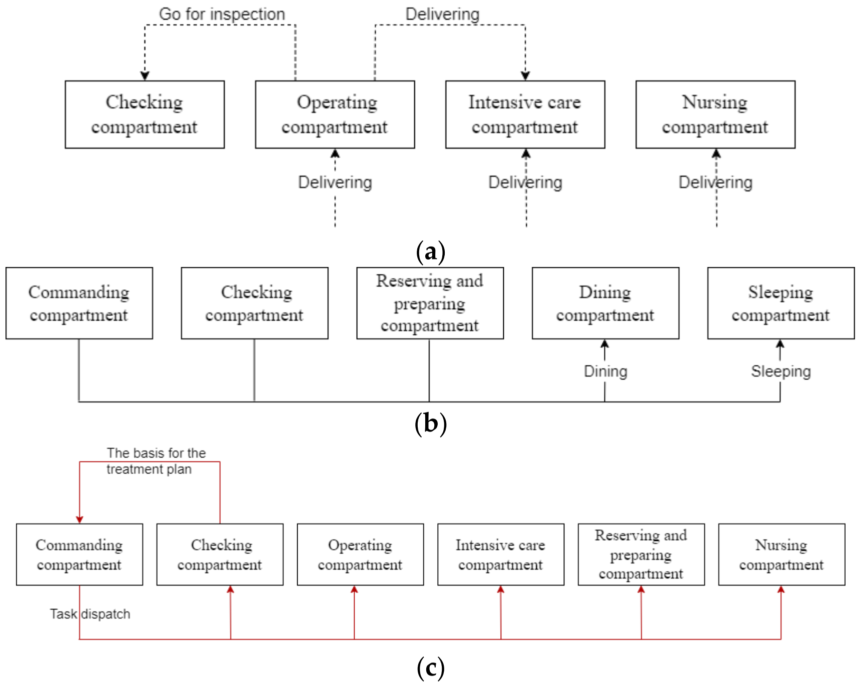


Figure 3. Non-logistics relationship of high-speed sanitary trains. (**a**) Movement of the wounded and sick. (**b**) Flow lines of medical staff (except logistics). (**c**) Information flow.

2.3. Analysis of the Relationship between Carriages

Aiming at the characteristics of high-speed trains with a single line at the beginning and the end and a single corridor, and comprehensively considering the moving lines of each operation, this paper puts forward five principles for the arrangement of different functional carriages of high-speed health trains: (1) to separate the medical area and living area; (2) to reduce the intersection of task streamlines; (3) to reduce the route distance of task activities; (4) to avoid mutual interference of different functions; and (5) to avoid a local accumulation of people and cause blockages. Based on the above five principles, the logistics- and non-logistics-related graphs are integrated, the computer is used to search for all of the marshaling methods, the total number of people passing through the carriage is the goal to minimize the traversal, and the total number of people passing through the carriage under all marshaling methods is obtained. The specific simulation process is as follows:

Step 1: Define the element attributes of the injured and sick personnel, with the total number of injured and sick personnel being *Sb*, the number of injured and sick personnel requiring surgery as *Su*, the number of critically ill personnel as *Ze*, and the number of lightly injured nursing personnel as *Qs*;

Step 2: Define the logistics relationship between elements, analyze the constraints between elements, and generate the marshaling order of all carriages based on n; define a logistics and information relationship as the location where medical personnel pass through two carriages, and record the number of times they pass through the carriages.

Step 3: Read the grouping order of the carriages in order, and use the logistics relationship and configuration resources shown in Figure 3 to record the number of times the medical personnel on board pass through the carriages under relevant working conditions, to obtain the total number of times the medical personnel on board pass through the carriages during the execution of diagnosis and treatment tasks with fixed patients;

Step 4: Write the marshaling order and total number of traverses into the reserve matrix;

Step 5: Update and read the next carriage marshaling order, and execute **Step 3** until traversing $n!$ times;

Step 6: Output the marshaling order of the minimum passing carriages;

where n represents the total number of carriages. The total number of passengers passing through the carriages under all marshaling methods is shown in Figure 4.

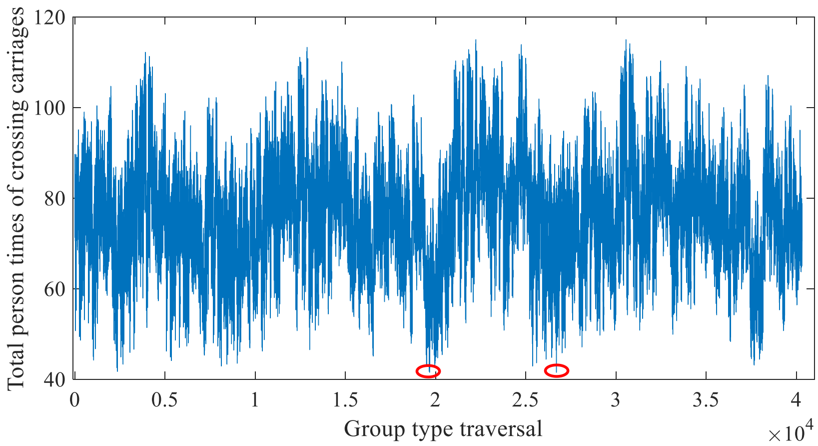


Figure 4. Map of the total number of passengers crossing the carriages in all marshaling modes.

Based on the traversal results in Figure 4, by analyzing and comparing the number of times the person crosses the carriages in different marshaling orders, two minimum values are identified and marked as shown in the red oval in Figure 4. Then, the two minimum values marked in red are decoded to obtain the two marshaling schemes A and B with the minimum number of crossings. Finally, the optimal train carriage marshaling order is obtained, as shown in Figure 5.

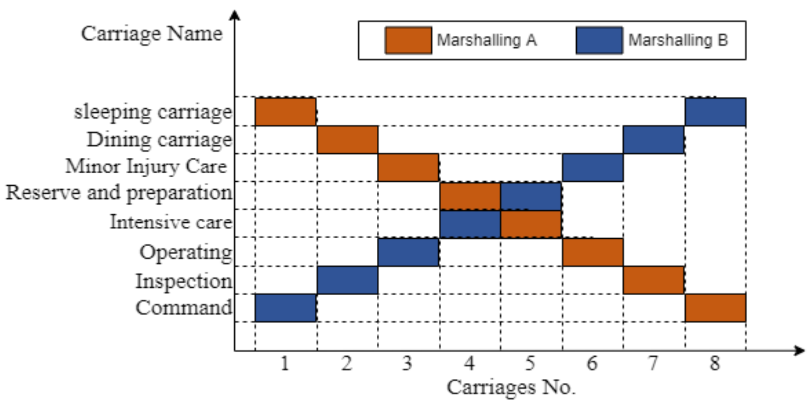


Figure 5. Decoding results of the optimal marshaling of carriages.

It can be seen from Figure 5 that marshaling scheme A and marshaling scheme B belong to different sorting orders of the same marshaling scheme, that is, the marshaling of A is equivalent to the marshaling of B, which is recorded as: A< = >B. Therefore, the computer simulation results conform to the actual marshaling situation, which verifies the correctness of the model. Because schemes A and B are equivalent, this paper randomly selects formation B as the formation scheme of the high-speed health train, and the schematic diagram of the comprehensive formation diagram of the interrelationship between carriages can be obtained as shown in Figure 6.

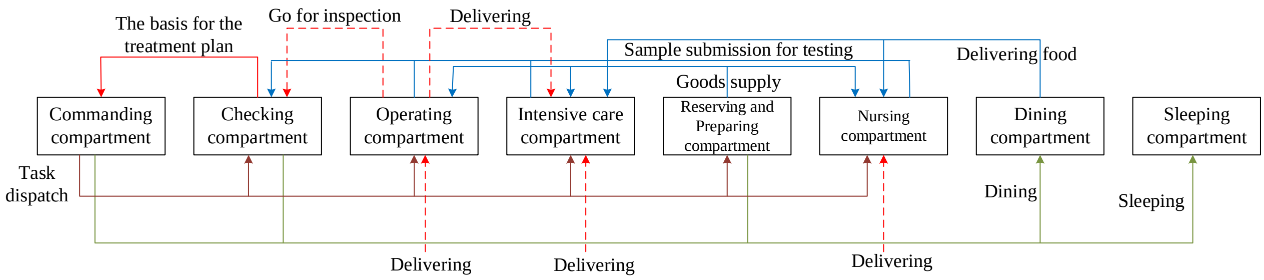


Figure 6. Comprehensive diagram of the mutual relationship between functional carriages of high-speed sanitary trains.

In the comprehensive relationship diagram shown in Figure 6, the dining carriage and the sleeping carriage are distributed at both ends of the medical area, composed of the living area and other carriages, and the streamlines do not interfere with each other. The operating carriage and the intensive care carriage are functionally accumulated as strongly associated carriages. Reserve and preparation carriages require a frequent supply of medical equipment, consumables, and medicines to intensive care and nursing carriages, so these carriages should be clustered. Surgical behavior usually requires testing equipment, so the examination carriage should be adjacent to the operating carriage; at the same time, the test results will be used for treatment planning, so it should also be adjacent to the command carriage. The command carriage of the high-speed health train is responsible for internal and external communication and the real-time monitoring of the train status. At present, these systems are integrated into the lead carriage, so the command carriage of the high-speed health train needs to be set in the lead carriage.

3. Carriage Layout Design Method

3.1. Requirements for Ergonomics

The ergonomic principles that high-speed health trains need to follow are not only based on the Chinese standard EMUs and the comfort of the passengers, but also the criteria involved in the handling of transport equipment during the transportation of the wounded and sick, the relationship between human muscle activity and movement path [19], the man–machine adaptation of medical staff's behavioral posture and working space in diagnosis and treatment activities, the man–machine adaptation of diagnosis and treatment facilities and anthropometry, and the streamlined avoidance of human flow and logistics, etc. It mainly includes the following four aspects: (1) the transportation of equipment and personnel passage. The high-speed train carriages adopt a longitudinal formation and a central corridor layout. In order to maximize functional space and continuity, high-speed health trains adopt a single side corridor style. (2) The size of the working space is suitable for anthropometry of different operation behaviors, and the layout of functional facilities needs to ensure the effective implementation of dynamic behaviors of medical staff. (3) Adaptability of operation facilities to anthropometry. In the operation facilities of high-speed health trains, including tabletop facilities, cabinet facilities, and equipped diagnostic and treatment equipment, it is necessary to combine the height of the tabletop to ensure the optimal operational performance of medical personnel. (4) Reachability is the basis for functional layout in the area suitable for manual operation. Based on the above analysis, space size calculations are required for onboard equipment and layout. The minimum functional size of the product can only ensure that the operator can complete the necessary operations, but the operator will experience negative psychological emotions due to the small spatial scale, so the size of the product needs to be corrected; this is called the psychological correction amount. The size is the minimum functional size plus the size of the psychological correction, as shown in Equation (1):

$$Sopm = S_\alpha + \Delta f + \Delta p \tag{1}$$

where $Sopm$ is the best functional size, S_α is the α percentile body size data, Δf is the functional correction, and Δp is the psychological correction. The layout of functional facilities needs to ensure the effective implementation of the dynamic behavior of medical staff, so it is necessary to analyze the space requirements of different working postures. The working postures of medical staff on high-speed health trains mainly include standing, squatting, and sitting. These working postures are similar to the working postures proposed in ergonomics and require specific space dimensions.

3.2. Space Layout Design of the Carriage

(1) Command carriage

The command carriage is arranged in carriage No. 1, is responsible for internal and external communication, and keeps track of the train's running status and location. At the same time, the aerodynamic shape of the head carriage of the high-speed train makes the available space of the head carriage smaller than that of ordinary carriages, and cannot form a continuous medical, functional unit. Therefore, the command carriage with relatively scattered functions is arranged in the lead carriage, as shown in Figure 7.

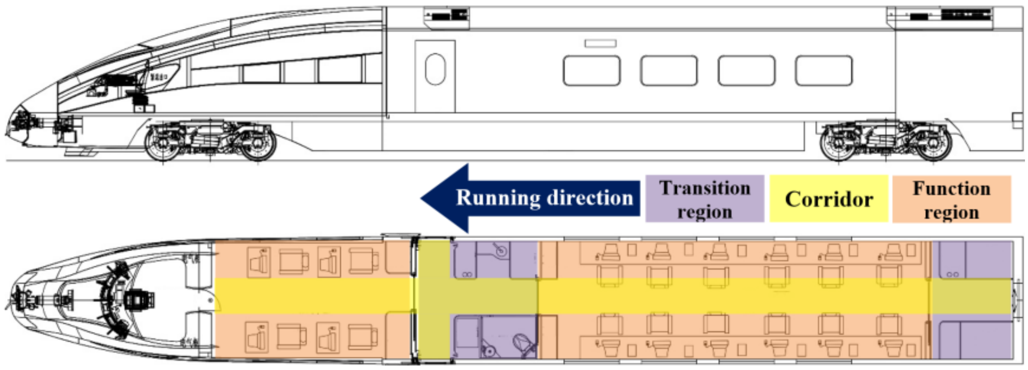


Figure 7. Carriage No. 1 of the high-speed sanitary train: spatial layout of the command compartment.

(2) Inspection carriage

Carriage No. 2 of the high-speed health train is an inspection carriage. The transition area and the functional area are separated by an inductive sliding door to ensure a relatively independent health environment in the inspection area. The functional area of the inspection carriage is mainly divided into three functional departments: the comprehensive inspection room, the ECG ultrasound room, and the radiology room, which improves the inspection efficiency, as shown in Figure 8.

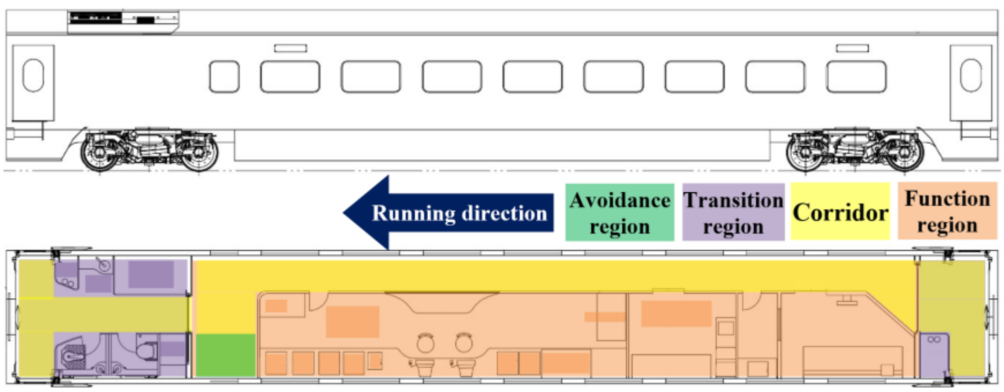


Figure 8. Carriage No. 2 of the high-speed sanitary train: space layout of the inspection carriage.

(3) Operating carriage

Carriage No. 3 of the high-speed health train is surgical, and the door aisle is separated from the surgical, functional area by an induction door. The surgical, functional area adopts a unilateral layout, and the functional space includes a dressing room, a disinfection room, an operating room, a dirt-packing room, a cleaning room, and a drying and packing room, as shown in Figure 9.

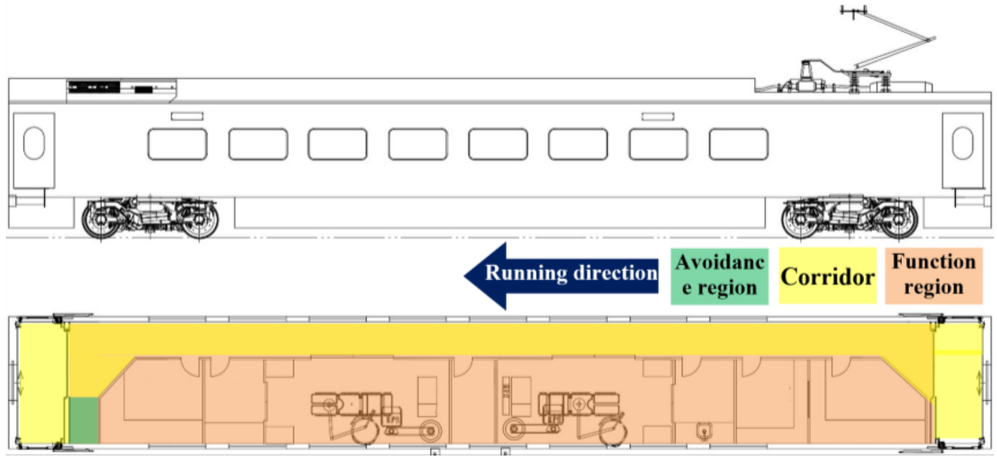


Figure 9. Carriage No. 3 of the high-speed sanitary train: spatial layout of the surgical compartment.

(4) Intensive care carriage

Carriage No.4 of the high-speed health train is an intensive care carriage, which is connected to the operation carriage, and the wounded and sick can be transferred to the intensive care unit after surgery. The functional area in the intensive care carriage adopts a unilateral layout, the intensive care unit is arranged on the left side of the running direction, and the passage corridor is on the right side, as shown in Figure 10.

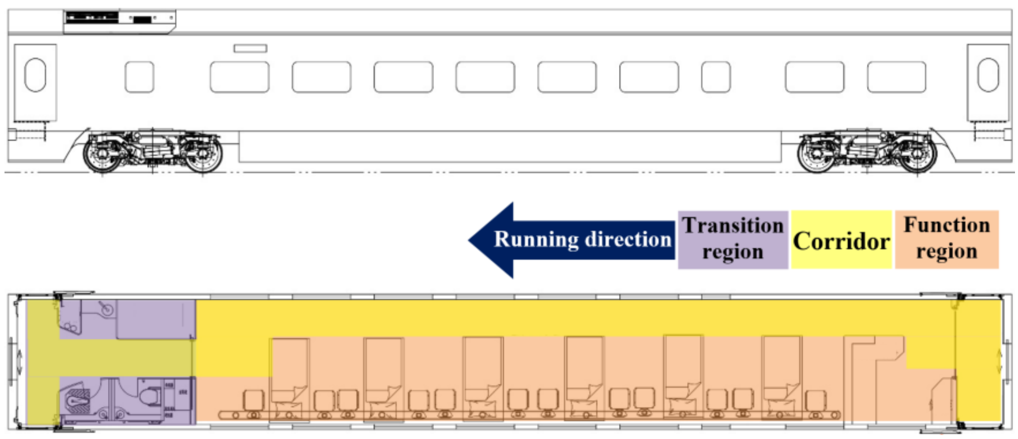


Figure 10. Carriage No. 4 of the high-speed sanitary train: space layout of the critical illness compartment.

(5) Reserve and preparation carriage

Carriage No. 5 of the high-speed health train is a reserve and preparation carriage. The functions are three medical consumables rooms, pharmacy, liquid medicine preparation room, medical transport equipment storage room, and daily material storage room in order of running direction, as shown in Figure 11.

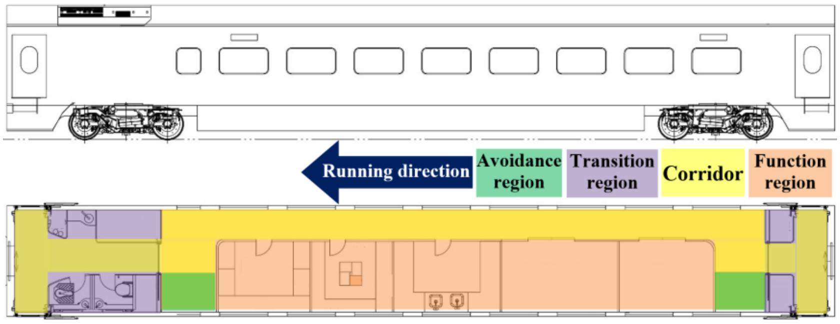


Figure 11. Carriage No. 5 of the high-speed sanitary train: space layout of the reserve and preparation carriage.

(6) Minor injury care carriage

Carriage No. 6 of the high-speed health train is a minor injury nursing carriage. The minor injury nursing carriage adopts a spatial layout similar to that of the intensive care carriage. The left side of the running direction is the nursing unit, and the right side is the passage corridor, as shown in Figure 12.

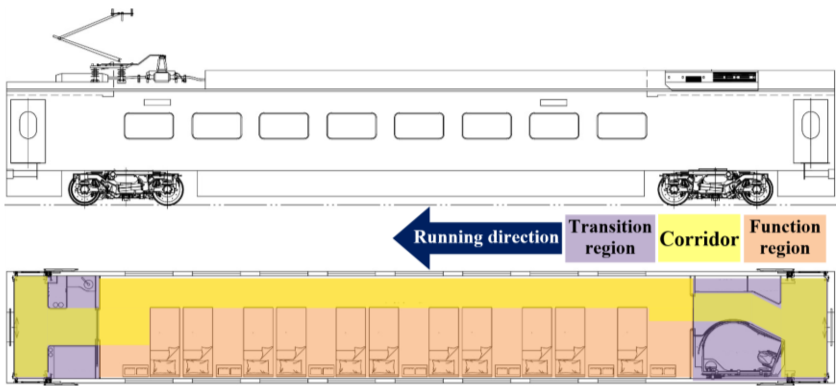


Figure 12. Carriage No. 6 of the high-speed sanitary train: spatial layout of the minor injury care compartment.

(7) Dining carriage

Carriage No. 7 of the high-speed health train is a dining carriage, and the functional area is divided into three parts: dining room, preparation room, and meal storage room, as shown in Figure 13.

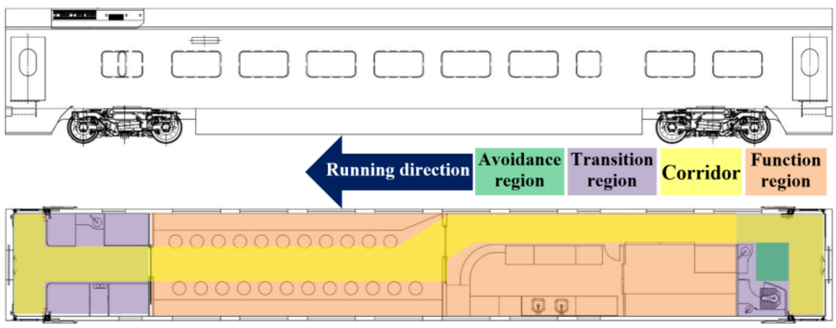


Figure 13. Carriage No. 7 of the high-speed sanitary train: dining car spatial layout.

(8) Sleeping carriage

Carriage No. 8 of the high-speed health train is a sleeping carriage, that is, a tail carriage, which mainly provides a place for the train staff and medical staff to rest for continuous operation, as shown in Figure 14.

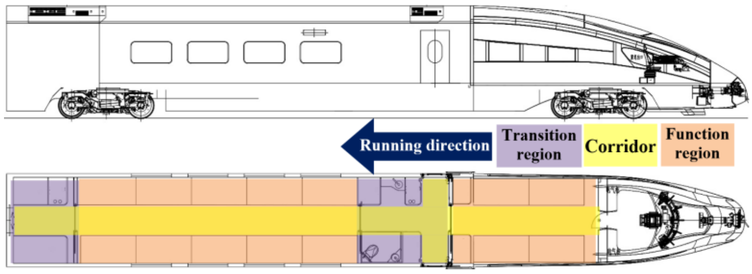


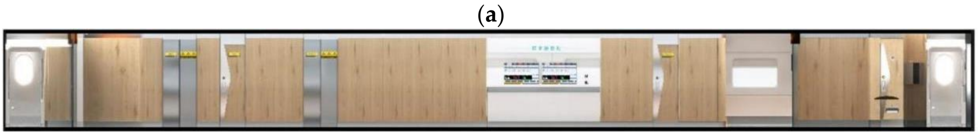
Figure 14. Carriage No. 8 of the high-speed sanitary train: space layout of the sleeping carriage.

3.3. Interior Design Effect of the Carriage

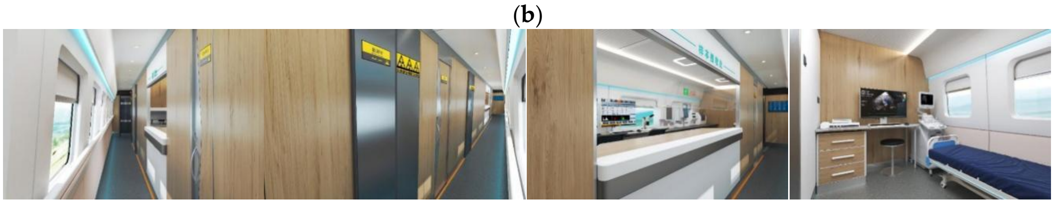
The industrial design of the internal space of the medical carriage within the high-speed health train is based on the internal space of the high-speed train carriage, with considerations given to both visual and emotional perception factors. The research process also needs to consider the environmental perception and restorative environmental needs of place psychology: influencing people's perception of design, aesthetics, spatial layout, and environmental cues, promoting relaxation, reducing stress, and improving mental health. Extensive research on relevant institutions and suppliers has been conducted to analyze and design the composition elements, diagnosis and treatment stages, composition relationships, and characteristics of the medical system in the high-speed health train. The internal space of the high-speed health train is designed using rhinoceros digital modeling software and Vary rendering software. The design effect of the inspection carriage is shown in Figure 13, the surgical carriage is shown in Figure 14, the intensive care carriage is shown in Figure 15, the minor injury care carriage is shown in Figure 16, the intensive care carriage is shown in Figure 17, and the minor injury care carriage is shown in Figure 18.

(1) Inspection carriage

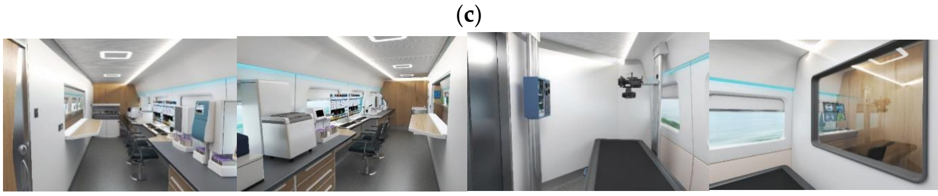
(**a**)



(**b**)



(**c**)



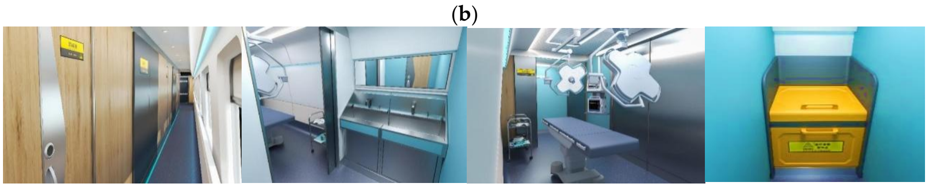
(**d**)

Figure 15. Effect drawing of the inspection compartment of the high-speed sanitary train. (**a**) Plan of the inspection compartment of the high-speed sanitary train. (**b**) Elevation view of the corridor of the inspection compartment of the high-speed sanitary train. (**c**) View of the corridor of the inspection carriage, the sample receiving station, and the echocardiography laboratory. (**d**) View of the comprehensive inspection room, ray room, and ray control room of the inspection compartment.

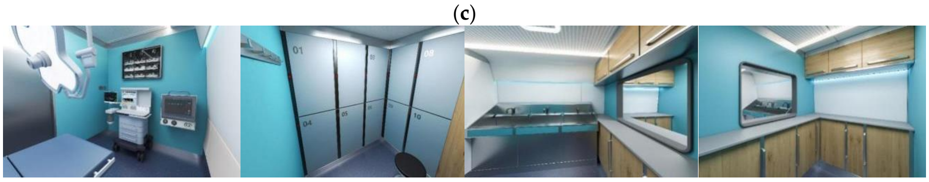
(2) Operating compartment

(a)

(b)



(c)



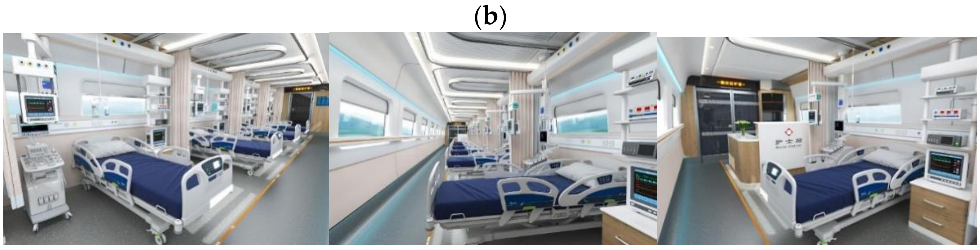
(d)

Figure 16. Effect drawing of the operating compartment of the high-speed sanitary train. (**a**) Plan of the operating compartment of the high-speed sanitary train. (**b**) Elevation view of the corridor of the operating compartment of the high-speed sanitary train. (**c**) Views of the corridor, disinfection room, operating room, and waste disposal room of the high-speed sanitary train. (**d**) View of the operating room, dressing room, washing room, and drying and packing room in the operating compartment of the high-speed sanitary train.

(3) Intensive care compartment

(**a**)

(**b**)



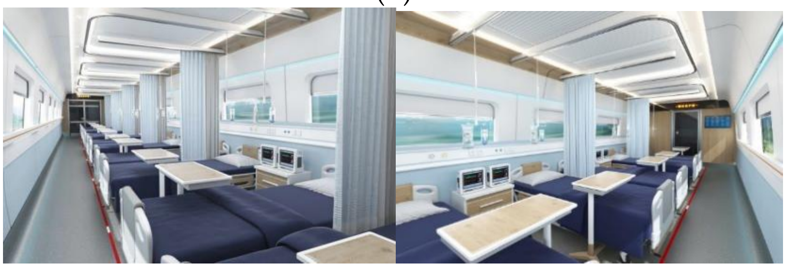
(**c**)

Figure 17. Rendering of the intensive care compartment of the high-speed sanitary train. (**a**) Plan of the intensive care compartment of the high-speed health train. (**b**) Elevation of the intensive care compartment of the high-speed sanitary train. (**c**) View of the intensive care compartment of the high-speed sanitary train.

(4) Minor injury care compartment

(**a**)

(**b**)



(**c**)

Figure 18. Rendering of the minor injury care compartment of the high-speed sanitary train. (**a**) Plan of the minor injury care compartment of the high-speed sanitary train. (**b**) Elevation view of the minor injury care compartment of the high-speed sanitary train. (**c**) Minor injury care compartment of high-speed sanitary train.

Based on the interior layout plan of the high-speed health train, the interior spaces of four medical carriages, namely, the inspection carriage, the operation carriage, the intensive care carriage, and the minor injury care carriage, are designed. The overall style of the interior space of the medial carriage continues the passenger interface style of the Fuxing standard EMU [20]. The carriage adopts matte white painted wall panels and matte light wood grain, and the floor adopts dark gray rubber floor cloth, stainless steel for decoration, and white main lighting. There are lights and light blue mood lighting. The medical carriage space is simple, modern, bright, and warm, which is in line with the high quality of modern transportation and the emotionality of the medical space.

4. Results

4.1. Virtual Simulation Evaluation

4.1.1. Software Simulation Process

JACK is a commonly used digital virtual simulation software that allows for the analysis of the accessibility, visibility, comfort, passability, and fatigue of digital models. Both 3ds MAX and Rhinoceros are powerful 3D modeling and design software packages widely employed in industrial design, architectural design, model visualization, and other fields. In the industrial design scheme of the high-speed health train, the advanced digital modeling capabilities of 3ds MAX and Rhinoceros are utilized to construct the digital models of carriages and equipment facilities. Subsequently, JACK is employed to evaluate the ergonomics of the industrial design scheme for the medical carriage within the high-speed health train. The evaluation results serve as a basis for assessing the credibility of the internal space layout of the medical carriage and provide recommendations for space optimization. The virtual simulation steps are as follows:

(1) Evaluation criteria

The passability in the ergonomic evaluation standard of high-speed health trains includes the width limit of the corridor in the cross-carriage flow line and the width limit of the door in the upper and lower carriage flow lines. At the same time, JACK simulation software provides accessibility, visibility, comfort, fatigue, and other human–machine evaluation criteria according to different evaluation needs and can produce evaluation results.

(2) In-vehicle model construction

The digital model of four medical carriages of a high-speed medical train is constructed using 3ds MAX and Rhinoceros, and the model is imported into JACK digital simulation software.

(3) Human model construction

JACK digital simulation software in the standard Chinese male and female digital human model is based on Chinese adult body size standard GB/T 10000-1988. Based on the 2009 version of Chinese adult human body size, the 5th percentile (P5) female and 95th percentile (P95) male digital human body models were constructed in the JACK system for virtual high-speed health train workers and the sick and wounded.

(4) Simulation Analysis

Through the evaluation of spatiotemporal gait parameters and behavior process, it is possible to analyze whether the interior structure of the carriage meets the ergonomic requirements and the rationality of its layout under various interaction scenarios of the simulated train. Simulation analysis is divided into static simulation and dynamic simulation. The scene and behavior of the simulation are shown in Table 1.

Table 1. Simulation evaluation types and behavior.

Type	Behavior	Activity	Scenario
Static	Sitting posture	Office work	Comprehensive laboratory, ultrasonic laboratory, X-ray observation room
		Operating instrument	Comprehensive laboratory, ultrasonic laboratory
	Standing posture	Operating instrument	Comprehensive laboratory, operating room, drying and packing room, cleaning room, intensive care unit
		Accessing items	Comprehensive laboratory, drying and packing room, cleaning room
	Squatting posture	Accessing items	Comprehensive laboratory, drying and packing room, cleaning room
Dynamic	Walking	Single peer	Interior of carriage and corridor
		Personnel intersection	Interior of carriage and corridor
	Load carriage	Medical care implementation	Intensive care carriage, minor injury care carriage
		Double-push wheel-lifting stretcher	Operation compartment and intensive care compartment
		Double-carry stretcher	Intensive care carriage
	Wheelchair access	Wheelchair for nursing staff	Minor injury care carriage
		Use of a wheelchair by the patient	Minor injury care carriage

4.1.2. Simulation Results and Analysis

(1) Inspection of carriages

Figure 19 shows the scene of the P95 male digital person when checking the normal passage of the carriage and the scene of the intersection of two P95 male digital persons when checking the opposite walking inside the carriage. From the simulation results, it can be seen that the width of the carriage aisle meets the needs of all physical personnel walking through.

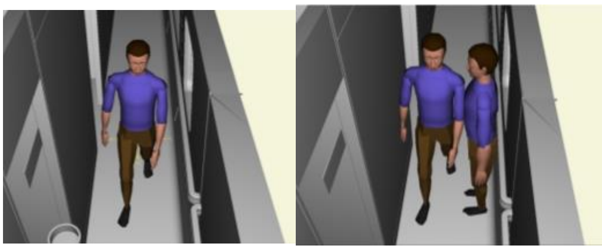


Figure 19. Simulation analysis of carriage aisle passability.

Figure 20a shows the reachable range of a P5 female digital person when operating a comprehensive inspection of indoor-related equipment in a standing position. Figure 20b shows a scene where a P95 male digital person works in a sitting position and obtains items in a squatting position, and the reachable range of a P95 female digital person standing at a sample collection station while collecting items. The simulation results show that the height and space size of each piece of equipment in the comprehensive story meet the requirements of the normal work of medical staff.

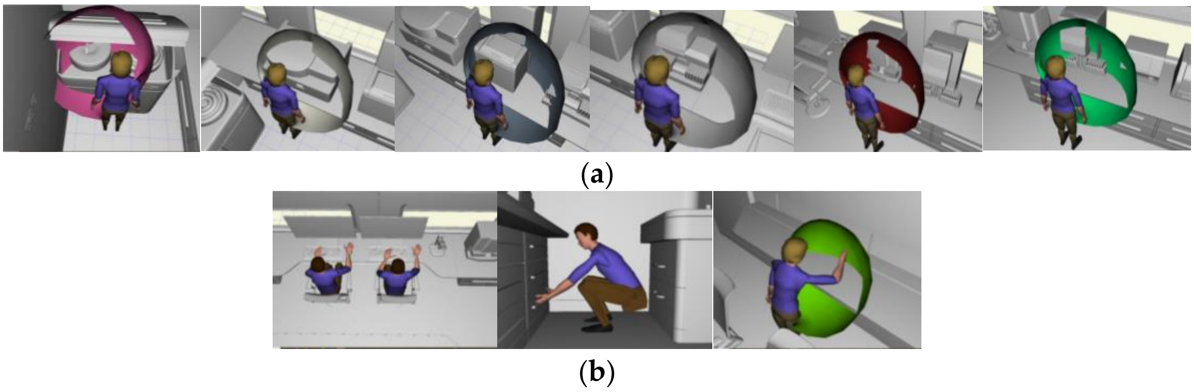


Figure 20. Simulation analysis of indoor operation behavior of comprehensive inspection. (**a**) P5 women operate equipment in the general laboratory. (**b**) P95 male, squatting to take items, and P5 female at the sample collection table to take items.

Figure 21 is a scene of a P95 male digital human sitting in the radiation observation room to operate computer equipment. The simulation results show that the medical staff can clearly observe the situation in the radiation room in the observation carriage, and there is enough space for the office and other related operations. Figure 22 shows a P5 female digital human sitting in the reachable range of the operating ultrasound workstation. The simulation results show that the scene layout of the ultrasound examination room conforms to ergonomics.

Figure 21. X-ray office.

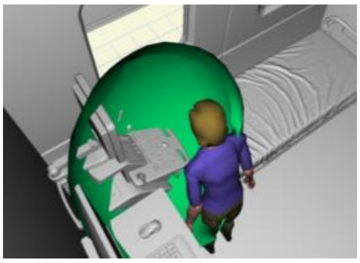


Figure 22. Ultrasonic instruments.

(2) Surgical carriage

Figure 23 shows the scene of two P95 male digital people passing through the aisle inside the inspection carriage. The simulation results show that the width of the corridor of the surgical carriage meets the needs of the physical personnel to walk through.

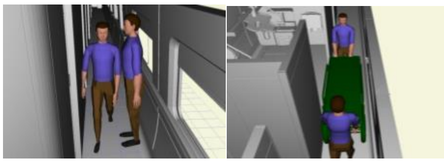


Figure 23. Simulation analysis of trafficability of the surgical carriage aisle.

Figure 24 shows the reachable range of a P5 female digital person when using an anesthesia machine, ventilator, and defibrillator in the operating room. The simulation results show that the instruments in the operating room are highly in line with the requirements of ergonomics, and the medical staff can use them normally.

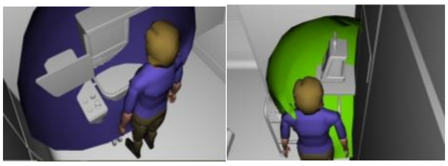
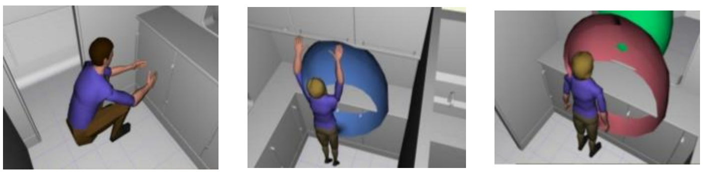


Figure 24. Simulation analysis of instrument operation in the operating room.

Figure 25a is the scene of the P95 male digital person picking up items in a squatting position in the dry packing room; Figure 25b shows the reachable range of the P5 female digital person as she stands in the dry packing room to pick up items in the upper cabinet; Figure 25c is a scene in which P5 women pick up items through the packing room window.



(**a**) (**b**) (**c**)

Figure 25. Simulation analysis of dry packing room behavior operation. (**a**) The scene of squatting and picking up items in the packaging room; (**b**) The reachable range when picking up items from cabinets in the dry packaging room; (**c**) The scene of picking up items through the packaging room window.

Figure 26a is a scene of three P5 female digital people performing cleaning tasks in the cleaning room and the reachable range of each digital person; Figure 26b shows the reachable range of the P5 female digital person standing in the dry packing room to pick up items in the upper cabinet; and Figure 26c shows the reachable range of the P5 female digital person as she passes items through the washroom window. The simulation results show that the delivery of items will not be out of reach for any body type.

(a) (b) (c)

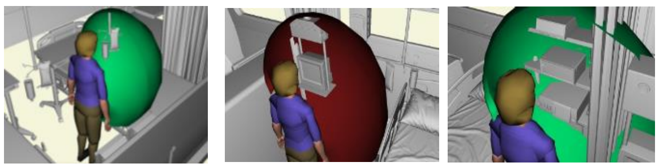
Figure 26. Simulation analysis of cleaning room behavior operation. (**a**) The scene of three P5 female digital people performing cleaning tasks in the cleaning room and the reachable range of each digital person; (**b**) The accessible range for retrieving items from the dry packaging room; (**c**) The reachable range when transferring items through the bathroom window.

(3) Intensive Care Carriage

Figure 27a is the scene of two P95 male digital people walking in the carriage with a 200 × 58 cm stretcher in both hands. Figure 27b shows two P95 male digital human hand-push two-wheeled lifting stretchers walking in the carriage; Figure 27c shows a scene of a P95 male digital hand-push medical trolley walking in the carriage. The simulation results show that the aisle width meets the conditions for medical staff to transport the wounded. Figure 28a shows the reachable domain of a P5 female digital human operating a vial in front of a hospital bed; Figure 28b,c show the reachable range of a P5 female digital person when operating various buttons in front of the bed. The simulation results show that the height and layout of each instrument inside the carriage are reasonable.

(a) (b) (c)

Figure 27. Simulation analysis of aisle trafficability of serious injury carriage. (**a**) The scene of walking in the carriage. (**b**) Manually push a two wheeled lifting stretcher to walk inside the carriage; (**c**) The scene of a hand propelled medical vehicle walking inside the carriage.

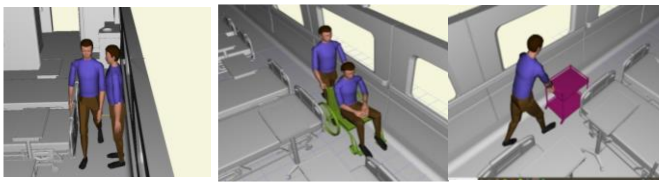


(a) (b) (c)

Figure 28. Simulation analysis of the operation of related instruments in the serious injury carriage. (**a**) Accessibility range for operating small bottles in front of the hospital bed; (**b**) P5 female digital person is operating the button. (**c**) The reachable range of female digital humans when operating buttons.

(4) Analysis of light injury nursing carriage

Figure 29a is the scene where two male digital people meet in the aisle of a lightly injured carriage; Figure 29b is a P95 male digital hand-push wheelchair scene; and Figure 29c is a P95 male digital man pushing a medical trolley in the aisle. The simulation results show that the aisle width of the lightly injured carriage meets the needs of all kinds of people.



(**a**) (**b**) (**c**)

Figure 29. Simulation analysis of aisle trafficability of minor injury carriage. (**a**) The scene where two male digital figures meet in the hallway; (**b**) Hand propelled wheelchair scene; (**c**) Pushing a medical handcart in the hallway.

Through the above static and dynamic simulations, the relevant results in the static and dynamic situations can be observed when simulating digital people in sitting, standing, working, and interacting scenarios, which shows that the simulation results are relatively good in terms of visibility, the adaptability of space settings, and the reachability of equipment.

4.2. Subjective Fuzzy Evaluation

4.2.1. Evaluation Course

The design scheme evaluation of high-speed health trains is mainly used for the quantitative evaluation and comparison of the schemes. The design scheme evaluation of high-speed health trains belongs to the multi-factor and multi-index structures. Therefore, the evaluation index system of the industrial design scheme of high-speed health trains is constructed based on the hierarchical structure of the factor index. The fuzzy evaluation method is used to calculate the index and factor weight, and the comprehensive evaluation value of the industrial design scheme of the high-speed health train is calculated according to the hierarchical structure [21]. The evaluation objects of the industrial design scheme of the high-speed health trains include four factors: function, layout, space aesthetics, and space utilization and their detailed indexes, as shown in Table 2.

Table 2. Evaluation factors and indexes of industrial design scheme of high-speed sanitary train.

Index Types	**Index**
F_1 Function	A_1 Comprehensive functional configuration
	A_2 Reasonable functional configuration
	A_3 Spatial isolation
F_2 Layout	A_4 Rationality of carriage formation
	A_5 The rationality of space layout in the carriage
	A_6 Rationality of equipment layout in department
F_3 Space aesthetics	A_7 Modeling harmony
	A_8 Colour harmony
	A_9 Delicate details
F_4 Space use	A_{10} Space utilization
	A_{11} Medical carrying capacity
	A_{12} Injury-carrying capacity

The assessment steps are:

Step 1: Combined with Saaty's 1~9 importance scale method, the importance of each factor relative to another factor is compared. The scale and meaning of the evaluation matrix are shown in Table 3, and the fuzzy evaluation matrix $\boldsymbol{A}$ is constructed, as shown in Equation (2).

$$\boldsymbol{A} = \begin{bmatrix} a_{11} & \cdots & a_{1\,12} \\ \vdots & \ddots & \vdots \\ a_{12\,1} & \cdots & a_{1212} \end{bmatrix} \quad (2)$$

Table 3. Saaty's 1–9 importance scale method.

Scale	Meaning
1	Compared to two elements, they have the same importance
3	Compared to the two elements, the former is slightly more important than the latter
5	Compared to the two elements, the former is significantly more important than the latter
7	Compared to the two elements, the former is more strongly important than the latter
9	Compared to the two elements, the former is extremely important compared to the latter
2, 4, 6, 8	Intermediate value of adjacent judgments mentioned above
Reciprocal	If the importance ratio of element i to element j is a_{ij}, then the importance ratio of element j to element i is $1/a_{ij}$

Step 2: Normalize the judgment matrix $\boldsymbol{A}$ by column to obtain the matrix $\boldsymbol{B}$:

$$\begin{cases} G_i = \sum_{j=1}^{12} a_{ij} \\ b_{ij} = a_{ij}/G_i \end{cases} (i = 1, \ldots 12) \quad (3)$$

Step 3: Sum matrix $\boldsymbol{B}$ by rows to obtain matrix $\boldsymbol{C}$:

$$c_i = \sum_{j=1}^{12} b_{ij}\ (i = 1, \ldots, 12) \quad (4)$$

Step 4: Normalize the matrix $\boldsymbol{C}$; n is the number of elements in the matrix, and the eigenvector $\boldsymbol{W}$ of the matrix $\boldsymbol{B}$ is obtained:

$$w_i = \sum c_i/n \quad (5)$$

Step 5: Check the consistency of the weight; consistency indicators include CI and CR; when $CI < 0.1$ and $CR < 0.1$, the judgment matrix consistency is acceptable, otherwise, readjust the judgment matrix. RI is a different constant depending on n.

$$\begin{cases} \lambda_{\max} = 1/n \times \sum_i (c_i/w_i) \\ CI = (\lambda_{\max} - n)/n - 1 \\ CR = CI/RI \end{cases} \quad (6)$$

Step 6: Invite 20 high-speed health train research group experts and medical equipment experts to score qualitative indicators from 1 to 7, where 1 point means very dissatisfied and 7 points mean very satisfied. The quantitative evaluation value is standardized by the range variation method.

$$x' = \frac{x - \min\{x\}}{\max\{x\} - \min\{x\}} \quad (7)$$

Step 7: P is the average score of a single index scored by 20 experts, and W is the index weight obtained by Step 5. The evaluation results of factor F_n are as follows:

$$P_{Fn} = \sum_m P_{Am} \times W_{Am} \quad (8)$$

Step 8: High-speed health train industrial design scheme comprehensive score:

$$evl = \sum_{n} P_{Fn} \times W_{Fn} \quad (9)$$

4.2.2. Evaluation Results and Analysis

According to the above method, a total of more than 20 experts in the fields of transportation vehicle design, health service, and medical equipment were invited from the General Hospital of Western Theater Command, Southwest Jiaotong University and Third Military Medical University. The comprehensive importance and quantitative evaluation value of relevant factors were scored. The comparative research results mainly focus on the design environment of reference [22], the inspection carriage of reference [23], and the surgical carriage of reference [24]. The above research results are comprehensively evaluated and compared with the research results of this article. The comprehensive importance of the four factors $\boldsymbol{F}_1$, $\boldsymbol{F}_2$, $\boldsymbol{F}_3$, and $\boldsymbol{F}_4$ is evaluated through expert scoring. The matrix is as follows:

$$\boldsymbol{F} = \begin{bmatrix} 1 & 1/2 & 3 & 1 \\ 2 & 1 & 5 & 2 \\ 1/3 & 1/5 & 1 & 1/3 \\ 1 & 2 & 3 & 1 \end{bmatrix}, \quad \boldsymbol{W} = \begin{pmatrix} 0.2141 & 0.3957 & 0.0736 & 0.3166 \end{pmatrix},$$

and $\lambda_{max} = 4.1596$, $CI = 0.0532$, $CR = 0.0917$. By evaluating the type of $\boldsymbol{F}_1$, $\boldsymbol{F}_2$, $\boldsymbol{F}_3$, and $\boldsymbol{F}_4$ index, the matrix is as follows:

$$\boldsymbol{F}_1 = \begin{bmatrix} 1 & 1/5 & 2 \\ 5 & 1 & 6 \\ 1/2 & 1/6 & 1 \end{bmatrix}, \quad \boldsymbol{W}_1 = \begin{pmatrix} 0.1741 & 0.7226 & 0.1033 \end{pmatrix}, \text{ and } \lambda^1{}_{max} = 3.0293,$$

$CI_1 = 0.0147$, $CR_1 = 0.0253$;

$$\boldsymbol{F}_2 = \begin{bmatrix} 1 & 2 & 2 \\ 1/2 & 1 & 1 \\ 1/2 & 1 & 1 \end{bmatrix}, \boldsymbol{W}_2 = \begin{pmatrix} 0.5 & 0.25 & 0.25 \end{pmatrix}, \text{ and } \lambda^2{}_{max} = 3, CI_2 = 0, CR_2 = 0;$$

$$\boldsymbol{F}_3 = \begin{bmatrix} 1 & 1/3 & 2 \\ 3 & 1 & 4 \\ 1/2 & 1/4 & 1 \end{bmatrix}, \quad \boldsymbol{W}_3 = \begin{pmatrix} 0.2395 & 0.6232 & 0.1373 \end{pmatrix}, \text{ and } \lambda^3{}_{max} = 3.0184,$$

$CI_3 = 0.0092$, $CR_3 = 0.02$; $\boldsymbol{F}_4 = \begin{bmatrix} 1 & 2 & 2 \\ 1/2 & 1 & 1 \\ 1/2 & 1 & 1 \end{bmatrix}$, $\boldsymbol{W}_4 = \begin{pmatrix} 0.5 & 0.25 & 0.25 \end{pmatrix}$, and $\lambda^4{}_{max} = 3$, $CI_4 = 0$, $CR_4 = 0$.

According to the calculation, the above judgment matrices all pass the consistency test. A total of 20 expert evaluators scored the indexes of the design scheme proposed in this paper (scheme 1) and another scheme of the research group [22–24] (scheme 2), and the mean value of each evaluation index of the industrial design scheme of the high-speed health train is shown in Figure 30.

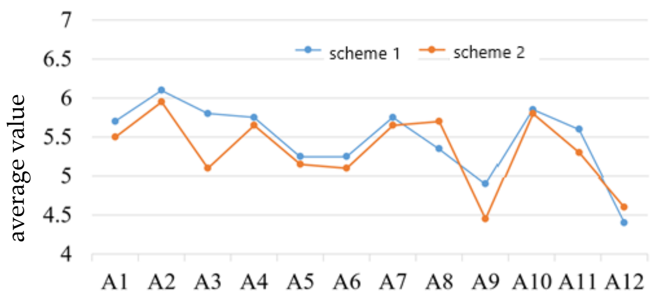


Figure 30. Comparison of mean values of index evaluation of high-speed sanitary train design scheme.

As can be seen from Figure 30, in scheme 1, among the 12 indicators, the evaluation values of scheme 1 are higher than those of scheme 2 in terms of comprehensive functional configuration, reasonable functional configuration, spatial isolation, rational combination of carriages, reasonable layout of interior spaces, reasonable layout of indoor equipment, harmonious appearance, exquisite details, space utilization rate, and medical load capacity. The evaluation value of scheme 1 is lower than that of scheme 2. The evaluation value of each factor of the industrial design scheme of a high-speed health train is calculated by Equation (8), as shown in Figure 31.

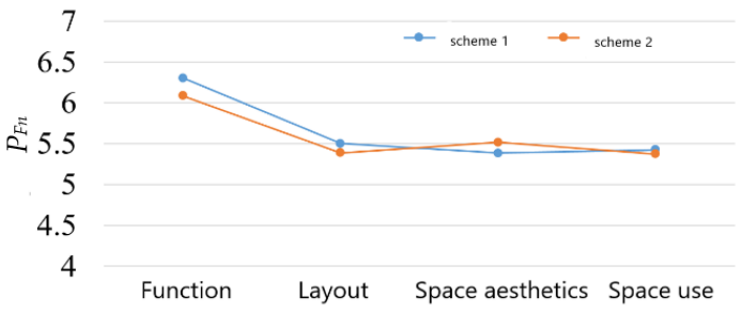


Figure 31. Comparison of the mean value of the evaluation of the design scheme factors of the high-speed health train.

The calculation of Equation (9) shows the overall evaluation results of industrial design scheme 1 and industrial design scheme 2 of high-speed health trains can be obtained, as shown in Figure 32.

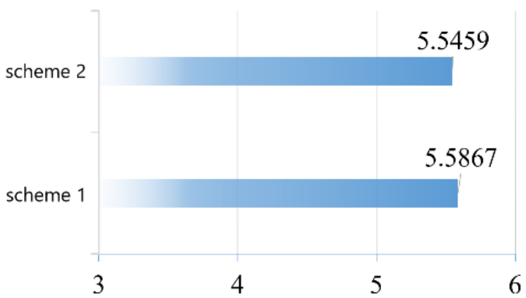


Figure 32. Scheme evaluation results.

From Figure 32, we can see that the overall evaluation values of the industrial design scheme 1 and scheme 2 of the high-speed health train are 5.5867 and 5.5439, respectively, and then the comprehensive evaluation of the industrial design scheme (scheme 1) of the high-speed health train proposed in this paper is obtained. Another set of schemes (scheme 2) is proposed in this topic. In summary, based on the layout plan of the interior space of the high-speed health train and the adaptability requirements of the human–machine environment system, a comprehensive comparison was made between the existing industrial design schemes of the appearance and inspection carriages, surgical carriages, intensive care carriages, and minor injury care carriages of the high-speed health train. The results show that the proposed scheme has comprehensive and reasonable functional configurations. The spatial isolation and other ten indicators are superior to the existing plans of the research group. The weight analysis calculation shows that the proposed plan in this study has significant advantages and can provide a theoretical basis and design reference for the development of high-speed health trains.

5. Conclusions

In this paper, SLP is improved according to the characteristics of high-speed health trains. Based on the improved SLP method, a high-speed health train carriage unit marshaling and carriage layout planning model are proposed. Through the analysis of the relationship between logistics and non-logistics in eight-carriage high-speed sanitation trains, a carriage marshaling scheme is proposed. Based on the space limitations of high-speed EMU and the adaptation requirements of the man–machine environment system, the layout scheme of eight marshaling carriages of a high-speed sanitation train is proposed.

Aiming at the industrial design scheme of other high-speed health trains, an evaluation method combining simulation implementation and subjective analysis is proposed. This method analyzes the adaptability of the human–machine environment relationship in the carriage through virtual simulation and compares the two design schemes according to the subjective evaluation analysis method. According to the quantitative evaluation results, the comprehensive effect of the design scheme in this paper is better, which can provide a basis and reference for the research and development of high-speed health trains. It is worth noting that the tasks, processes, and carriage formation plans of non-wartime high-speed health trains are also important components of the high-speed health train plan. In addition, sanitary trains based on 16-carriage train marshaling are not directly linearly stacked on the basis of 8-carriage marshaling. Therefore, high-speed sanitary trains with a 16-car formation should undergo carriage reconfiguration and formation research based on task requirements, which are future research directions.

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