A Distributed Framework for Indoor Product Design Using VR and Intelligent Algorithms

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***Abstract*—This paper presents an innovative approach to the digital design of indoor home products by integrating virtual reality (VR) technology with intelligent algorithms to enhance design accuracy and efficiency. A model combining the Red deer Optimization Algorithm with a Simple Recurrent Unit (SRU) network is proposed to evaluate and optimize the design process. The study develops a digital design framework that incorporates key evaluation factors, optimizing the SRU network through the Red deer Optimization Algorithm to achieve higher precision in design applications. The model's performance is validated through extensive experiments using metrics such as Mean Absolute Error (MAE), Root Mean Square Error (RMSE), and Mean Absolute Percentage Error (MAPE). Results show that the RDA-SRU model outperforms other methods, with the smallest MAE of 0.133, RMSE of 0.02, and MAPE of 0.015. Additionally, the model achieved an R^2 value of 0.968 and the shortest evaluation time of 0.028 seconds, demonstrating its superior performance in predicting and evaluating digital design applications for home products. These findings indicate that the integration of VR with intelligent algorithms significantly improves user experience, customizability, and the overall accuracy of digital design processes. This approach offers a robust solution for designers to create more efficient and user-centric home product designs, meeting growing customer demands for immersive and interactive design experiences.**

Keywords—Interior home products; virtual reality technology; digital design algorithms; improved simple cyclic units; intelligent algorithms for design application evaluation

I. Introduction

With the development and popularization of Internet technology and artificial intelligence (AI) algorithms, the design field is diversifying, especially in the direction of digital applications, which has become the trend of the times and has unlimited development potential [1]. Virtual reality (VR) technology as the development of active new technology, constantly integrated into people's lives, especially in the field of scene visualization is widely used [2]. The combination of VR technology and realistic real interior home product design, constructing an interior home design scene close to the real world, promoting the design of interior home products, improving the degree of tacit understanding between the product and the user to a certain extent, and improving the user's experience of the product [3]. With the arrival of the product experience-oriented consumer design era, indoor home product design needs to adapt to the needs of humanization, combined with VR technology has become one of the ways to solve the problem of meeting the needs of users in home product design [3]. Based on VR technology indoor home products digital design method from the visual can improve the sense of interesting online home operation experience, while improving the efficiency of product design [4]. The accurate evaluation of digital design technology as a combination of VR technology in the home product design process feedback is an important link to help improve the accuracy of customer-oriented demand indoor home product design, but also improve the integrity of the home product design process [5]. The research direction of the digital design of indoor home products under the VR scene mainly focuses on the construction of scenes in virtual home product design, product virtualization design, product interaction design, digital application test analysis and other aspects of the research [6]. Scholars have made many contributions. Basha et al. [7] optimized the method and scene of secondary modeling and proposes a rapid modeling system based on VR technology; Sobhy and Abouelnaga [8] studied the value of the integration of VR technology and indoor home product design and introduces the stage-by-stage method of integration design; Wei et al. [9] analyzed the development trend of VR technology and combines with the characteristics of the experiential display design, and analyzes the characteristics of the experiential display design from a variety of perspectives VR technology in indoor home design application characteristics; Ye and Li [10] puts forward a virtual scene optimization layout strategy that can adapt to the real-time interactive display of different cell phone devices, and realizes the virtual scene of indoor home product design; Hewitt et al. [11] researched the design and implementation of a three-dimensional product interactive display website using computer language; Rangaswamy et al. [12] built a digital design based on VR technology process, and extracted relevant digital design evaluation indexes, and used hierarchical analysis to solve the problem of digital design evaluation of indoor furniture products.

With the development of AI algorithms, digital design application methods based on machine learning algorithms and deep learning algorithms enter the field experts and scholars [13]. Currently, design application evaluation methods based on intelligent algorithms include k-means clustering algorithm, support vector machine, decision tree, neural network, deep learning and so on [14]. At present, the research on the method of digital design of indoor home products based on intelligent algorithms combined with VR technology is less, in its infancy, and the effect and accuracy of the application formed cannot meet the needs of customers [15, 16]. For this reason, this paper proposes a digital design method for indoor home products based on the Red deer Optimization Algorithm to improve the simple recurrent unit neural network [17, 18]. Focusing on the digitalization of indoor home products, the digital design framework of indoor home products is constructed by analyzing

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the digital design process, and the key technologies of digital design are illustrated and introduced; for the evaluation of the digital design application of indoor home products in combination with VR technology, the simple recurrent unit network is trained and optimized using Red deer Optimization Algorithm, and the digital design evaluation model based on RDA-SRU network is constructed; the digital design application evaluation model is verified through experiments. The digital design application evaluation model based on RDA-SRU network is constructed by using the Red deer optimization algorithm; the application feasibility and computational efficiency of the method proposed in this paper are proved through experimental verification.

II. Digital Design Framework for Interior Home Products

A. Virtual Reality

VR technology is through the comprehensive use of computer graphics science on the seeming, multimedia teaching science on the seeming, human-computer interaction science and technology, Internet information, sensors and check measurement technology, three-dimensional performance technology and simulation technology and other types of disciplines and technologies, to create a real audio-visual, touch one of the artificial virtual environment [19], specifically as shown in Fig. 1. In the virtual environment, the user with the help of professional technical equipment, the most natural way to interact with the objects in life, so as to achieve a stronger sense of immersion and real feelings.

The key components of VR technology include headset devices, intrusion devices, 3D audio and sound technologies, and simulated environment modeling and rendering [19] (Fig. 2), which are mainly used in the fields of gaming, education, healthcare, industrial design, entertainment, and military [20] (Fig. 3).

B. Digital Design Process

1) Definitions and key techniques, tools: Digital design of interior home products is the process of designing, simulating, optimizing and manufacturing home products using advanced computer technology, information technology and digital tools. This design methodology improves design efficiency, reduces errors, lowers costs, and allows for better customization and service. Digital design can also help companies achieve scale customization, flexible production, and networked services, thus improving competitiveness and market responsiveness [21].

The key technologies and tools used for the digital design of interior home products include CAD/CAE/CAPP/CAM/PDM integration software, parametric modeling technology, VR (VR)/augmented reality (AR) technology, product lifecycle management (PLM), and enterprise resource planning (ERP) systems, etc., as shown in Fig. 4.

The process of digital design for interior home products is shown in Fig. 5, with the following steps: a) Demand analysis: collecting information on customers' individual needs and market trends; b) Conceptual design: based on the results of the demand analysis, preliminary design ideas; c) Detailed design: using digital tools to carry out accurate product design, including dimensions, materials, colours, etc.; d) Simulation and testing: by computer simulation to verify the feasibility and performance of the design; e) Prototyping: making samples based on the design drawings for actual testing and evaluation; f) Production preparation: after completing the design, preparing the documents and processes required for production; g) Production and quality control: monitoring the product quality during the production process to ensure compliance with the design; and h) Feedback services: providing installation guidance, maintenance services and customer support [22].

Technology can help designers and clients preview and experience design solutions in three-dimensional space, improving the interactivity and realism of design, and is mainly used in the c) detailed design phase.

Fig. 1. Virtual reality technology.

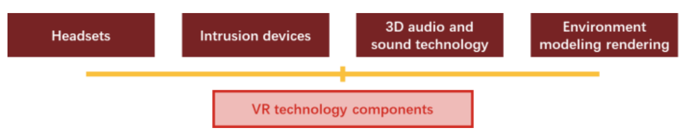

Fig. 2. VR technology components.

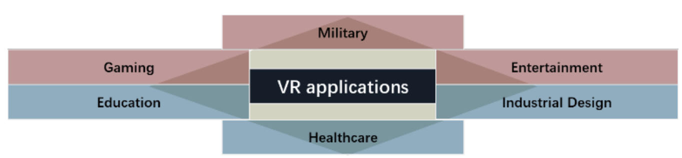

Fig. 3. Application areas of VR technology.

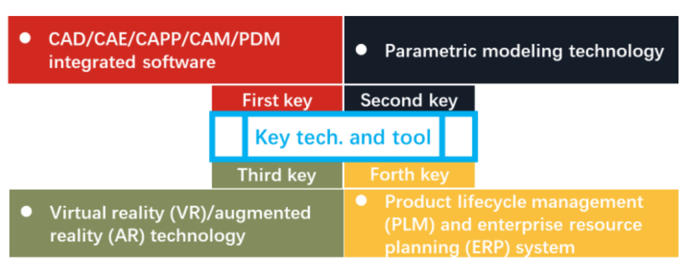

Fig. 4. Key technologies and tools for digital design of interior home products.

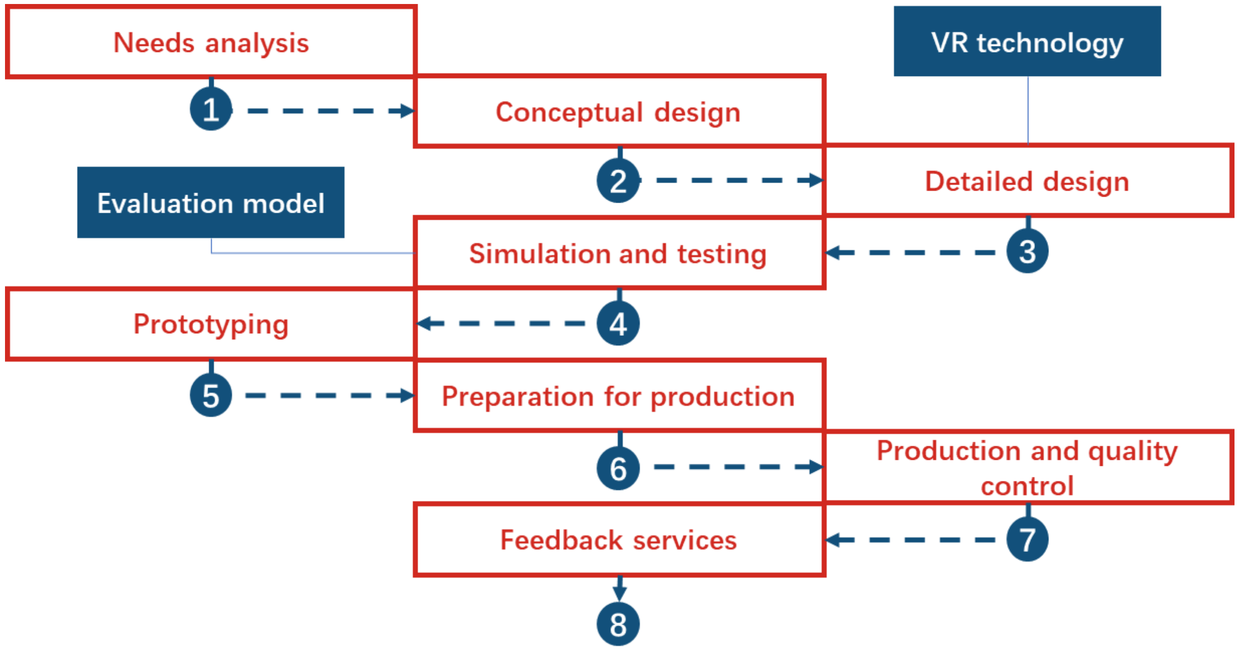

Fig. 5. Process of digital design for interior home products.

Digital design application evaluation can help designers quantify the suitability of interior home products and accelerate the improvement of the efficiency of digital design of interior home products, which is mainly used in the d) simulation and testing phases.

C. Digital Design Framework and Key Technology Analysis

1) Digital design framework: In order to improve the efficiency of digital design of indoor home products based on VR technology and enhance the evaluation accuracy of digital design application of indoor home products, this paper combines the intelligent optimization algorithm (Red deer Optimization Algorithm) and the deep learning algorithm (Simple Recurrent Unit Network) to propose a digital design method of indoor home products based on the RDA-SRU model, and the specific framework is shown in Fig. 6.

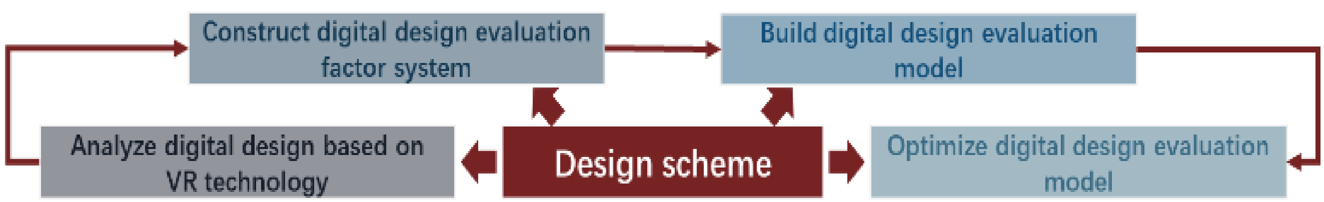

Fig. 6. Digital design framework for interior home products.

According to the analysis of the digital design framework, the digital design method of indoor home products based on RDA-SRU model by combining VR technology mainly consists of subsystems such as evaluation factor set construction, data preprocessing, digital design evaluation model construction optimization, evaluation performance analysis, etc., which are shown in Fig. 7.

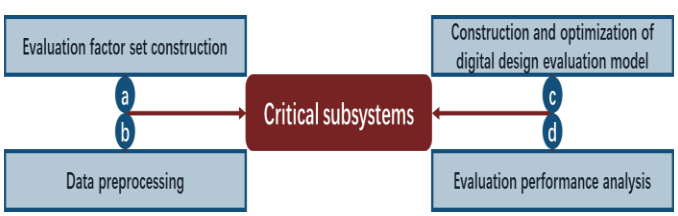

Fig. 7. Key subsystems for digital design of indoor home products.

2) Analysis of key technologies

a) Evaluation factor set construction: In the evaluation factor set construction subsystem, the digital design process of indoor home products combined with VR technology is analyzed to extract the digital design evaluation feature indicators and construct the evaluation factor set, and the specific subsystem inputs, outputs, and structures are shown in Fig. 8.

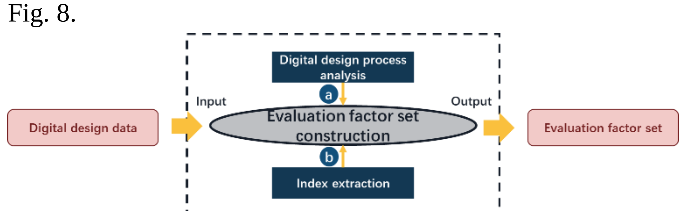

Fig. 8. Subsystem for constructing the factor set for digital design evaluation.

According to the principles of factor selection, such as demand orientation, objective scientificity, and quantitative comparability, the evaluation factors of digital design of indoor home products combined with VR technology are extracted from the phases of environment design F, 3D modeling S, and human-computer interaction T, and the evaluation factor set shown in Fig. 9 is constructed.

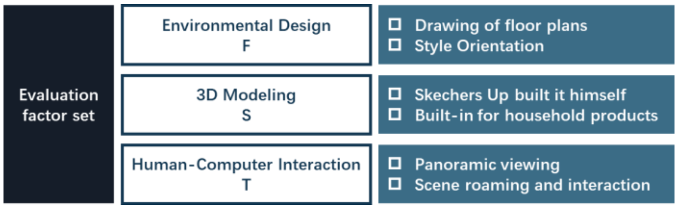

Fig. 9. Evaluation factor set construction.

b) Data pre-processing: In the data preprocessing subsystem of evaluation indexes for the digital design process of indoor home products, the data set used for training the evaluation model is obtained in a regular way through the outlier elimination technique, missing value regression filling technique, normalization processing technique, and dimensionality reduction technique [23], and the specific subsystem inputs, outputs, methods, and structures are shown in Fig. 10.

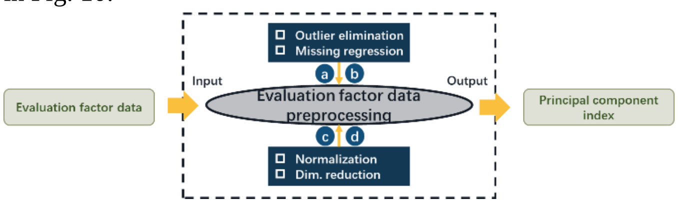

Fig. 10. Schematic diagram of the digital design evaluation data preprocessing subsystem.

c) Optimization of digital design evaluation model construction: In the optimization subsystem of evaluation model construction, the Red deer optimization algorithm is used to learn and train the weights and biases of the simple cyclic unit network, and to construct the digital design evaluation model based on the Red deer optimization algorithm-simple cyclic unit network, and the specific subsystem inputs, outputs, methods, and structures are shown in Fig. 11.

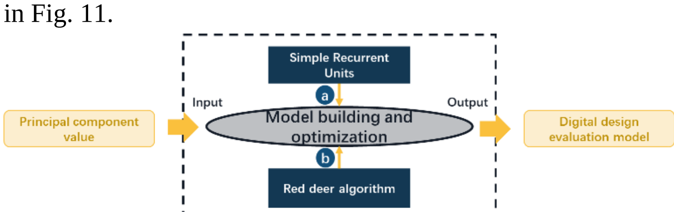

Fig. 11. Schematic diagram of the optimization subsystem for digital design evaluation model construction.

d) Evaluation performance analysis: In the digital design evaluation model performance analysis subsystem, MAE, RMSE, MAPE, R2, and evaluation time [24] are used as the performance evaluation indexes of the digital design evaluation model, as shown in Fig. 12.

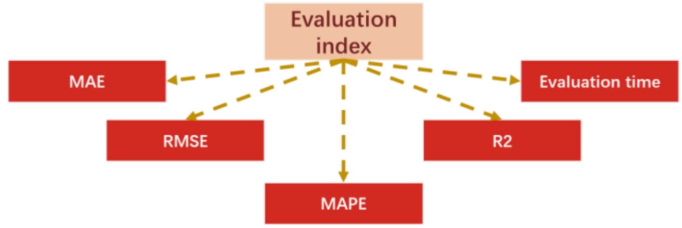

Fig. 12. Performance evaluation indicators.

III. Red Deer Optimization Algorithm for Interior Home Products

A. Simple Cyclic Unit Networks

1) Fundamentals: SRU (Simple Recurrent Units) [25] is a simplified recurrent neural network (RNN) architecture designed to increase the training speed of RNNs and allow for more efficient parallel computation. SRUs enable the network to be trained faster on modern GPUs by reducing the dependencies between time steps. SRUs are designed with the concept of optimizing the main portion of the computation is optimized to be a complete computation that does not depend on previous time steps, thus enabling an easily parallelizable network structure, the structure of which is shown in Fig. 13.

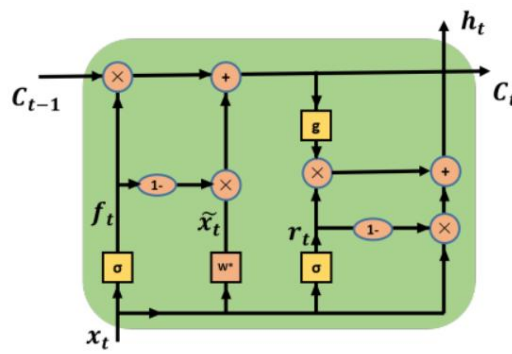

Fig. 13. Structure of SRU network model.

$$\tilde{x}_t = W x_t \tag{1}$$

$$f_t = \sigma\left(W_f x_t + b_f\right) \tag{2}$$

$$r_t = \sigma\left(W_r x_t + b_r\right) \tag{3}$$

$$c_t = f_t \odot c_{t-1} + \left(1 - f_t\right) \odot \tilde{x}_t \tag{4}$$

$$h_t = r_t \odot g\left(c_t\right) + \left(1 - r_t\right) \odot x_t \tag{5}$$

Where f_t is the forget gate and r_t is the reset gate.

2) Characteristics of SRU: The SRU network is characterized by the following features: 1) parallelization capability, 2) reduced computational complexity, and 3) gradient propagation improvement [26], as shown in Fig. 14.

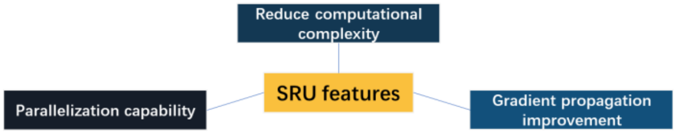

Fig. 14. SRU network characteristics.

3) SRU applications: SRU networks are suitable for a variety of deep learning tasks that require the processing of sequential data, including but not limited to the fields of natural language processing, speech recognition, and time series analysis, due to their improved training speeds and parallel computing capabilities [26] (Fig. 15).

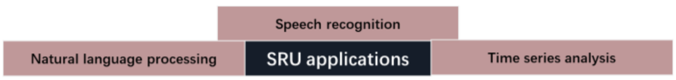

Fig. 15. SRU web application.

B. The Redouble Optimization Algorithm

1) Algorithmic principles: The Red deer optimization algorithm (RDA) [27] was inspired by observing the mating activity of the horse deer species living in the UK during the breeding season. The population of horse deer is divided into four main species: male deer (Male), female deer (Hind), commander deer (Com), and stag (Stag). The RDA algorithm simulates the behaviors of roaring, fighting, and mating in a group of horse deer to solve the optimization problem, and demonstrates a better performance in complex problems.

a) Generation of initialized horse deer populations: In the RDA algorithm, the optimization object is a horse deer and each horse deer is represented as follows:

$$X_i = [x_1, x_2, x_3, \cdots, x_n] \quad (6)$$

Where, X_i is the i^{th} individual horse deer and n is the dimension of the RDA problem to be optimized.

In order to evaluate the merit of individual horse deer, it is necessary to introduce a fitness function:

$$f(X_i) = f(x_1, x_2, x_3, \cdots, x_n) \quad (7)$$

where $f(X_i)$ is the value of X_i fitness function.

Based on the size of the fitness value, the better N_{male} stags were selected as males and the remaining stags as females ($N_{hind} = N_{pop} - N_{male}$), the size of N_{male} denotes the algorithmic elite criterion, which maintains the augmentation properties of the algorithm, and N_{hind} takes into account the diversification phase of the algorithm.

b) Roaring stage between male deer: The roaring phase (Fig. 16) is searching the neighborhood space, and if a better Red deer is found in the neighborhood, the previous Red deer is replaced by the better one, as modeled below:

$$New_{male} = \begin{cases} Old_{male} + a_1((UB - LB) \times a_2 + LB) & a_3 \geq 0.5 \\ Old_{male} - a_1((UB - LB) \times a_2 + LB) & a_3 < 0.5 \end{cases} \quad (8)$$

Among them, Old_{male} is the current position of male deer, New_{male} is the updated position of male deer, UB and LB are the upper and lower bounds of the search space, respectively, and a_1 , a_2 and a_3 are randomly generated numbers.

a) Commander deer selection: The division of males into Commander Deer (Com) and Stag (Stag), primarily to differentiate between stags that are more powerful in combat and more successful in expanding their territories, is calculated as follows:

$$N_{Com} = round\{\gamma \cdot N_{male}\} \quad (9)$$

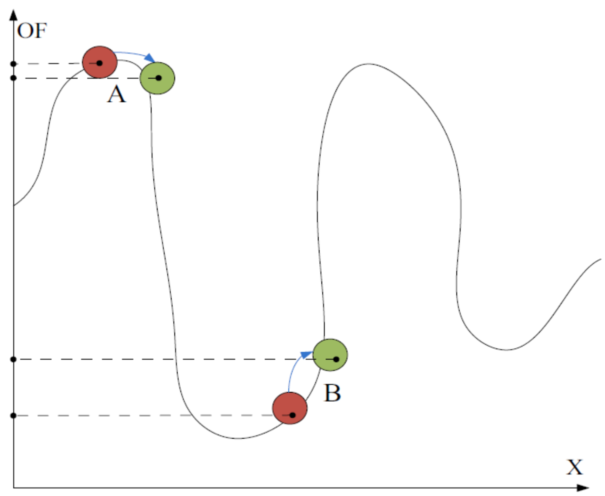

Fig. 16. The process of yelling.

Where, N_{Com} is the number of commander deer, γ is the initial value of the algorithm model, the value range is 0 to 1, the number of stags is $N_{Stag} = N_{male} - N_{Com}$, the specific distribution of the horse deer population is shown in Fig. 17.

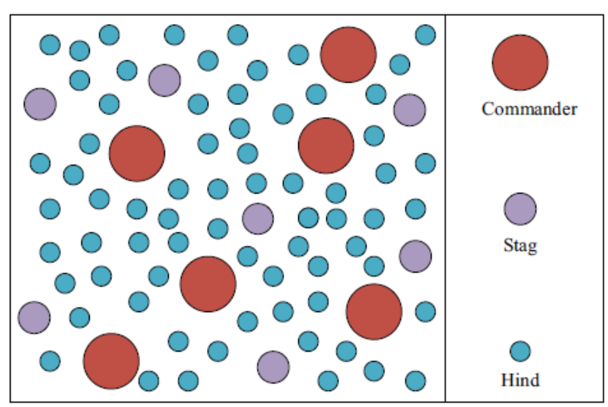

Fig. 17. Distribution of red deer populations.

b) Combat phase: From Fig. 18, Each commander deer will randomly fight a stag by approaching the other, causing a change in position, comparing fitness values, and replacing the commander deer with the superior stag individual, as calculated below:

$$New1 = \frac{(Com + Stag)}{2} + b_1 \times ((UB - LB) \times b_2 + LB) \tag{10}$$

$$New2 = \frac{(Com + Stag)}{2} - b_1 \times ((UB - LB) \times b_2 + LB) \tag{11}$$

Where $New1$ and $New2$ are two solutions generated by the combat process, Com and $Stag$ are commander deer and stag respectively, and b_1 and b_2 are uniformly distributed random numbers.

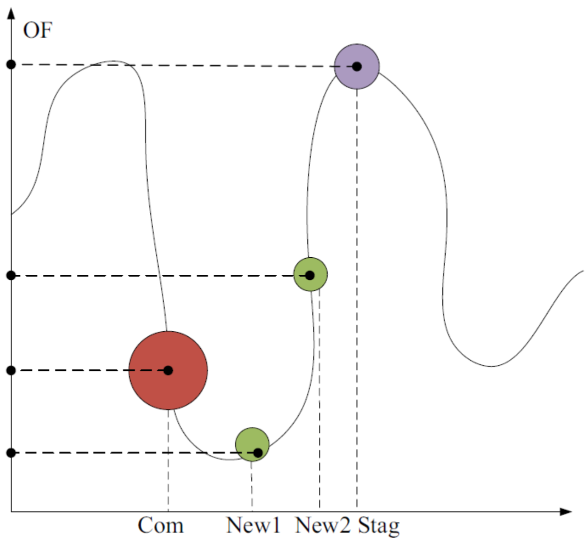

Fig. 18. Fighting process.

c) Formation of polygamy: The formation of polygamy can be referred to as the formation of a harem (Fig. 19), which is a group of female deer captured by a single commander deer. The number of female deer in the harem depends on the commander deer combat effectiveness. Forming a harem requires defining the commander deer standardized cost, which is modeled as follows:

$$V_n = v_n - \max_i \{v_i\} \tag{12}$$

$$P_n = \left| \frac{V_n}{\sum_{i=1}^{N_{Com}} V_i} \right| \tag{13}$$

$$N.harem_n = round\{P_n . N_{hind}\} \tag{14}$$

Where v_n is the fighting strength of the nth commander deer, $\max_i \{v_i\}$ denotes the maximum value of the fitness function for all stags, V_n is the standardized fighting strength, P_n is the standardized fighting strength, and N_{Com} denotes the commander deer. The standardized fighting power of commander deer includes a part of female deer, then the number of female deer in the harem is $N.harem_n$.

a) Mating stage: Commander deer mated with α% females, calculated as follows:

$$N.harem_n^{mate} = round\{\alpha . N.harem_n\} \tag{15}$$

Where, $N.harem_n^{mate}$ is the number of females in the nth harem that mated with the commander deer, and α is the value of the initial parameters of the RDA model. The locations of the next generation of mating-produced Red deer were as follows:

$$offs = \frac{(Com + Hind)}{2} + (UB - LB) \times c \tag{16}$$

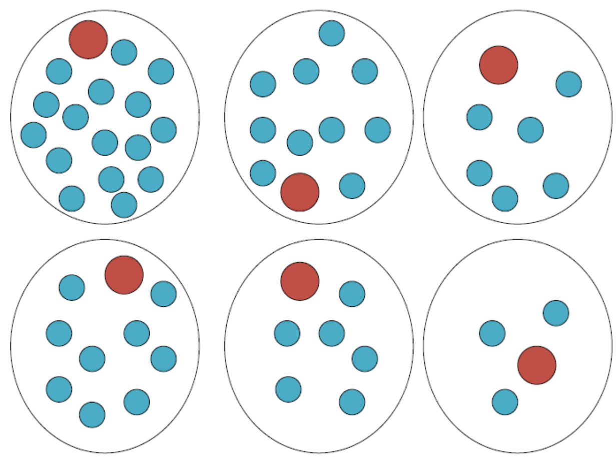

Fig. 19. Polygamy.

where $offs$ denotes a new problem-solving individual horse deer and c denotes a random number.

In the mating of a commander deer with a β% female, a harem is randomly selected and the commander road is allowed to mate with its β% female, mainly to exaggerate territory, calculated as follows:

$$N.harem_k^{mate} = round\{\beta . N.harem_k\} \tag{17}$$

where $N.harem_k^{mate}$ is the number of female deer in the k^{th} harem and β is the initial parameter that produces new individuals.

Male deer mated with the most recent female deer, calculated as follows:

$$d_i = \sqrt{\sum_{j \in J} (stag_j - hind_j^i)^2} \tag{18}$$

$$offs = \frac{(Stag + Hind)}{2} + (UB - LB) \times c \tag{19}$$

where d_i is the distance between the i^{th} female deer and the stag.

b) Choosing the next generation: In order to speed up convergence and avoid falling into local optimality, the RDA algorithm chooses two different strategies. The first strategy is to retain all male deer; the second strategy is to select among the fitness values and the offspring produced by the mating process using a roulette mechanism.

2) Algorithm flowchart: According to the optimization strategy and principle of Red deer's optimization algorithm, the flow of RDA algorithm is shown in Fig. 20.

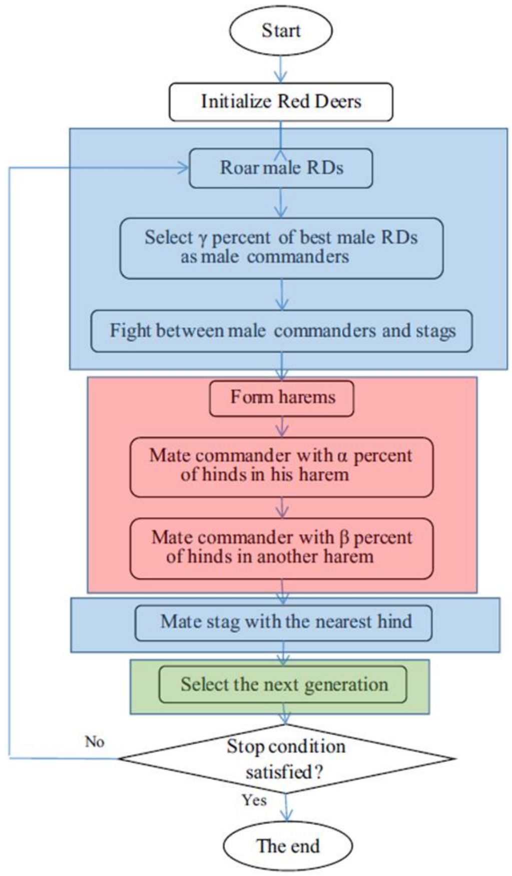

Fig. 20. Flowchart of the redouble optimization algorithm.

C. Digital Design Application Method Based on RDA-SRU Network

The application of RDA-SRU network for digital design of indoor home products is analyzed in three main aspects, i.e., decision variables, fitness function, and optimization steps.

In terms of decision variables, the optimized variables are W, W_f, W_r, b_f, b_r of the SRU network; in terms of the fitness function, the chosen function is the MAE value; the steps of the application of the RDA-SRU network model in the problem are shown in Fig. 21.

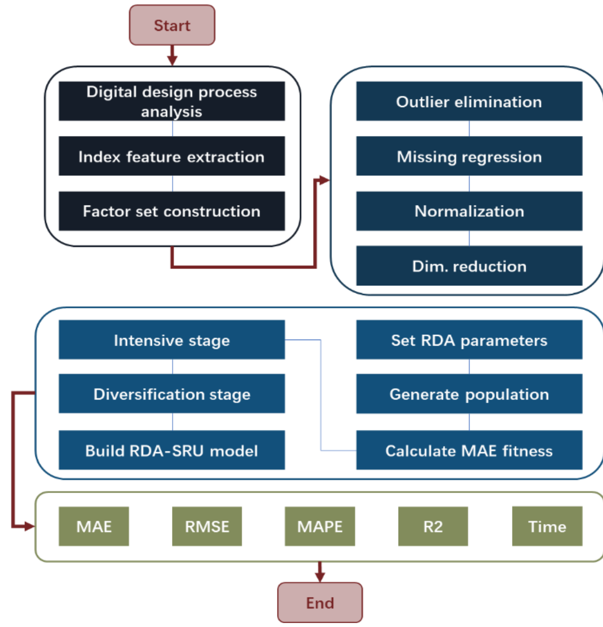

Fig. 21. Flowchart of RDA-SRU model application.

IV. EXPERIMENTAL ANALYSIS

A. Experimental Setup

Digital design software includes CAD, Photoshop, Sketch up and Unity 3D engine; the computer processor is Intel7 Core Quad Core i7-7700HQ 2.8GHz with NVIDIA GeForce GTX10708GB discrete video memory, and the VR headset device is Xiaomi headset.

Using the MIVR headset device in conjunction with the NOLO interactive positioning device, the built-in sensors go out to receive signals and transmit them to Unity3D for processing.

B. Analysis of Experimental Results

With the help of drawing tool AutoCAD, the indoor scene plan is drawn as shown in Fig. 22. After being processed by Photoshop software, it is imported into Sketch up software to get the 3D model, as shown in Fig. 23. Through the VR software, build the virtual furniture scene, as shown in Fig. 24. The virtual scene is refined to get the VR realization effect as shown in Fig. 25.

In order to evaluate the effect of digital design of indoor home products based on VR technology, RNN, LSTM, GRU, SRU, RDA-SRU and other evaluation models are used to compare and analyze the design methods, and the specific results are shown in Fig. 26, 27 and 28.

The MAE, RMSE, MAPE, R2, and evaluation time performance comparison of different algorithms is given in Fig. 26. In terms of MAE, the RDA-SRU model has the smallest MAE value of 0.133, followed by SRU, GRU, LSTM, and RNN; in terms of RMSE, the RDA-SRU model has the smallest value of 0.02; in terms of MAPE, the RDA-SRU model has the smallest value of 0.015, followed by GRU, LSTM, SRU, and RNN; in terms of R2 , the RDA-SRU model is the largest with 0.968, followed by GRU, SRU, LSTM, and RNN; in terms of evaluation time, RDA-SRU model takes the shortest time with 0.028.

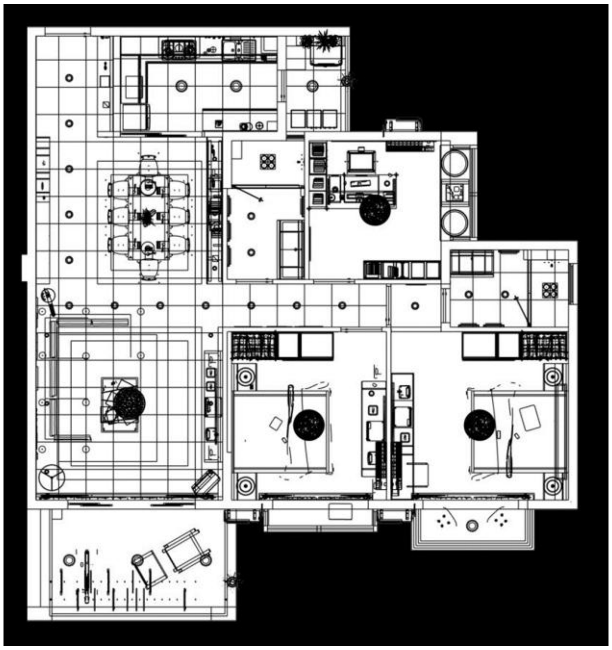

Fig. 22. Indoor scene floor plan.

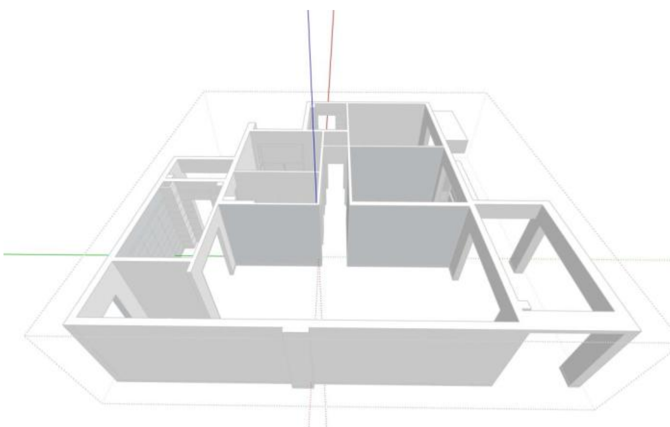

Fig. 23. Schematic diagram of 3D model.

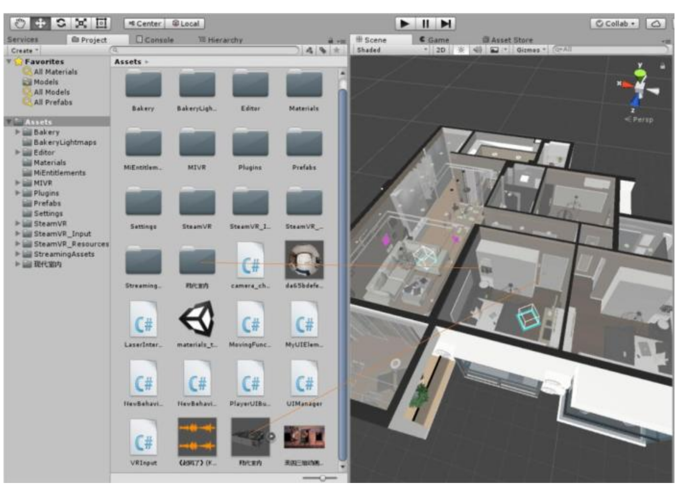

Fig. 24. Virtual engine scene.

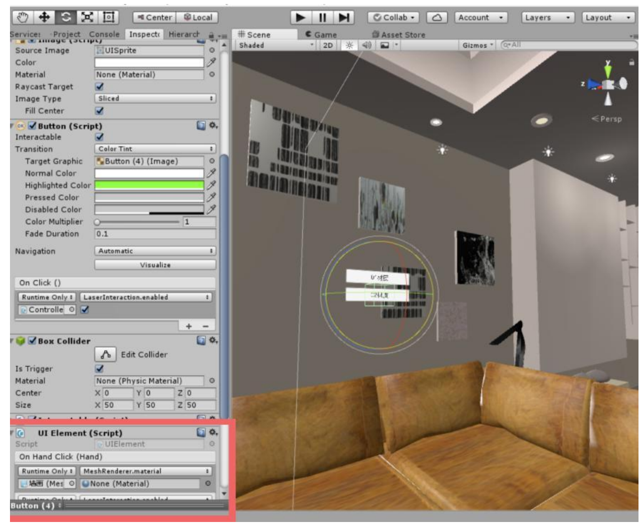

Fig. 25. Virtual reality interactive interface.

No.	Evaluation models	MAE	RMSE	MAPE	R2	Time/s
1	RNN	0.554	0.066	0.070	0.799	0.122
2	LSTM	0.480	0.045	0.042	0.846	0.089
3	GRU	0.443	0.058	0.017	0.956	0.085
4	SRU	0.257	0.044	0.066	0.881	0.036
5	RDA-SRU	0.133	0.02	0.015	0.968	0.028

Fig. 26. Comparison of performance metrics of the contrasting algorithms.

Fig. 27 gives the evaluation error of digital design application effectiveness of different comparison algorithms. From Fig. 27, it can be seen that the RDA-SRU model has the smallest RMSE value of 0.02 for evaluating the effectiveness of digital design application, followed by SRU, LSTM, GRU, and RNN.

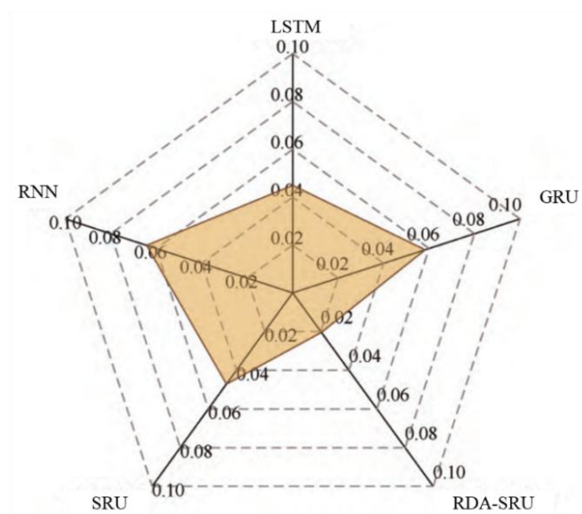

Fig. 27. Comparison of root mean square error of evaluation for contrasting algorithms.

Fig. 28 gives the convergence curve of the digital design evaluation of interior home products based on the RDA-SRU model. In Fig. 28, as the number of iterations increases, the value of the fitness function decreases until the RDA fitness value converges to about 0.184 at 50 iterations.

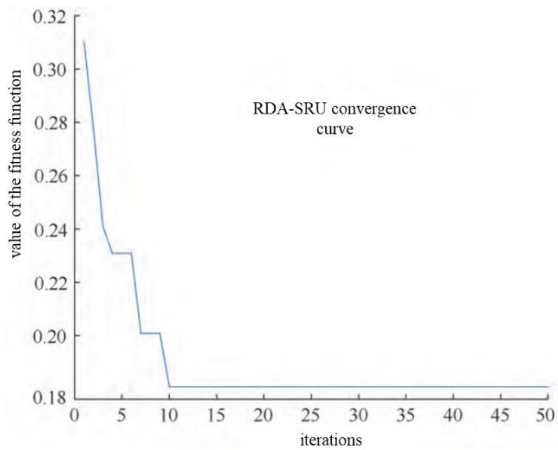

Fig. 28. Convergence curves based on RDA-SRU models.

V. Conclusion

In this paper, for predicting and evaluating the effect of digital design application combined with VR technology, firstly, according to the digitization process, we designed the evaluation framework of digital application effect, extracted the digital design evaluation factor set, and optimized the W, W_f, W_r, b_f, b_r of the Red Deer Optimization Algorithm degree SRU model to improve the performance of the digital design evaluation model; and then, through the experiment of digital design process of indoor home products, we chose to use the design process evaluation factor data set for training through pre-processing input into the RDA-SRU model. Then through the indoor home products digital design process experiment, the design evaluation factor dataset is selected to be input into the RDA-SRU model for training through preprocessing, and compared with the other four algorithms, and the results show that the RDA-SRU model proposed in this paper possesses a better accuracy, and good evaluation prediction results have been achieved.

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