

Research on Supermarket Layout Optimization based on SLP and AHP-FCE

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Abstract: The layout of a supermarket directly impacts customers' shopping experiences and operational efficiency. A well-designed layout facilitates smooth shopping experiences for customers while enhancing the operational efficiency and profitability of the supermarket. With the impact of e-commerce on traditional retail, redesigning supermarket layouts holds significant importance. This paper takes the layout planning of M Supermarket as a case study. It begins with on-site inspections and the creation of a floor plan. Subsequently, random surveys are conducted with customers who have completed their shopping. Instead of traditional SLP using the flow of goods, customer foot traffic is considered to refine non-logistical factors, resulting in relative position maps and feasible supermarket layout proposals. Finally, the effectiveness of both old and new layout schemes is evaluated using the AHP-fuzzy comprehensive evaluation method.

Keywords: Layout Optimization; SLP; AHP-Fuzzy Comprehensive Evaluation.

1. Introduction

With changes in people's living standards and consumption patterns (as shown in Table 1), traditional brick-and-mortar businesses struggle to meet the increasing material consumption demands of the populace. Since the 1990s, with the introduction of chain operations, China's chain supermarkets have experienced rapid development as an emerging retail industry. As competition among supermarkets intensifies in the 21st century, there is a growing necessity to improve supermarket competitiveness through rational layout planning. Careful design and the application of scientific knowledge in layout optimization can create a better shopping environment within these new commercial entities.

Table 1. Changes in types of consumption

Decade	The 1908s	The 1990s	Modernity
Type of consumption	Survivability	Survival and enjoyment	Experiential and service-oriented

Source: Beijing Statistical Information Network

2. SLP Methodology

Systematic Layout Planning (SLP) was proposed by American expert Richard Muther in 1961 [1]. This method is a systematic and logical approach that combines logistics analysis with the analysis of relationships between operational units to achieve an optimal layout. SLP utilizes concepts heavily quantified with mathematical relationships to establish logistics correlations between various operational units and non-logistical relationships. This forms a mathematical model for facility planning and layout. The combination of chart analysis, graphical models, qualitative, and quantitative analysis ensures the scientific rationality of the entire system's facility planning.

Initially, the primary focus of SLP was on the layout design of factories and production facilities [2,3], aiming to enhance production efficiency and working environments. As understanding and practical experience in applying SLP method accumulated, its application scope gradually expanded beyond factories and production facilities. It now

encompasses various types of facilities such as offices, medical facilities, commercial establishments, and others, reflecting its adaptability and effectiveness across diverse settings.

In 2005, Qi Xiumei shifted the focus from the perspective of operators to consumers and improved the traditional SLP method by replacing its original five basic elements with seven. This revised method was then applied to the planning and design of supermarket layouts [4]. Sun Junhua et al. (2006) conducted research on two large supermarkets in Shanghai, clarifying the fundamental elements and confirming that the SLP method could indeed be applied to the overall layout design of large supermarkets [5].

As the traditional SLP method becomes widely used in layout planning, its inherent limitations have gradually become apparent. For instance, it often fails to adequately consider various complex non-logistical factors and lacks validation and feedback mechanisms for selected layout schemes. Addressing these issues, Huang Zezhen et al. (2013) proposed considering customer foot traffic as the primary factor in determining the logistics relationships between various operational units [6]. Furthermore, Liu Zhihai et al. (2017) suggested conducting a more detailed analysis of non-logistical factors among operational units influencing supermarket layouts to ensure comprehensive layout schemes. They also recommended performing circulation analysis on selected schemes and incorporating the results as feedback to optimize the final layout plan [7].

Customer foot traffic has thus become a crucial consideration in the application of the improved SLP method for supermarket layouts. Wang Xueqin et al. (2016) made improvements to the traditional SLP method, focusing on logistics analysis to further explore relationships between functional areas. This enhancement aimed to improve the overall integration between functional areas and optimize the overall layout scheme [8].

Zhao Feng et al. (2018) conducted layout optimization using the movement line-based SLP method at a specific supermarket. They initially analyzed the interrelations between various merchandise sections. After obtaining relative position maps and new layout schemes, they utilized

the Analytic Hierarchy Process (AHP) for comparative evaluation of the new layout schemes [9].

This article takes the layout planning of M Supermarket as an example. Firstly, on-site inspections are conducted, and layout diagrams are drawn. Then, feasible layout schemes are proposed by replacing goods flow with customer foot traffic and refining non-logistical factors. Subsequently, the AHP-fuzzy comprehensive evaluation method is employed to assess the schemes.

3. Application of Improved SLP in Supermarket Layout

3.1. Introduction to M Supermarket

M Supermarket opened in 2006, specializing in vegetables, fruits, and household items. Operating hours are from 9:00 to 21:30. Through on-site investigation and layout mapping, it was determined that the supermarket is divided into 24 areas, covering daily commodities and household essentials, with alternating arrangements of these areas. The vegetable section is divided into two parts, located in the northwest corner along with the fruit, fresh meat and seafood, and grains and oils sections. Household items, kitchenware, books, paper products, bulk food, imported goods, and toys are arranged on both sides of the entrance to attract customers' attention. The areas for personal care products and stationery are arranged longitudinally, dividing the supermarket into two sections. The right half of the supermarket houses condiments, alcoholic and beverages, and snacks, with shelves arranged horizontally, resulting in narrow and densely packed aisles. The frozen goods and dairy products sections are located at the far right of the supermarket. The layout of the supermarket is illustrated in Figure 1.

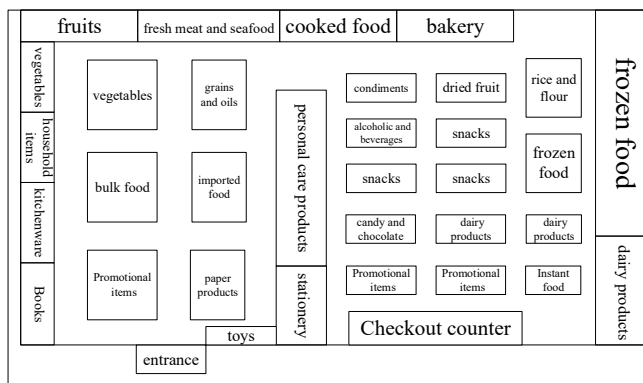


Fig 1. M Supermarket layout

From the observation of the layout diagram, it can be seen that in terms of logistics, the aisle width of the supermarket is also different due to the placement of shelves, which is easy to cause blockage in the area with dense customers, and the process of replenishment and withdrawal becomes cumbersome. For example, there is a potential risk of blockage in the corner formed by the three areas of fruit, fresh meat and seafood and vegetables. In terms of the size of each area, the difference in the number and size of shelves leads to the difference in the area of each area. The area of goods that customers most often buy is often larger, and the area of non-necessities such as candy and chocolate, snacks area is small and concentrated. Through the inquiry of the supermarket staff, we learned that the promotional items and paper products area are special containers because their products can be stored for a long time. There is storage space at the bottom, which can store some goods to be put on the shelves, and replenishment is easier. In order to ensure the freshness of the food, the fruit area and vegetable area need to pick up the goods from the warehouse behind the bakery area and the frozen food area every time, which is easy to lead to the replenishment of the goods is not timely and the route is far.

3.2. Analysis of Basic Elements

For a specialized service industry like supermarkets, it's crucial to identify the basic elements of raw data. The five fundamental elements are as follows: P - People, Q - Customer Traffic, R - Customer Shopping Routes, S - Checkout Counter Areas, T - Customer Shopping Time. Through a scientifically rational analysis of these elements, the interrelations between different areas can be determined [5].

3.3. Logistics Relationship Analysis

According to the improved SLP method [10], the logistics relationships and non-logistics relationships of each operational unit need to be determined sequentially. Finally, the comprehensive proximity of each operational unit is calculated by combining weights. Due to the different service nature of supermarkets compared to warehouses, this paper will use customer foot traffic of each operational unit instead of traditional SLP methods' flow of goods [6]. Surveys and statistics will be conducted to gather customer foot traffic data for each operational unit in the supermarket, obtaining the proportion of customer foot traffic for each unit, as shown in Table 2.

Table 2. The proportion of customer foot traffic

Area	proportion	Area	proportion	Area	proportion
A: vegetables	66.67%	I: dairy products	22.96%	Q: candy and chocolate	14.07%
B: fruits	46.67%	J: cooked food	21.48%	R: alcoholic and beverages	12.59%
C: grains and oils	33.33%	K: personal care products	20.74%	S: instant food	9.63%
D: condiments	32.59%	L: bakery	19.26%	T: toys	6.67%
E: fresh meat and seafood	28.15%	M: dried fruit	17.78%	U: kitchenware	5.93%
F: rice and flour	27.41%	N: bulk food	17.04%	V: imported food	4.44%
G: paper products	26.67%	O: household items	16.29%	W: stationery	3.70%
H: frozen food	25.19%	P: snacks	14.81%	X: books	1.48%

After obtaining the customer foot traffic data, the next step is to determine the closeness between each area. This is done

by categorizing the levels of closeness based on the differences in customer foot traffic between the units.

Specifically, the difference in customer foot traffic is calculated, and the closeness is determined according to the magnitude of these differences [6]. The formula for calculating the difference in customer foot traffic is shown in Formula 1 below:

$$Z = |P_i - P_{i+1}| \quad (1)$$

In the formula, P_i represents the customer foot traffic of the i -th area.

According to the relevant reference [6], the calculated differences in customer foot traffic should be assigned values based on the following ranges: 0%–6%, 6%–12%, 12%–18%, 18%–24%, 24%–30%, and above 30%. These ranges are categorized into five levels: A, E, I, O, U, X, with importance values assigned as follows: 5, 4, 3, 2, 1, 0, respectively. Based on the above, the logistics relationships between each area can be determined, as shown in Figure 2.

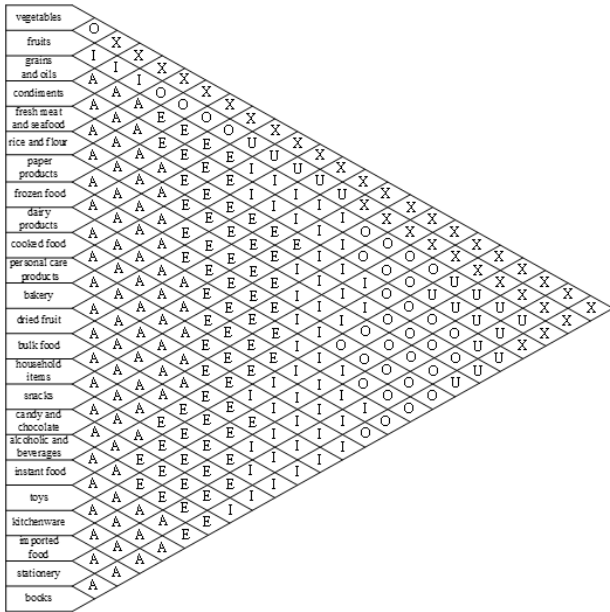


Fig 2. Logistics relationship

3.4. Non-Logistics Relationship Analysis

In supermarket layout planning, besides considering customer foot traffic as the primary logistics factor, non-logistics factors must also be taken into account. Based on inquiries with M Supermarket staff and relevant literature [6], the main non-logistics factors influencing inter-area relationships include the convenience of restocking, ease of staff communication, proximity to the exit, comfort of the shopping environment, continuity of space usage, complementarity of products, and the rationality of guided shopping routes. These factors are sequentially coded as 1, 2, 3, 4, 5, 6, and 7.

The non-logistics relationship levels between each area are categorized into six levels: A (Absolutely Related), E (Highly Related), I (Moderately Related), O (Generally Related), U (Lowly Related), and X (Not Related), with values assigned from high to low as 5, 4, 3, 2, 1, and 0, respectively [6]. The non-logistics relationships are judged and graded based on the distance factors between each area. The non-logistics relationships are illustrated in Figure 3.

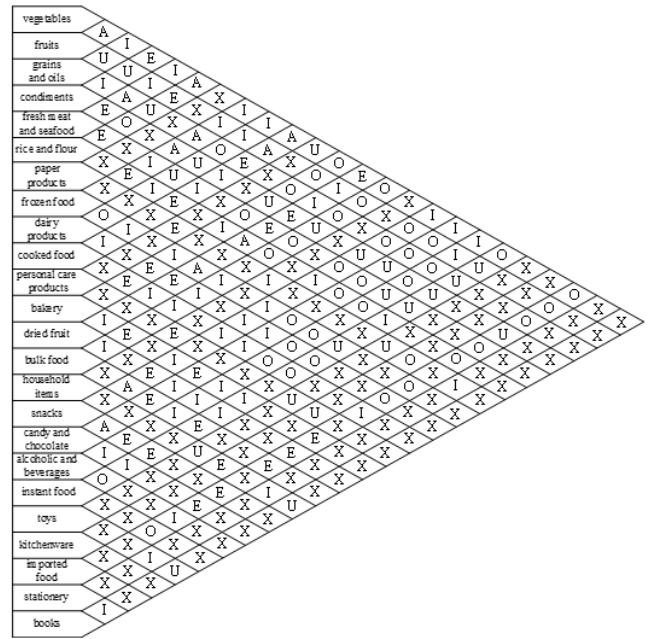


Fig 3. Non-Logistics relationship

3.5. Comprehensive Relationship Analysis

The comprehensive relationships between each area include logistics relationships (X) and non-logistics relationships (Y). Since customer foot traffic is a primary factor for supermarkets, logistics relationships should have a higher weight compared to non-logistics relationships, with a weight ratio of X:Y = 3:2. By using this ratio and the formula, the comprehensive mutual relationship scores and overall relationships between areas can be determined.

$$Z_{ij} = \frac{x}{x+y} \times X_{ij} + \frac{y}{x+y} \times Y_{ij} \quad (2)$$

In the formula:

Z_{ij} - Comprehensive relationship score between operational units i and j ;

X_{ij} - Logistics relationship score between operational units i and j ;

Y_{ij} - Non-logistics relationship score between operational units i and j .

In summary, the comprehensive mutual relationships are shown in Figure 4.

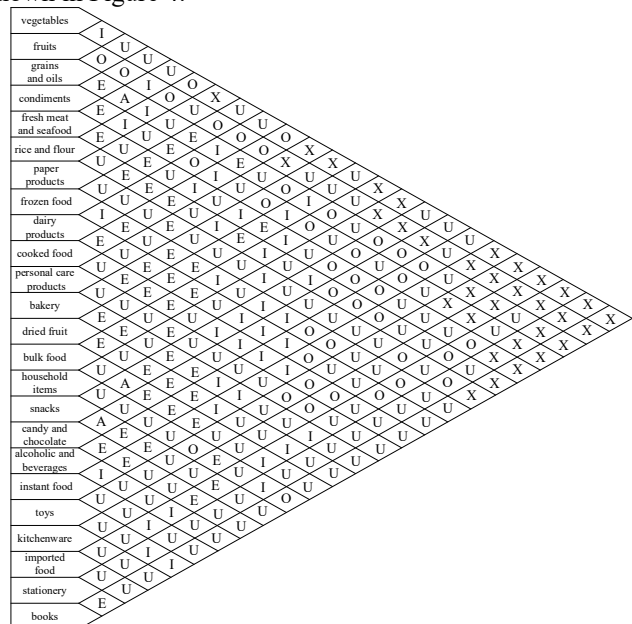


Fig 4. Comprehensive Mutual Relationships

3.6. Layout Based on Comprehensive Mutual Relationships

The values and rankings of the comprehensive proximity

of each area are shown in Table 3.

Table 3. Comprehensive Proximity Ranking Table for Each Area

Area Code	Area	Comprehensive Proximity	Ranking	Area Code	Area	Comprehensive Proximity	Ranking
A	vegetables	16	24	M	dried fruit	61	1
B	fruits	23	22	N	bulk food	57	3
C	grains and oils	44	12	O	household items	33	16
D	condiments	40	15	P	snacks	56	4
E	fresh meat and seafood	49	11	Q	candy and chocolate	53	7
F	rice and flour	53	7	R	alcoholic and beverages	50	10
G	paper products	28	18	S	instant food	43	13
H	frozen food	56	4	T	toys	26	19
I	dairy products	52	9	U	kitchenware	25	21
J	cooked food	60	2	V	imported food	41	14
K	personal care products	29	17	W	stationery	26	19
L	bakery	55	6	X	books	22	23

Based on the comprehensive mutual relationships and comprehensive proximity of each area, areas with higher proximity scores should be placed in central locations, while those with lower scores should be positioned at the periphery. According to the rankings, the "Dried Fruits Section" should be placed in the central position. Then, the positions of other areas are determined based on their comprehensive mutual relationship scores with the central area. For areas within the same level, those with higher overall scores should be prioritized.

Based on the positional correlation chart of each area, the comprehensive proximity, and the area of each area in the supermarket, adjustments were made to the original layout to derive the improved layout, as shown in Figure 5.

In terms of overall layout, the dried fruit section, with the highest comprehensive proximity, is placed in the central area of the supermarket, with other high-scoring areas surrounding it. Regarding aisles, compared to the old layout, the new spatial arrangement eliminates the vertical shelves in the middle of the supermarket, widening the aisles to facilitate the flow of both logistics and foot traffic. Additionally, some low-utilization checkout counters are removed, and three self-checkout lanes are added along with a no-shopping lane, increasing the checkout speed and dispersing foot traffic.

Regarding area settings, the new layout eliminates vertical shelving, resulting in all areas of the supermarket, except for the edge regions, having horizontal orientations. This reduces unnecessary turning routes for customers. Some areas are reduced in size, while the area for fresh meat and seafood is expanded. Furthermore, the fresh meat and seafood section is separated from the vegetable, fruit, bakery, and cooked food sections to prevent the odor from affecting other edible goods, thus enhancing customer satisfaction. In terms of replenishment convenience, the width of replenishment ports is increased, improving the overall flow of the supermarket's aisles and facilitating logistical circulation.

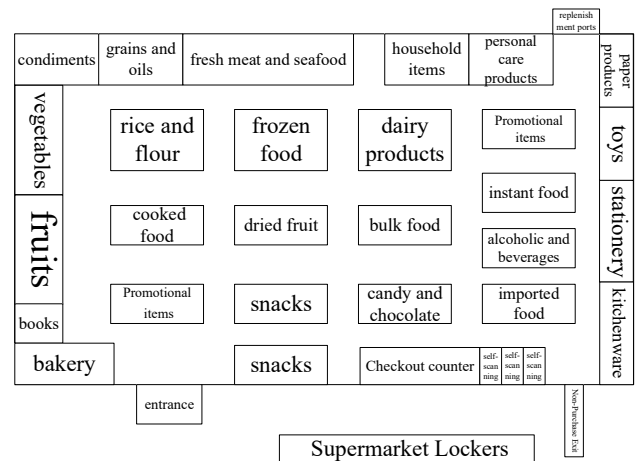


Fig 5. New M Supermarket layout

4. Evaluation of the Layout Optimization Effect of M Supermarket

4.1. Determine the Evaluation Criteria Weights based on AHP

A new layout plan has been developed for M Supermarket. To determine whether the new plan has advantages, the AHP-FCE method will be used to evaluate both the new and old plans.

4.1.1. Establish the Hierarchical Structure Model

The hierarchical structure model for evaluating the layout of M Supermarket is divided into three levels: the goal level (optimal layout), the criteria level (evaluation impact indicators), and the alternatives level (new layout plan and old layout plan). Based on research of relevant references [11] and consultations with supermarket personnel, five evaluation impact indicators were identified: supermarket environment and convenience, replenishment convenience, layout scalability, supermarket operational efficiency, and operational costs. The hierarchical structure model for the

evaluation impact indicators of M Supermarket's layout is shown in Figure 6.

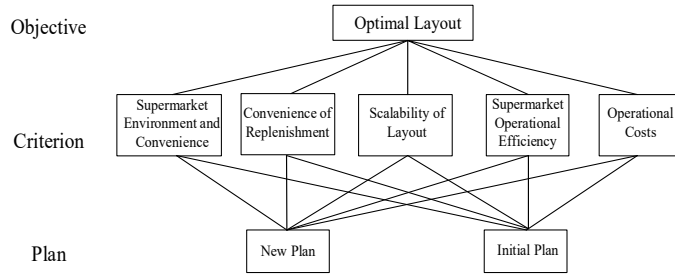


Fig 6. Hierarchical Structure Model

4.1.2. Constructing a Judgment Matrix

The importance relationships and assigned values between each influencing factor were established through opinions

gathered from specialized personnel responsible for internal layout, sales staff, and randomly interviewed customers. The constructed judgment matrix is shown in Table 4.

Table 4. Judgment Matrix

Indicators	supermarket environment and convenience	replenishment convenience	layout scalability	supermarket operational efficiency	operational costs
supermarket environment and convenience	1	2	3	$\frac{1}{2}$	$\frac{1}{3}$
replenishment convenience	$\frac{1}{2}$	1	2	$\frac{1}{3}$	$\frac{1}{6}$
layout scalability	$\frac{1}{3}$	$\frac{1}{2}$	1	$\frac{1}{5}$	$\frac{1}{8}$
supermarket operational efficiency	2	3	5	1	$\frac{1}{2}$
operational costs	3	6	8	2	1

4.1.3. Consistency Test and Calculation of Weights

After obtaining the judgment matrix, the characteristic vector W_i is calculated using Formula 3. Then, the weight vector W_i^o is calculated using Formula 4. Once the characteristic vector and weight vector are determined, the λ_{mi} for each indicator is calculated using Formula 5. The specific

data calculated is shown in Table 5

$$W_i = (\prod_{j=1}^n a_{ij})^{\frac{1}{n}} \tag{3}$$

$$W_i^o = \frac{W_i}{\sum_{i=1}^n W_i} \tag{4}$$

$$\lambda_{mi} = \frac{\sum_{j=1}^n a_{ij} W_j}{W_i} \tag{5}$$

Table 5. Data for Characteristic Vector and Weight Vector

Indicators	supermarket environment and convenience	replenishment convenience	layout scalability	supermarket operational efficiency	operational costs	W_i	W_i^o	λ_{mi}
supermarket environment and convenience	1	2	3	$\frac{1}{2}$	$\frac{1}{3}$	1.0000	0.1489	5.0185
replenishment convenience	$\frac{1}{2}$	1	2	$\frac{1}{3}$	$\frac{1}{6}$	0.5610	0.0835	5.0260
layout scalability	$\frac{1}{3}$	$\frac{1}{2}$	1	$\frac{1}{5}$	$\frac{1}{8}$	0.3342	0.0497	5.0262
supermarket operational efficiency	2	3	5	1	$\frac{1}{2}$	1.7188	0.2559	5.0178
operational costs	3	6	8	2	1	3.1037	0.4620	5.0201

After obtaining the λ_{mi} for each indicator, the maximum characteristic root is calculated using Formula 6 ($\lambda_{max} = \frac{5.0185+5.0260+5.0262+5.0178+5.0201}{5} = 5.0217$). To measure the magnitude of C.I., the Random Index (R.I.) is introduced. According to Table 6, the corresponding R.I. value is found to be 1.12. According to Formula 7, the Consistency Index (C.I.) is 0.0054 ($C.I. = \frac{5.0217-5}{5-1} = 0.0054$). The Consistency Ratio (C.R.) is calculated using Formula 8. Since the calculated C.R. value is 0.0049, which is less than

0.1, the consistency test is passed ($C.R. = \frac{0.0054}{1.12} = 0.0049 < 0.1$).

$$\lambda_{max} = \frac{1}{n} \sum_{j=1}^n \frac{\sum_{i=1}^n a_{ij} W_j}{W_i} \tag{6}$$

$$C.I. = \frac{\lambda_{max} - n}{n-1} \tag{7}$$

$$C.R. = \frac{C.I.}{R.I.} \tag{8}$$

Table 6. Average Random Index of Consistency

n	1	2	3	4	5	6	7	8	9	10	11	12	13	14
R.I.	0	0	0.52	0.89	1.12	1.26	1.36	1.41	1.46	1.49	1.52	1.54	1.56	1.58

After a one-time consistency test, the weight calculation results of the Analytic Hierarchy Process show that the weight score for Supermarket Environment and Convenience is 0.1489, the weight score for Replenishment Convenience is 0.0835, the weight score for Layout Scalability is 0.0497, the weight score for Supermarket Operational Efficiency is 0.2559, and the weight score for Operational Costs is 0.462.

4.2. Fuzzy Comprehensive Evaluation

4.2.1. Establishing an Evaluation Matrix

After obtaining the weights of each indicator, a set of factors $U = \{\text{Supermarket Environment and Convenience, Replenishment Convenience, Layout Scalability, Supermarket Operational Efficiency, Operational Costs}\}$ is established based on the five indicators. Then, a set of judgment criteria $V = \{\text{Excellent, Good, Moderate, Poor, Very Poor}\}$ is established, and each evaluation criterion is assigned a value. "Excellent" represents 10 points, "Good" represents 8 points, "Moderate" represents 6 points, "Poor" represents 4 points, and "Very Poor" represents 2 points.

After setting up the factor set and the criterion set, in-depth interviews were conducted with ten experienced supermarket staff and layout personnel. They were asked to evaluate the new and old layout plans based on the five evaluation indicators. The specific evaluation results are shown in Table 7 and Table 8.

Table 7. Evaluation of New Layout Plan

Evaluation of the New Layout Plan					
Indicators	Excellent	Good	Moderate	Poor	Very Poor
Supermarket environment and convenience	0.6	0.2	0.2	0	0
replenishment convenience	0.7	0.2	0.1	0	0
layout scalability	0.5	0.2	0.1	0.2	0
supermarket operational efficiency	0.6	0.3	0.1	0	0
operational costs	0.7	0.1	0.1	0.1	0

Table 8. Evaluation of Initial Layout Plan

Evaluation of the Initial Layout Plan					
Indicators	Excellent	Good	Moderate	Poor	Very Poor
Supermarket environment and convenience	0.2	0	0.4	0.2	0.2
replenishment convenience	0.2	0.1	0.2	0.3	0.2
layout scalability	0.2	0.1	0.4	0.3	0
supermarket operational efficiency	0.3	0.2	0.5	0	0
operational costs	0	0	0.4	0.3	0.3

Organizing the data, the evaluation matrices for the new and old plans are as follows:

Evaluation Matrix R_1 for New Plan

$$A = \begin{bmatrix} 0.6 & 0.2 & 0.2 & 0 & 0 \\ 0.7 & 0.2 & 0.1 & 0 & 0 \\ 0.5 & 0.2 & 0.1 & 0.2 & 0 \\ 0.6 & 0.3 & 0.1 & 0 & 0 \\ 0.7 & 0.1 & 0.1 & 0.1 & 0 \end{bmatrix}$$

Evaluation Matrix R_2 for Initial Plan

$$B = \begin{bmatrix} 0.2 & 0 & 0.4 & 0.2 & 0.2 \\ 0.2 & 0.1 & 0.2 & 0.3 & 0.2 \\ 0.2 & 0.1 & 0.4 & 0.3 & 0 \\ 0.3 & 0.2 & 0.5 & 0 & 0 \\ 0 & 0 & 0.4 & 0.3 & 0.3 \end{bmatrix}$$

4.2.2. Performing Fuzzy Comprehensive Evaluation

There are four commonly used fuzzy aggregation operators, as shown in Table 9. For comparing the comprehensive evaluation of plans, adopting the weighted average operator can more effectively reflect the effects of weights and expert evaluations.

Table 9. Commonly used fuzzy aggregation operators

Characteristics	Operators			
	$M(\Lambda, V)$	$M(*, V)$	$M(\Lambda, +)$	$M(*, +)$
Type	Dominant Factor Determination Type	Dominant Factor Highlighting Type	Take Minimum and Bounded Type	Weighted Average Type
Reflecting Weight Influence	Not Apparent	Apparent	Not Apparent	Apparent
Degree of Aggregation	Weak	Weak	Strong	Strong
Utilization of Evaluation Information	Insufficient	Insufficient	Comparatively Sufficient	Sufficient

Weight sets for each indicator on layout plans: $A = \{0.1489, 0.0835, 0.0497, 0.2559, 0.462\}$. Obtaining the fuzzy conclusion evaluation sets for the new and initial layout plans according to Formula 9.

$$B = A * R \tag{9}$$

The fuzzy conclusion evaluation set for the new plan A is denoted as $B1 = A * R1$
 $= [0.1489, 0.0835, 0.0497, 0.2559,$

$$0.4620] * \begin{bmatrix} 0.6 & 0.2 & 0.2 & 0 & 0 \\ 0.7 & 0.2 & 0.1 & 0 & 0 \\ 0.5 & 0.2 & 0.1 & 0.2 & 0 \\ 0.6 & 0.3 & 0.1 & 0 & 0 \\ 0.7 & 0.1 & 0.1 & 0.1 & 0 \end{bmatrix}$$

$$=[0.6496, 0.1794, 0.1149, 0.0561, 0]$$

The fuzzy conclusion evaluation set for the initial plan B is denoted as $B_2 = A * R_2$

$$=[0.1489, \quad 0.0835, \quad 0.0497, \quad 0.2559,$$

$$0.4620] * \begin{bmatrix} 0.2 & 0 & 0.4 & 0.2 & 0.2 \\ 0.2 & 0.1 & 0.2 & 0.3 & 0.2 \\ 0.2 & 0.1 & 0.4 & 0.3 & 0 \\ 0.3 & 0.2 & 0.5 & 0 & 0 \\ 0 & 0 & 0.4 & 0.3 & 0.3 \end{bmatrix}$$

$$=[0.1332, 0.0645, 0.4089, 0.2083, 0.1851]$$

After obtaining the fuzzy conclusion evaluation sets for the new and old plans, combined with the assigned judgment criterion set $V = \{10, 8, 6, 4, 2\}$, the comprehensive scores for the new and old plans can be derived. The comprehensive score for the new plan A is 8.84482, and for the initial plan B is 5.50476. Therefore, it can be seen that the new layout plan is more advantageous compared to the initial layout plan of the supermarket.

5. Conclusion

This study focuses on M supermarket, employing an improved SLP method tailored to its specific characteristics, substituting customer flow for goods flow to determine logistics relationships. Quantified data, combined with weighted calculations, determine the comprehensive relationship scores, and facilitate the creation of relevant diagrams and new layout plans. Five indicators were established to validate the advantages of the new plan, with AHP employed to determine weights. Experts were invited to score and establish evaluation matrices, ultimately confirming the superiority of the new plan. However, the study still has limitations, including a limited sample size affecting data representativeness, potential observation errors influencing the accuracy of customer flow calculations, expert scoring being subject to subjective and professional

factors, and the new layout not considering issues such as cost and difficulty.

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