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Snow Resource Reutilization: Design of Snow Collection and Compression Equipment Based on Functional Analysis Method

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Abstract: High-latitude regions of the Earth are rich in natural snow resources; however, owing to their negative impact on daily life, they have not been effectively utilized for a long time and are instead viewed as obstacles that require substantial resources for clearance. This waste of resources contradicts the principles of sustainable development. With the rapid development of the ice and snow industry, the social and economic value of snow resources is gradually becoming apparent. Therefore, to promote sustainable social and economic development, this study explores new methods for processing snow resources to achieve their recycling and high-value transformation. This study employs the functional analysis method to analyze and solve the functions of the design system, utilizing the Analytic Hierarchy Process (AHP) and fuzzy comprehensive evaluation for the objective assessment and selection of schemes. The obtained relative optimal principles are utilized to guide the parameter setting and innovative design of the scheme in terms of functional structure. After the final scheme is output, its feasibility is verified through finite element simulation. Ultimately, to address the issue of snow resource clearing and recycling, this study designs a product scheme capable of collecting and compressing snow on road surfaces, proposing the use of snow in the form of standardized compressed snow blocks for large-scale snow sculpture construction and other fields. This method significantly reduces the cost of snow sculpture production, enhances efficiency, realizes the comprehensive utilization and high-value transformation of snow resources, and provides a reference for the sustainable development of the low-altitude ice and snow tourism industry.

Keywords: functional analysis method; sustainability; snow resource utilization; snow collection and compression; AHP; equipment design

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1. Introduction

Winter snowfall brings abundant ice and snow resources and beautiful natural landscapes to the mid- to high-latitude regions of the Earth, but it also causes numerous inconveniences and safety hazards in daily life. Severe winter snowfall in the United States causes approximately 400,000 vehicle accidents annually, resulting in approximately 1300 fatalities and leading to traffic paralysis and social production halts, with total economic losses amounting to several billion dollars each year. To quickly restore the normal operation of social production, mid- to high-latitude countries invest substantial resources each year into snow removal operations [1], yet this approach merely treats snow as an obstacle to clearing, failing to fully utilize it as a resource. Due to the renewable character and low-cost acquisition of snow resources, they are often placed in an important yet undervalued awkward situation [2]. However, with the development of ice and snow sports and tourism, there is increasing awareness of this neglected resource. During the New Year holiday of 2024, Harbin, China received a total of 3,047,900 visitors, generating a total tourism revenue of 5.914 billion yuan. Ice and snow tourism also contributes more

than 100 million US dollars in revenue annually in New Zealand [3]. The boom in ice and snow tourism demonstrates the significant driving effect of ice and snow resources on social and economic development. However, with global climate warming, the demand for and cost of artificial snowmaking have been increasing annually. Ice and snow scenic areas are facing problems of high energy consumption, high pollution, and high costs. In particular, artificial snow contains cloud condensation nuclei particles at concentrations far exceeding those found in natural snow. Once these particles enter the atmosphere, they inhibit the formation of natural snow, and prolonged use can exert an unfavorable influence on the regional climate [4]. Therefore, the rational collection and utilization of abundant natural snow sources, coupled with the high value of snow resources, is of significant importance for maintaining ecological stability and promoting sustainable social and economic development.

Research on the recycling and utilization of snow resources generally focuses on aspects such as water resources, tourism, refrigeration, and power generation [5]. As early as 1247, people recognized snow as an important water resource and had already begun measuring snowfall. In 1906, Dr. James E. Church began researching snowpack measurements in mountainous areas to address issues related to agricultural irrigation in arid regions [6], urban drinking water, and power generation [7]. The conversion of snow into water resources is the most common method of recycling snow. In regions with abundant annual snowfall, open spaces and terrain modifications are typically utilized to collect and store snow resources to alleviate urban traffic pressure and mitigate water resource shortages [8]. Considering the negative impact of contaminated snow on the environment, Russia utilizes urban waste heat to melt snow and process meltwater for recycling [9]. Regarding the treatment methods for contaminated snowmelt, there has been a growing emphasis in research on the immediacy of treatment [10] and the low cost, efficiency, and sustainability of filtering materials [11].

Additionally, snow resources are widely utilized in ice and snow tourism and sports [12]. Ice and snow tourism (IST), as a popular recreational activity, can confer substantial economic benefits and stimulate job creation. For instance, the Alps, which hosts the world's largest market for inbound ski tourism, sees winter sports as a multi-billion dollar industry [13]. However, with global climate warming, the snow and ice tourism industry has experienced direct adverse effects [14], including diminished natural snowfall [15], the loss of picturesque snowy vistas, and escalating demands and costs for artificial snow production [16], and snow and ice tourism zones are compelled to extend to higher altitudes (above 3000 m) [17]. Therefore, addressing the aforementioned challenges and adopting adaptive strategies to foster the sustainable development of IST [18,19], especially in low-altitude regions, has emerged as a prevalent research focus [20]. Studies in the literature indicate that due to global warming, both the amount of natural snowfall and the duration of the snowfall period have decreased. In response, several countries, including China, Canada, the United States, Sweden, and Japan, have employed various technologies for snow storage [21]. On the one hand, stored snow can be supplied to the tourism industry through the establishment of snow storage facilities [22,23]. On the other hand, the low-temperature characteristics of snow can be utilized for food storage and preservation [24].

In the field of snow resource management equipment, research emphasis has been placed on disaster prevention and mitigation [25]. These devices are primarily designed for the efficient clearing and transportation of snow while neglecting the potential for the recycling and utilization of snow resources. Research on snow removal equipment generally focuses on exploring more efficient and economical snow removal methods [26]. According to different usage environments, they can be categorized into wheeled and tracked, heavy-duty, and medium–small types. Based on the snow removal methods, they can be classified as snow pushing [27], snow sweeping, snow melting [28], snow blowing, and snow throwing [26]. In the application of snow transportation equipment, dump trucks and snow trailers are typically used to transport and pile snow in designated areas away

from urban centers. While this approach can swiftly resume societal productivity and ensure the unimpeded flow of traffic, the large-scale relocation of snow has the potential to disrupt the hydrological balance in an area [29], leading to detrimental effects on the local ecosystem. Therefore, the sustainable clearing of snow has become a current research focus, such as the application of snow melting technology [30] for the onsite collection of snow. In addition, to facilitate the transportation of accumulated snow and achieve standardized stacking, researchers have proposed a method for compressing snow into blocks [31,32], which provides a theoretical basis for the subsequent recycling and utilization of natural snow.

In summary, the direct negative impact of snow on human life [33,34] has prompted a heightened focus on disaster mitigation and preparedness [35], resulting in the undervaluation of snow's potential as a renewable energy source. However, with the increase in ecological awareness and the development of the ice and snow economy, the sustainable utilization and high-value transformation of snow resources have gradually gained increasing attention. Therefore, to utilize valuable natural snow resources and explore innovative pathways for the sustainable application of snow resources, this study employs a functional analysis for design analysis and proposes a design scheme for snow collection and compression equipment. By collecting and compressing natural snow accumulated on road surfaces into uniformly sized standard snow blocks, it can be applied in areas such as the rapid construction of snow sculpture landscapes in urban settings and the cultural education of ice and snow sculptures. This method is expected to facilitate the collection and utilization of natural snow, reduce the use of chemical deicing agents, and decrease reliance on artificial snowmaking. This approach aims to protect the ecological environment, lower snow costs, and provide new adaptive strategies for the sustainable development of winter snow tourism in low-altitude regions of the world in the context of global warming. (This product previously won the Silver Award at the 2024 Global Chinese Art Design Award, the Gold Award at the Shenyang Industrial Design Competition, and the Second Prize at the National Finals of Milan Design Week).

2. Methods

2.1. Applicability of the Functional Analysis Method

The functional analysis method is an important method for realizing product functions. The core of this method lies in analyzing, decomposing, and recombining the complex and abstract overall functions to identify a rational functional structure for the design of new products, thereby providing more accurate guidance for designing and achieving the final solution [36,37]. As a complex and unknown engineering product, snow collection and compression equipment involves the collaborative functioning of multiple components and adaptability to external environments during its design process, which presents a certain level of complexity. The functional analysis method demonstrates a high degree of applicability in precisely addressing such complex and abstract challenges. The functional analysis method allows for a systematic examination of the functional requirements that a product must meet, as well as how these functions can be realized through the product's structure and operation:

- The functional analysis method can assist designers in clarifying the fundamental functions of a design, which is crucial for the development of innovative products. Taking this study as an example, the functional analysis method can abstractly summarize the problem as the collection, transportation, and compression of snow. Through functional analysis, it can be ensured that these basic functions are met, and further optimization can be conducted to increase efficiency and reduce costs. For example, by analyzing the physical properties of snow and the expected processing volume, designers can determine the optimal size and shape of spiral snow collection and compression devices to achieve maximum snow collection and compression efficiency;
- The functional analysis method can assist designers in identifying and optimizing the auxiliary functions of a product, such as ease of operation, convenience of maintenance, and durability, thereby increasing the overall value of the product;

- The functional analysis method also contributes to innovative design. In the design of snow collection and compression equipment, the functional analysis method can, to a certain extent, mitigate subjectivity and the interference of numerous factors, helping to overcome the limitations of traditional thinking and stimulate new design ideas [38];
- The functional analysis method adeptly converts intricate abstract issues into tangible functional manifestations, ensuring that creative designs remain within the purview of reason and feasibility, thereby enhancing the viability and implementability of inventive design schemes.

The above research indicates that the functional analysis method can be used to effectively conduct a systematic analysis of functional requirements for complex abstract problems. By employing a unique logical analysis approach, it assists designers in overcoming the limitations of traditional thinking and subjective factors, thereby stimulating innovative ideas and enhancing design efficiency. In conjunction with design objectives, as an important theoretical method in product design, the functional analysis method is highly effective and applicable to complex mechanical systems and engineering problems. Therefore, this study employs the functional analysis method for systematic analysis, seeking the optimal functional structure to meet the target requirements.

2.2. Design Process

This study employs functional analysis to analyze and select the optimal functional structure reference for the collection and utilization of snow resources, thereby devising a feasible conceptual scheme. Research on the design of snow collection and compression equipment has focused on urban road snow collection and utilization as the starting point of the design process. First, demand analysis and extraction are conducted via functional analysis, and the system boundaries are defined through task abstraction, followed by the definition of the overall system function, functional decomposition, and functional element resolution. Multiple principle solutions are obtained through a morphological matrix. The AHP (Analytic Hierarchy Process) and fuzzy comprehensive evaluation methods are used to screen and assess the schemes, leading to the decision of the relatively optimal principle solution for the problem. Subsequently, innovative design is carried out on the basis of the optimal functional structure derived from functional analysis, and a functional dimension conceptual model is established. Following this, product structural parameter design is performed, reasonable parameter combinations are determined through the adaptability calculation of collection and compression efficiency, and the feasibility of the scheme is verified through finite element simulation. Ultimately, a reasonable and feasible product conceptual scheme is output. The design process is illustrated in Figure 1.

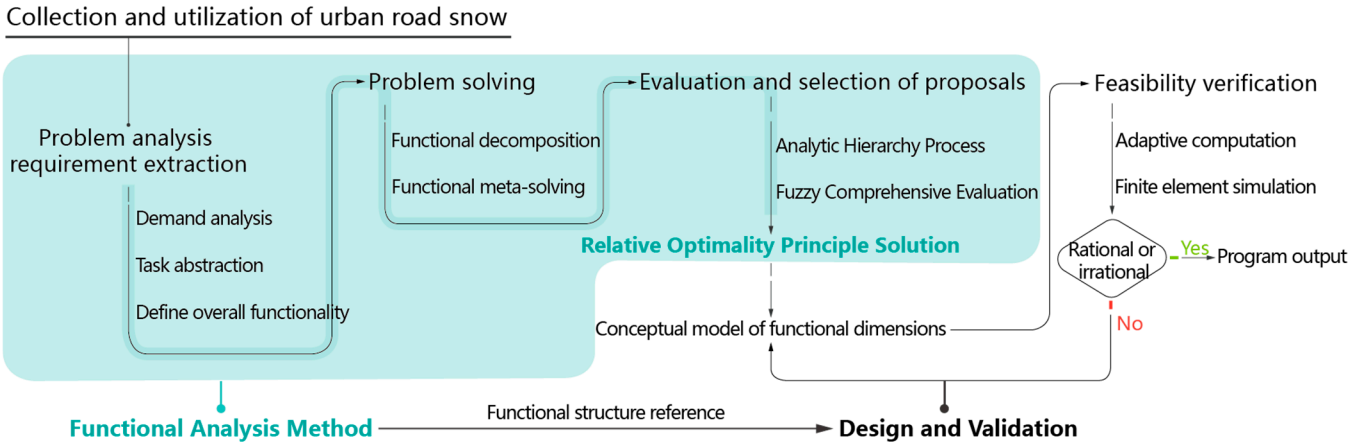


Figure 1. Design process.

2.3. Demand Analysis and Overall Function Definition

On the basis of the actual demand for the sustained and healthy development of the national economy and the assurance of road traffic safety, the effective clearing of snow from road surfaces is fundamental to design and research. Moreover, the surge in ice and snow tourism demonstrates that ice and snow cultural tourism, centered around snow sculptures and snowy landscapes, has a significant driving and leading effect on the urban regional economy [39]. Therefore, ice and snow tourism is selected as the research field for the innovative utilization of snow resources. By transforming abundant natural snow into urban-scale snow sculptures and snowy landscapes, snow resources can be fully utilized, creating an immersive experience for visitors and developing large-scale, distinctive ice and snow tourism, thereby achieving high-value conversion of snow resources. Additionally, for the utilization of large-scale natural snow, traditional methods of snow sculpture production have become inapplicable; the mechanization and intelligent automation of snow sculpture fabrication have emerged as predominant trends in development [40].

Therefore, the design requirements can be summarized as follows on the basis of the aforementioned needs assessment:

- Snow removal: Achieving the effective clearing of snow on road surfaces to meet basic snow removal needs;
- The facilitation of the transportation and construction of new types of snow sculptures: Snow is compressed into blocks to reduce the area occupied by accumulated snow, making it easier to store and transport while also meeting the construction requirements for new types of snow sculptures in the form of compressed snow blocks;
- High adaptability and plasticity: Compressed snow blocks are used for constructing snow sculptures and scenes, with parameters such as size and shape required to meet the construction standards for snow sculptures. To ensure the plasticity of the snow sculpture forms and the diversity of types, the produced snow blocks should be easy to stack. When the concept of modular design is incorporated, standardized square snow blocks are produced to satisfy the diverse shapes of snow scenes.

On the basis of demand analysis, the design task is abstractly described as follows: design snow collection and compression equipment that can efficiently and stably clear, collect, and transform accumulated snow on urban roads into standardized compressed snow blocks with high plasticity to meet the requirements for creating an ice and snow city IP that emphasizes the diversification of ice and snow landscapes, the scaling of quantity, and the regularization of layout. In summary, the overall functional definition of the research object is a snow collection and compression vehicle that can efficiently and stably collect and compress accumulated snow on roads into standardized snow blocks and output them. Its black box model is shown in Figure 2.

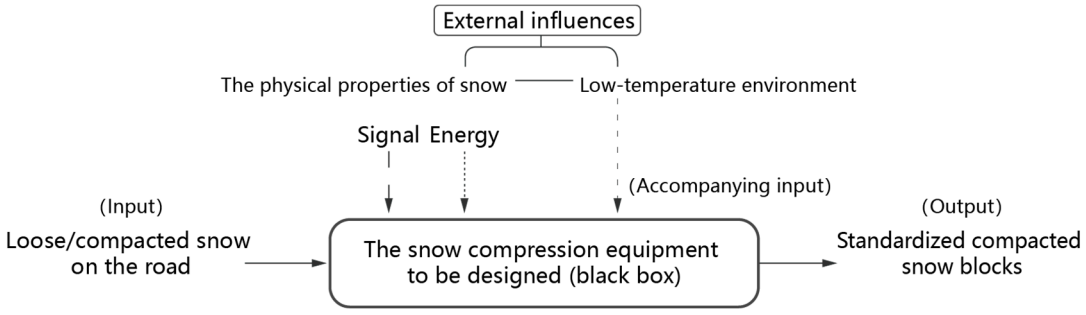


Figure 2. Black box model diagram of the snow collection and compression equipment.

2.4. Functional Decomposition

The overall functional definition of snow collection and compression equipment is relatively abstract, and the corresponding functional system is complex and unknown, making it difficult to intuitively propose design solutions that meet the requirements.

Therefore, it is necessary to decompose the complex functional system into a hierarchical functional structure tree diagram on the basis of functional types and the important hierarchy of functions until directly solvable subfunctions and functional elements are reached (Figure 3).

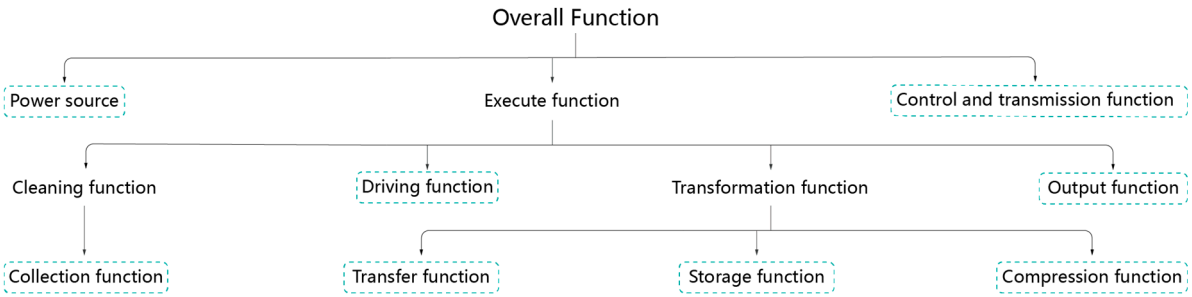


Figure 3. Functional structure tree diagram.

In summary, the functional elements of snow-collecting compression equipment are the control and transmission functions, power source, driving function, collection function, transfer function, storage function, compression function, and output function.

2.5. Functional Meta-Solving

The same functional element may have multiple solutions, which need to be determined on the basis of the physical properties of snow and its products, combined with the functional requirements and objectives. Methods such as intuitive judgment and investigative analysis are employed to solve for each functional element [41]. This paper utilizes a morphological matrix to solve for functional elements, with the vertical axis representing the system's functional elements and the horizontal axis representing the principle solutions of each functional element, as shown in Table 1.

Table 1. Morphological matrix.

Function Elements		Principle Solutions			
		01	**02**	**03**	**04**
A	Control and Transmission Function	Mechanical Control	Hydraulic Control	Electric Control	Hybrid Drive
B	Power Source	Internal Combustion Engine	Electric Motor	Hybrid Power (Combustion Engine + Electric Motor)	Hydrogen Energy
C	Driving Function	Wheeled	Tracked		
D	Collection Function	Rake Type	Spiral auger Type		
E	Transfer Function	Roller or Step-type Conveyor Belt	Rotating Centrifugal Impeller	Hydraulic Bucket	Lifting and Pushing Device
F	Storage Function	Compartment or Partition	Temporary Storage Compartment		
G	Compression Function	Hydraulic Compressor			
H	Output Function	Roller or Conveyor Belt	Inclined Chute	Hydraulic Lifting Platform	Push-Type Structure

On the basis of the morphological matrix, the principle solutions of the various functional elements obtained are cross-combined, ultimately resulting in 2048 functional schemes.

The morphological matrix can yield various functional schemes, which require screening and evaluation. Schemes that do not meet design requirements or are incompatible with various subfunctional solutions should be eliminated, and feasible schemes that align with the overall functional objectives should be selected. The following principles will be employed for the screening process:

1. Reliability of functional implementation. Ensure that the underlying principle solutions effectively meet functional requirements and satisfy basic performance and operational demands. At extreme winter temperatures, the motor struggles to serve as the primary power source; however, it offers high precision and energy efficiency. Therefore, hybrid power is adopted for the control and transmission functions. Additionally, to ensure the stable and reliable output capacity of the equipment, the existing principle solutions are subjected to structural extraction and combination, utilizing a pushing structure and inclined chutes. The combination schemes are reduced to 64 types;
2. Ease of operation and adaptability. To accommodate different application scenarios and enhance the mobility and flexibility of the equipment, a wheeled structure is adopted. To achieve a stable and efficient uninterrupted snow supply, a rotating centrifugal impeller is selected for the transmission structure. The combined solutions are reduced to 8 types;
3. Cost and technological maturity. Considering the production and operational costs and technological maturity of the principles [42], hydrogen energy sources that have not yet been widely promoted and applied are excluded. The number of combined schemes is reduced to 4.

In summary, by analyzing the compatibility of different functional elements in a vertical context and the prioritization of functional elements at the same level in a horizontal context, the following feasible functional solutions have been identified:

- P1 = A4 + B3 + C1 + D1 + E2 + F1 + G1 + H2;
- P2 = A4 + B3 + C1 + D2 + E2 + F1 + G1 + H2;
- P3 = A4 + B3 + C1 + D1 + E2 + F2 + G1 + H2;
- P4 = A4 + B3 + C1 + D2 + E2 + F2 + G1 + H2.

2.6. Program Evaluation

To reduce subjectivity in evaluation and enhance the comprehensiveness of the assessment [43], this study employs the Analytic Hierarchy Process (AHP) to determine the weights of various indicators, define the levels of these indicators, and construct membership functions via fuzzy mathematics. Finally, a fuzzy comprehensive evaluation model is constructed to evaluate and prioritize solutions.

2.6.1. Analytic Hierarchy Process Weight

On the basis of the overall functional definition and expert opinions, efficiency, reliability, economy, maintainability, environmental friendliness, safety, and adaptability are established as evaluation indicators, resulting in the evaluation indicator set $X = \{x_1, x_2, x_3, x_4, x_5, x_6, x_7\}$ = {efficiency, reliability, economy, maintainability, environmental friendliness, safety, adaptability}. Different evaluation indicators have varying levels of importance in assessments, and the set of weights corresponding to them forms a weight vector, denoted as $G = [g_1, g_2, g_3, g_4, g_5, g_6, g_7]$. To minimize subjective influence, the Analytic Hierarchy Process (AHP) is employed for the rational allocation of weights to each indicator.

To ensure the professionalism and authenticity of the evaluation data, this study invited 7 experts with extensive practical experience and authoritative knowledge in various fields such as mechanical engineering, industrial design, and environmental science to compare the evaluation indicators on the basis of their importance. The results were then discussed and refined in a group format, ultimately yielding a comprehensive comparative result, with the ratios between the various indicators forming a judgment matrix.

For two indicators of different natures, the Santy 1–9 comparative scale method (Table 2) was employed for comparison [44], thereby constructing the judgment matrix.

Table 2. The scale and meaning of the judgment matrix.

Scale Values	Meaning
1	The two variables (i and j) are of equal importance
3	One variable is slightly more important than the other
5	One variable is highly more important than the other
7	One variable is very highly more important than the other
9	One variable is extremely more important than the other
2, 4, 6, 8	Used when compromising between the other numbers
reciprocal	If variable i has one of the above numbers assigned to it when compared with variable j, then j has the value 1/number assigned to it when compared with i.

The second stage involves constructing a weight coefficient judgment matrix table (Table 3), where XAB (A, B = 1, 2, . . ., 7) represents the comparison result between XA and XB in the judgment table. When XA is deemed more important than XB, a value is assigned on the basis of the importance level according to the scale of the judgment matrix. Conversely, when XB is more important, a value is assigned on the basis of the reciprocal of the corresponding scale in the judgment matrix.

Table 3. Weight coefficient judgment matrix table.

Indicator	(X1) Efficiency	(X2) Reliability	(X3) Economics	(X4) Maintainability	(X5) Environmental Friendliness	(X6) Security	(X7) Adaptability
(X1) Efficiency	1	1/2	2	5	3	4	6
(X2) Reliability	2	1	3	6	4	5	7
(X3) Economics	1/2	1/3	1	4	2	3	5
(X4) Maintainability	1/5	1/6	1/4	1	1/3	1/2	2
(X5) Environmental friendliness	1/3	1/4	1/2	3	1	2	4
(X6) Security	1/4	1/5	1/3	2	1/2	1	3
(X7) Adaptability	1/6	1/7	1/5	1/2	1/4	1/3	1

After the weight coefficient judgment matrix is constructed, the geometric mean method is used to determine the weight vector. The values corresponding to each row in the weight coefficient judgment matrix are multiplied cumulatively, with the product formula being as follows:

$$U_a = \prod_{b=1}^{n} X_{ab} \quad (1)$$

where X_{ab} represents the criterion of column b of row a in the weight coefficient judgment matrix; n represents the order of the matrix.

The geometric mean calculation formula for the weight coefficient judgment matrix X_{ab} factors is as follows:

$$M_a = \sqrt[n]{U_a} \quad (2)$$

The above calculation results are normalized to obtain the relative weight values. The formula for calculating the relative weight is as follows:

$$G_a = \frac{M_a}{\sum_{a=1}^{n} M_a} \tag{3}$$

The calculation result of the weight vector is $G_a = (g_1, g_2 \ldots, g_n)$. To find the maximum eigenvalue and conduct a consistency check, the formula is as follows:

$$\lambda_{max} = \frac{1}{n} \sum_{a=1}^{n} \frac{(XG)_a}{G_a} \tag{4}$$

$$C.I. = \frac{\lambda_{max} - n}{n - 1} \tag{5}$$

where λ_{max} represents the largest eigenvalue of the weight coefficient judgment matrix; XG represents the value of the weight coefficient judgment matrix multiplied by the corresponding relative weight G and then accumulated by rows; and $C.I.$ represents the consistency index of the weight coefficient judgment matrix.

On the basis of the judgment matrix table and calculation formulas, the values of G_a, λ_{max}, and $C.I.$ are obtained. The calculated results, rounded to the nearest value, yield G_a = [0.241, 0.352, 0.160, 0.449, 0.104, 0.678, 0.308], the maximum eigenvalue λ_{max} = 7.195, and the consistency index $C.I.$ = 0.033. The analysis results are shown in Table 4.

Table 4. Analytic Hierarchy Process results.

Option	Eigenvector	Weight Value	Maximum Eigenvalue	*C.I.* Value
Efficiency	2.318	0.241		
Reliability	3.380	0.352		
Economics	1.534	0.160		
Maintainability	0.431	0.045	7.195	0.033
Environmental friendliness	1.000	0.104		
Security	0.652	0.068		
Adaptability	0.296	0.031		

To determine whether the constructed judgment matrix has any logical issues, it is necessary to test the consistency index. By comparing it with the random consistency index $R.I.$, the rationality of the judgment matrix can be verified. The table of random consistency indices is shown in Table 5.

Table 5. Random consistency index control table.

Order	3	4	5	6	7	8	9	10
$R.I.$ Value	0.52	0.89	1.12	1.26	1.36	1.41	1.46	1.49

The corresponding $R.I.$ is selected for comparison on the basis of the order of the matrix. When the consistency ratio $C.R.$ < 0.1, it is considered consistent, and the indicator weights are valid; otherwise, they are invalid, and the judgment matrix needs to be adjusted. The calculation formula for the consistency ratio $C.R.$ is as follows:

$$C.R. = \frac{C.I.}{R.I.} \tag{6}$$

The results of the consistency test are shown in the table, where $C.R.$ = 0.024 < 0.1, indicating that the consistency test has been passed. A summary of the consistency test results is presented in Table 6.

Table 6. Summary of the consistency test results.

Maximum Eigenvalue	*C.I.* Value	*R.I.* Value	*C.R.* Value	Results of the Consistency Test
7.195	0.033	1.360	0.024	pass

In summary, the weight vectors of the evaluation indicators are g_1 = 0.241, g_2 = 0.352, g_3 = 0.160, g_4 = 0.045, g_5 = 0.104, g_6 = 0.068, and g_7 = 0.031, which demonstrates that the results are valid.

2.6.2. Fuzzy Comprehensive Evaluation

After the evaluation indicators and weight vectors are determined, several fuzzy semantic expressions for evaluation are defined: "very good" (4 points), "good" (3 points), "average" (2 points), and "barely acceptable" (1 point). Therefore, the score set is K = {4, 3, 2, 1}. The resulting fuzzy evaluation set is Y = {y_1, y_2, y_3, y_4} = {very good, good, average, barely acceptable}. An evaluation team composed of researchers and engineering technicians from the project group conducts assessments of each structure on the basis of the indicator set X. The evaluation rule is a single-item vector evaluation, where only one vector is equal to 1 and the others are 0. Using a fuzzy statistical method, the statistical results of each element in the evaluation set Y are used to construct an evaluation matrix by calculating the ratio to the total count. The final score for each scheme can be obtained on the basis of the comprehensive weights and scores. The formula for calculating the scheme score is as follows:

$$H_m = G_a \times P_m \tag{7}$$

$$B_m = H_m \times K \tag{8}$$

where m represents the number of schemes; P_m represents the evaluation matrix of the m-th scheme; H_m represents the comprehensive membership degree vector of the m-th scheme; and B_m represents the score of the m-th scheme.

From Formula (7), the evaluation matrix and the comprehensive membership vector of p1 can be obtained:

$$m = 1,\ P_m = [Y_{x_1},\ Y_{x_2},\ Y_{x_3},\ Y_{x_4},\ Y_{x_5},\ Y_{x_6},\ Y_{x_7}] = \begin{bmatrix} 0.7 & 0.3 & 0 & 0 \\ 0.7 & 0.2 & 0.1 & 0 \\ 0.7 & 0.3 & 0 & 0 \\ 0.2 & 0.6 & 0.2 & 0 \\ 0.3 & 0.5 & 0.2 & 0 \\ 0.5 & 0.3 & 0.2 & 0 \\ 0.7 & 0.3 & 0 & 0 \end{bmatrix};$$

$$H_m = G_a \times P_m = [0.623\ 0.299\ 0.079\ 0].$$

By the same reasoning, the following conclusions can be drawn:

$$H_2 = G_a \times P_2 = [0.710\ 0.265\ 0.047\ 0];$$

$$H_3 = G_a \times P_2 = [0.739\ 0.244\ 0.018\ 0];$$

$$H_4 = G_a \times P_2 = [0.810\ 0.180\ 0.011\ 0].$$

From Formula (8), the scores for each scheme are as follows:

$$m = 1,\ B_m = H_m \times K = [0.623\ 0.299\ 0.079\ 0] * K = 3.547;$$

$$m = 2,\ B_m = H_m \times K = [0.710\ 0.265\ 0.047\ 0] * K = 3.729;$$

$$m = 3,\ B_m = H_m \times K = [0.739\ 0.244\ 0.018\ 0] * K = 3.724;$$

$$m = 4,\ B_m = H_m \times K = [0.810\ 0.180\ 0.011\ 0] * K = 3.802.$$

On the basis of the comprehensive calculations, the overall scoring ranking of the plans is as follows: $B_4 > B_2 > B_3 > B_1$. When $m = 4$, $B_m = B_4 = 3.802$. Therefore, plan P_4 is identified as the optimal solution.

2.7. Structural Parameter Design and Calculation

Through the above analysis and evaluation, the core functions of the snow collection and compression equipment were clarified, and the relative best solution P_4 was obtained after evaluation and screening, which includes functional structures such as a hybrid drive system, an internal combustion engine and electric motor, a wheeled drive structure, a spiral auger, a rotating centrifugal impeller, a temporary storage chamber, a hydraulic press, and an inclined chute. On the basis of functional requirements, these structures are optimized through combination to yield three devices capable of effectively completing design tasks: the spiral snow collection device, the temporary storage device, and the compression device. These devices are responsible for collecting, storing, transporting, compressing, and outputting snow, respectively. However, despite the fact that the aforementioned functional structures theoretically suffice for supporting the execution of snow collection and compression tasks, there are significant discrepancies in the operational parameters of existing technical entities, especially between the spiral auger and the hydraulic press, which may lead to issues of insufficient or excessive snow supply when they operate in conjunction. Therefore, it is necessary to conduct adaptive calculations on the operational efficiency of the spiral snow collection and compression devices and to adjust and confirm the relevant structural parameters to ensure smooth collaborative operation.

2.7.1. Calculation of Operational Efficiency for Temporary Storage and Compression Devices

First, the task volume for a single snow compression operation is determined. Given that the standardized snow blocks produced by snow collection and compression equipment are primarily used for the construction of snow sculpture landscapes, the dimensions of the output snow blocks should meet the requirements for large snow sculptures. However, traditional manual snow sculpture construction employs nonstandard wooden frames and does not specify clear dimensions for the snow blocks. Therefore, the dimensions of the output snow blocks are set to $1 \times 1 \times 1$ m^3, referencing the $3 \times 3 \times 3$ m^3 standard required for snow sculpture competitions. Additionally, owing to the varying densities of snow under different conditions, this calculation selects a commonly used density of 0.3 g/cm^3 for clean compressed snow as the processing medium. According to compression tests, when the pressure reaches 3 MPa, the displacement approaches 0, reaching the maximum compression limit of the snow, with a compression ratio of 3:1 [45], as shown in Figure 4.

From the clean snow compression ratio, the volume of snow to be compressed at one time is 3 m^3. The volume of the compression cylinder is set to $1 \times 1.5 \times 2$ m^3, and the volume of the temporary storage chamber is $1.4 \times 1.5 \times 2$ m^3. The compression and pushing cross-section is 1×1 m^2. To calculate the operational efficiency of the temporary storage and compression device, a mechanical analysis of the device is needed, along with the selection of appropriate working parameters.

The compression device has three hydraulic structures. When snow enters the compression cylinder, it is first capped by a rotary-type hydraulic press. In the second step, pressure is applied via a left–right hydraulic press, with a stroke distance of 500 mm. The third step involves pressure application via a front–back hydraulic press, with a stroke distance of 1000 mm. Finally, the hatch door located at the rear opens, and the front and rear hydraulic press continues to advance by 1000 mm, pushing the snow block out. On this basis, the maximum pressure required for each hydraulic press is calculated, and matching entities are identified. The formula for maximum pressure is as follows:

$$F_{max} = S_x P_{max} \quad (9)$$

$$M_{max} = F_{max} / g \tag{10}$$

where S_x represents the force application area of the hydraulic press; P_{max} represents the maximum pressure of 3 MPa; M_{max} represents the maximum compression weight; and g represents the acceleration due to gravity, taken as 10 m/s.

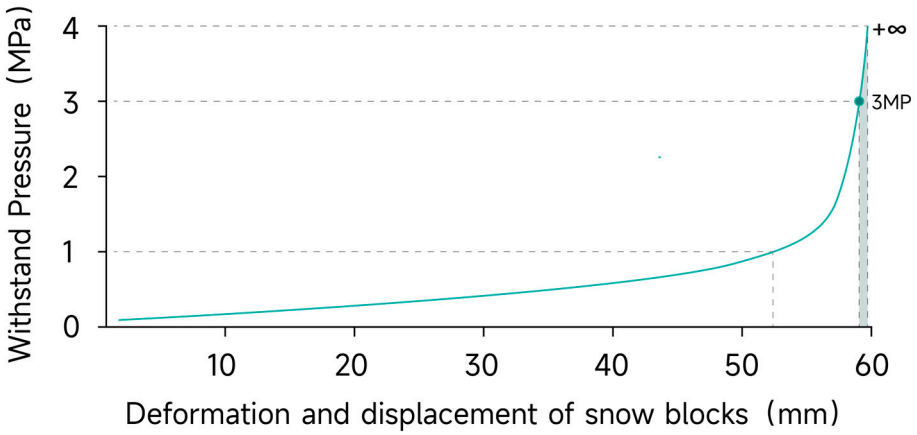


Figure 4. Displacement diagram of the snow block compression pressure. The green line in the figure represents the relationship between the pressure exerted on the snow during compression and the displacement of the snow as it is compressed.

The force application areas of the hydraulic press are as follows: for the left–right direction, 2000 × 1000 mm^2; for the front–back direction, 1000 × 1000 mm^2; and for the rotary type, 2000 × 750 mm^2. From Equations (9) and (10), the required rated maximum pressures are left–right direction F_m = 6 × 10 N, front–back direction F_l = 3 × 10 N, and rotary type F_s = 4.5 × 10 N. Converting these to maximum compression tonnage yields $M_m \approx 600$ t, $M_l \approx 300$ t, and $M_s \approx 450$ t, respectively. According to the design requirements, the YQ32-630 t-c model is selected for the left–right hydraulic press, the YQ32-315 t-c model is selected for the front–back hydraulic press, and the RC-400 t model is selected for the rotary-type hydraulic press. On the basis of the temporary storage tank volume, the servo-electric cylinder YDA94 is chosen for the feeding and conveying structure. The corresponding parameters for each model are shown in Table 7.

Table 7. Reference table for the physical component parameters. (Manufacturer: Shenyang Jiaqi Hydraulic Technology Co., Ltd.; Location: No. 4-2, Chongshan Middle Road, Huanggu District, Shenyang City, Liaoning Province, China).

Model of Hydraulic Press	Maximum Working Pressure (MPa)	Effective Itinerary (mm)	Workbench Dimensions in (mm²)	Rempty Run Descending Speed (mm/s)	Working Speed (mm/s)	Return Speed (mm/s)
YQ32-630t-C	25	500	2000 × 1000	200	125	200
YQ32-315t-C	25	1000	1000 × 1000	250	200	250
RC-400T	25	1000	2000 × 750	250	250	250
YDA94	3	2000	1500 × 1000	1000	500	1000

According to the above parameters, the calculation formula for the time taken to compress one block of snow is as follows:

$$T = t_1 + t_2 + t_3 + t_4 + t_5 \tag{11}$$

where t_1 represents the time taken for the push plate of the temporary storage chamber to push the snow; t_2 represents the time used for the closed compression cylinder of the rotary-type hydraulic press; t_3 represents the compression operation time of the left–right

hydraulic press; t_4 represents the time for the compression and advancement operations of the front–back hydraulic press; and t_5 represents the time used for the return stroke of the front–back hydraulic press.

Substituting the above parameters into Formula (11) yields $T = t_1 + t_2 + t_3 + t_4 + t_5 = 4 + 4 + 4 + 10 + 8 = 30$ s, which means that every 30 s, a snow compression operation of 3 m^3 is completed, with the working efficiency of the compression device being $\eta_y = 0.1$ m^3/s.

2.7.2. Calculation of the Operational Efficiency of the Spiral Snow Collection Device

The operational efficiency of the spiral snow collection device is specifically reflected in the volume of snow that the collection spiral can transport within a unit of time [46,47]. The snow collection efficiency formula for the spiral snow collection device is as follows:

$$\eta_j = Sv \tag{12}$$

where S represents the cross-sectional area of the snow layer transported in m^2 and where v represents the axial transport velocity of the snow layer in m/s.

The cross-sectional area of the transported snow layer is as follows:

$$S = \frac{\pi}{4}\left[(D + 2\delta)^2 - d^2\right]K_c \tag{13}$$

where D represents the outer diameter of the helical blade; d represents the inner diameter of the spiral blade; K_c represents the filling coefficient of new snow, $K_c = 0.93$; and δ represents the gap between the outer edge of the spiral blade and the snow shovel. The gap between the outer edge of the spiral blade and the snow shovel is generally between 0.005 m and 0.015 m; here, $\delta = 0.014$ m.

The axial transport speed of spiral blades:

$$v = LR/60 \tag{14}$$

where L represents the pitch; R represents the rotational speed of the helical shaft.

In order to ensure the smoothness of collaborative operations, the snow collection efficiency should be matched with the compression efficiency, $\eta_j = \eta_y$. By substituting the outer diameter of the spiral $D = 0.7$ m, the inner diameter $d = 0.4$ m, and the pitch $L = 1$ m into Formula (11), we calculate $R \approx 22.22$ r/min. When the rotational speed of the spiral snow collection device is $R = 22.22$ r/min, the snow collection efficiency of the compression equipment is compatible with the compression efficiency, enabling the device to successfully complete the task of compressing and outputting two standardized snow blocks, each with a volume of 1 cubic meter, per minute.

3. Results: System and Structural Design

After completing the precise calculation and confirmation of the key functional structural parameters, this chapter systematically designs the structure and form of the design scheme on the basis of the aforementioned quantitative data and the functional structure references provided by the relative optimality principle solution while integrating ergonomic principles and user behavior patterns. It is expected that through the optimization and integration of the functional structure, the best synergistic effect among the components within the system will be achieved while also considering the aesthetic value and practical performance of the design, ultimately resulting in an innovative product solution that meets the design objectives.

3.1. Overall Plan Design

On the basis of the overall functions, a design combination of the functional structure has been carried out. Taking into account human factor engineering, the operational environment of the equipment, and the functional workflow, the structural modeling and usage design of the snow collection and compression equipment have been developed. Addition-

ally, three-dimensional digital methods have been employed for conceptual presentation (Figure 5). The snow collection and compression equipment consists of a driving device, a spiral snow collection device, a transmission device, a temporary storage device, and a compression device. During operation, the snow collection and compression equipment collects snow via a spiral auger and uses a snow-throwing impeller to throw the snow into the temporary storage chamber. When the pressure in the temporary storage chamber reaches the rated value, the collected snow is pushed into the compression device for compression, resulting in standardized snow blocks (Figure 6).



Figure 5. Effect diagram of the snow collection and compression equipment.



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

Figure 6. Operational effect diagram of the snow collection and compression equipment. (**a**) Snow collection; (**b**) standardized snow block output.

According to the "Limits of Dimensions, Axle Load and Masses for Road Vehicles (GB 1589-2004)"(Ref. Citations: Tang, B.; Wang, Z.Q. Transportation efficiency and traffic safety need to be comprehensively considered. Discussion on the Revision of GB1589-2004 "Limits of Dimensions, Axle Load and Masses for Road Vehicles". Cars and Accessories **2013** *(25)*, 36–39), the designed dimensions of the snow compression equipment vehicle are 6500 × 3000 × 2900 (mm), as shown in Figure 7.

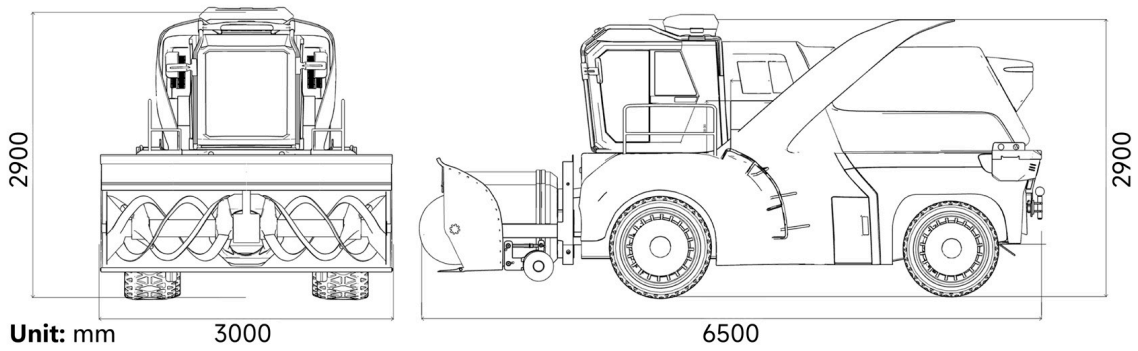


Figure 7. Overall dimension diagram of the snow collection and compression equipment.

In the design of the shape, a combination of traditional industrial forms with a sense of technology and aesthetically pleasing curves is employed, utilizing a simple and elegant black-and-white color scheme and incorporating a cautionary yellow hue to accommodate environments with reduced visibility, such as foggy and snowy conditions.

3.2. Core Structural Component Design

The snow collection and compression equipment mainly includes key structures such as a spiral snow collection device, temporary storage device, and compression device.

3.2.1. Design of the Structure of the Spiral Snow Collection Device

The spiral snow collection device consists of rotating blades, a baffle, and a snow-throwing impeller, which functions primarily to collect and transport accumulated snow. Its working principle involves the axial pushing of snow toward the central collection opening under the influence of the normal thrust and friction generated by the rotating blades, followed by the snow being thrown into a temporary storage device by the snow-throwing impeller. To break up large snow layers and accommodate different snow types while ensuring efficient and stable collection efficiency, the spiral blades are designed with a symmetrical serrated structure consisting of four blades (Figure 8).

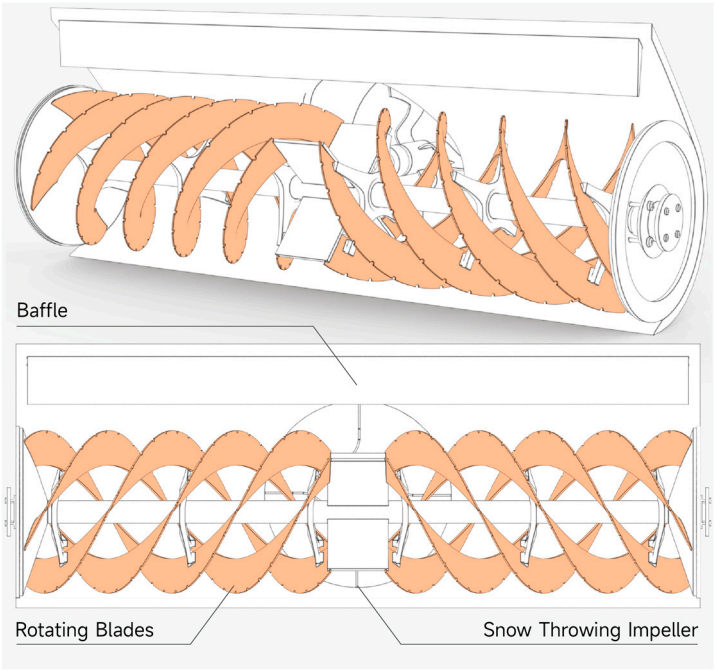


Figure 8. Structural diagram of the spiral snow collection device.

3.2.2. Design of Temporary Storage and Compression Devices

The temporary storage and compression device is responsible for the internal storage and morphological transformation of snow. After the spiral snow collection device completes the cutting and gathering of the snow, the high-speed rotating snow-throwing impeller, under the influence of centrifugal force, throws the snow gathered at the central collection point into the temporary storage chamber. When the pressure in the temporary storage chamber reaches the rated value, the lateral push rod advances the snow into the compression cylinder for compaction. The flow route of the snow within the device is illustrated in Figures 9 and 10.

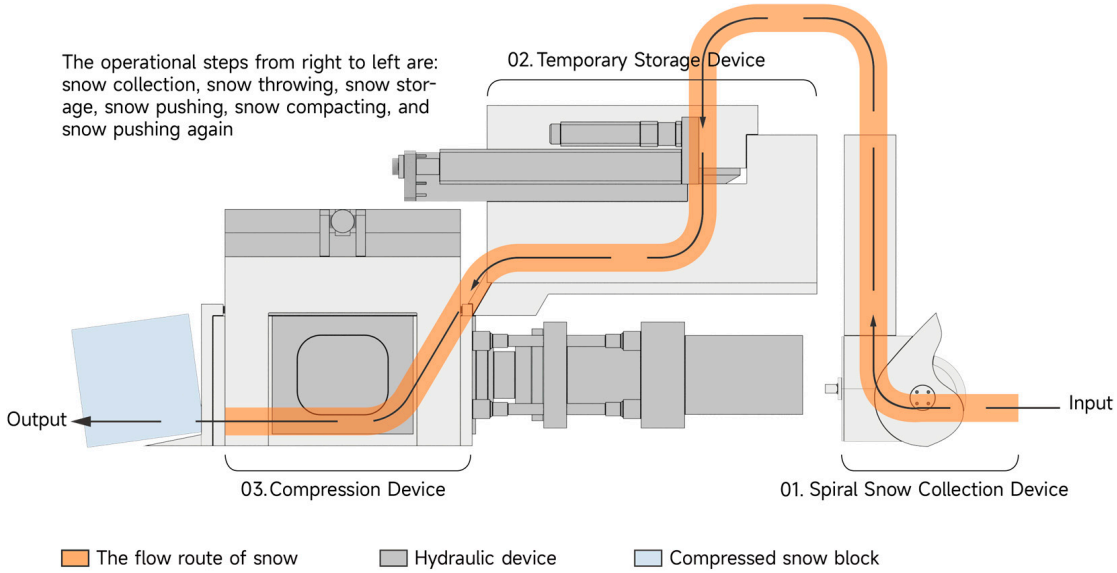


Figure 9. Right view of the internal flow path of snow in the equipment.

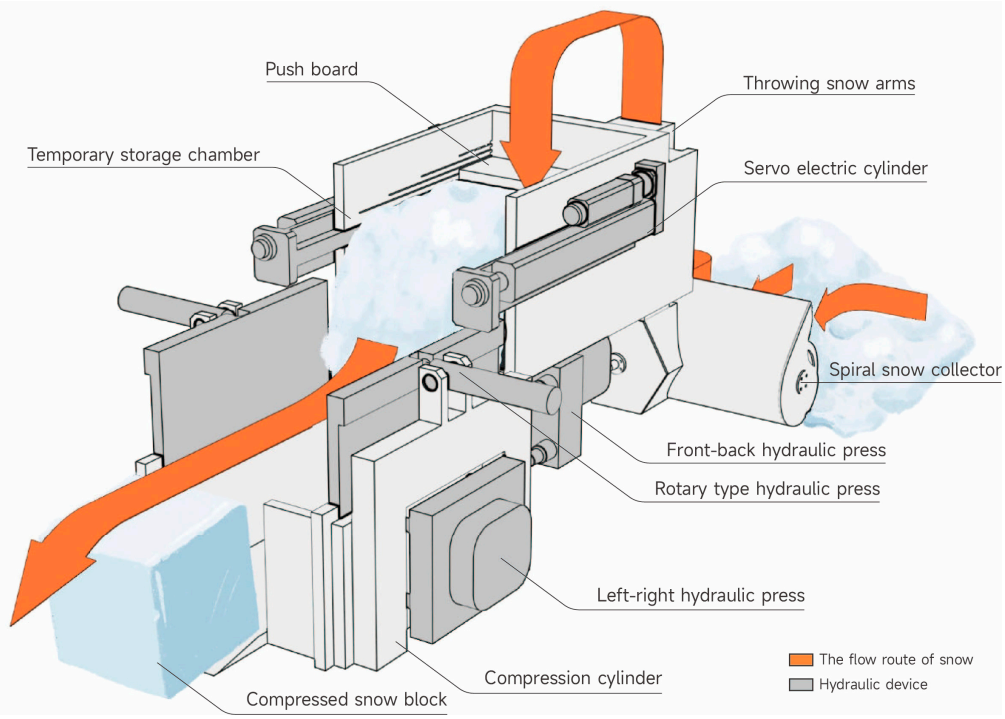


Figure 10. Schematic diagram of the axial flow path of snow within the equipment.

Similar to traditional methods [48], the temporary storage of snow was not considered during the initial design phase. The preliminary concept was to directly transfer the collected snow to a compression device for compaction. However, in conjunction with demand positioning and overall functional definitions, this method makes it difficult to control the amount of compressed snow and fails to meet the requirement for standardized snow blocks. Therefore, a temporary storage device with quantitative control functionality was added before the compression device, and pressure sensors were used to detect the internal snow pressure. Once the rated value is reached, the snow is then pushed into the compression device, allowing for precise control of the snow entering the compression device. In addition, the design of the temporary storage device provides a buffer space for the collected snow, with a storage capacity slightly exceeding the volume occupied by the snow at the rated pressure. This not only prevents the temporary storage device from overflowing when full but also reduces energy consumption, ensuring that the entire system can operate continuously for an extended period. The temporary storage system consists of a chamber body, a chamber door, a servo-electric cylinder, a transverse sliding rail push rod, and a ladder-type folding chamber cover, with the main material being alloy steel. When the amount of snow thrown into the temporary storage chamber reaches the rated pressure, the hatch opens, and the lateral sliding rail pushes the rod driven by the servo-electric cylinder to push the accumulated snow into the compression cylinder. During this operation, to meet the additional load-bearing and temporary storage functions for the accumulated snow, a ladder-type folding hatch is added to the top of the lateral sliding rail push rod to achieve isolation of the upper and lower spaces (Figure 11).

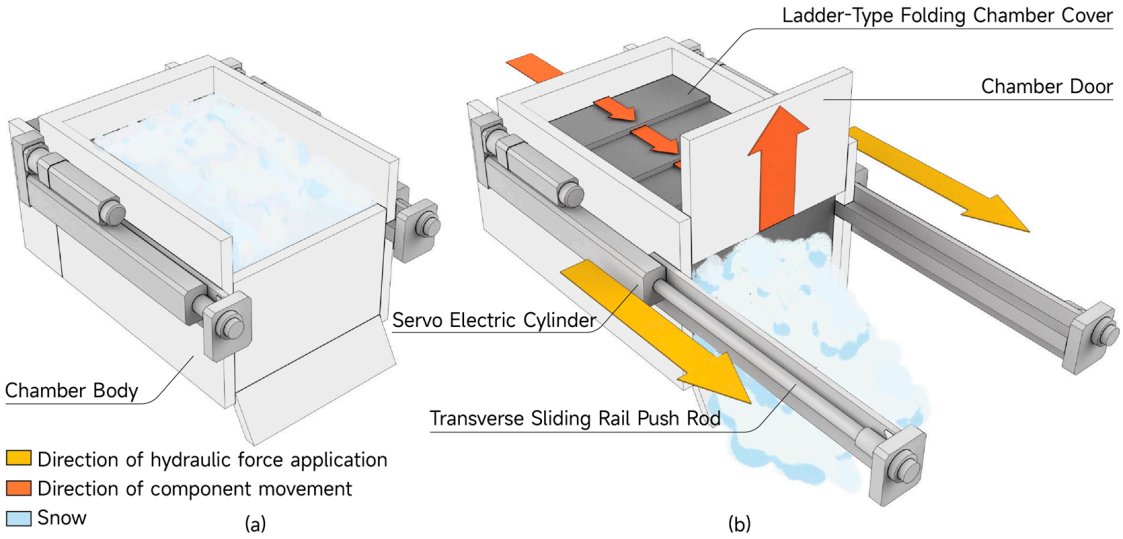


Figure 11. Schematic diagram of the working status of the temporary storage device. (**a**) Snow storage status; (**b**) pushing the snow into the compression device.

For snow block compression devices, existing research predominantly employs a unidirectional multiple repeated compression method. Although this method requires a small compression space, it exhibits low compression efficiency, high energy consumption, and struggles to ensure the quality of the snow blocks. Therefore, to ensure consistent specifications of the output snow blocks, this paper adopts a one-time forming compression method. Owing to the high compression ratio of snow, a larger compression space is required for one-time molding, and unidirectional compression can lead to an excessively long stroke of the hydraulic press, resulting in spatial layout conflicts with the overall equipment design. Therefore, to meet the design specifications for urban road vehicles, adjustments to the compression method are necessary to optimize the layout of the compression space. Ultimately, a triaxial compression device was designed on the basis of the

compression principles of a metal pressing machine [49,50], utilizing multiple hydraulic presses to achieve multidirectional compression (Figure 12).

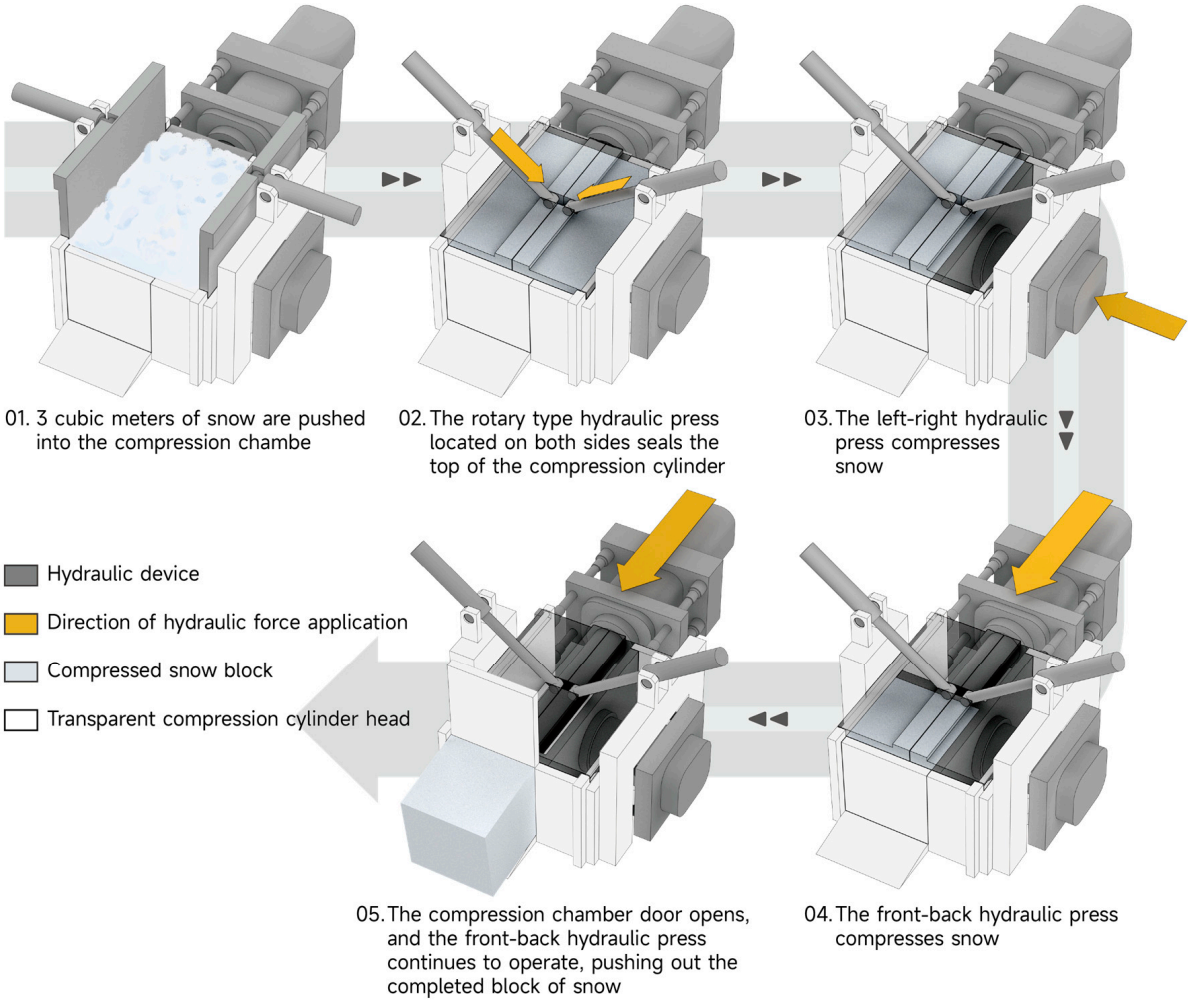


Figure 12. Schematic diagram of the compression device workflow.

4. Finite Element Simulation Validation

To further verify whether the design scheme meets the requirements of efficiency and stability defined in the overall functional specifications, finite element simulation is conducted on the temporary storage and compression device. By analyzing the stress and deformation of the applied materials and structures, the rationality and feasibility of the scheme can be further examined, and adjustments and improvements to the scheme can be made on the basis of the simulation results. In the finite element analysis of this study, alloy steel is used as the test material, assuming that it possesses homogeneity and isotropy. To simplify the calculations, it is assumed that the model adheres to linear elasticity and small deformation theory, and the model analysis is conducted under steady-state conditions.

4.1. Mechanical Simulation Analysis of Temporary Storage Devices

First, it is necessary to calculate the forces acting on the temporary storage device. The temporary storage device is responsible not only for the temporary storage of snow but also for the internal transportation of snow. The transportation system uses a servo-electric cylinder as the power source for transportation operations. Owing to the influence of friction and the rated working speed during the snow-pushing process, the servo-electric cylinder must provide a significant thrust to meet the operational requirements of the system. Therefore, to prevent excessive force on the pushing rod that could lead

to structural failure, it is necessary to calculate the maximum thrust required by the transportation system and incorporate it into a finite element analysis for static stress evaluation to verify the feasibility of the structural design.

To ensure structural stability, the transportation system pushes the snow with a maximum-rated thrust F_1, performing uniformly accelerated motion over a time period t_1. The calculation formula for the rated thrust F_1 is as follows:

$$F_1 = \mu_0 m_0 g + \mu m g + m a \tag{15}$$

$$S_1 = v t_1 + \frac{1}{2} a {t_1}^2 \tag{16}$$

where μ_0 represents the coefficient of internal friction of snow and ice; m_0 represents the mass of the upper layer of accumulated snow in the temporary storage chamber, taken at a full load value of 360 kg; μ represents the coefficient of external friction between snow and steel; m represents the mass of the lower layer of pushed snow in the temporary storage chamber, taken at a full load value of 900 kg; a represents the acceleration of the pushing operation; S_1 represents the pushing distance; and v represents the initial velocity. Research indicates that the coefficient of friction of accumulated snow varies with density, as shown in Table 8.

Table 8. The coefficient of friction between snow and steel.

Density of Snow (g/cm^3)	Friction Coefficient			
	0 °C~−6 °C		Below 10 °C	
	Internal Friction	Friction with Steel Materials	Internal Friction	Friction with Steel Materials
0.1	0.25	0.12	0.34	0.18
0.3	0.38	0.08	0.46	0.09
0.5	0.50	0.30	0.57	0.04

By substituting μ_0 = 0.38, m_0 = 360, μ = 0.08, m = 900, S_1 = 2, and v = 0 into Formulas (15) and (16), the maximum rated thrust F_1 = 2313 N is obtained. Therefore, during the pushing and transfer operation, the servo-electric cylinders on both sides provide a thrust of 1156.5 N each through the lateral sliding rail push rod, and the push rod acts as an intermediary to drive the pushing surface to perform uniformly accelerated motion.

A finite element model is established on the basis of the above calculation data to simulate the temporary storage device:

1. A finite element model is established. The temporary storage device model created via Rhino (6.0) 3D drawing software in .stp format was imported into SolidWorks (2022), and the Simulation plugin was used for simulation analysis;
2. Define the material properties. The material of the temporary storage device is alloy steel from the material library, with a modulus of elasticity of 210 GPa, a Poisson's ratio of 0.28, a shear modulus of 79 GPa, a density of 7700 kg/m^3, and a yield strength of 0.62 GPa;
3. Apply loads and constraints. Based on the aforementioned calculation data, a force of 1156.5 N is applied at each of the two piston rod ports, and fixed constraints are imposed on the pushing surface and the electric cylinder body (Figure 13);
4. Grid partitioning. High-quality grid elements are used for grid partitioning, with a default grid accuracy level set to moderate. The grid parameters are based on mixed curvature, with Jacobian points at 16. The total number of grid nodes is 28,619, the total number of elements is 14,716, and the maximum aspect ratio is 401;
5. Conduct simulation calculations. Through simulation analysis, a stress–strain contour map of the temporary storage device is obtained (Figure 14).

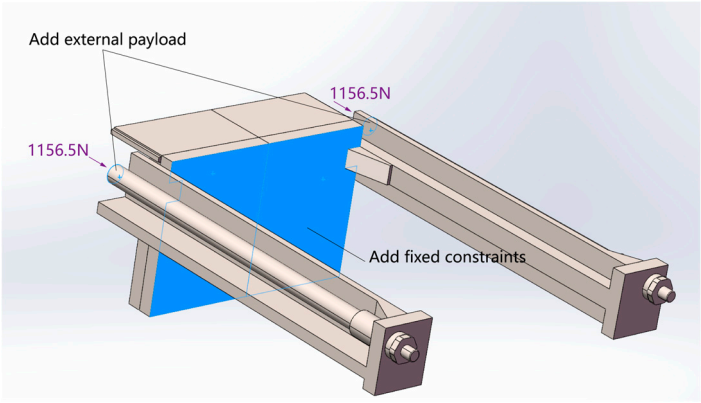
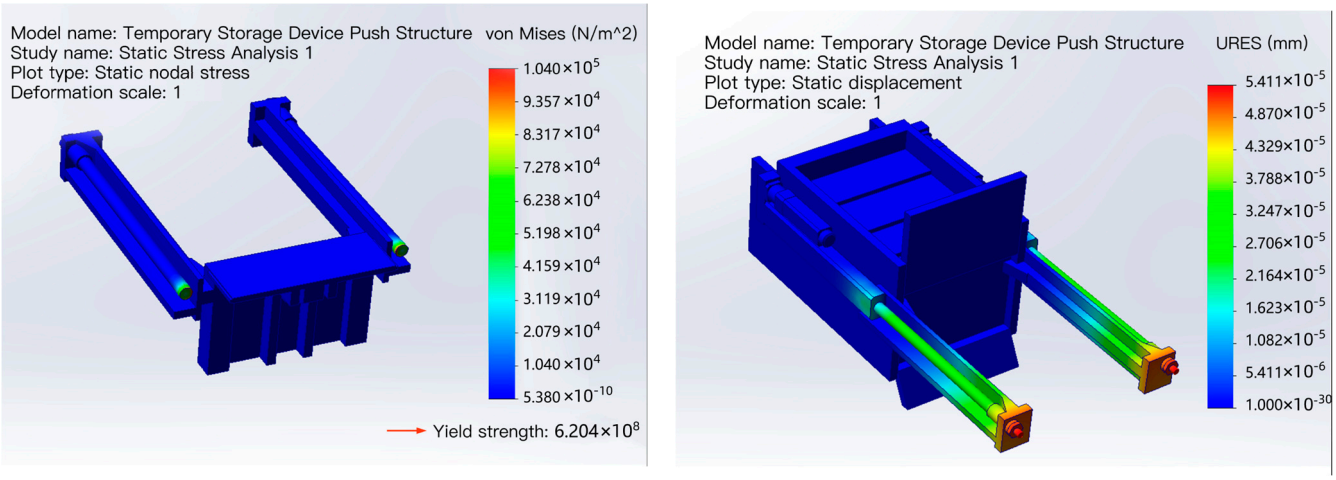


Figure 13. Load and constraint addition of the temporary storage device.



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

Figure 14. Stress and displacement cloud diagrams of the temporary storage device push structure in SolidWorks. (**a**) Stress diagram of the temporary storage device; (**b**) deformation displacement diagram of the temporary storage device.

The analysis results indicate that during motion, the stress concentration area is primarily located at the point of force application, with the maximum stress of 1.04×10^5 Pa, which is significantly lower than the yield strength of alloy steel, suggesting that the loading on the push rod structure is reasonable. Furthermore, the study indicates that the maximum displacement, recorded at 5.411×10^{-5} mm, indicates negligible structural deformation during operation. Therefore, the design of the temporary storage device is stable and reliable and is capable of meeting the task requirements.

4.2. Mechanical Simulation Analysis of the Compression Process in Compression Devices

When the snow reaches a state of ice and snow upon the completion of compression, the local pressure on the unit area of the snow brick reaches 3 MPa, and the compression device is under maximum load. At this point, the compressed snow brick exerts a reverse expansion force of 3×10^5 N on the inner surface of the compression cylinder. Therefore, it is necessary to secure the periphery of the compression cylinder and the contact surfaces of the three hydraulic devices and to analyze the stress conditions of the compression cylinder structure.

A finite element model is established on the basis of the above calculation data to simulate the compression device:

1. The process of establishing the finite element model and defining the material properties is consistent with that of the temporary storage device;

2. Loads and constraints are applied. Fixed constraints are added around the compression cylinder and on the three hydraulic unit contact surfaces, and an outwards force of 3×10^5 N is added to each of the six inner surfaces of the square formed after compression (Figure 15);
3. Grid partitioning. High-quality grid elements are used for grid partitioning, with a default grid accuracy level set to moderate. The grid parameters are based on mixed curvature, with Jacobian points set at 16. The total number of grid nodes is 48,513, the total number of elements is 25,347, and the maximum aspect ratio is 606;
4. Conduct simulation calculations. Through simulation analysis, a stress–strain contour map of the compression device was obtained (Figure 16).

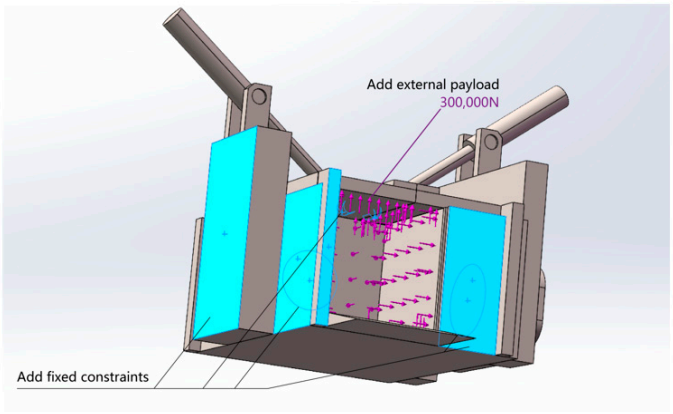
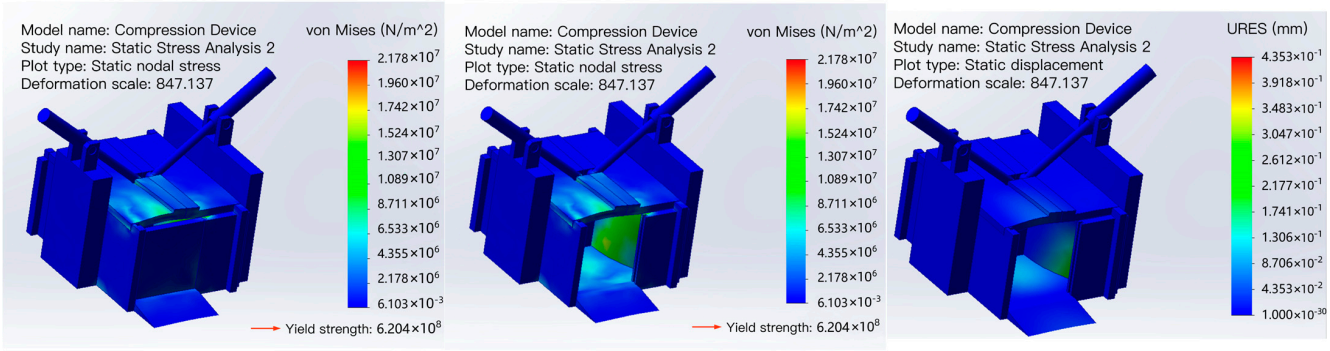


Figure 15. Load and constraint addition of the compression device.



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

Figure 16. Stress and displacement cloud diagrams of the compression device using SolidWorks. (**a**) Internal stress conditions of the compression device; (**b**) overall stress condition of the compression device; (**c**) internal displacement and deformation of the compression device.

The analysis results indicate that the overall maximum stress of the compression device is less than the yield strength of the alloy steel, thereby confirming that the structural strength meets the design requirements. Additionally, the maximum displacement of the compression cylinder is a lateral bending offset of 0.4353 mm from the hydraulic press head plate, which is within the normal deformation range.

4.3. Mechanical Simulation Analysis of the Rotary Axis Hydraulic Press

When the compression device reaches the maximum load, the shaft-type hydraulic press forms an angle of 45° with the compression cylinder. To meet operational requirements, each hydraulic press provides a force of $\frac{3\sqrt{2}}{2} \times 10^5$ N along the axial direction. To verify the structural load-bearing capacity, a static mechanical analysis of the rotary axis hydraulic press is conducted:

1. A finite element model is established with the coordinate axis as the center of the hydraulic press head, and the process of defining the material properties is consistent with that of the temporary storage device;
2. Loads and constraints are applied. A force of 1.5×10^5 N is applied in both the vertical direction (along the z-axis) and the horizontal direction (along the x-axis) on the hydraulic press head, and a fixed constraint is added at the rotation axis of the hydraulic press (Figure 17);
3. Grid partitioning. High-quality grid elements are used for grid partitioning, with a default grid accuracy level set to moderate. The grid parameters are based on mixed curvature, with Jacobian points at 16. The total number of grid nodes is 15,756, the total number of elements is 9163, and the maximum aspect ratio is 5.7;
4. Conduct simulation calculations. Through simulation analysis, the stress–strain contour map of the rotary axis hydraulic press was obtained (Figure 18).

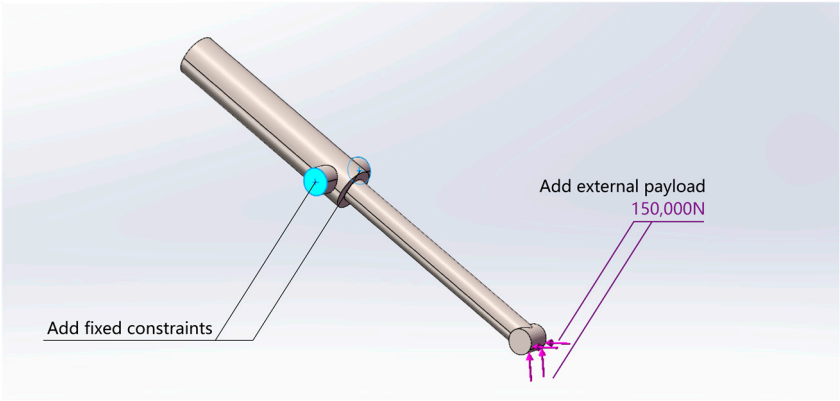
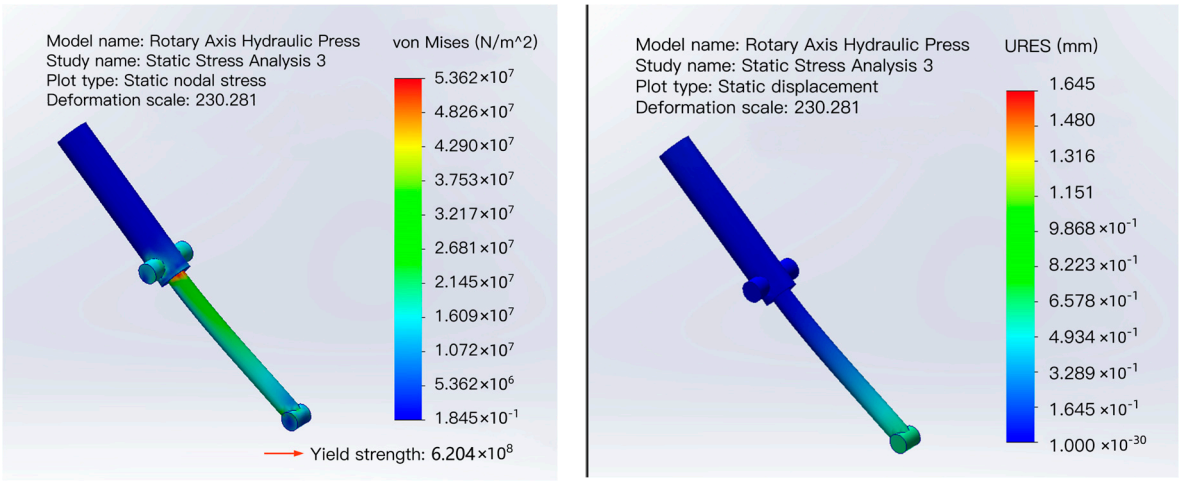


Figure 17. Load and constraint addition of rotary axis hydraulic press.



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

Figure 18. Stress and displacement cloud diagrams of a rotary axis hydraulic press in SolidWorks. (**a**) Stress diagram of the hydraulic press; (**b**) deformation displacement diagram of the hydraulic press.

The analysis results indicate that when the hydraulic pressure reaches its maximum output, the maximum stress point is located at the intersection of the cylinder body and the piston rod, measuring 53.62 MPa, which is far below the yield strength of alloy steel, and the maximum displacement is less than 1 mm.

In conclusion, the temporary storage devices and compression systems have demonstrated the capability to fulfill their design objectives effectively and stably, thereby satisfy-

ing the comprehensive functional requirements. The core structural design is both rational and feasible.

5. Discussion

Previous research on snow has focused largely on its negative impacts, with a particular emphasis on the domain of disaster prevention and mitigation. In terms of response measures, snow is typically regarded as an obstacle that needs to be cleared, overlooking its valuable potential as a renewable resource. This study addresses the issue of waste regarding the abundant natural snow resources in mid- to high-latitude regions. Through functional analysis and the AHP–fuzzy comprehensive evaluation method, snow collection and compression equipment have been designed to achieve efficient collection, compression, and conversion of snow resources. The research findings reveal the potential of this equipment in reducing the costs of constructing ice and snow sculptures, alleviating environmental and public safety pressures, and providing innovative solutions for the sustainable development of the ice and snow tourism industry.

5.1. The Role and Limitations of Functional Analysis Method

This study employs the functional analysis method to conduct problem analysis, successfully deriving product solutions aligned with the design requirements. Practice has shown that the functional analysis method can simplify complex issues during the design analysis phase, assisting designers in quickly clarifying their thoughts and defining design objectives. It provides a realistic structural reference for functionality in the form of relatively optimal solutions, thereby enhancing the feasibility of the proposals to a certain extent. However, relying solely on functional analysis is insufficient to support the comprehensive output of a plan. Designers must also integrate factors such as aesthetic form, ergonomics, usage environment, and behavioral patterns for a comprehensive analysis to guide design practice collectively.

5.2. Comprehensive Application of Analytic Hierarchy Process and Fuzzy Comprehensive Evaluation

This study employs the Analytic Hierarchy Process (AHP) and fuzzy comprehensive evaluation method to evaluate and select functional schemes, aiming to increase the objectivity and scientific nature of decision-making. The AHP is predominantly utilized for determining the weights of the evaluation criteria, establishing an indicator system for snow compression equipment that encompasses factors such as efficiency, reliability, economic viability, maintainability, environmental friendliness, safety, and adaptability. These indicators comprehensively cover the critical performance dimensions of snow collection and compression equipment. Through the comprehensive scoring of these evaluation indicators by experts in multiple fields, the design program can be evaluated comprehensively and objectively. A judgment matrix is established based on the expert evaluation data, and the weight vector of each indicator is calculated by the geometric mean method, ensuring the logical rationality of the evaluation system through the consistency test. On this basis, the fuzzy comprehensive evaluation method is utilized to provide a comprehensive score for each program. The key to fuzzy comprehensive evaluation is to transform the qualitative evaluation criteria into quantitative values and address uncertainty and ambiguity through fuzzy mathematics so that the evaluation results are more in line with the actual situation. By defining a fuzzy evaluation set and constructing an evaluation matrix, the subjective evaluations from experts are transformed into a quantifiable affiliation function, addressing the challenge of quantifying program evaluations.

In this study, a key point is the integration of the weight vector determined by the AHP (Analytic Hierarchy Process) with fuzzy quantitative evaluation [51]. By combining the objective weight vector with quantifiable membership functions, the objectivity and comprehensiveness of the evaluation results are enhanced. Additionally, through con-

sistency testing and the application of fuzzy mathematics, the logical rigor and scientific nature of the evaluation process are ensured.

5.3. Strategies for the Sustainable Utilization of Snow Resources

The snow collection and compression equipment provides a new solution for the recycling of snow resources by compressing natural snow into standardized snow blocks. The standardized compressed snow blocks enrich the application scenarios of snow resources, facilitating their use in the form of standard parts in the fields of ice and snow tourism, ice and snow education, and cold chain logistics.

For ice and snow tourism, a new strategy for the sustainable utilization of snow resources with strong adaptability is proposed in this study [52]. A special phenomenon has been revealed through research: outside of snow and ice tourism areas, a significant amount of accumulated snow on roads is regarded as a safety hazard and is cleared and discarded; in contrast, within snow and ice tourism areas, due to insufficient natural snowfall, people are compelled to rely on artificial snowmaking, which negatively impacts the ecological environment, to meet the demand for snow. The reasons for this phenomenon can be succinctly summarized in two aspects: the purity of the snow and the costs associated with collection and transportation. In response, this study proposes a sustainable utilization strategy that involves the recovery and reuse of natural snow through snow collection and compression equipment and its application in the construction of urban snow sculpture landscapes. The core of this strategy revolves around onsite utilization, entailing the direct construction of small snow sculptures from the collected and compressed standardized snow blocks at the original site or in broad areas within the city (such as parks and squares). This approach not only economizes on the costs related to the long-distance transportation of snow to traditional scenic areas but also avoids the disruption of regional water resource regulation caused by the large-scale transfer of snow resources, thereby minimizing the environmental impact of resource utilization. Secondly, regarding the purity of the collected snow, this strategy does not require the purification and refinement of the collected snow but rather achieves this goal by altering the utilization methods of the recycled snow. On the one hand, snow blocks of lower purity can be employed as internal support structures within snow sculptures, overlaid with a thin layer of artificially produced snow, and refined through a process of spraying and freezing; on the other hand, dirty snow blocks can serve as dark accents for snow sculpture, further enriching the visual experience of sculpture. The two utilization methods of dirty snow and the process of building snow sculptures are illustrated in Figure 19.

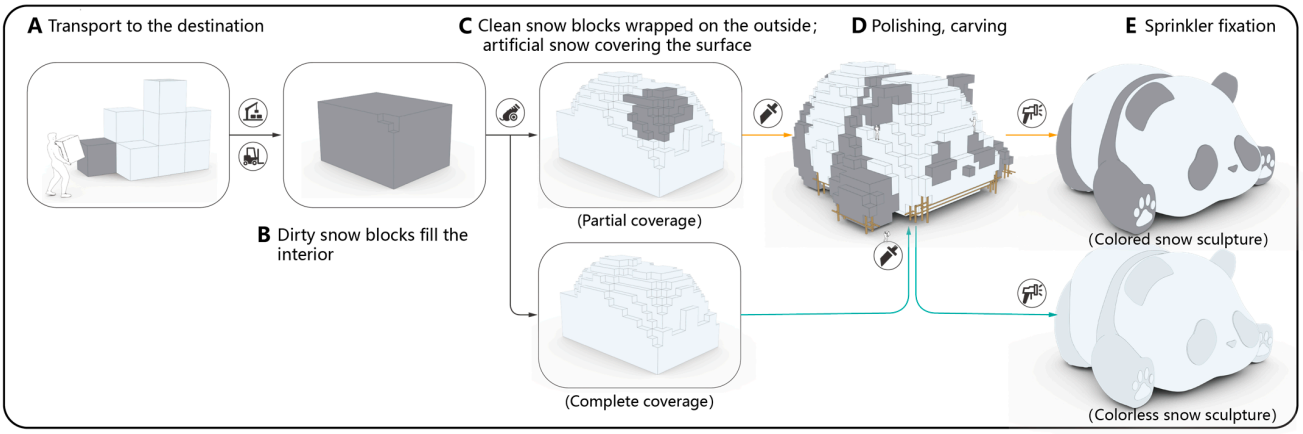


Figure 19. Flowchart of snow sculpture production.

This strategy revolutionizes the traditional approach to the development of ice and snow tourism, aiming to foster the growth of urban ice and snow tourism initiatives. It fully utilizes abundant natural snow resources, replacing artificial snowmaking with

the construction of snow sculptures using natural snow blocks, thereby breaking the geographical limitations of traditional ice and snow attractions at extremely low cost and enabling the large-scale creation of snow sculpture landscapes (Figure 20). Furthermore, by extending the reach of ice and snow tourism across the entire city, this strategy establishes distinct zones that celebrate the unique cultural identities of different regions. Given that cities and towns are a collective embodiment of regional culture, the integration of snow sculpture art with local culture creates regional characteristics [53], providing visitors with an immersive experience while further deepening their understanding and awareness of local culture. This strategy is expected to provide effective references for the sustainable utilization of global snow resources.



Figure 20. Rendering images of real scene effects.

5.4. Research Limitations

In the later phase of the study, finite element analysis software was employed to simulate the design scheme, conducting a detailed analysis of the stress and deformation in several critical structural components. The results indicate that the design scheme is reasonable and feasible. However, since feasibility testing of the final scheme remains at the stage of software simulation, the results may not fully capture the complexities and uncertainties of real-world conditions, which introduces certain limitations. In the future, physical prototype testing and experimental validation will be conducted to further enhance the credibility of the results. The actual measurement data obtained from the experiments provide key references for the calibration and optimization of the simulation model, ensuring that the final product has the expected performance and stability in practical application scenarios.

5.5. Future Prospects

Given the impact of global climate change on snow resources, snow collection, and compression equipment has broad application prospects. Research indicates that regions with well-developed snow and ice tourism are primarily concentrated in high-latitude and high-altitude areas such as the Alps, the South Island of New Zealand, and the Rocky Mountains in North America. However, with global warming, these areas are facing challenges such as reduced natural snowfall, shortened snow seasons, and environmental pollution and resource waste resulting from an overreliance on artificial snowmaking. Consequently, these regions are actively pursuing innovative strategies to enhance the utilization of snow resources. Moreover, owing to the significant impact of heavy snowfall on residents' lives during the snow season, countries at mid to high latitudes, such as Canada and Russia, have incorporated the effective clearing and proper disposal of winter snow into their fundamental management practices. Therefore, the snow collection and compression equipment and sustainable utilization strategies for snow resources proposed in this study have broad application prospects. Additionally, the snow compression properties of snow collection and compression equipment provide a mechanized solution for the

construction of ice and snow houses in polar regions. By adapting the snow collection and compression equipment according to the specific conditions of different regions, efforts are made to promote its global application as much as possible, thereby making a substantial contribution to the sustainable utilization of snow resources worldwide.

Future research will continue to focus on the size adjustment and performance optimization of this equipment under different climatic and regional conditions around the world to ensure its widespread application globally.

6. Conclusions

In response to the issue of snow resource waste caused by indiscriminate snow removal in mid- to high-latitude regions, this study employs functional analysis and the AHP–fuzzy comprehensive evaluation method to propose a design scheme for snow collection and compression equipment, as well as strategies for the sustainable use of snow resources. By collecting and compressing snow into standardized snow blocks and applying them to the construction of snow sculptures, this approach achieves the recycling and high-value transformation of natural snow resources, providing an innovative solution for the sustainable utilization of snow resources. Research indicates that the design of this equipment can effectively increase the efficiency of snow sculpture construction, reduce the costs associated with snow sculpture buildings and the use of natural snow, decrease reliance on artificial snowmaking, and alleviate, to some extent, the pressure that accumulated snow exerts on the environment and public safety.

Moreover, this study explored the potential for fully utilizing natural snow resources outside traditional fixed ice and snow scenic areas to develop urbanized ice and snow tourism. This strategy has a significant positive effect on maintaining the balance of regional water cycles, providing an innovative adaptive strategy for the sustainable development of the global snow and ice tourism industry by offering solutions to address snow quality pollution and transportation costs.

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