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ELUCIDATING PRODUCT BASED ON SYSTEM-LEVEL DESIGN PHASE: INTELLIGENT FROST PREVENTION EQUIPMENT DESIGN FOR TEA

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Abstract. The purpose of this study is to address the challenges of conceptual design creativity and functional derivation for complex products in the System-level Design Phase, filling the research gap in design strategies at the conceptual design stage. Conceptual design of complex products is recognized as a challenging and ill-defined problem involving various interdisciplinary aspects such as technological trends, social factors, functional requirements and aesthetic preferences. Based on a literature review, this study integrates Bytheway's FBD model and Benami & Jin's Creative Stimulation method, exploring a new research framework for creative inspiration and design strategies in industrial design during the conceptual design. Leveraging the characteristics of complex product conceptual design and its requirement for diverse knowledge, the study conducts a practical exploration during the product system-level design stage. Using a combination of subjective and objective research methods, the investigation analyzes information related to tea antifreeze equipment. The findings highlight creative stimulation in the conceptual design stage, offering applications for the tea planting equipment industry. The results of this study have practical significance for the design of tea frost prevention equipment. It provides a systematic research strategy for the product conceptual design phase, contributing to the understanding and application of systematic methods in industrial conceptual design.

Keywords: *Conceptual design, equipment, frost prevention, product design, system-level.*

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1. Introduction

With the rapid development of science and technology and the economy in modern society, advanced technology has widely penetrated every field of People's Daily life. It has a huge impact on the industrial product design industry. Industrial product design is a creative process that combines engineering and art. It usually starts with identifying a need opportunity, goes through a series of activities to find the best solution to the problem and ends with a detailed description of the product. In their research (Beitz *et al*., 1996), Pahl and Beitz have categorized the design process into four distinct phases: (1) Planning and clarifying the task; (2) Conceptual design; (3) Embodiment design and (4) Detail design. Figure 1 delineates each of these phases, presenting the requisite steps

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for their execution. In the planning and clarifying the task phase, requirements are systematically compiled, encompassing demands, wishes and constraints, ultimately leading to the establishment of a requirements list. The conceptual design phase involves the development of the principal solution. The embodiment design phase, through the process of developing the construction structure, yields a Preliminary layout, followed by the definition of the construction structure. The detail design phase primarily involves the preparation of production and operating documents, resulting in the generation of Product documentation, ultimately addressing and resolving the identified design challenges.

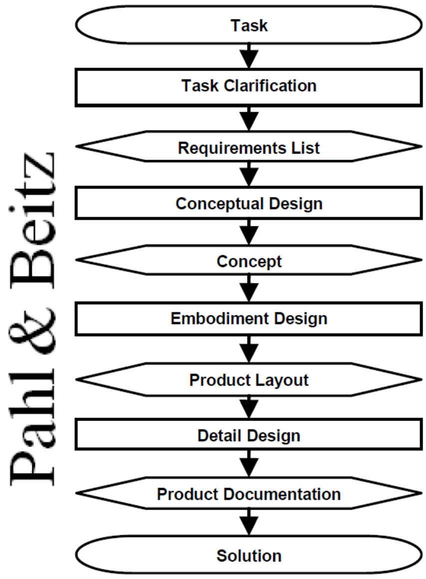


Figure 1. The phases of design (Beitz *et al*., 1996)

Industrial product design mainly involves people consciously conceiving the product design process through modern science technology and theoretical knowledge. In this process, product conceptual design requires designers to have a high degree of professional quality and design experience and can integrate innovative elements into the actual design needs to form a systematic and comprehensive product conceptual framework. On the basis of this framework, based on modern technology such as structure, materials and manufacturing processes, industrial products are given the connotation and performance that can be achieved in certain fields in the future for a certain period of time, so as to better meet people's growing material and cultural needs with advanced social science and technology. Therefore, the conceptual design of complex products is a poorly defined problem and the process involves multi-disciplinary issues such as technological development trends, complex social factors, diverse functional requirements and aesthetic preferences for styling (Zhang *et al*., 2016). The study analyzes the product conceptual design stage through a systematic method, summarizes the creative stimulation in this stage and provides a reference for producing better designs.

2. Analysis of previous research

Conceptual design

Conceptual design is a stage in the product design cycle. Based on the problems discovered in the product design specification stage and the concepts proposed, detailed solutions are produced to formulate basic problem-solving paths (Micheli *et al*., 2019). Conceptual design transforms high-level descriptions of requirements into high-level descriptions of solutions styling (Wu *et al*., 2022). It involves expressing abstract design ideas with relatively specific representation methods such as hand drawings, CAD renderings, models, etc. (Hu *et al*., 2022). The early or conceptual stage of the design process is primarily about the exploration of ideas, followed by in-depth refinement based on the relevant concepts involved in the product. In this process, as more data factors are considered and some more practical functions are gradually verified, designers need to make choices between competing alternatives (Jeannet *et al*., 2021).

Conceptual design runs through all stages of product design, creating, analyzing and structurally designing product functions according to the product life cycle. This is a process of design and creation, but also a process of experimental solutions to meet various design needs and indicators and to select the most reasonable design plan from multiple design plans. In the conceptual design process, designers need to have a high degree of professional knowledge and design experience, be able to adopt more advanced design methods and commercial operation knowledge and keep pace with the times to more comprehensively respond to consumers' personalized design needs.

Concept design is crucial, especially when designing new innovative products, or when generating entirely new designs for existing products. At this stage, the information is very vague and incomplete, which makes the design process quite difficult and challenging. With the continuous development of science and technology, the design of modern industrial products begins to involve more and more interdisciplinary knowledge, information and technology. For example, the development process of aircraft, automobiles, smart home appliances, complex electromechanical products, etc. involves machinery, electronics, control, mechanics, big data and other disciplines, its design is a collaborative creation and highly coordinated R&D process by design groups in different disciplines. At present, research on the conceptual design of complex products at home and abroad mainly focuses on the modeling of the conceptual design process of complex products (Gero & Kannengiesser, 2004), functional reasoning and solution of complex product conceptual design (Yap & Fok, 2002) and collaborative design and conflict resolution of complex product concepts (Yin *et al*., 2008), computer-supported solution collaborative design environment and tools (Komoto & Tomiyama, 2012) etc. However, due to the complexity of the product itself and the coupling between various disciplines, multidisciplinary optimization analysis in the conceptual design stage of complex products is more difficult.

Systematic approach to conceptual design

Product system design is based on the theory of modern industrial design and incorporates principles from other disciplines (Vasantha *et al*., 2012). Taking system theory as the starting point, this approach emphasizes that the entire product functions as a system. It views each component as a subsystem within the larger whole and establishes the internal and external systems of the product. The internal system refers to the relationship between the various elements of the product itself and its structure, while the external system refers to the relationship between the product itself and the external environment (Shoshany-Tavory *et al*., 2023). The internal and external systems mutually promote and complement each other and they are present throughout the entire life cycle of the product.

Bytheway's research (1965) provides a formal method of conceptual functional design based on functional logic rules, resulting in the functional block diagram (FBD) shown in Figure 2. The functional block comprises the function name, denoting the executed action, articulated as a generic noun/verb pair elucidating the functionality of the product or process. The structure tree traces back to the left to explain step by step why the corresponding function is needed, Nodes situated to the left of a function node delineate the rationale for the inclusion of a function, representing higher-level functions. Conversely, the derivation to the right explains how to implement it in levels and nodes to the right encapsulate functions detailing the execution methodology, embodying lower-level functions. Each higher-level function establishes connections with lower-level functions within an and-tree structure, thereby maintaining the integrity of the how/why relationship.

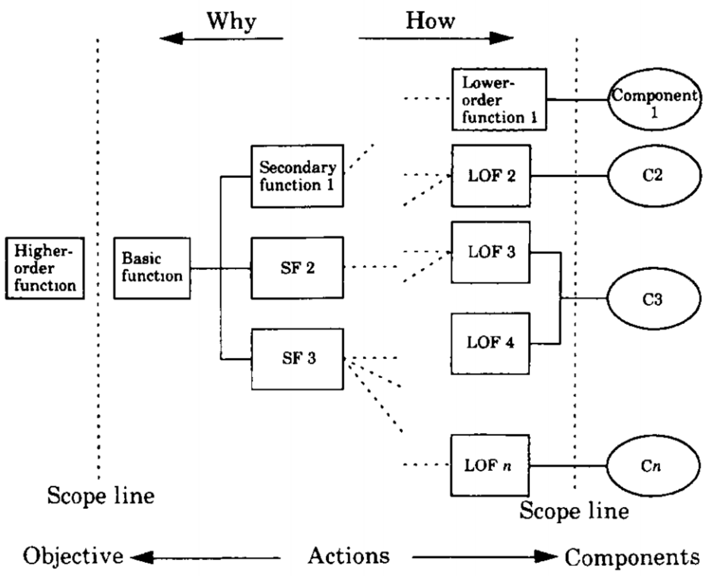


Figure 2. The general form of a function logic diagram (Bytheway, 1965)

The outcome of the synthesis of functional logic is a reasoned structure that establishes a relationship between each component and the fundamental function within the design. However, notably absent is the management of preliminary specification data (Sturges, 2015). When dealing with solving vague problems, the process involves multidisciplinary considerations. It requires not only logical reasoning but also the stimulation of creativity. Comprehensive considerations encompass technological trends, social factors, functional requirements and aesthetic preferences in design. While design method research has successfully identified crucial design principles, the interconnection between creativity, cognitive processes and design operations remains unexplored.

Creative stimulation in conceptual design

Prior studies on the design process have acknowledged the existence of design entities, which serve as representations of cognitive content (Gero & Mc Neill, 1998). Additionally, cognitive processes have been identified as generators of creative ideas (Siemon & Robra-Bissantz, 2018) and design movements or operations have been recognized as mechanisms propelling the advancement of a design (Garbuio & Lin, 2021). The investigation conducted by Benami and Jin (2002). represents an initial endeavor to systematically examine the interrelationships among cognitive processes, design operations and design entities within the realm of creative conceptual design. Design entities, foundational elements of a design artifact, assume a central role in this context. Cognitive processes materialize as cognitions that culminate in the generation of design operations—crucial actions facilitating the integration of design entities into the design framework. Following their inception, design entities stimulate supplementary cognitive processing, thereby catalyzing the continued generation of design operations (Figure 3).

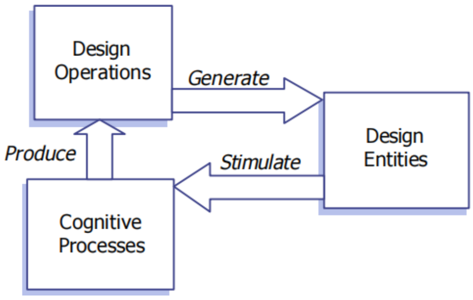


Figure 3. Framework for creative conceptual design (Benami & Jin, 2002)

Derived from their experimental findings, it was observed that ambiguous entities elicit a higher degree of behavioral stimulation compared to non-ambiguous entities. Notably, behaviors, being inherently ambiguous aspects of an entity, yielded twice the number of ideas compared to function and three times the number of ideas compared to knowledge entities. This empirical evidence substantiates the proposition that creative patterns can be discerned through designer profiling and subsequently incorporated into the design process, thereby enhancing idea generation. However, in this process, due to the uncertainty of fuzzy entities, the direction of generated creative ideas and the incorporation of relevant constraints may be influenced, thereby impacting the effectiveness of the final solution. Therefore, exploring how to impose constraints while generating more creative ideas and fostering effective creative stimulation and ideas among different designers may require further exploration.

Research framework

Based on the above analysis, there is a research gap in design strategies for product conceptual design, the possibility of integrating logical reasoning and creative stimulation. This can allow for the comprehensive consideration of various constraints when solving ill-defined problems, generating more creative ideas while enhancing the effectiveness of the ideas. Therefore, this study adopts the formalized method of Conceptual Functional Design proposed by Bytheway and draws on the experimental results of Benami and Jin. Both methods are combined to guide design practices, as shown in Figure 4.

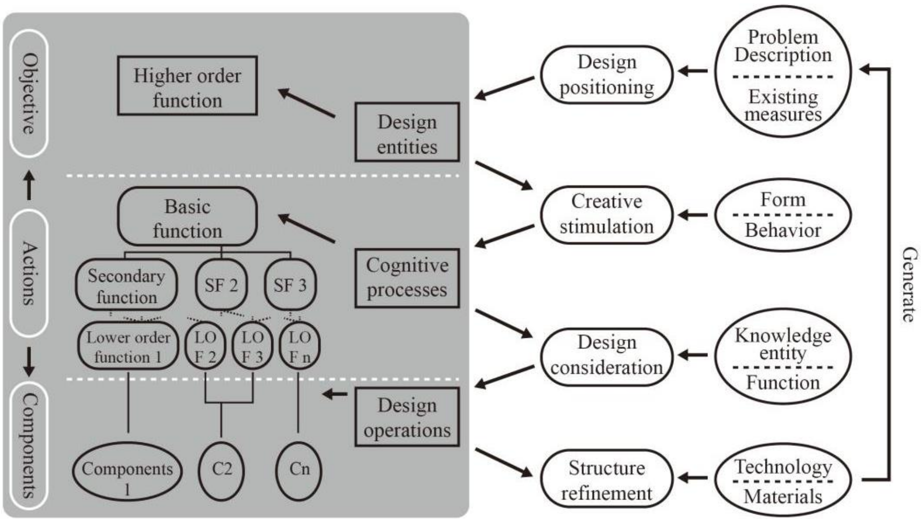


Figure 4. Research framework
Source: Drawn by the author

Feasibility of developing tea frost prevention equipment

The tea planting industry has long been plagued by the issue of frost damage to tea. Despite having some measures against frost, significant economic losses are incurred every year due to frost. With advancements in technologies such as artificial intelligence and the Internet of Things, there is now a possibility of developing new frost protection devices for tea. In this process, it is necessary to consider various constraints in design, including technological trends, social factors, functional requirements and aesthetic preferences. Additionally, the involvement of more professionals in industrial design, electronic information engineering, structure, materials, etc., is crucial to ensure the direction and effectiveness of these solutions while generating more creative ideas.

Hence, this study adopts the formalized method of conceptual function design proposed by Bytheway and drew upon the experimental findings of Benami and Jin. Based on the above research framework, a practical study on the design of frost protection devices for tea has been conducted.

3. The current research of frost prevention for tea

Tea, as one of the important economic crops in China, has a long history of cultivation and holds high ecological and economic value. However, due to climatic factors, tea production in many regions of China is susceptible to low-temperature frost disasters, such as the "reverse spring cold" in early spring. These events often lead to reduced production and varying degrees of economic losses (Peijuan *et al*., 2021). The research on agricultural equipment for tea frost prevention helps reduce the risk of future tea disasters, promotes the production of high-quality and high-yield tea, effectively ensures the resilience and sustainability of the tea industry and advances the mechanization, informatization and modernization of tea production.

The current situation of tea frost

After the germination of tea tree buds, their resistance to low temperatures is weak. When the minimum temperature of the day is lower than 4 °C, the buds will appear coking, browning and curling after freezing, thus losing economic value and causing huge losses. This is the most important meteorological disaster in the process of tea production at the present stage. In recent years, tea frost has caused huge economic losses (Kotikot *et al*., 2020). For example, in March 2018, the frost disaster in tea gardens in Zhejiang Province affected about 1.5 million mu of tea gardens and the loss of early spring tea was more than 30%. The economic loss is estimated to be about 1.8 billion yuan. Therefore, researching this disaster is of great significance.

Research and solutions of tea frost prevention

The research focus on tea frost disasters, both domestically and internationally, primarily revolves around identifying meteorological indicators for frost occurrence, assessing the severity of tea disasters, examining the impact of frost disasters and analyzing their spatial and temporal distribution (Snyder & Melo-Abreu, 2005). However, there is limited research on the development of frost-proof equipment. At present, the solutions to frost problems mainly include topographic frost protection, covering frost protection, smoke frost protection, water spray frost protection, fan frost protection and other measures, as shown below.

- Topographic method: Plant roadside trees on both sides of the main roads and ditches and sow grass on the slopes. Select the leeward and sunny areas and avoid constructing tea gardens in valleys and areas prone to strong winds.
- Grass covering method: Covering the tea garden with grass can help reduce soil thermal radiation, maintain soil moisture and minimize frost damage to the tea plants.
- Smoke method According to the terrain, the tea garden's wind direction, area and other factors pile up several slightly wet firewood heaps in the tea garden in advance. When the temperature drops to about 3°C, the smoke is ignited and the smoke cover can increase the temperature of the tea garden by 0.5℃ ~ 2°C.
- Water spray method: Water freezes and releases heat when it is cold, which can remove the frost that has formed and help maintain the temperature of the plant leaves at around 0°C, providing protection against frost.
- Fan method: Utilize fans to blow the warmer air from higher altitudes in the tea garden downwards, thereby increasing the temperature near the ground and preventing frost.
- Others: Timely cleaning of frost on plants after a frost, prompt removal of snow after rain and snowfall, pruning of severely frozen branches and leaves and timely application of tea fertilizer as a supplement.

The mainstream frost prevention equipment available in the market includes air disturbance, water spray and smoke products, as shown in Table 1. Air disturbance products consist of rotor blades that disrupt the air, causing the air with higher temperatures in the upper layer to be blown towards the surface. The fan is relatively large and the installation height is generally 6~8 meters, requiring the number of installations. The use of UAV to disturb the air is not widely used for frost prevention, but for tea gardens that are not convenient to install frost-proof fans, it can be protected in time when frost occurs; water spray products are fixedly installed and the coverage of a single spray is limited. The use of a fog gun is more flexible as it can be mounted on a vehicle, providing wide coverage and the ability to spray pesticides. Smoke products, on the other hand, only require the lighting of a solid smoke agent and placement, with a simple functional structure provided by the supporting automatic ignition device. The smoke diffuser itself utilizes pulse atomization technology, making it suitable for disinfection and pesticide spraying, as indicated in Table 1.

Table 1. Type of frost protection equipment

Type	Air disturbance equipment	Water spray equipment	Smoke products
Image			

Significance of design practice

Frost disasters are difficult to early warning. Although some regions have carried out pilot work on tea low-temperature meteorological index insurance, the research has not been widely used due to the lack of equipment and the many factors affecting tea. At present, most regions rely on artificial defense methods for frost prevention, as there is a lack of specialized mechanical equipment for auxiliary production. The development of 5G technology, the Internet of Things, big data, cloud computing and other new generations of digital technologies provides an opportunity for the development of intelligent frost prevention equipment. Product innovation is a systematic engineering. The comprehensive strategy to realize the function of the system, not only lies in the innovation of technology, but also includes the selection of innovative product categories, the determination of innovation modes and methods and the coordination with users, the environment and other aspects (Abidin, 2009). The research on frost prevention agricultural equipment based on product system design will improve the intelligentization and mechanization level of tea gardens, promote the development of the tea industry and enhance the scientific and technological innovation ability, which is of great significance to individuals, industries, society and countries at all levels.

4. Design practice

Design positioning

Based on research on the design of tea frost protection equipment, the first step is to establish a design positioning based on product and user research. This includes defining its modeling, functionality, user needs and the environment in which it will be used. This positioning helps determine the development direction of the product and assists in advancing the project (Anwar *et al.*, 2015a), as indicated in Table 2.

Table 2. Design positioning

	Design Direction
Appearance Positioning	1) In line with the characteristics of unmanned intelligent operation. 2) Requirements for agricultural product appearance characteristics. 3) The color combination is eye-catching and aligns with the product's positioning. 4) The appearance structure is designed to meet the requirements of the terrain.
Function Positioning	1) Meet the hilly area tea garden walk requirements. 2) Machinery, information integration. 3) Meet the frost prevention tasks of different terrains. 4) Function modularization. 5) Response to the concept of sustainable development, the use of clean energy.
Demand Positioning	1) Simple operation. 2) Energy-saving and efficient. 3) Emergency response function is perfect. 4) Safe and reliable work.
Environmental factor	1) Hilly area with complex terrain. 2) The soil is moist and sticky.

Creative stimulation

As shown in Table 3, in terms of modeling (Abidin *et al*., 2008), the predominant product is the rod-shaped anti-frost fan, which has a height of 6~8 meters. Additionally, it can be combined with other methods to prevent frost on the tea, resulting in a comprehensive protective effect. Color matching is primarily based on the current color scheme in the market (Tokumaru *et al*., 2002), taking into account environmental and user factors (Guo *et al*., 2008). Generally, there are three types of colors: primary colors, secondary colors and accent colors. The visual color proportion is typically about 6:3:1.

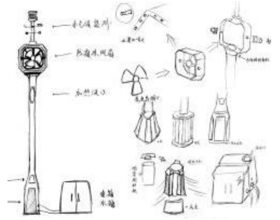
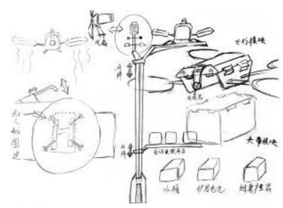
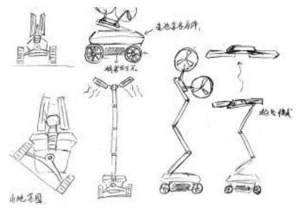
Table 3. Design stimuli

Item	Stimulating images	Design highlights
Forming structure stimuli		Modeling should be compatible with functions: it should meet the requirements of air disturbance, smoke dispersion, water spray, hilly area walking, etc.
Color scheme stimuli		Color matching is generally three colors, and the proportion of visual color proportion is about 6:3:1.

Design consideration

In summary, the tea frost protection method should meet the comprehensive requirements of rapid emergency response, high speed and adequate protection and effective combination with mechanization and information technology of equipment. Frost protection measures can be used such as fumigation, fans, UAV air disturbance, water spray, etc. To carry out sketch consideration (Abidin *et al*., 2011) and evaluate the scheme through the expert scoring method (Anwar *et al*., 2015b), the design and evaluation results are shown in table 4.

Table 4. Sketch of frost protection equipment

Scheme	Column-type frost protection equipment	Column-type integrated frost protection base station	Base station-type frost protection terrain vehicle
sketch			
evalua-tion	Simple structure and comprehensive function, but limited protection range due to fixed space.	The function and technical difficulties of UAV module are difficult to achieve.	Comprehensive function, flexible operation, wide protection range.

The design of the base station-type anti-frost terrain vehicle is deepened by using computer-aided design software (Krause *et al*., 1993) and the design effect is shown in table 5.

Table 5. Computer-Aided Design

Item	Design Presentation		
Sketch & effect picture			
Instructions	Telescopic robot arm for air disturbance frost protection	Intelligent flight to the tea garden over the air disturbance frost prevention work.	Vehicles are used to store energy, electronics and water for spraying

Structure refinement

The design of the frost prevention equipment for tea includes two parts: the anti-frost terrain vehicle and the climate monitoring module, as shown in Figure 5 and Figure 6.

The anti-frost terrain vehicle mainly includes: (1) UAV anti-frost module, (2) water tank body modules, (3) crawler all-terrain travel module, (4) smoke anti-frost module, (5) telescopic robot arm.

Figure 5: The anti-frost terrain vehicle rendering
Source: Drawn by the author

The climate monitoring module mainly includes: (1) climate monitoring enclosure, (2) solar panels, (3) data storage module, (4) mounting bracket, (5) telescopic pole.

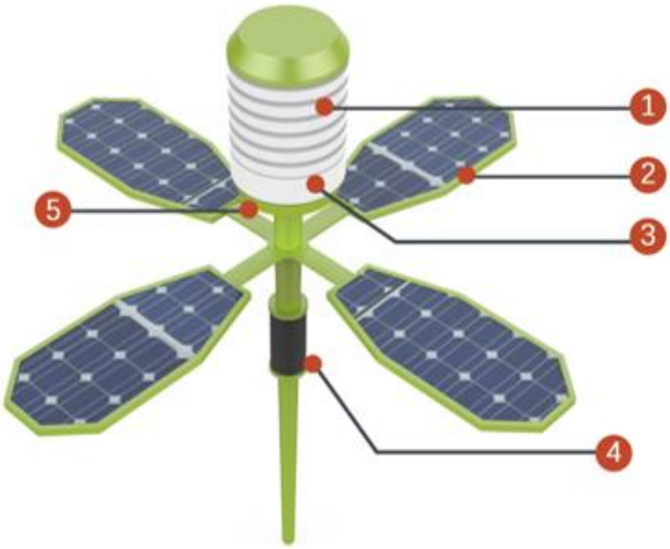


Figure 6. The climate monitoring module rendering
Source: Drawn by the author

Analysis and discussion

In the design process, we provide the design team with relatively vague stimuli based on the integration of Bytheway's FBD model and Benami & Jin's Creative Stimulation method. Formal and behavioral stimuli are employed to inspire the design team to generate more creative ideas and logical deductions are made on the functions and knowledge entities to generate constraints, ensuring that the multiple design ideas generated in the end possess a certain directionality and effectiveness. Before starting the design, the design team should have a certain understanding of existing design problems and previous inventive entities to ensure the directionality of creative ideas. The stimuli provided to the design team should be meaningful, relevant and ambiguous to attract attention. When providing information during function deduction, it should be novel and futuristic, so that designers are not restricted by existing conditions and will make efforts to explore. Finally, when describing functions, factors from social, technological and user perspectives should be considered comprehensively to ensure the effectiveness of the final solution.

The design practice research on the development of tea frost prevention equipment provides a reference for our research framework based on the integration of Bytheway's FBD model and Benami & Jin's Creative Stimulation method. In the current research, the FBD model is more inclined to deduce through functional logic, but there is a lack of clarity on how to determine preliminary specification functional data. Moreover, Benami & Jin's Creative Stimulation method can utilize form and behavior stimuli to generate more creativity, but it may have an impact on how to deduce specific functional derivations. Therefore, the contribution of this research lies in integrating these two aspects, providing appropriate inspirational stimuli for designers and conducting functional logic deductions to guide design practices.

5. Conclusion

Building upon the foundation of system-level design, this paper elucidates that industrial product design is fundamentally the effective integration of information from various parts of the product system. Through the integration of Bytheway's FBD model and Benami & Jin's Creative Stimulation method in the research framework, it achieves the organic combination of practical value and aesthetic requirements. This not only embodies advanced science but also reflects aesthetic artistic qualities, achieving the synergistic development of “human-machine-environment”. The research applies it to the design and research of tea frost-proof equipment. Through investigation and analysis, the internal and external systems of the product are combined, the tea frost-proof measures are integrated and the design practice of a multi-functional intelligent tea frost-proof terrain vehicle is carried out. It provides references for the frost-proof problems encountered in the construction of modern tea gardens and the transformation and upgrading of old tea gardens. This helps ensure the stable production of the tea industry.

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