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An IoT-based Sharing Plant Factory System for Nature Connectedness Improvement in Built Environment

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Abstract: Under the influence of urbanization, the relationship between human and nature gradually separated, therefore it is difficult for people to obtain the benefits of nature connectedness. In this paper, an IoT-based sharing plant factory is described to improve nature connectedness of people in an indoor environment. The ecological service process of indoor environments is studied through user interviews and surveys, to understand the contact points of ecological services and the design points of sharing plant factories. Based on these points, a product prototype is realized. Finally, the nature connectedness is tested by 13 users comparing the sharing plant factory with traditional plant pots through the revised Inclusion of Nature in the Self and Connectedness to Nature Scale. The results prove that the designed sharing plant factory can effectively improve a user’s nature connectedness. In addition, the efficiency of plant maintenance is greatly improved with the help of a sharing plant factory. The introduction of nature connectedness into ecological design can guide design to pay more attention to the service effect of products. In addition, the introduction of plant factory technology indoors can help ecological service products to function better and provide new ideas for the research of indoor ecological service products.

Keywords: plant factory; sharing plant; nature connectedness; sustainable design; indoor nature

1. Introduction

Human–nature connection is an emerging research field that is receiving increasing attention in sustainability science [1]. Recent research shows that enhancing nature connectedness not only can improve one’s happiness, physical/mental health and work efficiency [2,3], but also can motivate more pro-environmental [4] or environmentally sustainable behavior [5], and even improve one’s character [6]. Specifically, researchers argue that nature connectedness research can contribute to sustainability science from many aspects: first, nature connectedness provides effective psychological-behavioral path to engage the public with sustainability issues [7]; second, as shown in Reference [8], public concern for the sustainability is largely driven by an existing, historically embedded sense of human/nature connection; last but not least, the study of nature connectedness brings new multidisciplinary consideration of sustainability, for example, Reference [9] suggests a broader conception of nonhuman nature and a co-evolutionary theory of genetic response and cultural learning be incorporated to study sustainability.

However, despite the importance of nature connectedness, nature connection/exposure of people is often inadequate [10], because built environments usually serve as barriers that segregate people from nature [11]. Therefore, it is necessary to enhance interiors of buildings and homes to provide more opportunity for nature connectedness [10,12], such as introduce plants and even pictures or objects from nature in indoor environment, or simulate natural experiences using VR/AR technologies. Among them, the introduction of plants in indoor environments is considered to be one of the most effective methods.
Generally, traditional potted plant and emerging plant factory are two common ways to introduce plants into indoor environment. Compared with a potted plant, a plant factory has the advantages of automation, controllable planting environment and good plant cultivation effect [13]. However, there are also disadvantages such as higher cost, difficulty to use, centralized placement, hence this hinders interaction with users [14]. According to previous research, user interaction and participation may have significant impacts on nature connectedness [15], while nature connectedness is proven to be an effective factor of promoting users’ pro-sustainability behavior as well as their own well-being [16]. Hence, this paper develops a prototype system of sharing plant factory based on IoT technology (MSPF) to evaluate how it may impact nature connectedness and further change a user’s attitude and motivation of pro-sustainability behavior. We argue that MSPF expands the application of plant factories, not only to cultivate plants, but also to promote contact and interaction between people and plants, thus improve the natural connectivity of the indoor office environment and positively influence a user’s attitude and motivation towards environmental sustainability. Specifically, the prototype system use the shared mode to reduce personal costs, automatically adapt to multi-region environments and multi-user needs based on IoT technology, and deploy a highly usable human–plant interface to motivate users to interact with plants, thereby improving the nature connectedness of indoor office space.

The remainder of this paper is organized as follows. Section 2 Literature Review: The concept, meaning and measurement methods of nature connectedness are summarized, and the general methods and influencing factors of improving built environment nature connectedness are also presented. The value of indoor plants to enhance nature connectedness, the common schemes of introducing indoor plants (pot plants, plant walls, plant factory) and its advantages and disadvantages are paid special attention. Section 3 User Study: Through user interview, questionnaire survey and behavioral mapping, the user technology acceptance (Perceived usefulness, Perceived ease of use) requirements and sustainable built environment (Perceived Nature Connectedness, Perceived benefit) requirements were investigated to facilitate the balance of these two needs in design. Section 4 System Design: This section introduces the idea of improving the human–plant interaction and nature connectedness based on the redesign of the plant factory system, including an improved design solution combining user expectations (availability, interactivity, cost) and nature-connectedness requirements, a technology stack of the prototype system and the service architecture and interaction interface. Section 5 Evaluation: The user experiments based on the prototype system are introduced, and the positive effects of the sharing plant factory system on meeting user needs, improving user experience, and promoting human–plant interaction behavior and nature connectedness are verified. Section 6 Conclusion and Discussion: This section summarizes the key results of this article and proposes some points for future work.

2. Literature Review

2.1. Nature Connectedness

There are many terms and evaluation standards for the study of the connection between humans and nature, such as Connectedness to Nature Scale (CNS), Inclusion of Nature in the Self (INS), Connectivity with Nature (CWN), Nature Relatedness (NR). This article uses Nature Connectedness (NC) as the evaluation criterion. NC refers to the physical contact and psychological connection and comprehensive measures of human and nature. Numerous research results in psychology and behavior have shown that NC is beneficial to human health, well-being and physical and mental pleasure. In these studies, the scales corresponding to the four concepts are scientifically measured and managed, as shown in Table 1.
Seppelt and Cumming [19] believed that humans must reduce their distance from the natural world in terms of knowledge in contact with nature, while increasing the “distance” in the sense of the direct impact of human activities on the ecosystem. Gullikson found that experiment participants attach importance to connect with nature every day [20]. However, in modern life, people spend most of their time indoors. Thus, people generally lack connection with nature, and it is easy to miss the benefits of being connected to nature, which leads to a decline in happiness [21]. In addition, most of the literature focuses on people’s passive acceptance of the ecological benefits brought by plants, for example plants can regulate the indoor environmental conditions of buildings [22,23], improve air quality, etc., but it should be recognized that more active participation in the environment may bring better benefit [24].

In view of the fact that most literature studies focus on outdoors and lack effective methods for indoors, and modern people spend most of their time indoors, it is necessary to study the causes of NC and explore the re-implementation of this connection indoors. We believe that indoor plants may play a key role in establishing connections and relationships between people and nature.

### 2.2. Factors Affecting Natural Connection

Although a lot of research show that nature has a beneficial effect on our cognitive, emotional, mental and physical health, as a mental health strategy, nature-based interventions have not been fully researched and used [25]. Ives et al. proposed a conceptual framework that summarizes five links between humans and nature: material, empirical, cognitive, emotional, and philosophical, and discussed how actions that reconnect humans and nature can help for transforming society into sustainability [1].

At present, most of the research on natural connection focuses on the visual aspect. In fact, humans are multi-sensory organisms, and natural connections can rely on more channels. Franco et al. reported the following evidence: watching nature through pictures and windows can improve health and mood; sounds like bird song and natural sounds can restore and enhance emotions; smell can provide many physiological and psychological benefits [23]. Understanding the benefits of nature through various senses can truly understand the interdependent and sustainable relationship between human health and nature. Franco et al. summarized the evidence of pathways through sound, smell, taste, tactile sensory pathways, and non-sensory pathways. They also concluded that non-visual pathways are potentially important for gaining benefits from natural experiences. Therefore, more in-depth exploration of these approaches is needed [23]. In fact, Dijk et al. have shown that stimulating multiple senses simultaneously may lead to additional benefits of natural experiences [26]. People can also enhance their connection with nature through diverse activities and gain happiness from exposure to nature. Craig et al. report that those who grow their own food are happier than those who do not grow food and associate with nature [27]. In addition, by showing plant contamination by tracking plants, human actors can be involved in the design process. Researchers have also pointed out that the concept of sustainability does not emerge as a pure result of a design process, but first as a behavioral attitude, and design is a tool to achieve this attitude [28].

### 2.3. Explorations to Enhance Indoor Natural Connection

Urban life requires not only smart and efficient, but also natural pleasure to be more sustainable [29]. The benefits of indoor plants to those who care about them are obvious, and many of the ecosystem
services generated outdoors are consumed indoors. Indoor space has great potential in providing some of the services currently available outdoors. Clearly innovative and comprehensive research is needed to combine insights from indoor and outdoor environments. Researchers believe that focusing on indoor spaces and the interface between indoor and outdoor can provide a useful perspective on ecosystem services [30].

In recent years, the exploration of ways to provide similar effects to outdoor ecology through environmental transformation, introduction of green products, and virtual experience based on information technology has become a focus of the design community, namely, indoor ecological service design [30,31]. Typical examples include introducing natural elements, paying attention to environmental health, and enhancing human–nature interaction. A lot of practical exploration has been done for this purpose, which reflects some widely adopted design directions, including:

1. **Physical connection**: increase the frequency and chance of contact with nature, and use multiple sensory channels to contact nature in action [32];
2. **Cognitive connections**: promoting plant knowledge and establishing ecological beliefs, affecting people’s attitudes towards sustainable development and green environmental protection behaviors [15];
3. **Experience connection**: such as entertainment in a green environment, experience in a virtual green environment [33];
4. **Emotional attachment and emotional response**, such as fostering connections and feelings with plants through the adoption of plants [34];
5. **A philosophical perspective on the relationship between humans and the natural world**, a philosophical perspective to understand the relationship between humans and nature, a visual display of the relationship between plants and human activities, etc. [35].

One of the most important and common design strategies is to introduce plants that could only grow outdoors to indoors to increase the physical, human, and emotional connections between nature and people. Common design forms and design objects include:

- **Immersive natural design**: Make nature visible and touchable
  
  Microsoft, Amazon, and other companies in the office environment designed around the natural environment, embed nature into daily work. This design can bring a better natural experience connection, but in the promotion of the model, there is irreproducibility due to issues such as cost and location.

- **Plant wall design**: Improve nature accessibility
  
  The plant wall is currently mainly used in architectural and environmental design. It increases the visibility and accessibility of plants to indoor users through space and place conditions, provides more opportunities for actual contact with nature, or attracts users to actively approach nature. A good and sustainable indoor plant wall system requires manual maintenance and does not have the function of intelligently regulating the plant growth environment. Later plant maintenance and ensuring plant diversity are pain points that must be resolved.

- **Potted plants green design**: Strength nature experience in everyday life and work
  
  It is a place that widely covers human learning, work, and life, and integrates it into indoor scenes, so that users can enjoy green plants anytime, anywhere, and get a natural experience. A survey of about 450 interviewees found that among all 10 job satisfaction criteria, employees with plants score higher, and indoor plants are better than plants outside the window [36,37]. Studies have shown that only one plant in each work space can greatly enhance the mental state of employees, thereby improving employee happiness and work performance [38]. Although this design strategy is the most common with lowest cost, the focus is more on plants to improve the health of the indoor environment, and it is not obvious to increase the natural connection between people and plants.
• **Introduction of indoor plant factory**

  The biggest problem when outdoor plants are introduced indoors is the lack of environmental elements necessary for growth, such as water, light and nutrients. The plant factory is an emerging technology that can be used indoors to build an environment suitable for outdoor plant growth, an efficient agricultural production method that is not restricted by natural conditions or rarely. It is an advanced stage of the development of protected horticulture [39,40] that was initially used in vertical farming, i.e., growing edible and medicinal plants in urban buildings. Recent review [41] showed that this new method may bring innovative solutions to address many issues of sustainability from both social, economic and environmental aspects. Although most research focus on producing edible plant for the rising demand of green urban food, there also emerged great interests on using a plant factory for sustainability purpose in recent years. Reference [42] provided a systemic review to argue that the plant factory may positively affect sustainability because it usually uses less labor, water, nutrition and light energy comparing to traditional method such as greenhouse. Reference [43] introduced the research of using a plant factory to improve quality of life in an indoor environment. Reference [14] discussed how a plant factory may affect users’ attitude, concern and acceptance for sustainable food. However, most of the plant factory systems involved in the current research lack interaction with users, and therefore failed to discuss the impact of this interaction on nature connectedness. The remainder of this article will further discuss this issue by designing and evaluating a novel prototype system.

• **Smart plant products**

  Designers have developed various forms of virtual cultivated plants, smart flowerpots, voice flowerpots, etc. to meet the needs of people to maintain plants. Plant–human dialogue is also an emerging research direction, such as Google Tulip, however, in view of the high cost of smart products and the low popularity of production, further research is needed to improve the sense of connection between humans and nature.

  Although the above explorations have achieved varying degrees of success, most of them focus on the design and maintenance of plants in the interior. They do not connect users with plants well, allow users to perceive the state of plants, and help users to do more with plants sensory interaction, improving the connection between human and nature, etc.

  Based on previous design practices, this article further concludes that: First, compared with the more mature outdoor ecological design and environmental design, there are fewer explorations to improve NC through interior design and product service design. Second, modern cities spend much more time indoors than outdoors, and they spend much more time in contact with artificial products and services than in the natural environment. Third, emerging interactions and smart products and services can also provide more options for creating natural connectivity. Although different in form, they may have the same or similar NC effects as traditional methods.

  Introducing natural elements, especially plants, indoors can improve nature connectedness in many ways, such as multisensory experience, positive physical and mental health impact, etc. However, this improvement can only be maximized through effective design. The rest of this article will discuss an approach based on the IoT and plant factories, and verify its effectiveness through prototyping.

3. **User Study**

  Specifically, we need to further study the user needs, determine a design object, and then use the comprehensive design of hardware-appearance, software-interaction and service process-experience to make this object in order to truly achieve the design goals, establishing people and plants material, experience, and emotional connections.

3.1. **User Interview Method**

  Most of the previous literatures are based on theoretical research and provide guidance for specific practices. However, there are few verification practices to improve the connection between man
and nature. How to improve the sense of natural connection in indoor environments has not been thoroughly studied and fully synthesized. In order to carry out effective design, we first surveyed five companies of different sizes and types and interviewed 30 office employees, as shown in Figure 1. As listed in Table 2, we concluded the following results:

- People in the office space usually only want to enjoy the ecological benefits of plants and do not want to consider themselves incapable of taking care of the plants;
- Plant products have both physiological value (reducing air pollution, etc.) and experience value (improving closeness with natural ecology, etc.); for ordinary consumers, the value of experience often exceeds actual physiological value;
- The development of lifestyle (fast-paced, high-stress, urban life), consumption concepts (shared economy), intelligent technology, etc., have led to the trend that the demand for flexible and personalized reliance on social service networks to obtain ecological services has gradually replaced the past alone purchase and possess plant products.

![Figure 1. User interview.](image)

**Table 2. User interview results.**

| Defects               | Ping An Technology | Baidu Technology | Hong Kong University | Tencent Technology | IBM                      | Shanghai Jiao Tong University |
|-----------------------|--------------------|------------------|----------------------|--------------------|--------------------------|--------------------------------|
| Too few green plants, don’t know how to maintain | | | | | | |
| Don’t know how to maintain | | | | | | |
| Short life cycle and high maintenance costs | | | | | | |
| Don’t know how to maintain, can’t feel the presence of plants | | | | | | |
| Whether to purify the air, concerned about the amount of oxygen released | | | | | | |
| Don’t know how to maintain, can’t feel the presence of plants | | | | | | |
| Suggestions | More plants | Increase plant species and numbers | Automatic watering | Personal care | Be part of the environment | Automatic irrigation |
| Hope to change to a well-lit office | Professional take care of the plants | Voice interaction | Absorption of formaldehyde | Love the smell of real plants | Professional take care of the plants |
| Plants relieve boredom, plants have aura | Plants can relieve fatigue | Plants are good for people | Increase the vitality of the environment and breathe life | Plants can clean the air | Plants can bring good luck and improve the environment |

It can be concluded that people living in indoor environments believe that plants are an ecological product, which adds more ecological value to indoor environments. When ecological value becomes a service, we have reason to believe that plants are just product expression forms of ecological services. Exploring how to better let people enjoy this ecological service, increase the ecological benefits brought by plants, and improve the sense of natural connection in the interior are the main contents of this article.
3.2. Survey

In order to further confirm our design strategy, we conducted a relatively large-scale user survey, distributed 160 questionnaires through the Internet, and recovered 157 valid copies. The results of the questionnaire are as follows:

- **Plant attitudes and value perceptions for office environments**

  This part includes whether you like the natural office environment, and whether you think the natural environment can bring you a sense of integration with nature and happiness. According to the analysis of the survey results, 86% of people like to work in a natural ecological environment, 93% think that plants can bring a sense of integration with nature, and more than 90% think that plants can bring happiness. It shows that the natural connection feeling brought by plants can be perceived and considered important by users.

- **Investigate the status of existing indoor plant ecological services and user preferences**

  According to the survey results, more than 40% of people do not feel the sense of integration of plants in the normal working environment, which proves that the existing indoor ecological services cannot bring a good sense of ecological connection. The research on the way of providing plants shows that users care more about the plants themselves, and that the way to obtain plants is not the most critical, but they tend to provide them uniformly.

  For plant distribution, more than 68% of people hope that uniform distribution and centralized distribution are unified. According to return visits, users believe that concentrated plants can bring better ecological benefits, and uniformly distributed plants can give users in the office bring the same ecological benefits.

  Further analysis of whether users choose to bring their own plants or choose to provide plant discovery uniformly. Among the reasons why users do not choose to bring their own plants, 92% choose people who do not understand conservation. In addition, more than 56% because they forget to water, and think they will bring trouble for others and wasted time are 45% and 34%, respectively. These results prove that the main reason users do not choose to bring their own plants is related to conservation and maintenance costs.

  When investigating the problems that the users think of the unified supply method, it is found that, in a comprehensive view, the users believe that the plants that are provided uniformly have the most problems in plant conservation, followed by the variety and number of plants, and finally the distribution mode and location of plants.

- **Investigate specific factors affecting the natural connection between indoor plants and users**

  People who are willing to contact plants, including the options that will be used every time and sometimes, reach 83.4%. Among the reasons why they do not want to contact plants, the three most important reasons are plant health issues, they are not their favorite plants, and they do not want to take care of the plants.

  In the survey of plant varieties that affect the sense of natural connection, it can be found that more than 50% of users believe that pure green plants can bring more sense of natural connection, while only 7.6% of users think that brightly colored flowering plants can bring natural feelings. This proves that the plants most users want to access are simple, but not fancy.

  For the relationship between plant contact and nature, we found that more than 65% of users believe that seeing plants and smelling flowers can bring better natural feelings. Touching plants and taking care of plants account for 41% and 28%, respectively. This proves that most people think that taking care of plants cannot or rarely bring closeness to plants, and the interaction of touching plants is not as deep as directly seeing plants and feeling the fragrance of flowers.

  For the location of plants and their connection with nature, 53% of users believe that the plants placed on the desktop make them feel closer to the plants, while 26% of users believe that the plant
walls that are far away from themselves can bring themselves closer good natural feelings, only 21% think that the corner plants can bring better natural feelings to them, which proves that the number of plants and the distance between plants affect people's natural feelings about plants, different people have different tendencies, combined with the previous part. According to the survey results on plant distribution, it can be known that even single plant distribution around the user and centralized distribution in a fixed place are necessary conditions for the user to feel the nature indoors.

Finally, 47.8% of people think that contacting plants five times a day can bring an experience of intimate contact with nature, and 12% of people think that only touching once a day can bring about a natural experience.

Summarizing the above surveys, the green design in the offices of China is more of an embellishment, instead of turning this natural ecology into a service provided to employees. Office space is divided into public space and private space, with clear division of attributes. The number of plants in public space is much larger than the number of plants in private space, which leads to the close relationship between the acquisition of plants and the allocation of office space. In previous literature research, we have concluded that natural connection is a common demand. When we extract the demand for ecological services, ecological services are an essential service for office space and are very suitable for targeted design. On the one hand, the company's number of people is sufficient to turn low-frequency and low-volume ecological service needs into high-frequency mass production needs. On the other hand, office space as a small indoor ecosystem has important guiding significance for the practice of ecological service design.

Plant factory technology provides the basis for sharing ecological services, and can meet the common needs of a large number of people. The essence of the sharing economy is to achieve short-term transfer of the right to use idle resources through technical means, and to enable owners of idle resources to obtain corresponding income rights. Some studies believe that the value of the sharing economy mainly comes from customer service experience, not product purchase [44]. It shows that we can help users get a better experience by providing more enjoyable and valuable services. In fact, studies have found that a service that may be slightly more expensive than traditional services, but that provides ecological benefits, may be preferred by those with environmental sustainability values [45].

As a result, the design of a sharing plant factory based on IoT technology can change the traditional indoor ecological service design. Through transforming the original fragmented and fixed ecological service product portfolio into a new product service system, turning the green space of public space into a freely shared and recycled space, users and plants can be more freely and fully matched, so as to provide more efficient and accurate ecological services for the office, and the ecological benefits of indoor greening will be greater. As a result, the connection with nature will be greatly enhanced.

4. System Design

This section introduces the redesign of a plant factory to improve human–plant interaction and nature connectedness. The modified design scheme, technology stack of prototype system, service architecture and interaction interface based on user expectations (usability, interactivity, cost) and nature connectedness requirements.

4.1. Purpose of Design

In this sharing plant factory design, we pay attention to the harmony between people and nature, enhance the sense of natural connection in the interior, feel the breath of life in the indoor space, and enhance the closeness between people and nature. Introducing ecological service design into the indoor environment does not mean completely abandoning people-centered design ideas and modern intelligent technology. On the contrary, we must pay more attention to human needs and use computer technology, information technology, IoT technology, etc. The intelligent means organically integrates with the existing indoor space, fuses people and nature, and develops toward the goal of indoor ecological services that enhance nature connectedness.
Combined with the existing indoor nature connectedness research mentioned in the background, we believe that the design of indoor ecological service products needs to reflect the benefits of products and services to users. The individual differences of users determine the experience of adapting to different users. In addition, cognitive differences require smarter products to sense differences in user needs and changes in the environment. We believe that indoor plant factories can use IoT integrated methods to organically combine indoor ecological factors to monitor and identify indoor plant planting equipment, optimize ecological service resources, and make adaptive operations by sensing the environment and human behavior.

The traditional plant service industry is classified as a service area of low-tech industries, and it is more common to use timed and manual methods. Ordinary plant factories are placed in closed spaces and used by special persons in specific environments. The technical characteristics of traditional plant factories, such as large size, bulkiness, and low degree of intelligence, also limit its application in ordinary indoor environments. At present, the design of plant factories is usually an environment isolated from people, which cannot help to improve the natural connection of the indoor environment.

Designing things is “combining people with non-human resources, and people assume systems to create things that may connect people, things, and value” [46]. From the perspective of interaction designers and developers, the design of indoor ecological shared service systems based on plant factory technology provides exciting new opportunities. In addition, the use of sensor networks, art and other means can explore more user needs and provide better micro-services.

The MSPF designed in this article enhances the possibility of interaction with people based on the function of the original plant factory to create an indoor ecological environment. This interaction can enhance the connection between people and nature from multiple aspects. These issues will need to be considered: how the product is perceived by the user, how well the user understands the product, how the user feels when using the product, how adaptable and useful the product is, and how a smooth user experience will become more contextual and natural in the future. For example, the multi-sensory interaction mentioned above: human and plant devices enhance natural connection through multi-sensory interaction and other methods. This is not necessarily related to the plant factory, but it can increase the connection between human and nature, thereby improving the natural connection of the indoor environment.

We break down the overall design goals into the following sub-goals:

- The user experience of plants can attract users to the plants as much as possible;
- People can perceive the health of plants and participate in the care of plants in an easy way;
- MSPF can automatically identify and adapt to the conservation needs of different users, the environment and plants, and scientifically maintain plants.

4.2. Design Method

First, an indoor plant conservation station, as shown in Figure 2a, is designed and set up based on plant factory technology, so that poorly managed traditional potted plants can be taken care of, and plant knowledge can be communicated to users. At the same time, intelligent potted containers are used to increase human and plant interaction and emotional connection. The intelligent potted containers, as shown in Figure 2b, detects the growth status of the plant through the embedded sensor, and reminds the user by the emotional light in the absence of care. Touching plants can trigger sensor and make corresponding feedback. The container can be placed in the plant factory for conservation, and the plant factory can communicate with the mood light through the local area network, and remind the user to retrieve it through the mood light after the maintenance is completed. The hardware system is shown in the Figure 2c, including: (1) smart plant pot subsystem, (2) ventilation, water, and light subsystems, and (3) communication and notification subsystem. The smart plant pot integrates various sensors to monitor plant state and interact with users. When plants need automatic maintenance, the emotional light on top of the pot will turn red to remind the user to put them into the plant factory. Then the plant factory will communicate with the plant pot to formulate a customized caring plan. According to
the plan, the plant factory will control the ventilation, water and light subsystems to automatically care for the plants. A prototype of these sub-systems are shown in Figure 2d: the ventilation sub-system contains an array of electric fans mounted on the frame, the water subsystem consists of water tank and programmable pump, the light sub-system controls grow light precisely. All the subsystems are coordinated by the central processor. While in maintenance, users can detach the emotional light from the pot and carry with themselves, as shown in Figure 2e. If the maintenance is finished or the plant is back to healthy state, the emotional light carried by the user will receive the messages from the communication subsystem and turn into different colors accordingly to notify the users.

Figure 2. System configuration. (a) indoor plant conservation station, (b) intelligent potted containers, (c) hardware system architecture, (d) plant pot, ventilation, water, and light sub-systems, (e) detachable communication and notification sub-system.

In summary, the schematic diagram of our final design scheme prototype system is shown in Figure 3. System consists of 5 levels:

- **Sensor layer**
  - Including light sensor, humidity sensor, infrared proximity switch, RFID plant return switch and plant identification camera, to collect plant status and interactive data.

- **Data layer**
  - Collect the data collected by the sensor and store it in the MySQL database.

- **Decision layer**
  - Call the plant photos taken by the plant identification camera to identify plant species through the plant recognition API of the Alibaba Cloud platform, retrieve the corresponding plant conservation plan via the network, and package the plant species and conservation plan into json data and pass it to the execution layer through the network.
• Execution layer

This layer is divided into two modules, conservation execution and interactive execution. The conservation module invokes the corresponding plant state data to perform corresponding water and light maintenance operations. The interactive execution module reminds the current plant generation status (whether water or light is lacking), and multi-sensory interaction with the user (auditory vocal, olfactory fragrance).

![Design prototype system diagram.](image)

Figure 3. Design prototype system diagram.

• Interaction layer

In addition to the direct interaction with plants available through the interactive execution module, this layer also has the operation interface interaction of the conservation cabinet. This system adopts multi-level control method. The maintenance cabinet uses Raspberry Pi as the main control hardware, and the flowerpot end uses Arduino as the control hardware. The two communicate via Wi-Fi. Bluetooth is remotely controlled by the Raspberry Pi.

The system combines multiple plant-data collection for multiple human-machine-plant interactions and enhances NC through multi-sensory interactions between human–plant. In addition, based on the intelligent identification of plant species and the acquisition of conservation schemes, intelligent and automatic conservation of plants is carried out, and friendly reminder interactions with users are conducted to reduce the difficulty of user maintenance and use.

The process of using the system is shown in Figure 4, and the specific process is as follows:

First, the plant species is identified through the Alibaba Cloud Recognition API based on the plant photo by the camera. Additionally, the corresponding plant conservation process can be obtained. Compared with traditional plant factories, this system has the function of intelligent identification of plant species and conservation solutions, which can optimally maintain different plants in the conservation station, with higher versatility and intelligence.

Then, users select a favorite plant according to the conservation station interactive interface, and taken it out from the conservation station for use. This design improves the form of information interaction between traditional plant factories and users. It allows users to intuitively feel the variety information, growth status of plants and conservation process. Moreover, it improves the information exchange of user and plants.

The flowerpot interaction system determines whether the user has multi-sensory interaction with the plant. By visual-auditory-olfactory multi-sensory fusion interactive, users can obtain better natural
connectivity. The plant status is indicated according to the sensor data. The built-in system of the flowerpot detects whether there is a lack of water or light, and whether the user returns the plant to the plant factory for conservation and obtains new plant. This design point is helpful for bringing plants closer to the plant factory, and it also provides a basis for sharing plants in the same space, and encourages users to participate in sharing plants.

In the process of using plants, at the same time, the user can choose to retain the detachable status indicator and wait for the reminder of the status of the plant’s conservation. This design point allows the user to establish a closer emotional connection with the plant in the initial stage of the investment in the shared plant factory.

The above characteristics of the system make indoor plants better integrate with the office environment and users, while reducing plant maintenance, extending the life of plants, playing the best role of indoor plants, and greatly promoting indoor office environmental sustainability.

5. Evaluation

The user experiments based on the prototype system are introduced, and the positive effects of the shared plant factory system on meeting user needs, improving user experience, and promoting human–plant interaction behavior and nature connectedness are verified in this section.

The purpose of designers using prototypes for experiments is not necessarily to test the complete ending solution, but may be to explore the best user experience, so we want to use prototypes to understand how users recognize and participate in the service, and then use the obtained knowledge to build a seamless and coherent user experience. NASA-TLX evaluation test table and natural connection scale are used to verify the validity of the design scheme. We require the subjects to use ordinary

![Figure 4. Using process.](image-url)
flowerpots and plant factory systems to complete the conservation and use of plants in the same environmental space, and guide the subjects to evaluate the health of the plants, imagine the free growth of the plants through instructions and make controlled, sensible natural contact, as shown in Figures 5 and 6.

In this paper, the test of the intimacy between the user and the plant is measured using INS and CNS. In the INS measurement, we replaced the concept of nature with plants. Additionally, the Chinese version of CNS revised by Li Na et al. in 2016 is adopted [47]. Its internal consistency reliability is 0.783, retest reliability is 0.901 ($p < 0.01$), and compatibility validity is 0.491 ($p < 0.01$), which meets the statistical requirements and can be used as an effective tool for measuring the relationship between individuals and nature. Based on this natural scale, this article screens out nine questions related to this test, and replaces the concept of nature with plants, and scores for user evaluation. In addition, the NASA-TLX task scale is applied to test whether the design can significantly reduce the burden and improve efficiency for normal office use and plant conservation.

The results are listed in Table 3. The experimental and control samples showed significant differences in mental strength, physical strength, effort, completion, and frustration ($p < 0.01$), meaning that the experimental and control samples were different. The specific comparison shows that the average mental power of the plant factory group (4.00) will be significantly lower than the average value of the ordinary flowerpot group (11.08). The average physical strength of the plant factory group (4.38) will be significantly lower than the average value of the ordinary flowerpot group (9.15). The average effort level of the plant factory group (6.00) will be significantly lower than the average value of the ordinary flowerpot group (8.38). It can be concluded from the above that the average frustration of the plant factory group (3.38) will be significantly lower than the average value of the ordinary flowerpot group (12.31). The average degree of completion of the plant factory group (17.31) will be significantly higher than the average value of the ordinary flowerpot group (11.23). The average degree of completion of the plant factory group (17.31) will be significantly higher than the average value of the ordinary flowerpot group (11.23). The average degree of completion of the plant factory group (17.31) will be significantly higher than the average value of the ordinary flowerpot group (11.23). The average degree of completion of the plant factory group (17.31) will be significantly higher than the average value of the ordinary flowerpot group (11.23). The average degree of completion of the plant factory group (17.31) will be significantly higher than the average value of the ordinary flowerpot group (11.23).
the ordinary flowerpot group (8.38). It can be concluded from the conclusion that the efficiency and satisfaction of the task experiment using the plant factory prototype is generally higher than that of the flowerpot group, which proves that the design of the intelligent shared plant factory service system is reasonable and valuable.

Table 3. Nature Connectedness test results.

| Scale                        | Items                          | Flowerpot         | MSPF             | Samples | p       |
|------------------------------|--------------------------------|-------------------|------------------|---------|---------|
| NASA-TLX (Task Load Index)   | Mental strength                | 11.08 ± 4.61      | 4.00 ± 2.38      | 13      | 0.000 ***|
|                              | Physical strength              | 9.15 ± 5.87       | 4.38 ± 3.20      | 13      | 0.004 **|
|                              | Time                           | 9.92 ± 3.95       | 6.46 ± 3.97      | 13      | 0.029 *  |
|                              | Effort                         | 11.23 ± 4.68      | 6.00 ± 3.08      | 13      | 0.000 ***|
|                              | Completion                     | 12.31 ± 5.92      | 17.31 ± 1.55     | 13      | 0.003 **|
|                              | Frustration                    | 8.38 ± 5.89       | 3.38 ± 3.64      | 13      | 0.004 **|
| Revised INS (Inclusion of Nature in the Self) | Relationship with plants       | 3.00 ± 1.73       | 4.23 ± 1.64      | 13      | 0.000 ***|
| Revised CNS (Connectedness to Nature Scale) | I feel separated from the plant | 2.77 ± 1.30       | 2.08 ± 0.86      | 13      | 0.006 **|
|                              | Plants make me feel kind       | 3.62 ± 0.87       | 4.46 ± 0.52      | 13      | 0.014 *  |
|                              | Understand the impact of behavior on plants | 3.23 ± 1.01       | 4.15 ± 0.69      | 13      | 0.004 **|
|                              | Think plants are wise          | 3.62 ± 1.33       | 4.00 ± 1.29      | 13      | 0.209   |
|                              | Feeling in the same environment as plants | 3.85 ± 0.56       | 4.31 ± 0.63      | 13      | 0.027 *  |
|                              | Happiness has nothing to do with plant conditions | 2.54 ± 0.88       | 2.00 ± 0.91      | 13      | 0.047 *  |
|                              | Yourself as part of the natural cycle | 4.31 ± 0.75       | 4.23 ± 0.73      | 13      | 0.337   |
|                              | Nature is my home              | 4.38 ± 0.65       | 4.38 ± 0.65      | 13      | /       |
|                              | Plants and I are part of nature | 4.38 ± 0.67       | 4.62 ± 0.51      | 13      | 0.190   |

*p < 0.05, **p < 0.01, ***p < 0.001.

In the INS measurement, the t-test of the two sets of experimental data found that p < 0.01, and the mean value of the relationship between the user’s experimental plant factory prototype selection and the plants showed a significant difference. The plant factory average (4.23) was significantly better than the average flowerpot group average (3.00). Additionally, through specific sample analysis, among the 13 groups of samples, except for one experimenter, there was no significant difference before and after using the plant factory prototype and the flowerpot prototype. The other 12 testers showed that using the plant factory prototype can improve people and plants compared to ordinary flowerpot relationship intimacy.

In the plant connection test based on the CNS, a total of five questions were found in the t-test with p < 0.05. They are that I feel separated from the plant, the plant gives me a sense of intimacy, I know very well that my behavior change the way it affects me, I feel that I belong to a whole environment with plants, and my personal happiness has nothing to do with the conditions of the plants in the environment. Specific experimental data show that in these five test questions, the plant factory prototype is significantly better than the ordinary flowerpot prototype. In summary, the plant factory can bring better natural connection feelings in terms of human and plant cognition and feeling. In the tests of plant wisdom, plant and nature, and life relations, the two sets of data did not show significant differences. The possible reason is that such questions are more biased towards the recognition of human and nature values, which is a long-term process.

Further analysis of the subjective evaluation data of the plant factory group and the ordinary flowerpot group after the experiment, the results are shown in Table 4. It can be known that after using MSPF, you can feel the existence of plants more than the ordinary flowerpot prototype, and it is easier to care about the plants around you. Users can also think that the plants are beneficial to life and have higher conservation efficiency. The attitude survey on plant factories shows that users generally believe that plant factories have a better experience in maintaining plants, and are willing to introduce plants in office and learning places, and are willing to pay a certain fee to obtain such services.
Table 4. Subjective evaluation test results.

| Items                                      | Flowerpot | MSPF   | Samples | p       |
|--------------------------------------------|-----------|--------|---------|---------|
| Subjective comparison                      |           |        |         |         |
| Plants can be more felt after the test     | 3.92 ± 0.28 | 4.46 ± 0.52 | 13       | 0.012 * |
| Get more concerned about plants after the test | 3.54 ± 0.52 | 4.46 ± 0.52 | 13       | 0.002 **|
| The beauty of plants is more noticeable after the test | 3.69 ± 0.48 | 3.92 ± 0.64 | 13       | 0.337   |
| Think that the plants are good for life after the test | 3.23 ± 0.73 | 4.08 ± 0.86 | 13       | 0.002 **|
| More willing to take care of plants after the test | 3.23 ± 1.09 | 4.08 ± 0.64 | 13       | 0.051   |
| More efficient plant maintenance after the test | 2.54 ± 0.78 | 4.69 ± 0.48 | 13       | 0.000 ***|
| Attitude survey                            |           |        |         |         |
| Better user experience                     | /         | 4.31 ± 0.48 | 13       | /       |
| Hope to introduce plant factory mode       | /         | 4.38 ± 0.51 | 13       | /       |
| Willing to pay a fee for the experience    | /         | 3.92 ± 0.49 | 13       | /       |

*p < 0.05, **p < 0.01, ***p < 0.001.

Based on the above analysis, it can be seen that the prototype of the plant factory design has significantly improved the traditional methods of maintaining plants, improving efficiency, and improving user convenience, which provides a reference for the office to further popularize green ecology and sustainable development.

6. Conclusions

There is a big gap between the human demand for environmental ecological services and the existing ecological service products. The detachability of ecological services and ecological products has brought the feasibility of sharing ecological services. In this paper, a novel IoT-based sharing plant factory is designed to solve this problem. First, the ecological service process of office space is studied through user interviews and surveys, to understand the contact points of ecological services. Then, compared with the traditional existing ecological service products, the verification test and system usability test based on the sense of NC were completed. The results show that the designed MSPF can effectively help the user to improve the closeness to the plant, and feel the benefits of the plant. In addition, the efficiency of plant maintenance is greatly improved with the help of MSPF. In a word, the IoT-based sharing plant factory designed in this paper can greatly increase the intimacy of people and nature, and meet the basic needs of indoor ecological service products.

The features of this design are as follows: The introduction of nature connectedness into ecological design can guide design to pay more attention to the service effect of products, and the introduction of plant factory technology indoors can help ecological service products to function better and provide new ideas for the research of indoor ecological service products.

There are many cross-integrated fields of indoor ecological design and industrial design, such as green design, environmental protection design, and sustainable design. Through this work, it can be found that the introduction of plant factory technology into indoor ecological service design can improve the natural connection of indoor environment. Indoor ecological service design is a new type of design field. Most of the research is still in the conceptual stage, and data-driven dynamic responsive design is rare. This work provides some meaningful exploration. Due to time and cost constraints, this study cannot explore all the possibilities, but the design process, methods and accumulated experience used in the research process can provide some reference for the similar work in the future. This research focuses on plant factory products and related services, but the content explored can also be extended to other product and service designs.

In this study, some functions required by the plant factory for indoor applications, namely the scalability and performance issues in real business environments, the evaluation of natural connections based on user experience and the usefulness of technical usability, have not been fully resolved. Therefore, further research can be done in the future. This will help to solve the problem of how to better promote the combination of indoor plants and sustainable development.

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