Feature Articles

Renewal Project of TAKENAKA Research & Development Institute

Planning and Evaluation of Renewed Research Facilities in Consideration of Human Diversity

Summary

Society has a wide variety of needs owing to the complexity of social issues. In this light, corporate technology research institutes are expected to “create new value” to solve social issues through the effective use of various advanced technologies. Recent years have seen increasing interest in wellness, and it has become desirable for each person to be healthy and motivated to work and to be able to work by interacting with colleagues inside and outside the company to improve intellectual productivity and creativity. Toward this end, the main concepts for the renewal of the workplace of the Technical Research Laboratories 25 years after its establishment were (1) creation, for the improvement of creativity, and (2) open innovation, for the promotion of various exchanges. During the renewal, these two concepts as well as green environmental policies were implemented through a workshop involving multiple working groups of researchers. For fostering creation, the activity-based working (ABW) style was introduced. This is an advanced work style in which workplaces are selected according to the nature of work to promote exchanges among researchers in different fields. Further, for fostering open innovation, a space was established for disseminating technology to the outside world and for utilizing and cocreating resources within the laboratory. At the same time, in consideration of the environment, efforts were made to improve the energy-saving performance, and “SHI-RA-BE” was established as an R&D and demonstration field for biodiversity conservation and green infrastructure.

Chapter 2 provides an overview of the renewal plan. To create a cohesive and open space, the walls of the existing courtyard were removed and a roof light was installed; further, two different stairs connecting the first and third floors and a bridge connecting the north and south living rooms were added. The zoning concept was arranged to reveal important work activities of researchers and to provide a suitable space for each activity. A variety of spaces with different compositions, furniture planning, and color schemes were created to provide flexibility in choosing a workplace. In terms of equipment, multiple types of personal lighting and air-conditioning devices were installed to suit the diverse needs of people. Further, to provide a degree of freedom of choice in terms of the environment, different types of work environments were created. Y-shaped electric louvers that can be adjusted according to the season and the time of day were installed in the roof light in the courtyard. A building plan was established in consideration of energy savings via heat insulation and heat use. This building plan also considered the use of natural light, the use of lighting fixtures to ensure brightness, and a brightness control system that considers human comfort; overall, the lighting environment was planned so as to provide a combination of comfort and energy conservation. In addition, to increase the degree of freedom in choosing workplaces, various information and communications technology (ICT)-based display systems were installed to display the indoor environmental conditions (e.g., temperature, illuminance) and available seats.

Chapter 3 describes the performance and evaluation of the work environment. First, the measurement results of the indoor thermal environment and lighting environment and the results of the questionnaire survey are presented. As a result, various comfortable thermal and lighting environments were established. Further, the questionnaire survey revealed that workers had a higher satisfaction level with the environment after its renovation. Next, the evaluation results of a desktop personal fan, a heat radiation device at the feet, and furniture with an air-conditioning function as personalized thermal environment control devices are presented. The equivalent temperature adjustment range was shown for each device, and it was found that each device could satisfy different comfort preferences.

Chapter 4 describes efforts to improve the workplace productivity of workers. First, details of the workplace after renovation and the personality traits of workers are explained. Next, the daily seat selection tendency of workers in the ABW office is analyzed. As a result, it was found that the higher the degree of satisfaction with seat selection, the higher was the productivity of workers. Correlations were observed among the job position, degree of openness of selected seat, distance to main flow line, age, brightness, personality (cooperation), and degree of openness. Further, the questionnaire survey revealed that workers gave the workplace a higher rating in terms of environmental satisfaction, office activities, and productivity after its renovation.

Finally, future expectations for the evolved ABW workplace are described.

Keywords: ABW(activity based working), diversity of environment, thermal environment, light environment, productivity, personality characteristic

1 Introduction

Masaaki Higuchi*1

The Takenaka Research & Development Institute has been cultivating specialized research for over 60 years as the research institute of a construction company. There has been a wide range of support for Sustainable Development Goals (SDGs) and environmental, social, and governance investment required in recent years. Social issues have become increasingly complex as the social situation changes rapidly, and its accompanying social needs are also diversifying. Various cutting-edge technologies aimed at achieving Society 5.0 are also evolving, and solving such social issues by effectively utilizing these technologies is needed. The Research & Development Institute has had higher expectations for "creating new value" as the company's direction moves from just construction to comprehensive engineering for community development. Moreover, the Research & Development Institute has implemented various measures with the objective of promoting and accelerating diverse research & development (R&D) by intersecting specialized fields and integrating internal / external resources. The workplace of The Research & Development Institute has also been renovated 25 years after its construction, and the research planning / execution process and R&D organizational structure have been reviewed and improved.

In addition, there has been increased interest toward wellness in society, as well as calls for "working style reforms" to promote healthy and lively work. Individuals working with high motivation, working while interacting with colleagues inside and outside the company, and improving their intellectual productivity and creativity as a result of those interactions have been aspects increasingly demanded from society.

The main renewal concepts incorporated considering the above perspectives were (1) "creation" : for improving creativity; and (2) "open innovation" : for promoting various exchanges. The process of individuals thinking about their ideal workplace on their own was emphasized during the renewal, and multiple working groups where researchers participated were organized. Visits of advanced workplaces and 14 workshops were held, where discussions on "what the Institute should be" were promoted. As a result, the slogan was set as "Creating a prosperous future through the co-existence of people and the environment", and the catchphrase that indicates the project goal was set as "'Future Design CANVAS', where we draw our own future on the blank canvas while we think freely and dream of a future that we have not yet seen". The idea here is to "respond to all social needs by enhancing the 'creation of new value' to solve social issues." Lively discussions were subsequently repeated while utilizing the consultation method using "office activity cards", where the two concepts and policies for environmental consideration were finally set as follows.

① Creation: improving creativity: improving the workplace

The zoning layout for each research field was changed to a space that encourages "exchange" to combine knowledge from different fields. "Activity based working (ABW)," which is a new working style in which locations are selected according to the work content, is introduced in a further developed form to promote exchanges between researchers in different fields.

② Open Innovation: promoting various exchanges

Showrooms and discussion spaces are set up to disseminate technology to the outside world and find seeds for co-creation.

A co-creation area that utilizes resources in the Institute and has the objective of "creating new value" is established.

③ Promotion of environmental concepts (co-existence with the environment)

Considerations are given to improving energy-saving performance, health of workers, and intellectual productivity / creativity.

"SHI-RA-BE" is established as an R&D and demonstration field for biodiversity conservation and green infrastructure.

A concept that goes one step further from the conventional concept of simply having individuals select a location based on the content of their work was incorporated when introducing ABW. Based on the results of more than 10 years of research conducted by the company, which focused on "people", a workspace that incorporates the importance of diverse and varied environmental stimuli for people was created. The details are described below.

People are engaged in various jobs during working hours. Even for intensive work, the degree of concentration changes. Is the conventional thought process of providing a given environment the solution? The research of "A study on Architectural Environment for Optimal Psycho-Physiological Functioning"[1-6] started from this question. Research has been conducted from the perspective that positive comfort and individual performance improvement should be set as objectives by allowing various people to feel appropriate changes in environmental stimuli according to the situation. The content and actions of work change on a constant basis, but preferences and personalities also differ for each individual, as well as moods and physical conditions. Measures that consider the different sensitivity toward environmental stimuli such as light or heat also need to be considered. This is an extremely difficult research issue, and there is insufficient evidence obtained, but two major findings have been obtained.

・Various fluctuating environmental stimuli can have a positive effect on “people;”
・Satisfaction improves by self-selecting the environment.

In addition, based on the mechanism of creativity from findings in brain science, it has been said that new combinations of different knowledge and information lead to new ideas. Therefore, inputting various information into the brain and continuing to think about new connections with the motivation of thinking about new concepts are important. The moment of inspiration is when the brain feels “good” after continuing to think about new connections. That moment suddenly appears with some stimulus. For example, when casually taking a walk or when in the bathroom.

Considering these aspects, this renewal plan focused on increasing interdisciplinary communication that can be realized by ABW (increases in information input) and improvements in self-efficacy by self-selection of the workplace (maintenance and improvement of motivation), and also creating a space where changes in various environmental stimuli could be felt. With the aim toward the next ABW, the designer was asked to embody the following concepts: (1) individuals are able to self-select their workplace according to their personality, preferences, mood, physical condition, etc., and not based on the content of their work; and (2) individuals are provided a variety of places influenced by nature, where they can feel changes in space such as an atrium, low ceiling space, line of sight changes, etc.

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＊1 Executive Manager, Research & Development Institute, Dr. Eng.

2 Outline of Renovation Plan

Shota Irie*1 Masayuki Okada*2 Ken Hatanaka*3

2.1 Building Overview

This project is a renovation of the Takenaka Research & Development Institute that was completed in 1993. The construction overview is shown in Table 1. There is a need at the Institute for rapid cross-disciplinary R&D that integrates knowledge from multiple fields to create new value reflected in a society heading toward Society 5.0. Work was performed with researchers in this Plan with the objective of "creating an integrated space" and "zoning according to the activities of researchers."

Table 1 Building overview

Design and construction	Takenaka Corporation
Site area	65,000.08m^2
Building area	19,591.30m^2
Total land area	39,150.88m^2
Extension area	420.09m^2
Repair area	6,275.00m^2
Number of floors	Underground: 1 floor Above ground: 4 floors
Structure	Reinforced concrete construction
Construction period	July 2018 – September 2019

2.1.1 Creating an Integrated Space

The objective was to create a workplace where researchers can freely select working environments themselves, and researchers in different fields can be stimulated through natural exchange, engaging in healthy and creative research. The previous laboratory was a structure consisting of an elongated volume of approximately 48 m × 8 m with a courtyard in the middle, and the zoning concept was grouped by research field and specialized for the "concentration" of researchers. The Renovation Plan gathered researchers from all fields in the central area of the research building, with the zoning concept redesigned to encourage "exchange" among researchers. The outer walls of the existing courtyard were removed, a roof light and automatically-controlled louver were placed above to convert the courtyard into an internal space, and a theater-style grand staircase that connects the first and second floors was set up as a confluence for exchange. A north-south bridge as well as a hanging staircase connecting to the third floor were set up in the center of the atrium on the second floor, and the workplace was integrated by connecting in a planar and cross-sectional manner.

The activities of the researchers extracted from the workshops were incorporated into each space to create a variety of venues, including planning and color schemes of furniture for "concentration" and "exchange".


Photo 1 Workplace and courtyard before renovation

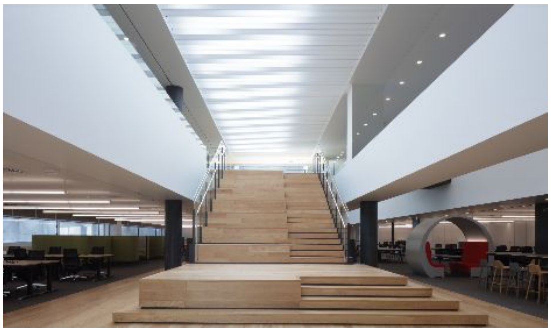
Photo 2 Grand staircase integrated with workplace after renovation

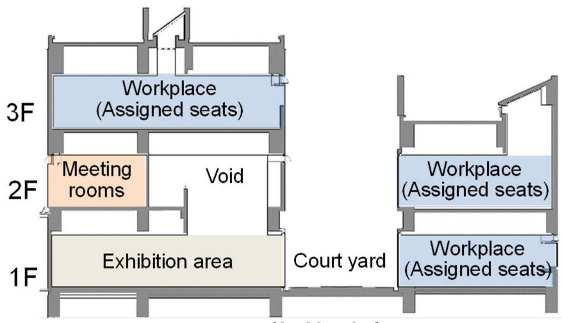

Fig.1 Cross-section of building before renovation

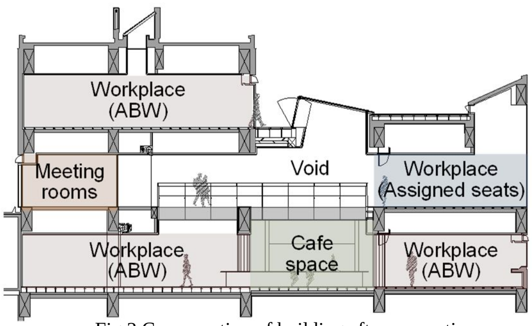

Fig.2 Cross-section of building after renovation

*1 Chief, Design Department, Tokyo Main Office
*2 Manager, Workplace Produce Department, Dr. Eng.
*3 Chief, Design Department, Tokyo Main Office

2.1.2 Zoning According to Researcher Activity

The workplace prior to renovation had a decentralized zoning concept that was divided into five rooms according to research field, thus the interaction between researchers from different fields of specialization was limited. Gathering all researchers in the central area of the research building after the renovation removed barriers between departments and also introduced ABW, where each researcher could freely choose a place to work according to their preferences, moods, and behavior. It is said that the ability to choose working environment freely would lead to improvements in environmental satisfaction and productivity. The objective of allowing for selection of the working location each time was to increase the “fluidity” of researchers and activate communication with researchers in different fields.

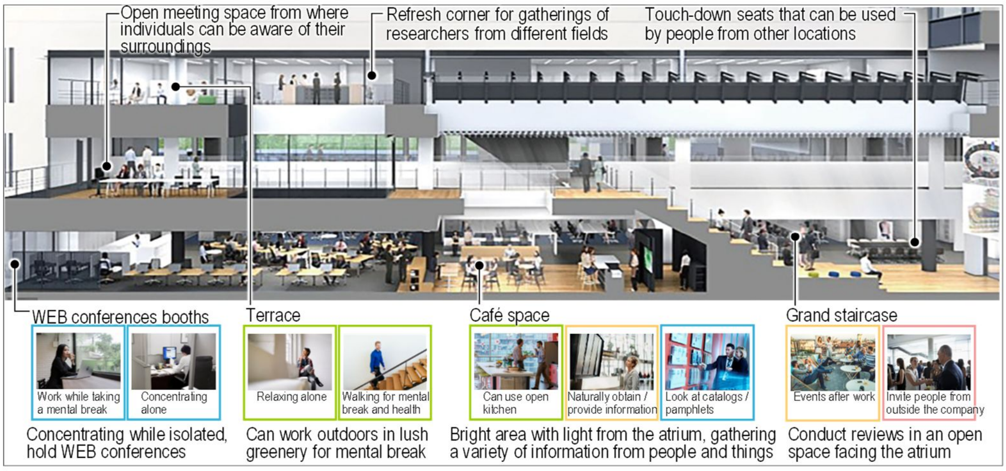

Fig.3 Assumed activities and workplace

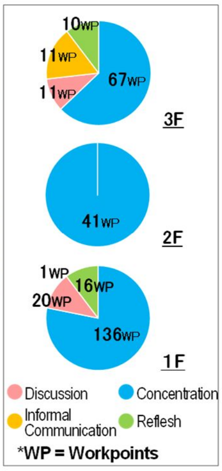

Fig.4 Number of workprints

The problem-seeking methodology was applied in the requirements arrangement 1). Workshops were held to actualize work behaviors (=activities) that are important for researchers and take measures to correspond with the space, and arrangements into a clear zoning concept were implemented to achieve the “ideal form” of the Institute 2). A variety of highly selective locations (ABW), with furniture layouts that consider the diversity of spaces and environments, were planned in response to these aspects (Photos 3 – 7). The spaces where researchers work were mainly set on the first and third floors. A “department-dedicated area,” which serves as the base for each of the eight research departments, was set up on the first floor, as well as solo-work booths for ABW, a café space, and a meeting booth. A grand staircase that serves as a confluence for exchange was installed in the center. There were various spaces such as an open meeting space or café counters facing the outdoor terrace centered around desks for intensive work and a shared PC area on the third floor.

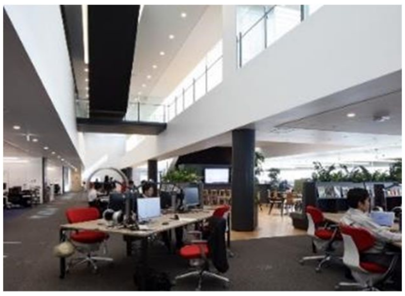

Photo 3 Bright and open ABW workspace

Photo 4 Cafe area used for multiple purposes

Photo 5 Department-dedicated area

Photo 6 Outdoor space for relaxing and feeling nature

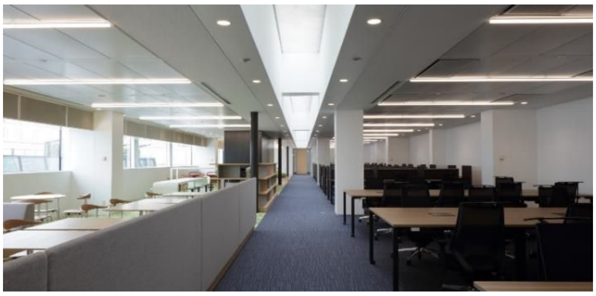

Photo 7 Open meeting space and enclosed environment for concentrated work

2.1.3 Exhibition Zone for Transmitting Technology Outside the Company

Functional updates were made to the technical exhibition zone in the second and third floors of the administration building near the entrance. The second floor was set as an “i-farm” where the latest technology, including hands-on experiences, was exhibited; the ceiling system could be used for various exhibitions by making the picture rail and lighting duct orthogonal to each other (Photo 8). On the third floor, a green lounge, with a large display showing the company profile as well as a large amount of greenery (Photo 9), and an archive lounge, where exchanges could be deepened by understanding company technology and expertise of researchers (Photo 10), were set. A new set of stairs was built to improve the mobility of the second and third floors. Furthermore, systems that utilize IT such as “Giken Watch,” which is a 3D-simulated experience system that introduces the entire picture of the renovations (Photo 11); and “Mandala”, which is used for introducing researchers (Photo 12, 13), were developed to serve as seeds for co-creation.

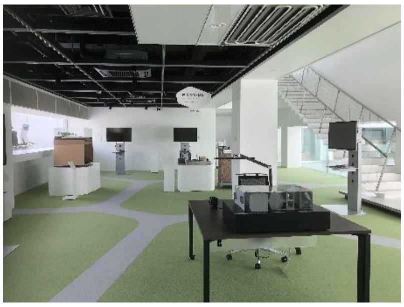
Photo8 Exhibition space ”i-farm”


Photo9 Green lounge


Photo10 Archive lounge


Photo11 Renewal space introduction system


Photo12 Researcher information display system


Photo13 Researcher information: detail screen

2.1.4 Co-Creation Zone for Gatherings of Researchers Inside and Outside the Company

A co-creation zone was set up in the west wind of the research building as a workspace that makes full use of research resources, such as experimental and analytical equipment owned by the Research & Development Institute, along with researchers from startups, universities, partner companies, and client companies. A kitchen and various furniture were arranged in the common area on the third floor (Photo 14), which could be used as a workshop as well as a workspace (Photo 15). Four large and small project rooms that could be secured and occupied were also established. A napping space in addition to spaces for solo-work and meetings was established on the second floor. The first floor was re-developed as a hall that can accommodate approximately 200 people (Photo 16). The three screens could be used individually as well as for multiple seminars and pitch events.


Photo14 Co-creation zone: Café aria


Photo15 Co-creation zone: Workplace

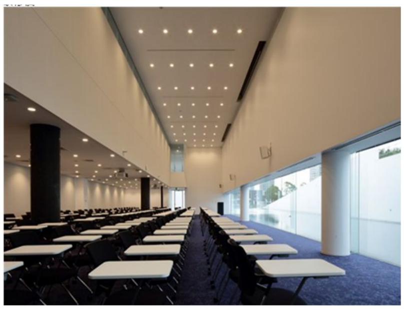
Photo16 Multipurpose hall

2.2 Overview of Environment and Equipment Plan

Figure 5 shows an overview of the building equipment technology introduced in this renovation. Efforts were made to pursue contributions to improve the creation of new value by introducing the four equipment technologies of a "**workplace tailored to the diversity of people,**" "**balancing natural energy use and comfort,**" "**lighting control considering brightness,**" and "**promoting work styles by utilizing information and communication technology (ICT),**" as well as developing research fields such as biodiversity conservation with the "Inzai forest used and grown by everyone".

2.2.1 Workplace Tailored to the Diversity of People

A Plan focusing on ambient and task areas was established to achieve an Environment and Equipment Plan that considers the diversity of people. The ambient area had the outer walls, floor, and openings heat-insulated such that a comfortable space could be obtained with less energy input. The air conditioning was set such as to be a floor-blown air conditioning system in the first floor and a latent heat / sensible heat separation air conditioning system in the second / third floors, using radiant air conditioning and a humidity-controlled outside air treatment unit. These were utilized to create a thermal environment of ambient space that matches its spatial characteristics. As for the task area, a personal environment control system consisting of task fans, task lighting, and a radiant air conditioning device (Photos 17, 18) was introduced such that workers could freely adjust the heat and light of the environment.

Air-conditioned furniture (Photo 19) was also developed in spaces where temperature differences were likely to occur (e.g., atrium spaces) to control the thermal environment in the space near the body while maintaining comfort and having a wide response to the user's temperature preferences. This was a personal air conditioner that controlled the thermal environment near the body by convection / radiation from the canopy surrounding the individual, as well as heat transfer on the contact surface (e.g., seat surface).

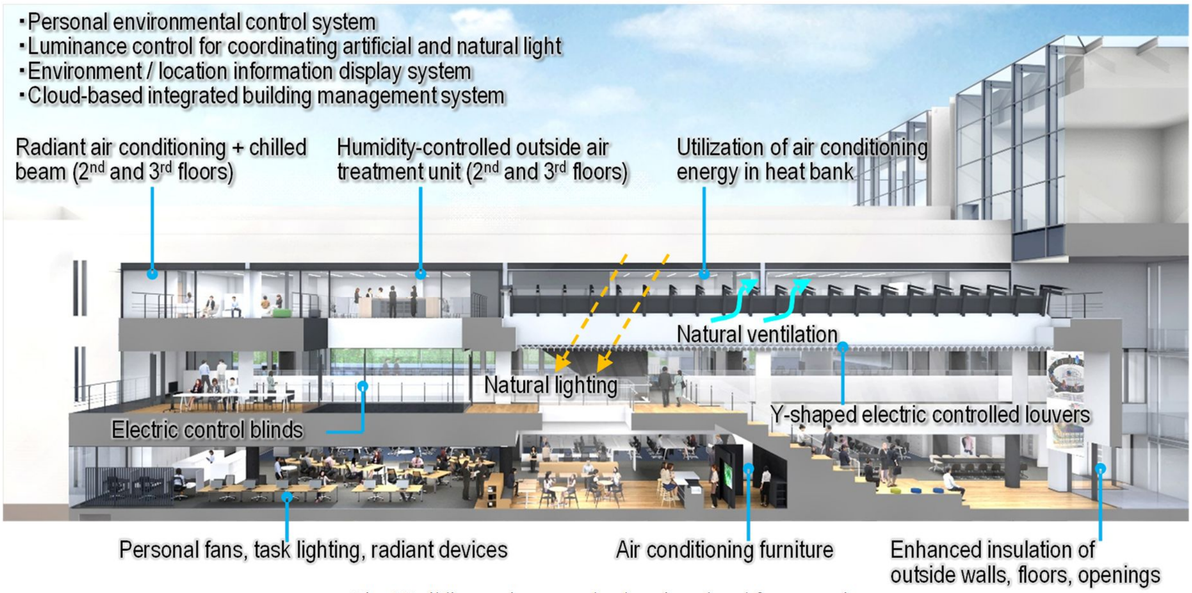

Fig. 5 Building equipment technology introduced for renovation

Photo 17 Personal environmental control system

Photo 18 Radiant air conditioning device

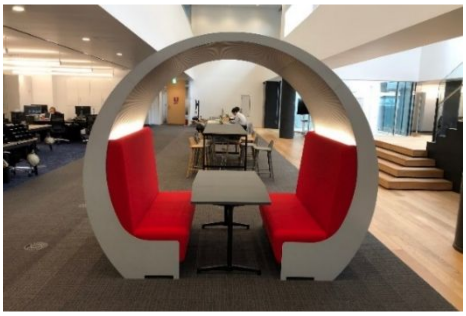

Photo 19 Air-conditioned furniture

2.2.2 Balancing Natural Energy Use and Comfort

Y-shaped electric controlled louvers, which were newly developed in this renovation, were installed underneath the top lights to integrate the atrium space, which is often planned in the communication promotion office. The plan was to actively conduct top light-based natural lighting and ventilation by changing the louver angle by season and time. A system that collects solar heat in the upper air layer of the Y-shaped electric controlled louver was introduced, and the heated air that was collected was used for recycling desiccant air conditioning and floor-blown air conditioning in the winter. The use of solar heat was controlled and a comfortable external stimulus was felt indoors; at the same time, comfort was considered by controlling the luminance of natural light.

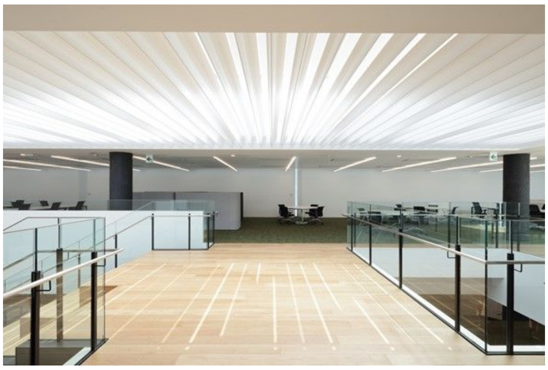

Photo 20 Efficient use of natural energy with Y-shaped electric controlled louvers

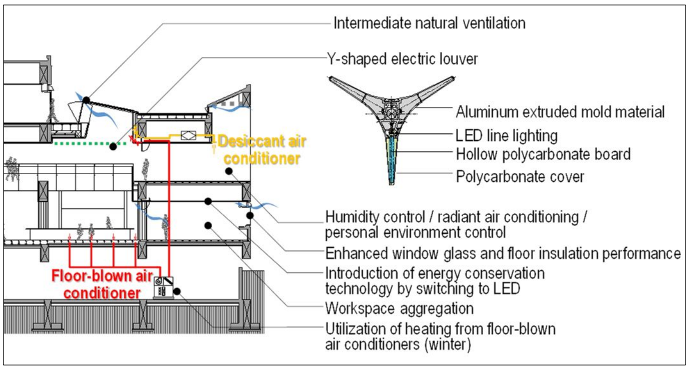

Fig. 6 Detailed cross-section of Y-shaped electric controlled louvers

2.2.3 Lighting Control Considering Brightness

Light environment simulations were conducted from the design stage, and consideration was given to creating a light environment that does not generate an extreme luminance ratio while actively incorporating natural light. Pendant illumination fixtures emitting light up and down were developed in areas with limited natural light (Fig. 7, Photo 21) to improve the luminance of the ceiling surface. These were equipped with a communication function that allows for individual dimming and tone adjustments in the vertical direction in terms of functionality, and the specifications allowed the user to individually set the desired color temperature. Unlike conventional grid lighting, in which luminance of the ceiling surface was secured by reflecting downward light distribution, this fixture is less affected by the reflectance of floor surfaces and furniture in the room. A light environment that achieves both energy conservation and worker comfort was achieved by setting the target average luminance of the ceiling / wall surface and controlling the luminance.

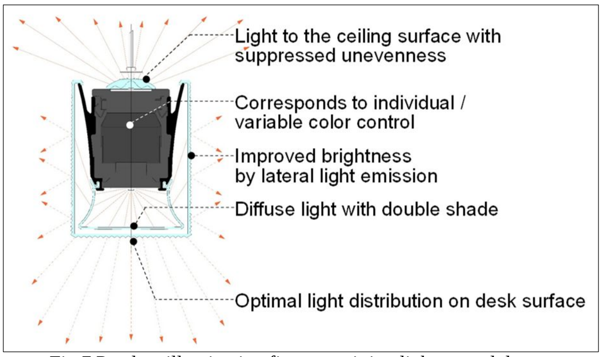

Fig.7 Pendant illumination fixture emitting light up and down

Photo 21 Workspace with pendant illumination fixture

2.2.4 Promoting Work Styles by Utilizing ICT

Seat selection support was enabled by introducing a display system that superimposed indoor environment information (temperature, humidity, illuminance, noise value) and visualizing various information on the monitor at the entrances / exits of office areas and on smartphones of workers (Fig. 8). A seat registration system was also introduced by holding a smartphone over the NFC tag on the table to determine the accurate seat position information of individuals, allowing for the determination of where individuals are located even in an ABW environment. The operation screen of the personal device associated with the seat could also be activated and operated on a smartphone with seat registration (Fig. 9). The operation of the personal equipment was also linked with seat information and has the function of automatically ceasing operation when the worker leaves the seat. The operation of the personal equipment was designed such that workers could customize it to their individual preferences. The operation / intensity preferences could be used at any seat by saving these settings.

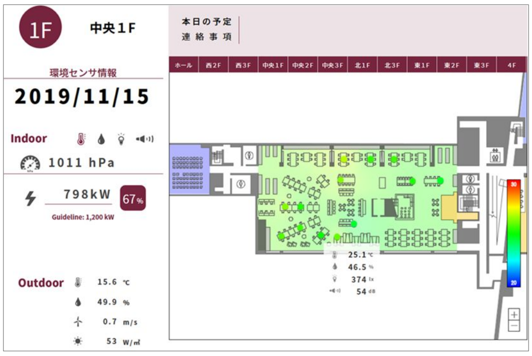

Fig.8 Indoor environment information on signage

Fig. 9 Example of remote control screen of personal device

2.2.5 Inzai Forest Used and Grown by Everyone

The demonstration field "SHI-RA-BE" was established in the northwestern part of the site to allow for R&D such as biodiversity conservation (Fig. 10, Photos 22, 23). Local ecological networks were strengthened by investigating the landscape of the "satoyama" and aquatic areas in the Inzai region and reflecting the ecosystem and characteristics in the field. New initiatives such as demonstrating rainscapes for reducing the risk of urban flood damage through proper treatment of rainwater during heavy rain, conservation of precious aquatic plants, monitoring of flying birds and dragonflies, cultivation of pesticide-free vegetables, beekeeping, etc., have been started while collaborating with experts inside and outside the company as well as with local residents.

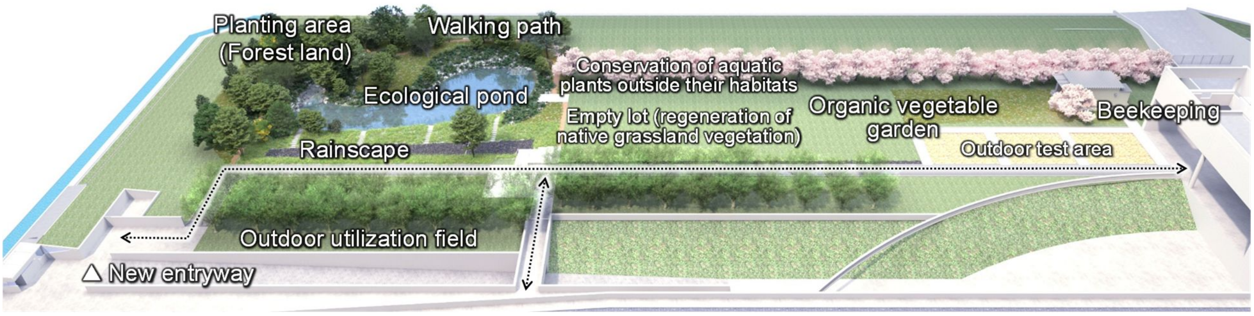

Fig.10 Demonstration field for research and development such as biodiversity conservation

Photo 22 Demonstration field "SHI-RA-BE": View from southeast

Photo23 Demonstration field "SHI-RA-BE": View from southeast

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3 Work Environment Performance and Evaluation

Kazuki Wada＊1　Takuro Kikuchi＊2　Kitoshi Tanaka＊1

3.1 Thermal Environment

3.1.1 Measurement Overview

The thermal environment of the work area was measured to verify the effects of the improved thermal environment after the renovation and diversity evaluation. Figure 1 shows the plan for the first to third floors and the thermal environment evaluation points after the renovation. The positions of the window surfaces, courtyard, and top lights that incorporate fluctuations in the outdoor environment into the room are also shown alongside the evaluation points. The temperature / humidity / wind speed / globe temperature at FL+600 mm and the temperatures at FL+100 mm / + 1,100 mm were measured at 5-min intervals to evaluate the thermal environment in the representative workplace (symbol in figures: Wp) and common areas (symbol in figures: Com) that could be used for meetings, mental refreshment, and personal work for each floor.

The standard working hours data (weekday: 8:30–17:15) in the winter season of February were analyzed in this section.

Fig.1　Thermal environment evaluation points after renovation

3.1.2 Thermal Comfort Zone by Psychrometric Charts

The measured data after the renovation were plotted based on the evaluation of the thermal comfort zone by the psychrometric charts of ASHRAE55-2017. Figures 2 and 3 show the workplace (Wp) and common area (Com) results, respectively.

The comfort range in the workplace was generally an amount of clothing of 1.0 clo, and the relative humidity was distributed at 40–50%. There was a large amount of time plotted for the common area on the warm side, particularly on the third floor, which was easily affected by the outdoor environment (e.g., sunlight). The workplace after the renovation could be selected according to the work and preferences of the worker under an environment that was generally distributed in the thermal comfort zone.

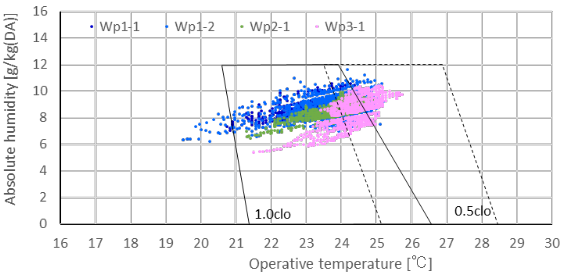


Fig.2　Thermal comfort zone of ASHRAE55 -Workplace-

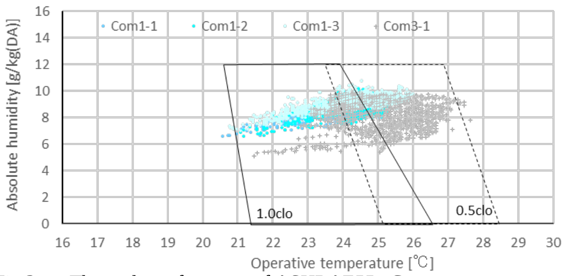


Fig.3　Thermal comfort zone of ASHRAE55 –Common areas-

＊1　Chief Researcher, Research & Development Institute
＊2　Chief Researcher, Research & Development Institute, Dr. Eng.

3.1.3 Equivalent Temperature

Figure 4 shows the frequency of equivalent temperature at each measurement point during standard working hours before and after the renovation as a box-and-whisker plot. The evaluations were performed using Bedford's equivalent temperature as there were many instances where the air flow velocity was less than 0.1 m/s in the heating environment. The workplace (Wp) and common areas (Com) were distinguished as white and gray, respectively. In the figure, the lines where there was slight air flow (0.1 m/s), amount of clothing of 1.0 clo, and predicted mean vote (PMV) of ±0.5 corresponding to a metabolism amount of 1.2 Mets are also shown.

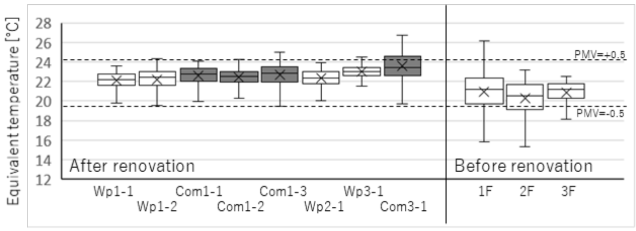


Fig.4 Frequency of equivalent temperature during standard working hours

The equivalent temperature of the workplace after renovations was generally within the range of ±0.5 PMV, and the median value was a slightly warmer thermal environment. In addition, the equivalent temperature before the renovation had a wide range of occurrence, and a slightly colder thermal environment was formed. High heat insulation of the windows and floor slabs were also conducted in this renovation, which was considered as the reason for the suppression of the temperature decrease outside the air conditioning times. The range of equivalent temperatures that appear after the renovation also tended to be somewhat wide in the common areas, which were easily affected by the daylight and outdoor environment.

Next, the changes in equivalent temperature during standard working hours were analyzed. Figure 5 shows a box-and-whisker plot for each time period divided by workplace (Wp) or common area (Com).

The equivalent temperatures in both the workplace and common area tended to increase from 8:00 to 12:00 as the heat storage load was removed and solar heat was acquired after the start of air conditioning at 6:00 in both the workplace and common area. Slightly cold data at the start of work and slightly warm data in the afternoon could be confirmed in the workplace, but it can be seen that the temperature was within a comfortable equivalent temperature range at almost all time period. The environment in the common area was warmer than that of the workplace and had higher variation in almost all working hours. A comfortable equivalent temperature range was maintained at most time periods, and environments where slightly warmer locations could be selected were formed during the winter season for the research facility in which workers can choose their place of work.

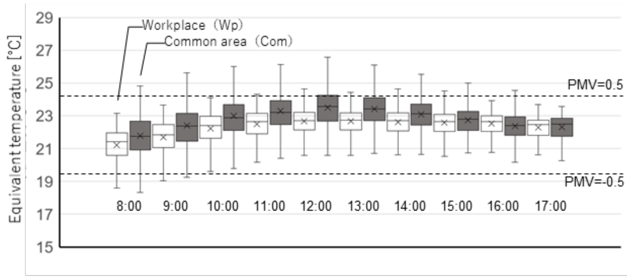


Fig.5 Changes in equivalent temperature during standard working hours

3.1.4 Vertical Temperature Difference

Figure 6 shows a box-and-whisker plot of the frequency of vertical temperature differences during standard working hours before and after renovations. The vertical temperature differences assumed a sitting position, with temperature differences set at FL+1,100 mm and 100 mm.

The vertical temperature difference after the renovation was within 3 K, where the percentage of dissatisfied individuals was less than 5% in the local discomfort evaluation, which was a large improvement compared to results before renovations. Figure 7 is a thermal image of the representative points after the renovations (shooting points are also shown in Figure 1), and no decreases in floor temperature were observed.

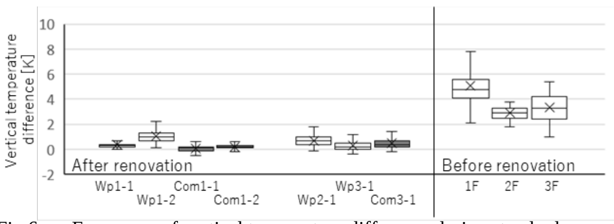


Fig.6 Frequency of vertical temperature difference during standard working hours

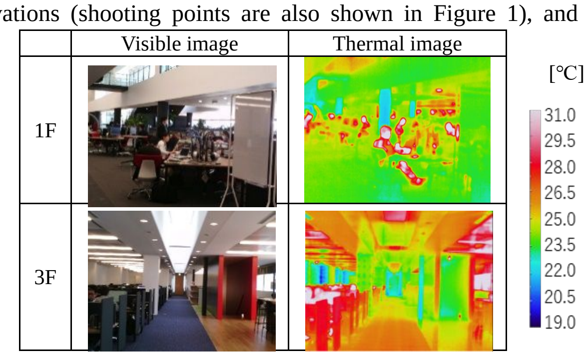


Fig.7 Workplace surface temperature after renovation

3.1.5 Equivalent Temperature for Each Part by Thermal Manikin

Equivalent temperature evaluations for each part were conducted using a thermal manikin in the workplaces of the underfloor air-conditioning system used in the first floor, and the ceiling radiant heating / cooling system used in the third floor. Measurements were conducted by placing the thermal manikin in the representative seats shown in Photo 1.

Photo1 Thermal manikin measurement –Leftside:1F, Rightside:3F-

Table 1 Thermal manikin measurement conditions

Measurement location	1F (underfloor air-conditioning system)	3F (ceiling radiant heating / cooling system)
Measurement time	2020/2/7 12:00	2020/2/12 13:00
Ambient air temperature	24.5 ºC	24.8 ºC
Mannequin used	Manufactured by PT Teknik 22 divisions	
Mannequin clothing	Leather shoes, socks, boxer shorts, slacks, short-sleeved underwear, long-sleeved shirt, tie, long sleeve jacket	
Mannequin control	Comfort control	

Table 1 shows the thermal manikin measurement conditions. The thermal manikin used was the thermal manikin 6 manufactured by PT Teknik [1)]; the clothing worn was a suit (leather shoes, socks, boxer shorts, short-sleeved underwear, long-sleeved shirt, tie, long-sleeved jacket); and measurements were performed under comfort control. The changes in equivalent temperature over time in Figure 5 showed that the equivalent temperature from 12:00 to 13:00 was stable in the workplace, thus the evaluations were performed using the data in which the thermal manikin reached a steady state during this time period. The ambient air temperature was 24.5 ºC on the first floor and 24.8 ºC on the third floor.

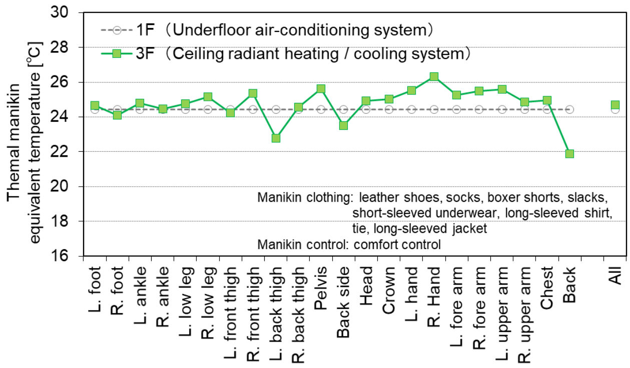


Fig.8 Thermal manikin equivalent temperature

Figure 8 shows the measurement results of the thermal manikin equivalent temperature. The measurement data of the first floor were set as the standard conditions and compared with the measurement data of the third floor to evaluate the effects of air conditioning systems on equivalent temperature for each part. No differences in equivalent temperature were seen for the lower body, but the equivalent temperature of the upper body (head, face, arms, hands) tended to be higher on the third floor (which has a ceiling radiant heating / cooling system), which considered to be an effect of the warm ceiling. The equivalent temperature of the back was approximately 2 ºC lower on the third floor, but this was probably due to the difference between chairs depending on the workplace. The chair on the first floor in Photo 1 was a urethane seat and backrest, whereas the chair on the third floor had a mesh backrest and was breathable.

Evaluations of the equivalent temperature for each part confirmed that differences in the air conditioning system or chair generated differences in local thermal environment characteristics, even when the equivalent temperature of the entire body was almost identical.

3.1.6 Questionnaire Evaluations

Table 2 shows a summary of the questionnaire surveys before and after renovations. The renovation work was completed at the end of September 2019, and the main office space was used from April 2019. The evaluations after the renovations consisted of a survey approximately 10 months after the start of use. Respondents answered the following degrees of sensation / satisfaction of light environment, thermal environment, air quality environment, sound environment, visual environment, ICT environment, and spatial environment in seven levels (four levels only for air flow sensation). In sequence, the respondents answered the overall degree of satisfaction for the above aspects in seven levels. The thermal environment results

Table 2 Summary of questionnaire survey

	Period	Work style		Valid answers
		Fixed seats	ABW seats	
Before renovation	Feb. 7-16, 2018	203	27	88
After renovation	Feb. 7-21, 2020	23	188	148

are reported here.

Figures 9–11 show the results of thermal sensation, humidity, and airflow. The thermal sensation results showed that there were fewer responses for the colder side and more responses for the warmer side. The improved temperature and humidity conditions could be attributed to the improved insulation of the floors and windows of the first floor, underfloor air-conditioning system in the atrium space, and internalization of the courtyard. The humidity sensation results showed that there were fewer evaluations for the drier side, and the effects of the humidity control system were noted. The airflow sensation results also showed fewer evaluations for slightly and higher sensing, which was a result of the effects of radiant air conditioning, underfloor air-conditioning, and free seat selection by ABW.

Figures 12 and 13 show the satisfaction dissatisfaction factors with the thermal environment, respectively. There were more satisfied responses for thermal, humidity, and airflow sensation, which were in agreement with the evaluation results. Thus, the renovations were considered effective. This could be confirmed by the decrease in dissatisfaction factors such as cold, dry, wind exposure, and vertical temperature differences. There were also fewer dissatisfied responses and more satisfied responses for air conditioning controllability. The installation of task fans (though unlikely to be used in winter), installation of local but variable seats (air-conditioned furniture), and the degree of freedom in seat selection by ABW were influencing factors. There were fewer dissatisfied responses and more satisfied responses for the overall evaluation of the thermal environment as well.

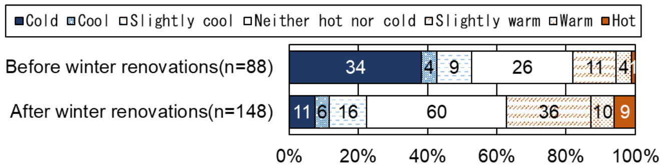


Fig.9 Thermal sensation vote

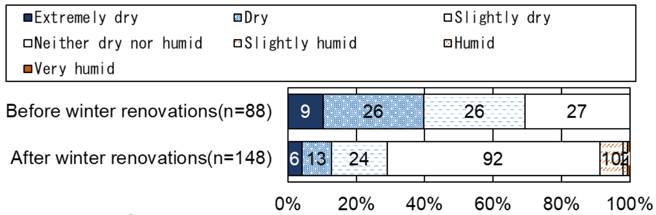


Fig.10 Humidity sensation vote

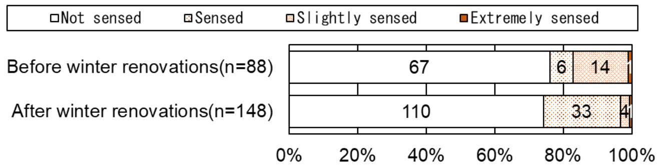


Fig.11 Airflow sensation vote

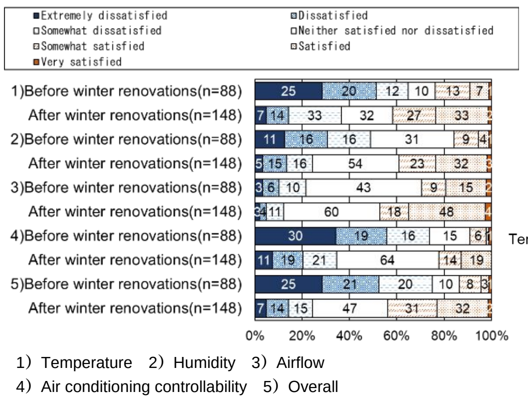


Fig.12 Satisfaction with thermal environment

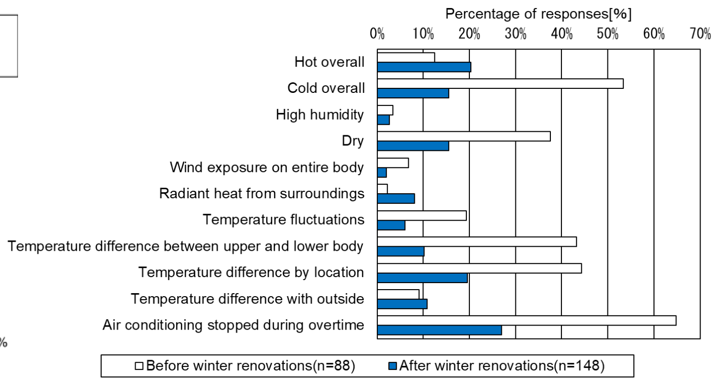


Fig.13 Dissatisfaction factor of thermal environment

3.2 Light Environment

3.2.1 Measurement Overview

The light environment of the work area was measured to verify the corresponding improvements after renovations and the diversity evaluation. Figures 14 and 15 show the plan view and horizontal illuminance measurement points before and after renovations, respectively. The illuminance was measured from May 7–23, 2018 before the renovation and March 1–31, 2020 after the renovation. The measurement seasons for both before and after renovations were different from winter, but the tendencies of fluctuations affected by natural light from the south window, courtyard, and top light could be determined.

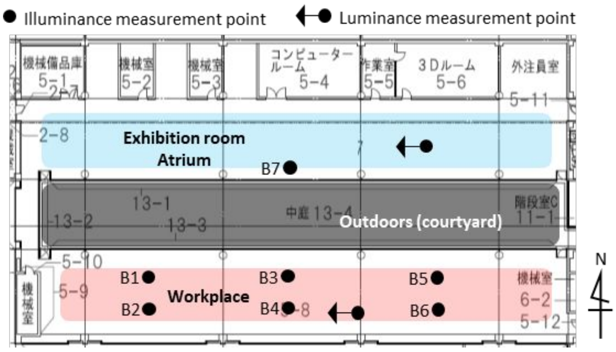


Fig.14 Illuminance measurement points before renovation

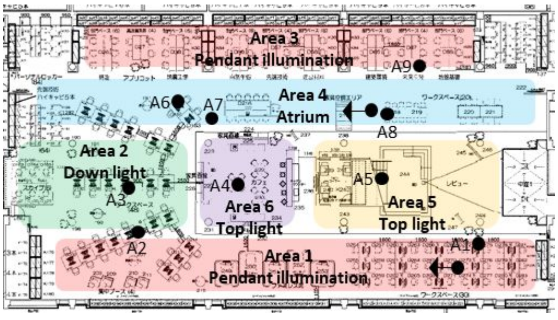


Fig.15 Illuminance measurement points after renovation

3.2.2 Range of Illuminance Fluctuations

Figures 16 and 17 show the fluctuation range of horizontal illuminance with samples at 13:00 and 16:00 on weekdays during the measurement period before and after renovations, respectively. The illuminance fluctuated depending on the time and weather for both before and after renovations. The tendencies for before the renovation varied between the aisle / courtyard side (B1, 3, 5) or the workspace / south window side (B2, 4, 6). The south window was used with the manual blinds almost fully closed, and the effect of natural lighting was small. High horizontal illuminance and large fluctuations were observed after the renovations in A4 and 5 of area 5, where the top light was directly overhead. Fluctuations and weather effects were small in A6, 7, 8, and 9 of area 4. The variation in the average value and fluctuation range of horizontal illuminance increased depending on the area after renovations, and there was an increased diversity of the environment obtained by selecting the seat as intended at the design stage.

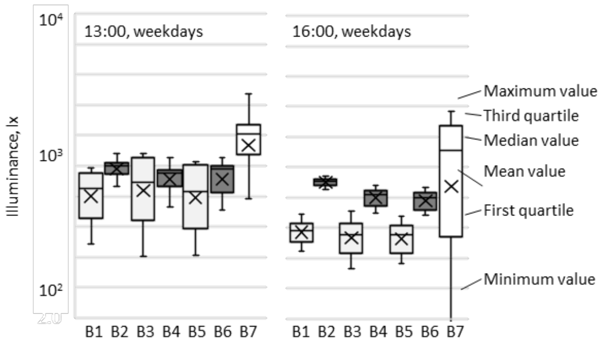


Fig.16 Range of horizontal illuminance fluctuation before renovation

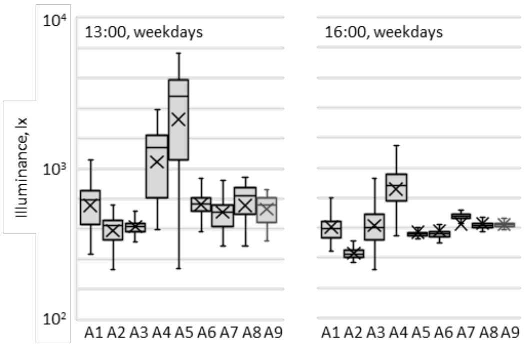


Fig.17 Range of horizontal illuminance fluctuation after renovation

3.2.3 Brightness

Figure 18 shows the distribution of a brightness scale [2] from a typical viewpoint. The ambient illumination in area 1 is a pendant-type, and the brightness of the ceiling was improved. Area 4, which was an exhibition room with underfloor air-conditioning, had light from the top light illuminating the upper part of the wall surface, which improved the brightness. Next, Figure 19 shows the brightness sensation index in eight directions at the points representing each area. The range of NB that lowers the brightness sensation was set to 4.0–6.5 [3], and the area ratio that occupied the field of view was used as the brightness sensation index. Only the results at 13:00 are shown. It can be seen that the area ratio differs considerably depending on the area and line of sight.

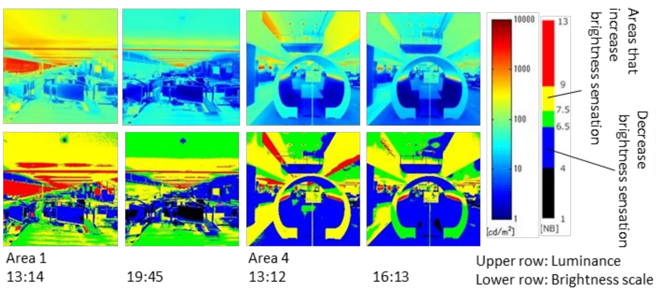


Fig.18 Distribution of brightness scale "NB" after renovation

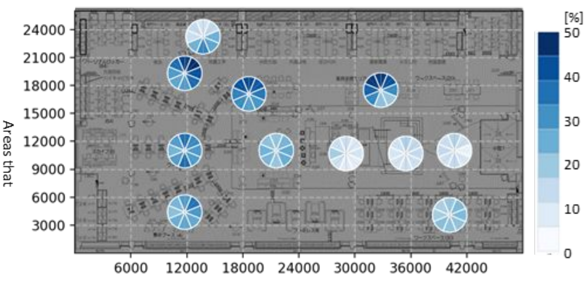


Fig.19 Area ratio to reduce brightness sensation by 8 directions

3.2.4 Glare

Figure 20 shows the glare index at the same locations as Figure 19. Daylight glare probability (DGP) [4], which could be used in any direction of the line of sight with respect to the glare light source, was used here; results at 13:00, which had the highest DGP, are shown. Glare is a hindrance if DGP is 40% or more. The value was less than 40% in all viewpoints and lines of sight with the exception of the viewpoint of the main traffic line. There was a reduction in the DGP at viewpoints with relatively high values by shifting the line of sight by 45° or more from the direction facing the window. No data were shown for this, but the predicted glare sensation vote [5] in the line of sight facing the window also had values below 40%, in which glare discomfort was felt (with the exception of the measurement points of the aisle).

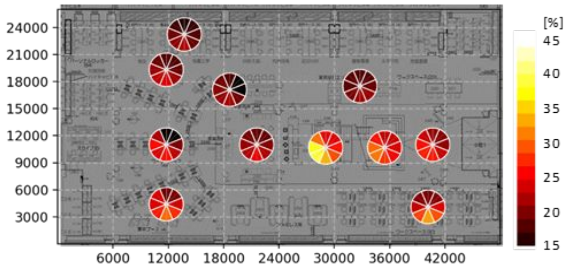


Fig.20 Glare index “DGP” by 8 directions

3.2.5 Questionnaire Evaluation

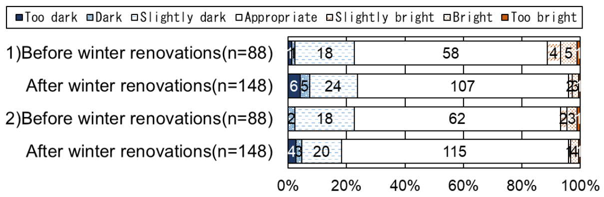
The questionnaire results of the light and visual environments from the questionnaire survey mentioned in the previous section are reported.

Figure 21 shows the brightness sensation evaluation results. The brightness sensation responses on the desk and the room overall showed no major differences for the dark side before and after renovations, whereas the responses for the bright side decreased and responses for the appropriate side increased.

Figure 22 shows the light environment satisfaction evaluation results. Responses for the satisfied side increased for the amount of natural light, quality of illumination, and controllability. Responses for the satisfied side slightly increased overall as well.

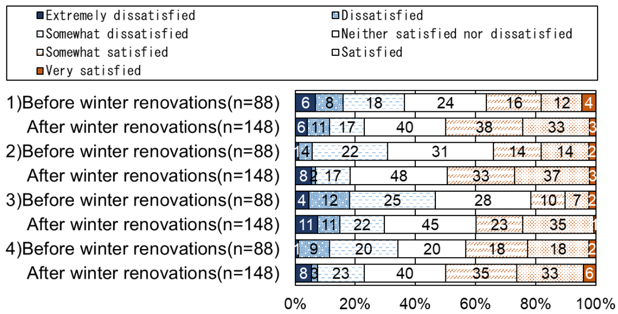
Figure 23 shows the light environment dissatisfaction factor evaluation results. The percentage of dissatisfied responses for overall darkness, glare of illumination, and color of illumination decreased. This was due to increased ceiling surface brightness due to pendant illumination equipment, increased brightness of the space immediately below the top light introduced in the internalization of the courtyard, decreased fixture luminance due to illumination fixtures, which considered glare prevention, and the adoption of variable color temperature lighting fixtures. In addition, self-selection, which considers the light environment, was enabled by increased freedom of individual seat selection through the adoption of ABW in addition to reductions in a working environment with extremely high illuminance with a layout that avoids windows.

Figure 24 shows the visual environment satisfaction evaluation results. The responses on the dissatisfied side considerably decreased for the view from inside the office to outside after renovations, and there were more responses on



1) Brightness of desk 2) Brightness of room overall

Fig.21 Brightness sensation vote



1) Amount of natural light 2) Quality of illumination 3) Controllability of illumination 4) Overall

Fig.22 Satisfaction of light environment

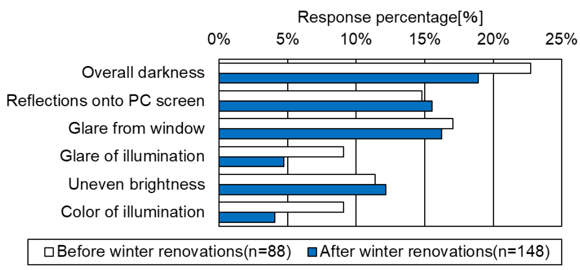
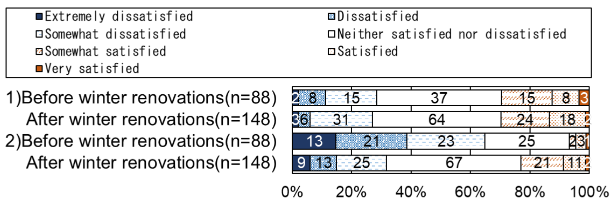


Fig.23 Dissatisfaction factor of light environment



1) Line of sight from others 2) View from inside office to outside

Fig.24 Satisfaction of visual environment the satisfied side. There were many window seats and many blinds were almost fully closed before renovations, whereas reducing the window seats and the introduction of automatic control of blinds after renovations increased the open time of the blinds. There were no major changes in evaluations before and after renovations with regard to the line of sight from others as the seats that turned their backs to the main traffic lines were limited.

3.3 Personalized Thermal Sensation Control Devices

3.3.1 Arrangement of Personalized Thermal Sensation Control Devices

This renovation adopted ABW to allow for the selection of places for workers to work and also various types of personally adjustable thermal sensation control devices (hereinafter mentioned as "personal devices"), which consider individually variable comforts and preferences. Figure 25 shows the zoning of the adopted personal devices.

The following sections report results of equivalent temperature evaluations for each part using a thermal manikin to evaluate the cooling / heating effects of personal devices on the human body. The personal fan shows the results of cooling effects, and the radiant heating device / air-conditioning furniture show the results of heating effects in winter.

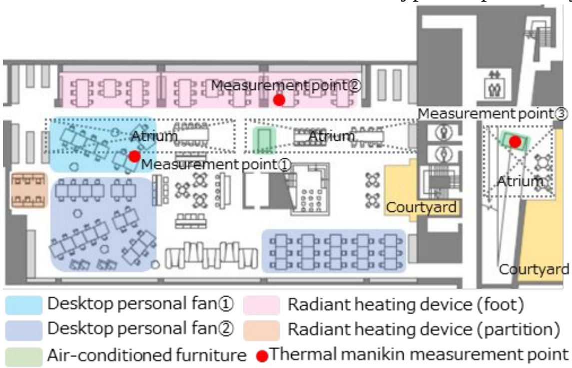


Fig.25 Zoning of personalized thermal sensation control devices

3.2 Desktop Personal Fan

Desktop personal fans in Photo 2 were placed in many seats as one of the easiest cooling methods to introduce. Their air volumes could be individually adjusted in four stages of OFF / weak / strong / rapid cooling, allowing for cooling effects by increasing airflow velocity. It is the simplest in terms of equipment, and retrofitting is easy.

Equivalent temperature evaluations were conducted using a thermal manikin for each of the four air volume stages of the desktop personal fan (1) at the seat on the first floor (Fig. 25: measurement point (1)). Table 3 shows the measurement conditions. The maximum air volume of the personal fan was 78 m^3/h, and the air velocity near the face 50 cm away from the outlet was approximately 1.3 m/s. The thermal manikin 6 manufactured by PT Teknik [1)] was used for thermal measurements. The clothing was assumed to be that for the summer season and was set as leather shoes, socks, boxer shorts, slacks, short-sleeved underwear, and short-sleeved shirt, with evaluations conducted under comfort control. The room temperature during measurements was 24.5–25.0 ºC, and the evaluations for all operation modes were performed using data where the surface temperature of the manikin reached a steady state. Figure 26 shows the measurement results of the thermal manikin equivalent temperature. The equivalent temperature was calculated with the fan off as the

Photo2 Desktop personal fan

Table 3 Measurement conditions of desktop personal fan

Date	2019/9/11			
Operation mode	OFF (Standard condition)	Weak	Strong	Rapid
Air volume	-	36m^3/h	58m^3/h	78m^3/h
Air velocity*	-	0.5m/s	1.0m/s	1.3m/s
Ambient temperature	25.0?	24.5?	25.0?	24.6?
Manikin clothing	Leather shoes, socks, boxer shorts, slacks, short-sleeved underwear, short-sleeved shirt			

* Maximum residual air velocity at a point 50 cm from air outlet

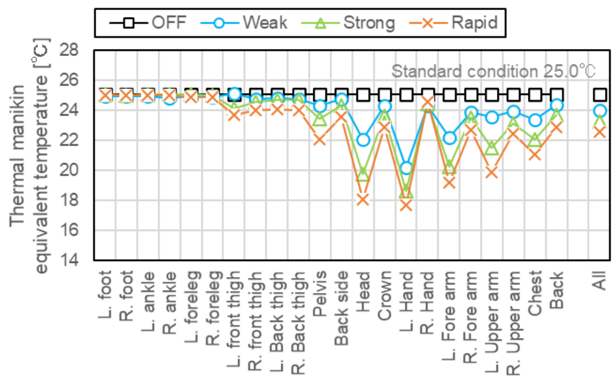


Fig.26 Equivalent temperature of desktop personal fan

standard condition. It could be confirmed from the figure that the upper body (face, chest, arms, front thighs), which was particularly exposed to airflow, was cooled. Comparisons of the equivalent temperature of the entire body showed that the temperature during rapid operation was 22.6 ºC, and that an equivalent temperature decrease of up to 2.4 ºC could be expected when compared to when a personal fan was not used. The equivalent temperature of the left arm was smaller than that of the right arm because the personal fan was installed on the left side.

3.3.3 Radiant Heating Device

Environmental surveys conducted before the renovations showed that the vertical temperature difference on the first floor was large, with cold sensations at the foot level during winter being a particular dissatisfaction factor of the thermal environment. Therefore, with the renovations, floor insulation and underfloor air-conditioning and radiant heating devices shown in Photo 3 at the bottom of some seats on the first floor as well as in seats near windows were installed. This system used the same panels as the water-type ceiling radiant heating / cooling panels used for ambient air conditioning in the rooms on the second and third floors, and they are operated with an on-off control using a two-way hot / cold water valve.

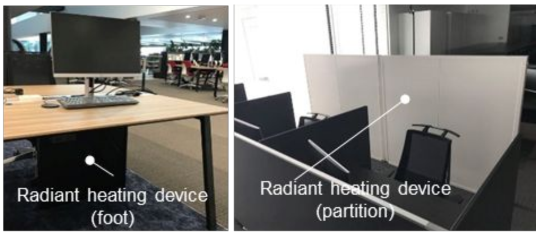


Photo3 Radiant heating device

The effects of a radiant heating device installed underneath desks were evaluated at the north seat on the first floor (Fig. 25: measurement point (2)). The measurement conditions are shown in Table 4. The panel surface of the radiant heating device was 33–34 ºC, and this was approximately 10 ºC higher than room temperature. Assuming a winter season, the manikin was dressed in a suit (long-sleeved jacket, tie, long-sleeved shirt, short-sleeved underwear, slacks, boxer shorts, socks, leather shoes). The seat at measurement (1), which does not have a radiant heating device, was set as the standard conditions.

Fig. 27 shows the measurement results. the results indicate that heating the feet with a radiant heating device increased the equivalent temperature of the lower body by approximately 1 ºC, and that it was effective for workers who felt cold sensation discomfort in their feet.

Table 4 Measurement conditions of radiant heating device

Date	2020/2/7	2020/2/6
Measurement location	Radiant heating device absent Measurement point ① (Standard conditions)	Radiant heating device present Measurement point ②
Ambient temperature	24.5?	24.6?
Panel surface temperature	-	33~34?
Chair material	Seat: urethane Backrest: urethane	Seat: urethane Backrest: mesh
Manikin clothing	Leather shoes, socks, boxer shorts, slacks, short-sleeved underwear, long-sleeved shirt, tie, jacket	

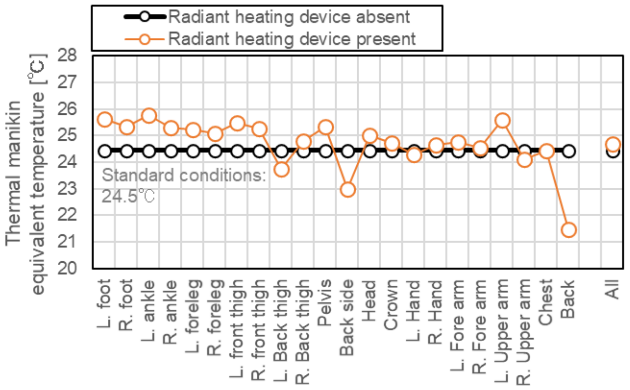


Fig.27 Equivalent temperature of radiant heating device near foot

3.3.4 Air-Conditioned Furniture

An overview of air-conditioned furniture is shown in Fig. 28. Air-conditioned furniture is a personal air conditioner that controls the thermal environment near the body by convection / radiation from the canopy surrounding the person and heat transfer on the contact surface (e.g., seat surface). These were also developed such that the thermal environment in the space around the body was controlled while maintaining comfort in spaces where temperature differences were likely to occur (e.g., atrium spaces), and to have a wide range of responses to user temperature preferences [6].

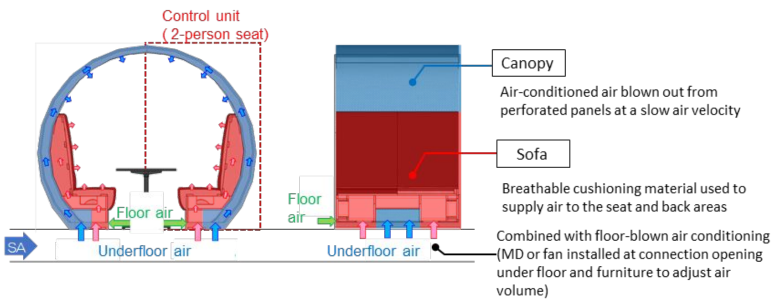


Fig.28 Air-conditioned furniture

Air-conditioned furniture had a partition inside to separate the flow paths of the seat system (red) and canopy system (blue), and these were equipped with multiple fans and motor dampers (MD) installed at the floor connection section. This allowed for the air-conditioned air in the OA floor to be incorporated inside the furniture, and controlled air volumes could be supplied to each system separately. There were also fan-equipped MDs on the sides of the furniture, and floor air could be mixed and blown out only in the seat system. The air-conditioned furniture could seat a maximum of four people (2-person seats × 2), and the settings could be controlled for each 2-person seat. There were four operation mode patterns (use with only canopy, or combination with sofa), as shown in the operation mode of the air-conditioned furniture in Fig. 29.

Thermal environment measurements were made at the air-conditioned furniture set up in the atrium space facing the courtyard (Fig. 25: measurement point (3)). The installation location and measurement points are shown in Fig. 30. The measurement location was the atrium space with a ceiling height of 14 m, where part of the east and south sides were large glass surfaces, and the air conditioning adopted a underfloor air-conditioning system. A local air-conditioning system such as air-conditioned furniture could efficiently conduct air conditioning only near the body in spaces where such vertical temperature differences were likely to occur. The measurements were performed for each of the four operation modes shown in Fig. 29. Each measurement was made continuously for three hours or more until the fluctuations in the skin temperature and sensible heat loss measured on the thermal manikin reached a periodic steady state. The operative temperature when seated on a wooden chair installed in the same atrium space (18.1 ºC) was set as the standard condition.

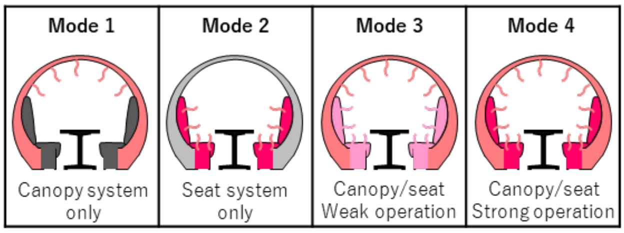


Fig.29 Operation modes of air-conditioned furniture

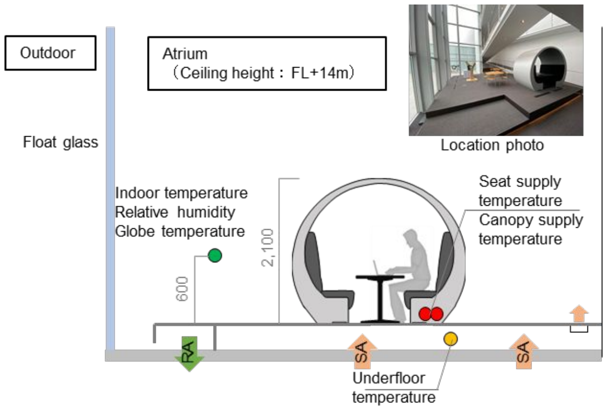


Fig.30 Measurements of air conditioned furniture

Table 5 Indoor thermal environment of each operation mode

Condition (Date)	Indoor temp.(?)	Mean radiant temp.(?)	Operative temp. *2 (?)	Underfloor temp.(?)	Seat supply air temp.(?)	Canopy supply air temp.(?)
Wooden chair (1/7)	17.6 (0.2)	18.5 (0.1)	18.1 (0.1)	33.8 (4.1)	33.3 (3.4)	33.5 (3.5)
Mode 1 (1/16)	18.9 (0.3)	19.9 (0.2)	19.4 (0.2)	33.5 (5.0)	32.9 (2.9)	33.3 (4.2)
Mode 2 (1/9)	19.3 (0.2)	20.2 (0.1)	19.8 (0.1)	33.0 (4.9)	32.9 (4.0)	32.9 (2.2)
Mode 3 (1/9)	20.3 (0.4)	21.5 (0.5)	21.0 (0.4)	33.5 (5.1)	33.5 (3.9)	33.4 (4.3)
Mode 4 (1/15)	18.3 (0.5)	19.6 (0.4)	19.0 (0.4)	34.1 (4.1)	33.9 (3.5)	34.0 (3.4)

? 1…Mean radiant temperature was calculated from measured globe temperature
? 2…Operative temperature was calculated assuming convective heat transfer coefficient of 3.8 W/m^2 and radiant heat transfer coefficient of 4.7 W/m^2.
Values inside () indicate the standard deviation.

Table 5 shows the indoor environment measurement results during the measurement of each mode, and Fig. 31 shows the thermal manikin equivalent temperature for each body part. It can be seen from the figure that the equivalent temperature for each body part in contact with the seat surface (i.e., thighs, buttocks, hips, back) increased when air-conditioned furniture was used. However, different measurement days for each mode measurement resulted in differences in the operative temperature of

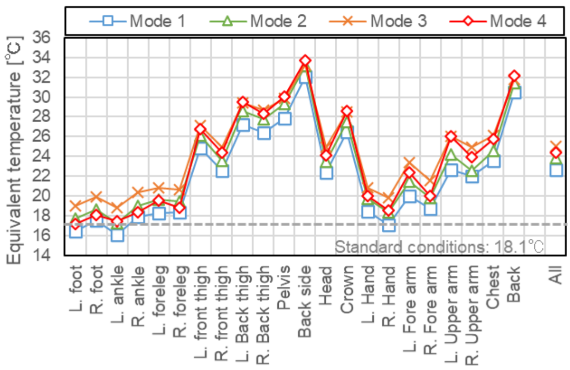


Fig.31 Equivalent temperature of air-conditioned furniture

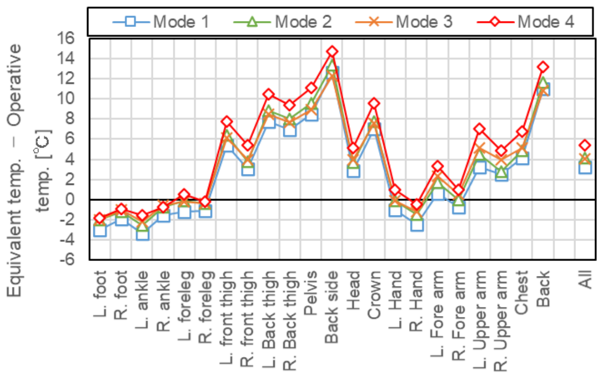


Fig.32 Difference between equivalent temperature and operative temperature

the ambient environment, etc., and using these equivalent temperatures to compare between modes was not appropriate. For example, mode 4, which should have the highest air-conditioning ability, had an equivalent temperature in Fig. 31 that was lower than that in mode 3.

Therefore, it was assumed in this study that the temperature distribution around the manikin and the surface heat transfer coefficient were approximately equal even if the ambient operative temperature changed by approximately 3 ℃ due to local air-conditioning characteristics in the air-conditioned furniture. It was decided that each mode would be compared by setting the difference of the thermal manikin equivalent temperature and operative temperature as the air conditioning effect to exclude differences in the ambient environment. Figure 32 shows the results of comparing the temperature difference between the thermal manikin equivalent temperature and operating temperature. It can be seen that the equivalent temperature for the entire body in mode 4, whose air conditioning effects were thought to be the largest, was the highest among all the operation modes, and that an environment with a temperature approximately 5 ℃ higher than the ambient operative temperature was formed. Comparisons of the equivalent temperature for the entire body for mode 1 (canopy system only) and mode 2 (seat surface system only) showed that mode 2 had a temperature that was 0.9 ℃ higher, and it could be seen that a heating effect on the human body could be effectively obtained by warming the seat surface closer to the body. The equivalent temperature of the part in contact with the seat surface was high even in mode 1, where only the canopy was used. However, this was not only due to differences in thermal resistance between the wooden chair and the sofa section of the air-conditioned furniture but also due to the relatively low airtightness of the MD, which resulted in air-conditioned air under the floor leaking into the seat system even when the seat was fully closed, thereby warming the seat.

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4 Efforts to Improve Workplace Productivity

Tomoko Tokumura*1　Hiroki Takahashi*2　Tomohiro Kuroki*3

4.1 Outline of Renovations and Personality Traits of Workers

4.1.1 Concept of Workplace Productivity by ABW

There is a wide variety of workers in offices, each of whom takes actions that lead to workplace productivity[1)]. The workplace following the renovation of the Takenaka Research & Development Institute set a majority of researchers as ABW subjects without fixed seats with the objective of improving workplace productivity and facilitating diversification and location selection of spaces.

When introducing ABW, the actual conditions of various personalities and working behaviors of workers were investigated [2)3)4)], and opinions were gathered through workshops and used as evidence for design. The conceptual diagram for workplace productivity in ABW is shown in Fig. 1.

The office built on this evidence was moved to the operational stage from April 2019. The most important at this stage was to investigate the impact of ABW on workers in the field and to provide feedback for further improvement. The main items to be verified with the objective of continuous improvement of workplace productivity activities were (1) the actual situation of seat selection and (2) changes in the degree of satisfaction with each behavior in the office. These are described in detail in the following sections.

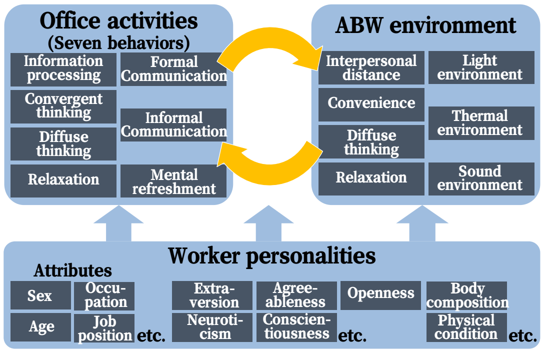

Fig.1　Conceptual diagram of workplace productivity at ABW

4.1.2 Workspaces / Area Characteristics

Characteristics of the workplace after renovations included the following:

・Placing a roof over the outdoor atrium space, which divided the old research building, and converting it into an indoor space, thereby creating a large integrated space connected vertically and from north to south;

・Preparing various workspaces / areas such as concentration booths, café spaces, sofa seats, and outdoor areas;

・Collecting lockers and shelves dedicated to storing personal belongings.

Figure 2 shows the floor plans of the first and third floors of the central building, which were mainly used by ABW workers. The "assigned area of each department" on the first floor and the "assigned seats with desktop computers" on the third floor were areas not subject to ABW that were exclusively used by specific researchers. The floor area (working space) per worker was 10.2 m² before renovations and 9.3 m² after renovations.

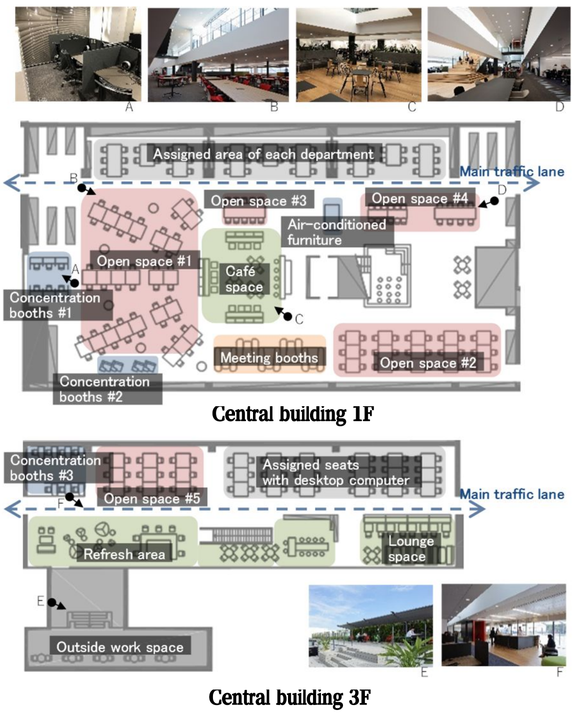

Fig.2　Layout of workplace (after renovation)

Table 1 Specification of furniture in each area

		Number of seats	Desk area[m²]	Monitor	Desk adjusta-bility	Chair adjusta-bility	Partition height [mm] Front	Back	Side
1F	Concentration booths #1	6	0.84			✓	1670	1670	1670
	Concentration booths #2	4	0.13				0	1250	1250
	Air-conditioned furniture	2	0.32				Front/top/back surrounded		0
	Open space #1	48	0.98	✓		✓	0	0	0
	Open space #2	30	0.91	✓	✓	✓	0	0	0
	Open space #3	10	0.56				0	0	0
	Open space #4	20	0.38				0	0	0
	Café space	12	0.36				0	0	0
3F	Concentration booths #3	7	0.66	✓		✓	1400	1400	1400
	Open space #5	18	0.98	✓		✓	1670	1670	1670
	Refresh area	10	0.56				0	0	0
	Lounge space	17	0.25				0	0	0
	Outside work space	5	0.25				0	0	0

*1　Chief Researcher, Research & Development Institute
*2　Associate Chief Researcher, Research & Development Institute, Dr. Eng.
*3　Chief Researcher, Research & Development Institute

1) Specifications of Furniture

Table 1 shows a list of specifications of furniture for seats arranged in each area. Partitions were used for seats intended for concentration. The desk area that could be occupied by one person for seats that were not separated by partitions changed depending on the nearby seat occupancy situation. Some seats have an external monitor and adjustable desks and chairs in terms of functionality.

2) "Selected Seat Openness"

The "selected seat openness" of each workspace was calculated as an example of spatial diversity. As shown in Figure 3, the selected seat openness was devised as an index for showing the expansion of the field of view in each seat[5]; the analysis points were set at FL+900 mm and calculated from the average value of the distance for a light ray, radiated in an upper hemispherical range at a pitch of 10º, to hit an obstacle.

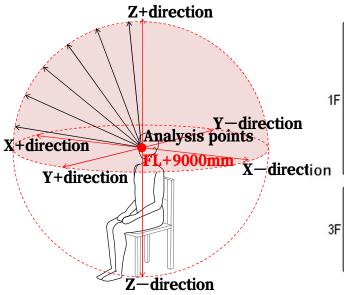

Fig.3 Calculation method of seat openness

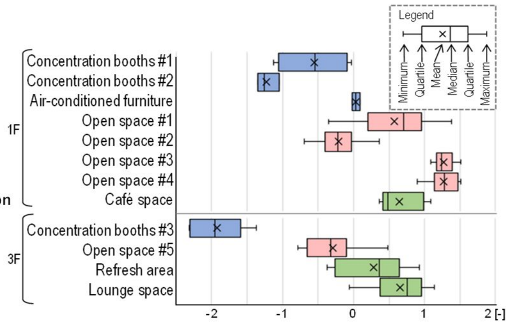

Fig.4 Distribution of seat openness

The selected seat openness of all target seats was calculated for each floor, and the standardized values are shown in Fig. 4. The index value tended to be low in the concentration booths and high in the open spaces, refresh areas, and lounge space. Open space #3 and #4 had particularly high values as the atrium is overhead, but there were also open spaces with a selected seat openness lower than that in the concentration booths. Thus, the seats correspond to a wide range of individual preferences of selected seat openness.

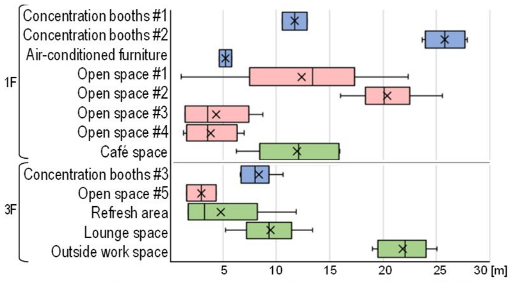

Fig.5 Distance from each seat to main traffic line

3) Distance to Main Traffic Line

Figure 5 shows the distance from the seat to the main traffic line in each work area, summarized for each area. The location of the main traffic line is shown in Fig. 2. For concentration booth (2), open seat (2), and the outdoor terrace, the distances were 15 m or more, but for other seats, they were generally less than 15 m.

4.1.3 Environment / Equipment

Photo 1 shows the workspaces in each area. The free selection of seats emphasized the diversity of the space and the environmental controllability of each seat. Equipment such as a personal fan, radiant heating panels underneath the desk, air-conditioned furniture, and task lights were introduced. The objective was to reduce passive seat selection, such as "wanting to sit in a certain seat but choosing another because it seemed hot."

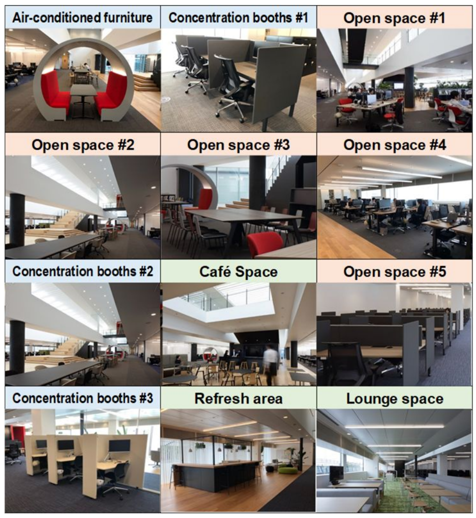

Photo 1 Workspace in each area

4.1.4 Operation / Rules

The introduction of ABW considerably changed the way researchers work on a daily basis. Reduced documents and paperless work were implemented such that individuals could freely choose their seats every day. Researchers were given lockers and storage shelves for personal use, but the capacity was set to approximately 64% of the conventional level based on the premise of paperless work. A digital signage was placed near the locker, and the seating status of other researchers and environmental information around the seats were displayed to serve as a reference when selecting a seat to work. A near field communication (NFC) tag[Note 1)] was attached to the desk to enable researchers to register their seat selection when seated.

4.1.5 Worker Personality Traits

The personalities of the workers themselves were factors that influenced their working style and needed to be fully understood when considering ABW. Here, the five personality trait factors (Big Five) clarified by the questionnaire before and after renovations[6] were considered. The questionnaire was conducted in October 2017 before the renovation and July 2019 after the renovation using a simplified version consisting of ten questions[7]. Responses were received from 114 and 113 people, respectively.

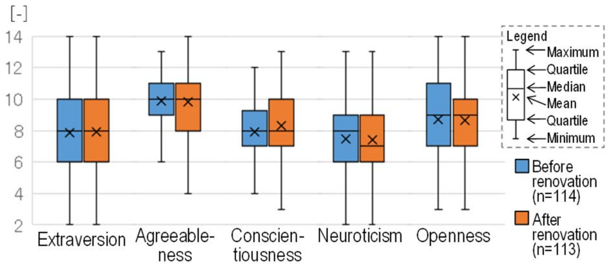

Fig.6 Worker personality trait distribution

Figure 6 shows the response results from all respondents before and after renovations. There was a higher tendency for agreeableness and openness both before and after renovations, with neuroticism being slightly lower. Comparisons between before and after renovations showed a slight increase in conscientiousness, but no significant differences were seen for all traits. Analyses were conducted after determining that the working environment and status at the time of response had sufficiently small effects on the responses.

4.2 Seat Selection of Workers at ABW Office

There have been few reports on the seat selection behavior of workers in the ABW office, and many aspects have not yet been clarified. This section focuses on the seat selection of workers in the ABW office and describes the results of behavioral and seat space surveys to gain a more detailed understanding of the status of worker seat selection and seat space environment.

4.2.1 Overview of Seat Selection Survey

Workers could freely select their workplaces on the first and third floors of the central building, with the exception of the “assigned area of each department” on the first floor and the “assigned seats with desktop computers” on the third floor (details shown in the plan view of Fig. 2 in Section 4.1.2). A behavioral survey of workers who work in areas where they could freely select their seats (ABW areas) was conducted. An overview of the survey is shown in Table 2.

Table 2 Overview of survey on seat selection

	Seat space environment survey	Behavioral survey
Date / time	October 10-24, 2019	
Survey target	1F / 3F	Workers in ABW area (1F, 3F)
Survey method	Actual survey	Questionnaire (filled out every day / when leaving work)
Survey objective	Understand seat space environment	Understand seat selection emphasis items
Survey items	1. Seat occupancy rate (visual survey every 90 minutes, 6 times a day) 2. Physical environment (indoor air temperature, relative humidity, desk surface illuminance) 3.Spatial environment	1. Attributes (managerial position, sex, affiliation) 2. Selected seat 3. Seated time 4. Work content 5. Whether or not it is a preferred seat 6. Seat selection emphasis items 7. Overall satisfaction (work) 8. Subjective workplace productivity

The ABW area of the office was surveyed every 90 minutes during the survey period, where the seat occupancy status of each seat was visually confirmed and recorded. A questionnaire survey was also conducted for workers in the ABW area.

When leaving work, respondents were asked to reflect on their day and answer the survey items shown in Table 2. These items included attributes such as the worker group and position, seat selection, seat selection emphasis items, work content and degree of satisfaction toward work, and subjective workplace productivity.

Table 3 Average seat occupancy rate of each area

	Selected area	Oct. 10	Oct.11	Oct. 15	Oct. 16	Oct. 17	Oct. 18	Oct. 23	Oct. 24
1F	Air-conditioned furniture	100%	0%	83%	0%	83%	0%	0%	0%
	Concentration booths #1	64%	81%	89%	58%	58%	53%	83%	75%
	Open space #1	60%	61%	75%	68%	65%	61%	71%	71%
	Open space #2	54%	46%	68%	51%	58%	63%	71%	65%
	Open space #3	44%	42%	53%	53%	53%	31%	39%	44%
	Open space #4	23%	11%	8%	12%	6%	8%	7%	18%
	Concentration booths #2	8%	4%	21%	21%	4%	0%	25%	21%
	Café space	7%	6%	15%	9%	9%	7%	0%	17%
3F	Open space #5	63%	43%	69%	65%	40%	61%	72%	56%
	Concentration booths #3	40%	33%	33%	64%	21%	26%	55%	26%
	Refresh area	4%	21%	25%	17%	8%	13%	8%	13%
	Lounge space	0%	4%	0%	8%	10%	10%	27%	2%

4.2.2 Seat Occupancy Rate of each Area

Figure 7 shows the seat occupancy rate during the survey period on each floor. The percentage of seated individuals to the number of seats for each floor was calculated based on the visually determined seat occupancy information of each seat. However, as the café and lounge spaces had a small desk area,

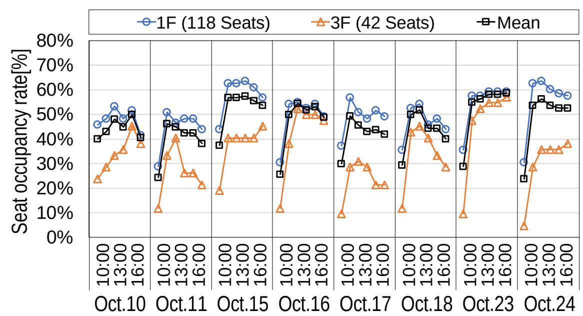

Fig.7 Seat occupancy rate of each floor

and individuals occupied multiple desks or seats, the seat occupancy rates for these areas were calculated after partially correcting the number of seats [Note 2)]. The seat occupancy rate of the entire target area (first and third floors) was approximately 60% even at its peak, indicating that there was a relatively large amount of free seats. The seat occupancy rate tended to be lower on the third floor than on the first floor. There was also no significant change in the daily seat occupancy rate during the survey period.

Table 3 shows the average seat occupancy rate for each area shown in Photo 1. Open space #1 and #2 had the largest number of seats and were intended for general work, whereas open space #3 and #4 were areas for short-term work. Concentration booths #1 and #3 were mainly for office work, whereas concentration booth #2 had furniture with integrated chairs and desks and could be used for various purposes such as rest and breaks. When analyzing by area, the seat occupancy rate of the concentration booth #2, open space #4, refresh area, and lounge space tended to be low, whereas those of the concentration booth #1, open space #1, #2, #3 and #5 tended to be high.

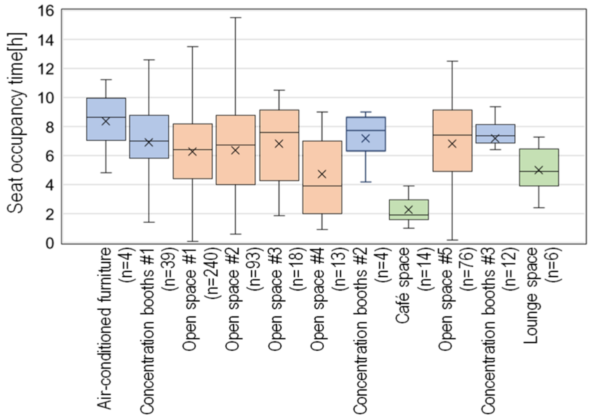

Fig.8 Continuous occupancy time of each area

Figure 8 shows the relationship between the work area and occupancy time. The average occupancy times of many of the areas were 6–8 h; however, the usage times of open space #4, lounge, and café spaces tended to be shorter than the average. The use of the café apace was prioritized for lunch during lunch breaks, thus it was often used only during the mornings, and the occupancy time was particularly short at 2–3 hours.

The tendency of workers working all day in the seats they chose when arriving in the office suggested that they may have chosen seats where it was easier to work for long periods of time.

4.2.3 Impact of Worker Attributes on Seat Selection

1) Impact of Job Position on Seat Selection

Figure 9 shows the relationship between job position and selected seat openness, and Fig. 10 shows the relationship between job position and distance to the main traffic lane. The main traffic lane (details shown in Fig. 2) was set as the line connecting entrances / exits to other entrances / exits, and the shortest walking distance from each seat to the main traffic lane that does not pass over furniture was calculated. Results confirmed that the line manager (organization manager) selected seats with high seat openness and tended to sit in areas close to the main traffic lane. Managerial workers were in a position to organize their subordinates, thus that they selected spaces with high openness to overlook the surroundings to check the status of group members.

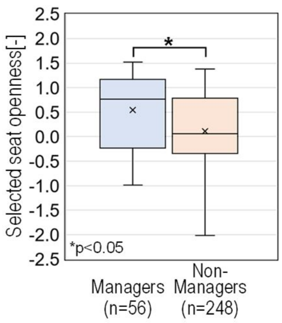

Fig.9 Job position and selected seat openness

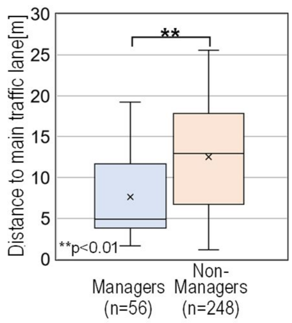

Fig.10 Job position and distance to main traffic lane

2) Impact of Personality Traits on Seat Selection

Response data of workers who answered that they were sitting in their preferred seat were extracted, their evaluation scores for each personality attribute were used, and the 13-stage evaluation was re-classified into five stages (2–4 points: low group#2, 5–7 points: low group#1, 8 points: middle group, 9–11 points: high group#1, 12–14 points: high group#2) to determine the relationship between the personality traits of workers and seat selection.

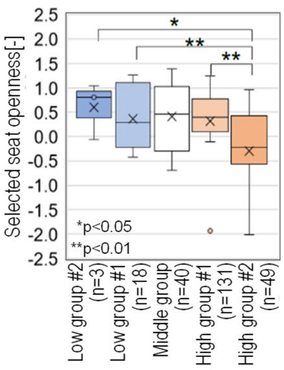

Fig.11 Agreeableness and selected seat openness

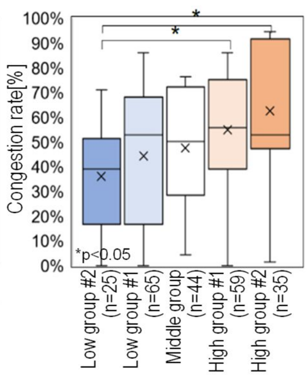

Fig.12 Extraversion and congestion rate

Figure 11 shows the relationship between agreeableness and selected seat openness. Workers with extremely high agreeableness tended to select seats with low selected seat openness. Agreeableness was correlated with negative relationship coping, which resulted in efforts to abandon or avoid stressful human relationships[8], thus highly agreeable workers may be looking for seats with a low degree of openness to allow for blocking communication with others.

Figure 12 shows the relationship between extraversion and congestion rate. Lower extraversion tended to result in preferential selection of seats with a lower seat occupancy rate for adjacent seats. It has been suggested that workers with low extraversion tended to seek non-reciprocal spaces where there was a large amount of space between adjacent seats and minimal traffic[9]. Therefore, the satisfaction of workers with low extraversion could be improved by preparing seats far away from adjacent seats.

4.3 Trends of Workers' Satisfaction and Workplace Productivity Before and After Renovations

4.3.1 Questionnaire Survey Overview

This section shows the changes in the questionnaire survey results on various satisfaction levels and workplace productivity before and after renovations, as well as the analysis results based on worker age and scores on the personality trait test scale.

The questionnaire surveys were conducted three times: before renovations (February 2018), three months after renovations (July 2019; hereinafter referred as "after renovations (1)"), and 10 months after renovations (February 2020; hereinafter referred as "after renovations (2)"). Table 4 shows the number of respondents to each survey, and Table 5 shows the survey items. The survey method was in a Web format, and the personality traits were not surveyed after renovations (1) as little changes were expected in the short term.

Table 4 Number of respondents to each questionnaire

		Before renovations (February 2018)	After renovations (1) (July 2019)	After renovations (2) (February 2020)
Number of respondents		88	113	148
Job position	Researchers	76	97	127
	Clerical workers	12	16	21
Sex	Male	75	93	128
	Female	13	20	20

Table 5 Details of each questionnaire

Survey item	Before renovations (February 2018)	After renovations (1) (July 2019)	After renovations (2) (February 2020)
Attribute	✓	✓	✓
Personality trait	✓		✓
Indoor environment satisfaction	✓	✓	✓
Ease of in-office actions	✓	✓	✓
Communication satisfaction	✓	✓	✓
Workplace productivity	✓	✓	✓

4.3.2 Changes in Subjective Evaluations Before and After Renovations

1) Visual Environment / Spatial Environment

Figure 13 shows changes in satisfaction levels by element of each environmental factor of the visual and spatial environments. The responses on the satisfied side decreased after renovations (1) when compared to before renovations for a) line of sight from others and b) storage space. This was considered to be caused by reductions in the number of workplaces with partitions after the renovations as well as the reduction in storage space from 5.1 fm[Note 3]/person to 3.3 fm/person. However, the number of responses on the satisfied side increased after renovations (2) when compared to after renovations (1) for a) line of sight from others and c) office layout. There were no facility changes between the time after renovations (1) and after renovations (2), thus this was considered to be a result of the comprehension of the facility characteristics and workers' ability to master its use. Evaluations for d) furniture usability increased both after renovations (1) and after renovations (2) when compared to before renovations.

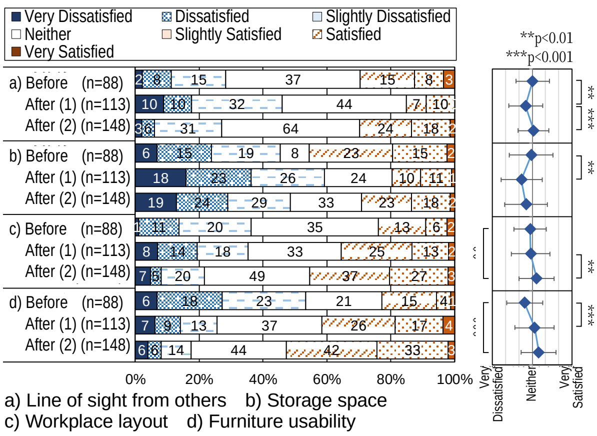

Fig.13 Satisfaction of each environmental factor

2) Actions in the Office (Behavior)

Figure 14 shows the changes in the difficulty of performing office activities. Responses for the satisfied side decreased after renovations (1) when compared to before renovations but increased after renovations (2) for a) information processing, b) information search / processing, and c) concentration, all of which often involve individual work. This is considered to be the result of requiring time to find a suitable workplace for personal work.

In addition, responses for the satisfied side increased after renovations (1) and after renovations (2) when compared to before renovations for d) knowledge creation, f) informal communication, g) relaxation, and h) refreshment (of the body and mind). This is considered to be a result of facility renovations, which promoted exchanges and emphasized the diversity of spaces.

The responses for the satisfied side with regards to the overall satisfaction level of office activities shown in Fig. 15 increased in order of “after renovations (1)” and “after renovations (2)” when compared to before renovations.

3) Workplace Productivity

Figure 16 shows changes in the degree of self-selection in the workplace. Responses for the high degree of self-selection increased after renovations (2) when compared to before renovations or after renovations (1). Figure 17 shows the changes in workplace productivity before and after renovations. Responses for the increased side increased after renovations (2). There were no major changes immediately after the introduction of ABW, but the productivity of each worker increased after a period of “familiarity” with the new working style.

Figure 18 shows the relationship between the degree of self-selection in the workplace and workplace productivity after renovations. Both the after renovations (1) and after renovations (2) showed that workers who felt that they were able to work where they wanted tended to have higher workplace productivity, and this was more significant after renovations (2). It could be said that there was a positive correlation between the degree of self-selection in the workplace and workplace productivity, and that these tendencies became higher as familiarity with the workplace increased.

Notes

Note 1) NFC refers to near field communication, which is a short-range wireless communication technology that uses a frequency of 13.56 MHz. An NFC tag with an embedded integrated circuit chip attached to each workplace is read by a smartphone with an NFC reader function to register the seat.

Note 2) One seat was counted for each table regardless of the number of chairs present.

Note 3) fm: file meter. A unit of document volume. The height in meters when documents are stacked vertically.

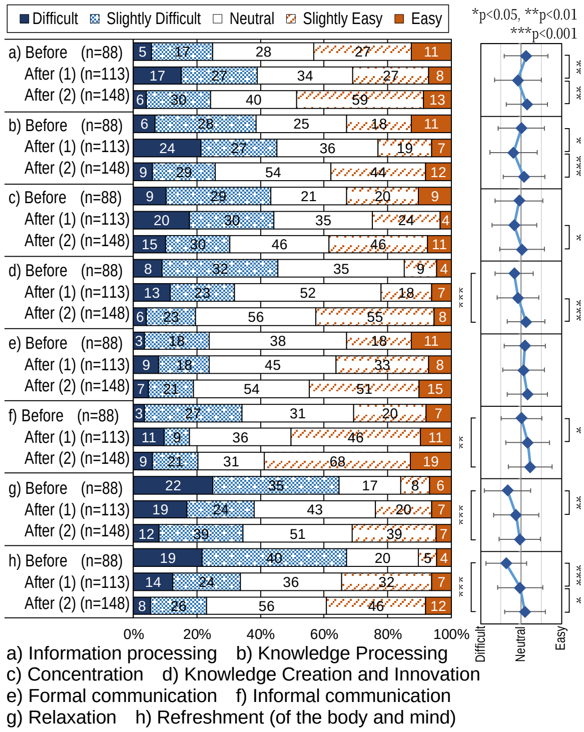

Fig.14 Difficulty of performing office activities

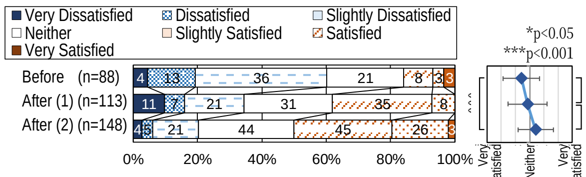

Fig.15 Overall satisfaction of office activities

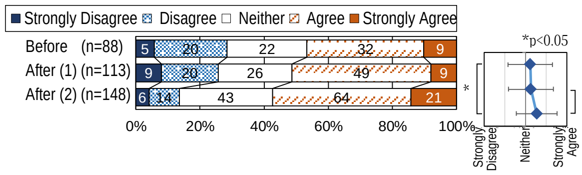

Fig.16 Whether occupants were able to sit at their desired seats

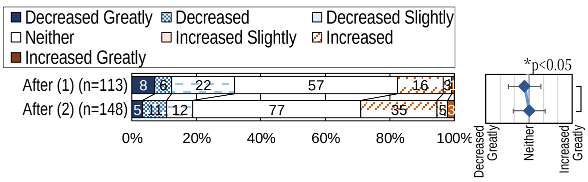

Fig.17 Workplace productivity before and after renovation

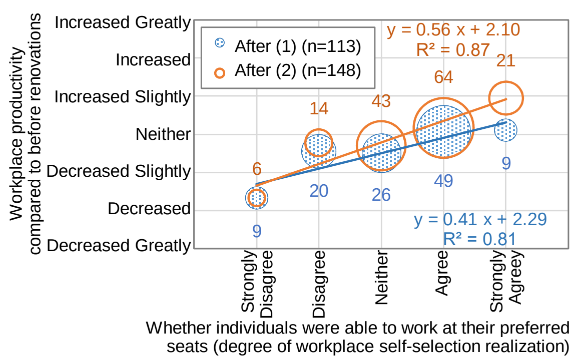

Fig.18 Relationship between seat selection and workplace productivity

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5 Conclusion

Masaaki Higuchi*1

During the renovation of the Takenaka Research & Development Institute, we have implemented proposals for new working styles based on the R&D results on “people,” design concepts that embody them, and methods for realizing this workplace. In this research report, we provided an overview of these concepts. We also reported on preliminary survey results of movement measurements of “people” and various questionnaire evaluations that contributed to design various environments during actual operation, actual circumstances of space utilization, and continuous questionnaire evaluations of movement measurements of “people.”

It was confirmed through this renovation that the diversity of space and physical environment depending on the location were achieved as intended. New findings were also obtained with regard to how space was used, such as how seat selection differed depending on the personalities and job roles of “people.” Such research is still in its infancy, and we will apply various improvements based on the comments by workers and utilize them as an experimental field such as for the verification of the corresponding effects to obtain further knowledge in the future. The data obtained here will be used to propose new working styles in the future and prepare design materials to achieve those working styles.

We would also like to engage in new challenges such as cooperating with outside the company by utilizing “SHI-RA-BE” and promoting open innovation by utilizing the co-creation space and existing research resources. At the newly renovated Research & Development Institute, we would like to promote new R&D and generate creative results with dreams toward the future.

This renovation focused on the workers of the Institute. In addition, creating a space that is influenced by nature may reduce energy when comparing it to creating a uniform environment regardless of fluctuations in the outside air. Energy conservation effects are expected to be produced by effective use of diverse spaces by people. However, spatial diversity and changes in the environment will make it difficult for individuals to choose the suitable workplace. Presenting the information necessary for selecting a location at the appropriate timing is necessary, but this will become possible in the era of Society 5.0, where information from multiple sensors can be obtained and fully utilized. “Personality-based working”, in which various people can work comfortably and choose a place according to each person’s condition, is considered to be achievable at this time as a next-generation ABW that evolved from current ABW. We would also like to propose “brain-centric working (BCW)”, in which the brain self-selects a place to work for feeling comfortable. Because the brain activity is the basis for feeling, thinking, and acting in various ways. We will aim for BCW as the next ABW.

*1 Executive Manager, Research & Development Institute, Dr. Eng.