NEW INSTALLATION SYSTEM FOR FLEXIBILITY OF EXISTING KOREAN APARTMENT

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ABSTRACT

This paper illustrates how a new installation system for reusing concrete apartments (Apatu), a representative residential type in Korea, can be studied and applied from the flexibility perspective. Through the analysis of the installation system used by the existing Apatu, the essential parts are identified, and a new climate installation (The Earth, Wind, and Fire Concept) is added to present various installation layout options that will make the second life of the old Apatu. In addition, the criteria for which flexibility can be measured for each option are described in various categories, and various weighting systems are compared and selected to evaluate the importance of the studied criteria. Finally, the proposed installation options are evaluated through flexibility measurement criteria, and scores are converted according to the preceding weight system for each item, resulting in a new installation system that can provide optimal flexibility to the old Apatu.

KEYWORDS: *Concrete reuse, Open building, Installation, The Earth Wind and Fire Concept, Flexibility, Evaluation Method, Weighting system.*

I. INTRODUCTION

Traditionally, Korea made buildings and formed villages by harvesting and using circular materials such as wood, straw and earth from nature. However, most of the traces of tradition disappeared during the Korean War in the 1950s, and they suffered severe housing problems. At the same time, housing problems caused by urbanization also increased, so the Korean government radically introduced the concrete high-rise housing system proposed by Modernist architect Le Corbusier in order to solve this problem. Such a system was an innovative way to provide housing in a short period efficiently and became very popular with the public in that it provides a new and modernized living environment. Such architecture has become a representative residential type in Korea so far under the unique name of "Apatu" and currently accounts for the highest proportion of about 63.5% among various housing types in Korea (National Statistical Office 2021).

1.1. Problem Statement (Background)

The problem is that all the Apatu repeat demolition and reconstruction every 30 years to rebuild around twice as tall concrete apartments. Most Apatu in Seoul have already been reconstructed, and some are waiting for re-reconstruction. The main reasons for the reconstruction culture that has become a social phenomenon are as follows.

Firstly, it is difficult to reuse concrete Apatu made by wet construction. Although maintenance and replacement work are required due to the ageing of the building's installation and structure over time, partial intervention is impossible because every building element is woven into one by wet construction. That is why inevitable demolition has happened.

Next, it is difficult to modify the space because the building itself is supported by reinforced concrete bearing wall structure. According to the "Population Census 2021," the average number of household members in the 1970s when Apatu were built in earnest on a large scale was 5.2, while there was more than a double decrease to 2.1 in 2021 (National Statistical Office 2021). However, since all the spaces inside the Apatu are divided into bearing walls, the house cannot be transformed to suit the changes in household members.

In conclusion, inflexibility caused by Apatu's bearing wall structure and concrete wet construction method was the most crucial reason for not reusing old Apatu. For existing Apatu to become flexible buildings that can be reused in the future again, in-depth research regarding not only existing installation but also new climate installation, which can reduce the complexity of the existing installation system, is conducted. Therefore, research on the natural air-conditioning system called The Earth, Wind & Fire Concept, founded by Ben Bronsema (2013), is the starting point for flexible Apatu. The new installation system will serve as a medium between existing concrete structures and the newly added infill to act like an organism. Also, depending on the position of the new installation, the program layout of future infill can be flexible, so it is possible to create a unique space configuration customized to the users' needs in each housing unit.

1.2. Research Questions

"How could a new installation system including natural air-conditioning (The Earth, Wind and Fire Concept) make existing Korean apartments (Apatu) more flexible?"

Sub Q1. What installations are basically needed for Apatu?

Sub Q2. What are the system and essential requirements of The Earth, Wind and Fire Concept (EWF Concept)?

Sub Q3. How to measure and quantify flexibility?

Sub Q4. Which layout of the new installation and service shaft maximizes the flexibility of infill customization?

1.3.Methods

Research on new installation systems that can make existing Apatu more flexible is divided into three parts. The first part is a study of the types and properties of essential installations that Apatu needs to operate. Through technical drawing analysis of Mapo Samsung Apatu selected as a context and another Apatu project constructed by the same company, general requirements such as the overall system and installation dimension will be studied. This research part will be the answer to sub-question 1.

The next step is a study of a new climate installation (The Earth, Wind & Fire Concept) that will reduce the complexity of existing climate installation and increase the flexibility of the building. As an answer to sub-question 2, the principle of the EWF Concept and its requirement will be studied through the literature study of Bronsema (2013), the founder of the concept. And then, through the research by design methodology, several different installation layout options for Mapo Samsung Apatu will be presented, derived from the research in the first and second parts.

The third part is research regarding flexibility. Along with the definition of flexibility, the criteria for measurement of the proposed installation layout option's flexibility are investigated. Through a literature study by Hatipoğlu (2020), appropriate criteria will be selected to compare the flexibility when each installation option is applied to the Apatu. In addition to the literature study, some selected criteria are adjusted to measure the flexibility of Apatu's unique condition, and some criteria suitable for measuring the flexibility of installation are added. This part will present the conclusion of the third sub-question.

Finally, a system that applies different weights for each criterion is studied to produce more accurate results in evaluating the presented options. A more accurate measurement method is selected by comparing the general method proposed by Saaty & Vargas (2012) and the simplified weight approach by Nick van Knaap and Jeroen van Veen. The final score is added for each option through the selected weight method, and the installation option that provides optimal flexibility is finally selected. This process answers sub-question four and will conclude the main thematic research question.

II. Existing Apatu Installation

In general, installations applied to the Apatu include electricity, water supply, drainage, air conditioning, heating, ventilation, sprinklers, and gas. Electricity, water supply, heating, and sprinkler pipes are supplied into the housing unit through vertical shafts in the core, and drainage and ventilation facilities are discharged to the outside through shafts installed in each housing unit. Finally, cooling and gas installations are installed on the facade of the building and are connected to the indoor unit. Basic features and detailed information of each existing installation with another Apatu reference project constructed by the same company are described in appendix 1.

Through this research, it was possible to study the existing installation system of Apatu closely. In addition, it was a process of investigating the requirements that must be premised when replacing new installations during the Apatu renovation process.

Since most of the existing installations are buried in the concrete structure, maintenance and replacement are difficult once installed. In addition, some installation systems had a limitation that it was difficult to envision various plan layouts because they were greatly affected by the position of the fixed vertical shaft. Lastly, as shown in figure 1, although the ceiling height of the existing Apatu was already low, most of the installations were located inside the ceiling finish, limiting the flexibility of the interior space. Therefore, through the subsequent study of the Earth, Wind & Fire Concept, the way to minimize existing climate installation and secure maximum ceiling height will be investigated.

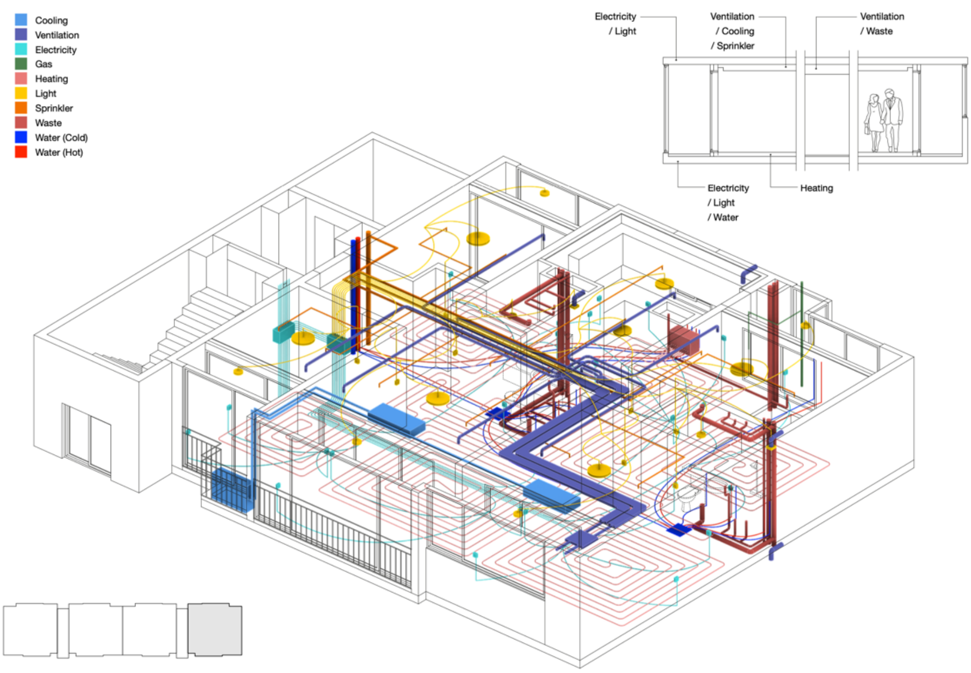


Figure 1. Existing Apatu Installation (by Author)

III. EARTH, WIND AND FIRE CONCEPT

Research on the Earth, Wind, and Fire Concept will be needed to overcome the situation of Apatu's inflexible problem because of the fixed installation system, low ceiling height, and excessive energy use for heating and cooling. The Earth, Wind and Fire system is a theory which uses natural energy to control the indoor climate of the buildings (Figure 2). It employs the environmental energy of earth mass, wind and sun to develop and supply energy throughout the building by stopping the help of HVAC systems, thereby minimizing the total energy consumption of the building and providing a healthy and productive working environment (Bronsema, 2013). This system eliminates the need for an air handling unit, and the building functions as a "Climate Machine" with the help of 3 Responsive Building Elements (RBE): The Climate Cascade, Solar Chimney and Power roof 3.0 (Bronsema et al., 2018).

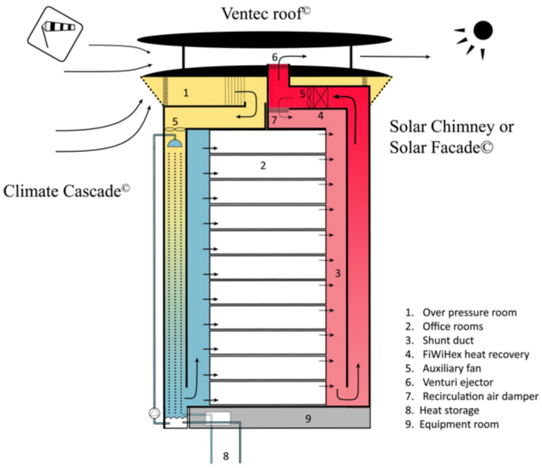


Figure 2. The Earth, Wind, and Fire Concept (Bronsema, 2013)

3.1. Climate Cascade

The climate cascade distributes air throughout the entire building. The air is fed to the climate cascade after entering the building through an overpressure chamber. The water sprinkler's cold water is sprayed on the incoming air at a temperature of 13°C in the climate cascade (Bronsema et al., 2018). The air is cooled to around 18°C in the summer and preheated to about 7-8°C in the winter as a result of the water droplets' lower temperature (Bronsema et al., 2018). With the aid of an underground Thermal Energy storage system, cold water is delivered to the climate cascade's top. The sprinkler's water droplets provide a large-surface area heat exchanger that allows the device to produce temperature differences between the water and the air (Bronsema et al., 2018). The pressure created at the bottom of the cascade by this heat exchanger is utilized to push cooled or heated air through the supply shaft and into the building. A climatie cascade of 1000x1000x6000mm can produce an air exchange rate of $1800m^3h^{-1}$, according to a physical test by Bronsema. Despite needing height to exchange heat, the climate cascade should not exceed than six storeys. It is necessary to subdivide the area when the climate cascade is higher than six stories (20.4 m), and each part should have an additional sprayer (Bronsema, 2013).

3.2. Solar Chimney

A shunt/exhaust shaft connected to the solar chimney at the bottom takes used air from the building. A structural shaft made of solar panels and insulating glass that faces south to maximize solar radiation is known as a "solar chimney." The air in the solar chimney warms up, drawing air from the exhaust shaft's base. A heat recovery system at the top of the solar chimney recovers the heat from the exhaust air. To restore thermal equilibrium, this heat is either carried to the ground or supplied to the building, while the used air is expelled through the roof (Bronsema et al., 2018). Auxiliary fans are added to maintain air circulation, and they are operated by the energy produced by the solar panels on the roof and in the solar chimney's façade (Bronsema et al., 2018). According to Ben's physical test, a solar chimney with dimensions of 2000x250x11000mm can deliver an air exchange rate of $1800m^3h^{-1}$ with an air velocity of 1m/s. The size of the solar chimney also affects how efficient it is. The air it can extract can be increased by both its height and width (Bronsema, 2013). The solar chimney should face south to receive the most sunlight in order to enhance the effectiveness of capturing solar energy. Additionally, facing southwest or southeast can provide more than 93% of the maximum of solar radiation per year (Bronsema, 2013). The solar chimney needs to be more than 0.65 m deep in order to clean and maintain the glass wall from the inside (Bronsema, 2013).

3.3. Ventec Roof

The Ventec roof uses positive wind pressures through an overpressure chamber to help in the delivery of fresh air intake into the Climate Cascade. On the other hand, by applying negative wind pressures and solar chimneys and venturi ejectors, the used ventilation air is extracted from the building (Bronsema, 2013). Both the venturi ejector and the overpressure chamber are necessary for the supply and extraction of air.

3.4. Layout Option

Through the EWF Concept research and the basic installation requirements carried out earlier, it was able to configure the size and principle of the installation system newly applicable to the existing Apatu. The specific size of the elements of the EWF Concept is explained in Appendix 2. The types of vertical shafts to be newly applied include electricity, water supply, drainage, air supply, exhaust, climate cascade, and solar chimney, also pipes to be connected to the shaft include electricity, water supply, water drainage, heating, sprinklers, air supply, and exhaust. Various layouts applicable to Apatu were derived in consideration of the types and sizes of each of the elements listed. There are four options, including De-centralized, Centralized, Wall, and Facade, and the features are shown in Appendix 3.

IV. Flexibility Evaluation

5.1. Definitions of Flexibility

Flexibility is the ability to easy adjustability an element of a system (Fricke & Schulz, 2005). This system allows for a variety of adjustments to be made at any moment, cost-effectively, in order to meet changing demands (Saleh et al., 2003). There are various ways to achieve flexibility, so it's important to plan strategically (Cristiana Cellucci & Michele Di Sivo, 2015). According to Till and Schneider, flexible housing should offer options for social usage and construction both during the project's design phase and after. Consideration at the design process is a key factor for ensuring flexibility throughout the lifetime (Schneider & Till, 2016). It is vital to identify the rules or standards that encourage flexibility because of this. The planners may be guided toward a flexible design if it is possible to examine the degree of planning flexibility.

5.2. Measurement of Flexibility

In order to make principles of flexibility more concrete, there are several studies for the assessment of flexible housing. There have been many attempts to describe these principles. Several measuring methods were investigated in the Hatipoğlu & Ismail (2020) research. The whole list is included in appendix 4. However, These evaluation systems lack a holistic approach that considers all indicators and evaluates them quantitatively. Understanding the hierarchy between these indicators is essential to ensure a flexible housing design. In this sense, the way to evaluate the flexibility of (Hatipoğlu & Ismail, 2020), which focuses on a more specific category, holistic approach, and consideration of cultural aspects, will be mainly adopted to assess the installation options. Along with this literature review, the authors adjust some criteria Hatipoğlu & Ismail suggested and make new specific criteria to evaluate flexibility from the exising old Apatu point of view.

5.3. Criteria

From the literature review of Hatipoğlu & Ismail (2020), the authors suggest the following three criteria and their sub criteria to assess flexibility from the Korean cultural and social point of view.

- Adaptability: (Schneider & Till, 2005) define adaptability as the design of the space that allows it to be used in a variety of ways. According to Moharram, adaptability includes both internal changes such space subdivision and combination as well as the capacity for individual adaptations to adapt to new circumstances. (Hatipolu & Ismail, 2020)
    - Circulation: Complex circulations limit the flexibility of space. The simpler the space of the circulation, the more freedom of design is guaranteed.
    - Neutrality (form): The simplicity of the form makes a certain indeterminacy and a better adaptation of the space for different conditions. Also, the neutrality of the shape of the space will determine the possibility of different furniture layouts.
    - Ceiling Height: The higher the floor height is provided, the more freedom of choice of ceiling, floor finish, and furniture of various heights. In particular, in the case of old Apatu, the context of this study, this category will be treated importantly because most of them already have low ceiling height problems.
    - Floor Area: The large area of space provides several flexibilities. Not only is it easy to divide the space according to the situation, but various functions can be added.
- Variability: It is the capacity for space to expand and compress. It enables adjustments to be made to shape, location, size, and other factors (Van der Voordt & Van Wegen, 2005). It can be described as the use of the space's potential with some interventions. Variability demands more formal, structural, and hard applications than adaptability. (Hatipolu & Ismail, 2020)
    - Opening Size: The larger the opening size, the more sun-light and ventilation are possible, so the space can be used for various functions.
    - Unit Separation: How many units an existing apartment can be split into according to changes in family members will be an important measure of flexibility.
    - Wet Space Area: Among the various programs in the housing, wet space, such as kitchens and toilets, is the most demanding of the various installations. Therefore, if wet space can be placed anywhere user want, the space will be evaluated as flexible.
    - Maintenance: Installation, one of the main components of the building, requires periodic maintenance and replacement. The flexibility of the building will be determined by whether it can be managed flexibly and easily without a large-scale construction process.

- Construction: Flexibility and construction methods are strongly correlated. Therefore, the majority of housing projects use simple and robust construction methods to allow for potential future intervention (Schneider & Till, 2005). Establishing a specific classification of building layers such as services, structure, envelope, internal partitions is crucial for a flexible design (Habraken, 2019).
    - Amount of Material: The amount of material is directly related to the cost of construction. At the same time, it is an important topic in flexibility because the degree of architectural intervention is determined by the construction cost.
    - Diversity of infill methods: According to the order of the planned construction, a new installation is created first, and an infill method suitable for the system is determined. Therefore, it is important to consider a service system that provides various infill methods.
    - Surface area of service: The user's flexible use of the service is determined by how much service area is in the space of one volume. Also, the location of the service installation determines the total thickness of the wall or slab. And the thicker it is, the higher the soundproofing effect. Therefore, various activities may occur in a space with good sound insulation performance.
    - Climate Performance: Climate performance will be determined depending on the installation location of the climate duct. Excellent climate performance provides flexibility in the use of indoor spaces.

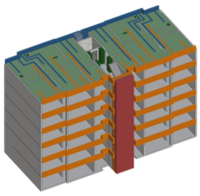
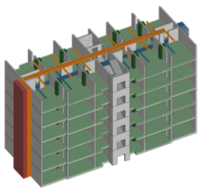
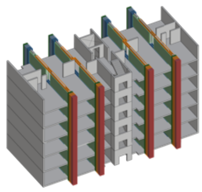
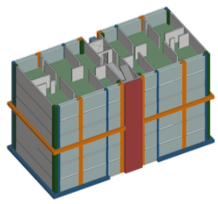
5.4. Weighting Criteria

One crucial stage in the procedure is to weight the criteria. Various criteria are used to evaluate the options, but by giving each criterion a different weight, the decision-making process can concentrate on the more essential criteria that the alternatives should meet. (Pozzi, 2019) The method suggested by Saaty & Vargas (2012), which use a matrix where pairwise comparisons between the criteria are performed, is the one that is most frequently used to assess the relative value of various criteria. The numerical scale used for these comparisons ranges from 1 to 9. The usage of this scale becomes laborious in terms of time and effort as the complexity of the decision problem rises. The simplified version borrows ideas from Nick van der Knaap and Jeroen van Veen's projects for the PD Lab in order to overcome this difficulty. Only the numbers 0 and 1 are used in this case for the pairwise comparisons. The more critical criterion is given a value of 1, and the less critical criterion is given a value of 0. Since it is impossible for two criteria to receive the same score, this straightforward comparison serves as a ranking method for the criteria. The process's simplicity and speed, which are based on fast comparisons and can handle a lot of criteria and options in a short amount of time, are its key advantages (Van der Knaap, 2016). The three matrices are compared using the three different systems in Appendix 5. The overall score and values from 1 to 3 are used to represent how essential each criterion is, with 3 being very important, 2 important, and 1 relevant.

5.5. Assessment (Result)

The four installation options presented in the early research were evaluated through flexibility measurement criteria from the literature analysis of Hatipoğlu & Ismail and new criteria suitable for the situation of Apatu in Korea. Each installation system is evaluated regarding every criterion using this numerical scale, with values from 1 to 4. For each item, the option with the highest relevance was given 4 points, and the option with the lowest relevance was given 1 point. The basis for each item's evaluation will be explained in appendix 6. These values are then multiplied by the criterion's weight, explained in chapter 5.4, and then summed to calculate the final score (Appendix 7). The evaluation results are shown in Table 3.

Table 3. Flexibility Evaluation

	Option 1	**Option 2**	**Option 3**	**Option 4**
	De-centralized	Centralized	Wall	Facade
				
Total Weighted Score	51	64	79	52

V. CONCLUSION & DISCUSSION

This paper studies the options of new installations that can enhance flexibility in reusing old Korean Apatu and shows how evaluation methods can be used to select optimal options. Through this study, conclusions can be drawn related to a new installation system that can make the existing Apatu as flexible as possible.

By analyzing the installation used in the existing Apatu, it is possible to develop an essential installation to be newly replaced. In addition, through researching a new climate installation (EWF Concept) that can overcome the limitations of existing ones, various layout options for the installation system can be suggested.

By scientifically evaluating the layouts of the various installation systems, the main advantages and disadvantages of each option that the infill system to be presented in the subsequent design phase can be flexibly applied are considered. In order to use the space flexibly, the form of the space must be simple to arrange furniture and flexible circulation, and a high ceiling height and a large area will be provided so that various space utilization can be achieved vertically and horizontally. In addition, the size of the opening and the way the installation and shaft are organized will determine the possibility of the flexible layout of various programs in the housing. Also, the space modification or ease of maintenance in using the space will be essential factors in determining the flexible space.

By exploring in-depth different weighting approaches used to evaluate the importance of the criteria in a decision problem, it can be confirmed that the scale system proposed by Saaty & Vargas (2012) is one of many valid options. Thus, Nick van Knaap and Zeroen van Veen's simplified weighting approach is used, which can reduce the time and effort of the decision-making process and devote more time to developing design steps.

Through these flexibility measurement criteria and evaluation methods, the third option, that the vertical shaft is installed outside and interior installation is located on the wall, received the highest score in terms of flexible space. In conclusion, the results of appendix 6 and 7 represent the best installation option to create maximum flexibility when existing Apatu are reused by applying Open Building principles.

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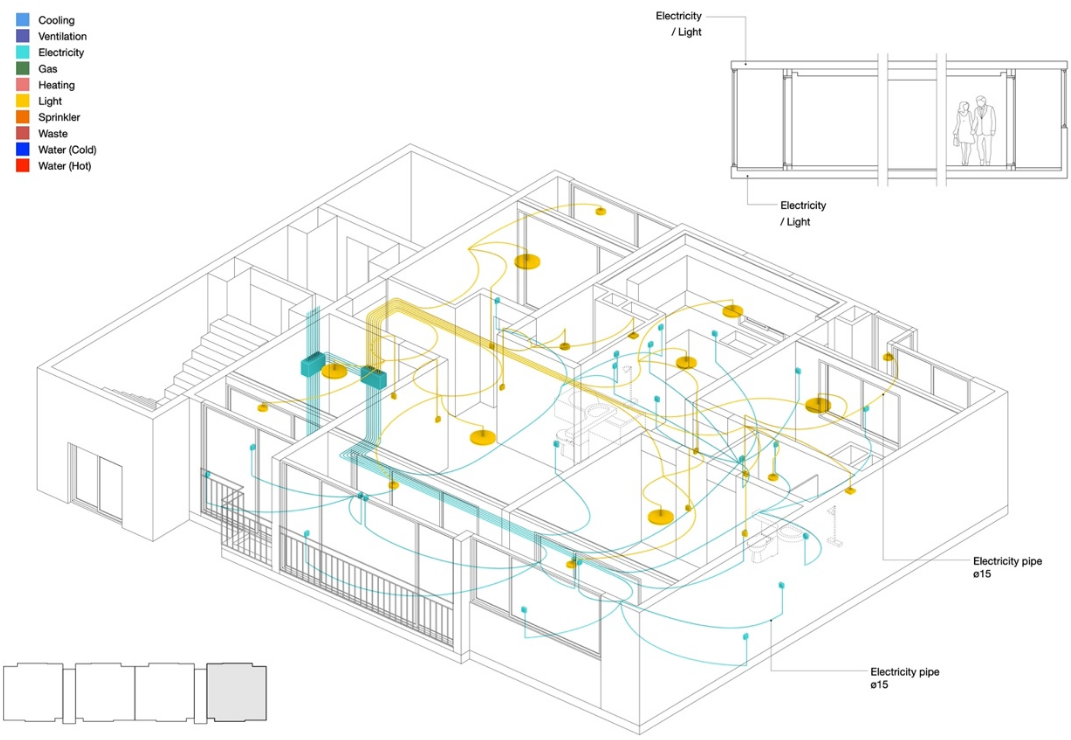
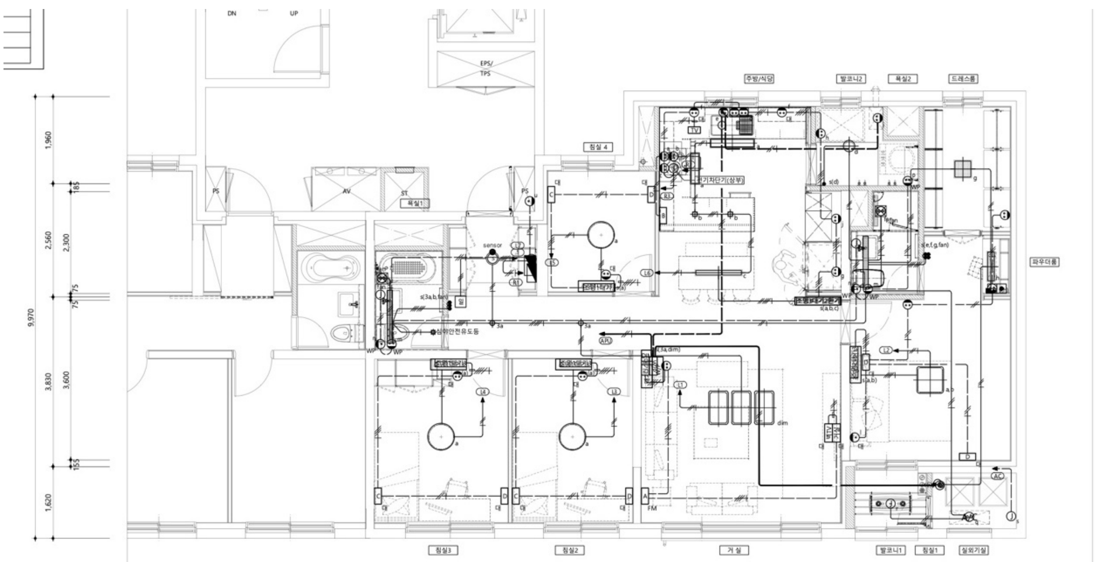
APPENDIX 1 (EXISTING INSTALLATION)

1.1.Electricity

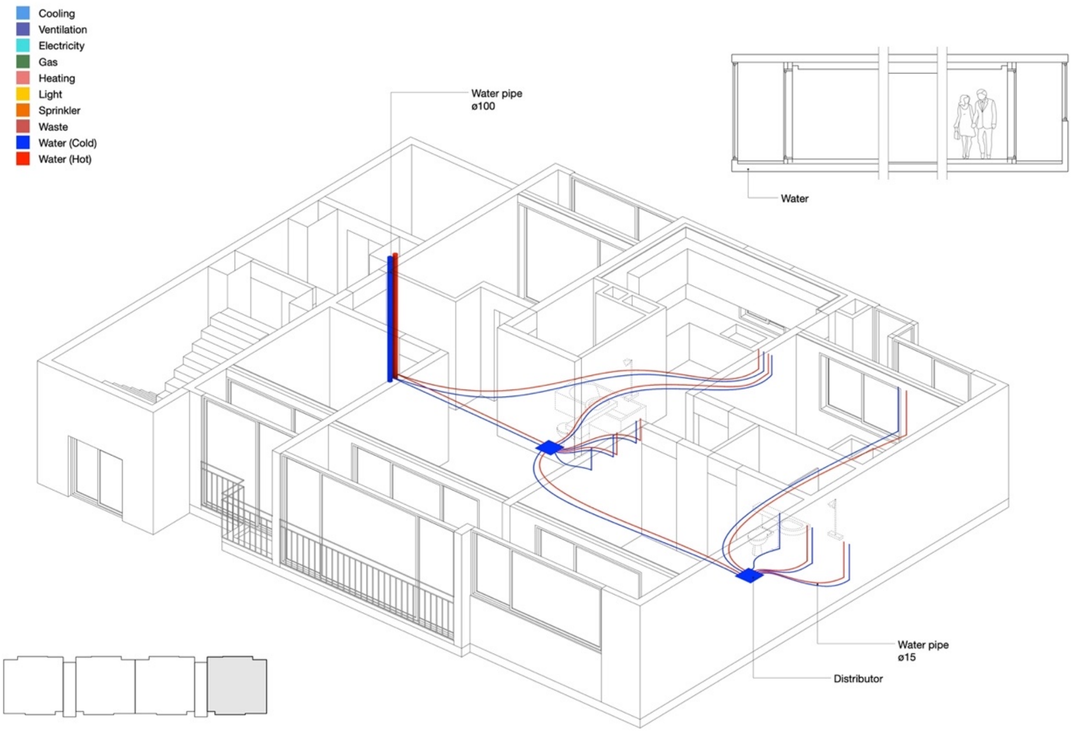
First, the electricity delivered to the building is sent to the Electric Pipe Shaft (EPS) in the core and connected to the distribution box in each housing unit. Moreover, the transmitted electricity to the distribution box is divided into the ceiling and floor parts. All electrical installations are buried inside concrete slabs and walls. So, they are installed between reinforcing bars before pouring concrete. The diameter of the pipe is 15 mm. The electric pipes arranged on the floor are connected to the socket to supply electricity, and the pipes arranged on the ceiling are used as electricity for lights.

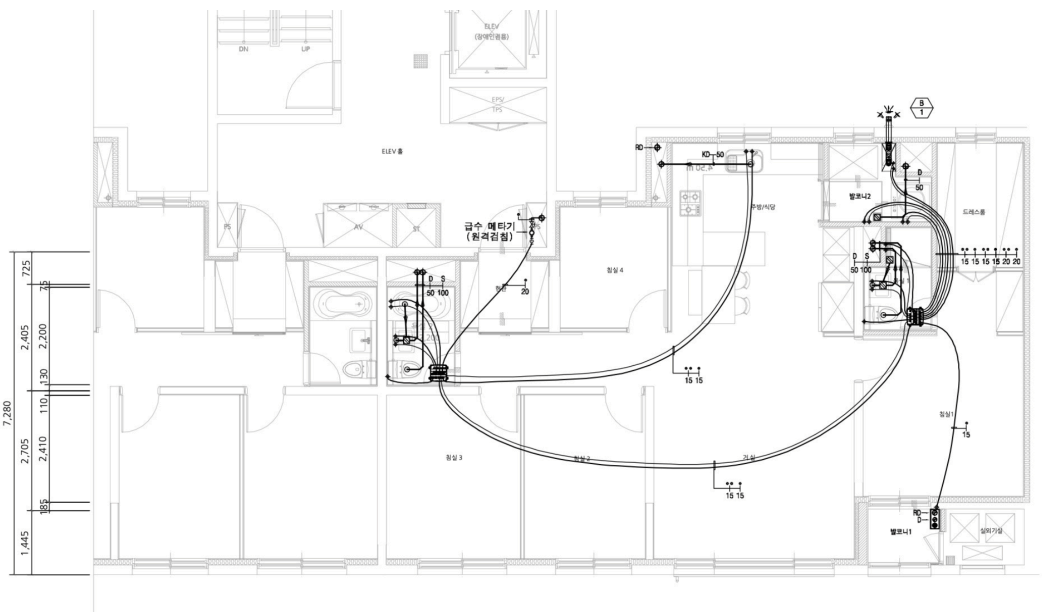




1.2. Water

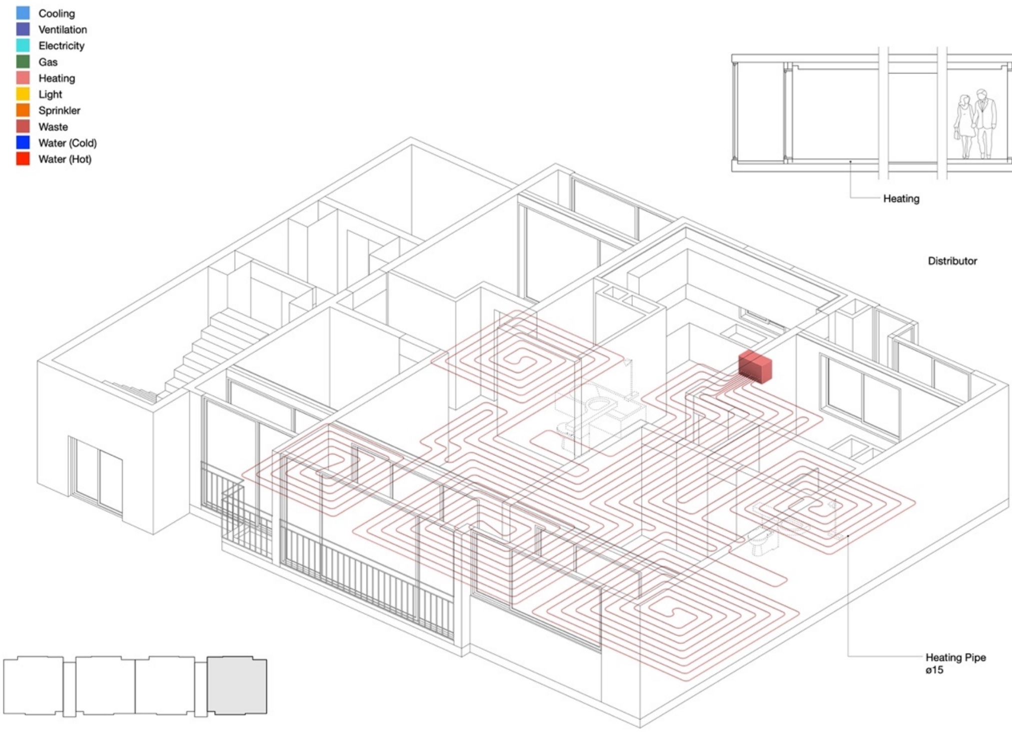
Next, in terms of the water supply, most Apatu built in the 1990s adopted district heating. Therefore, cold and hot water is supplied to the pipe (100 mm diameter) located at the shaft of the core and connected to an indoor distributor. Moreover, once again, the pipes divided into several strands (diameter 15mm) are connected to the wash basin, toilet, shower, kitchen sink, washing machine, floor heating distributor, etc. Like electricity, water supply pipes are also installed between reinforcing bars before concrete is placed and then buried.

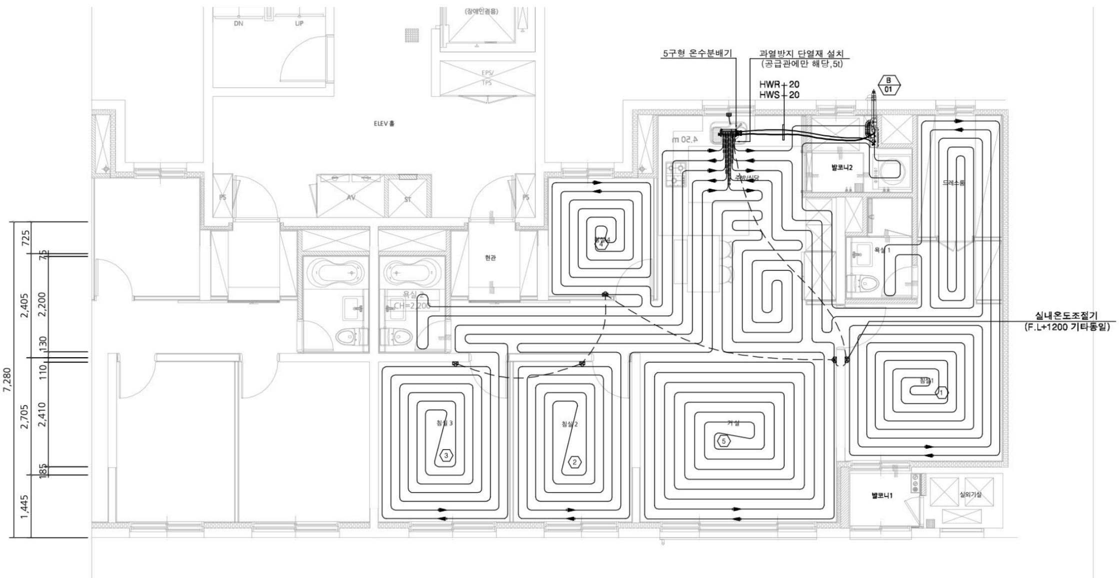




1.3. Heating

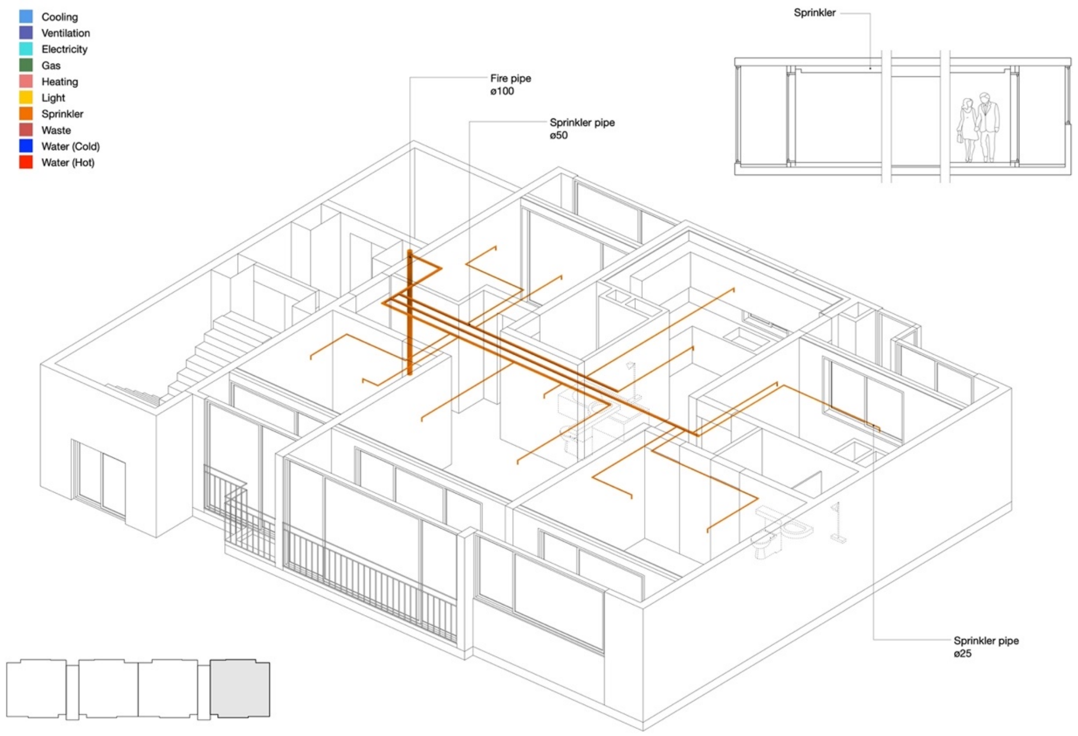
The heating installation has a lot to do with the water supply. As described above, since old Apatu use district heating, there is no separate private boiler in each apartment. One of the hot water pipes supplied through the water supply installation is connected to a heating distributor. From the distributor, several other pipes are uniformly placed on the floor to warm the room. Unlike electric and water supply pipes, heating pipes are installed inside of the floor finish, not embedded in the slab. The diameter of the pipe is also 15 mm.

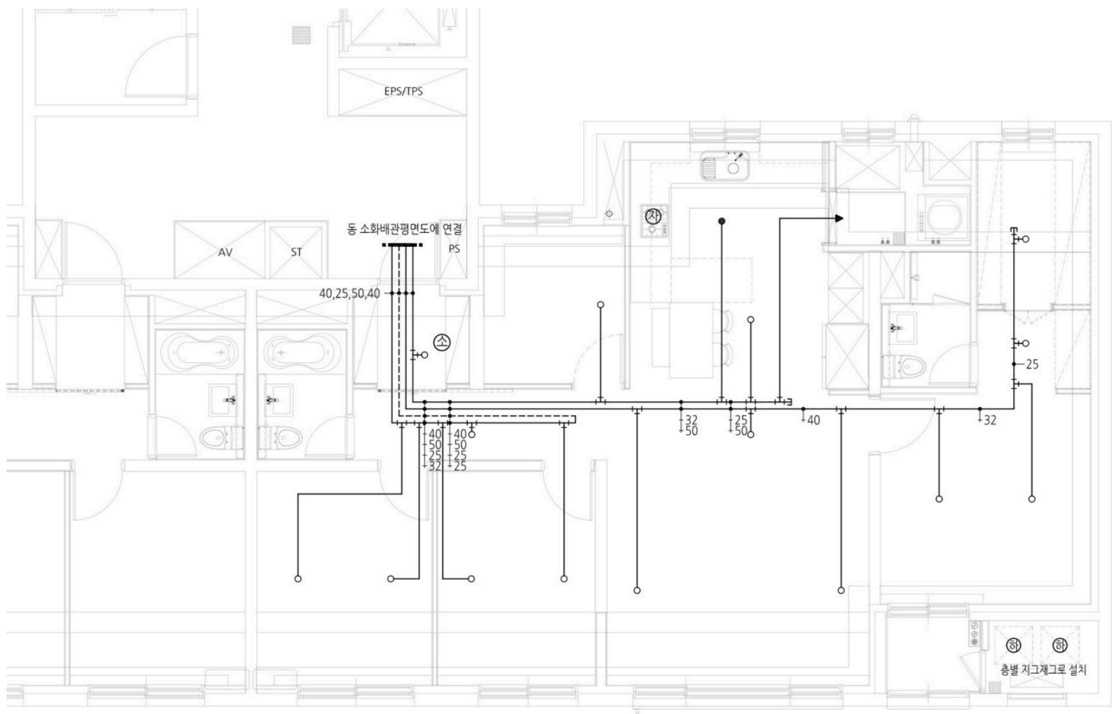




1.4. Sprinkler

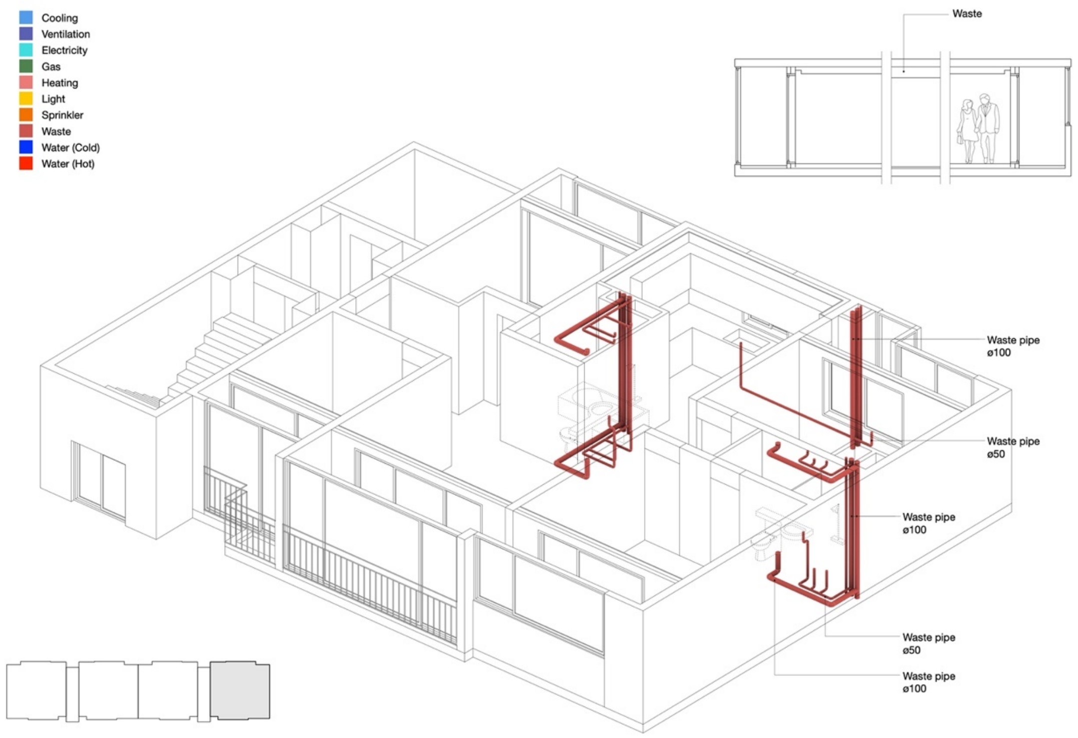
Each housing unit sprinkler pipes are also supplied from fire pipes located in the core (diameter 100 mm). The sprinkler pipe is connected (diameter 50mm and 25 mm) from the fire pipe of the core to the sprinkler head installed in each room through the ceiling to supply water in case of fire. Sprinkler piping is installed between the ceiling finish and the ceiling slab after the concrete is placed.

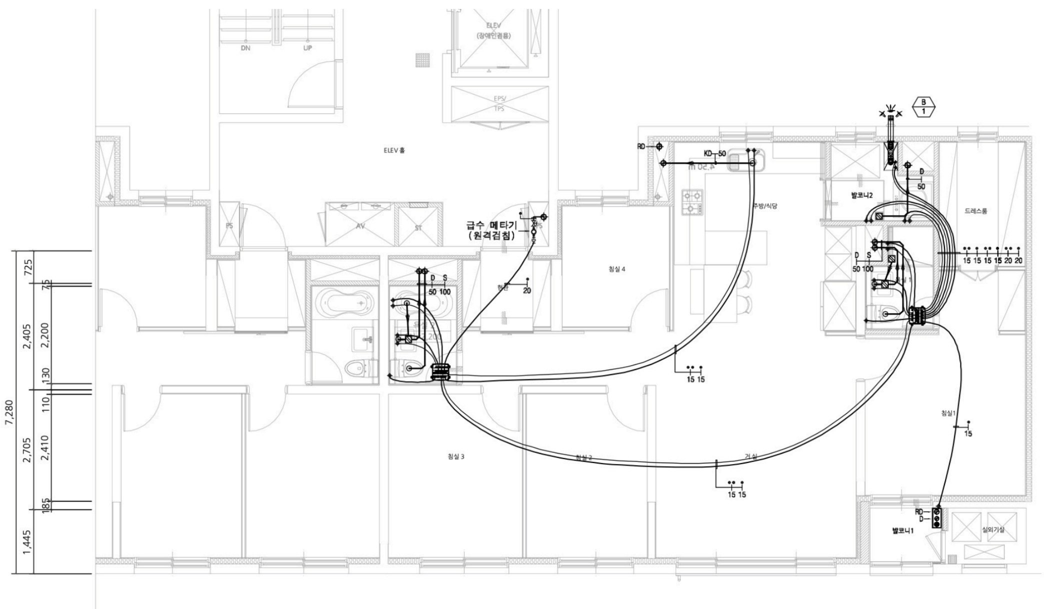




1.5. Sewage

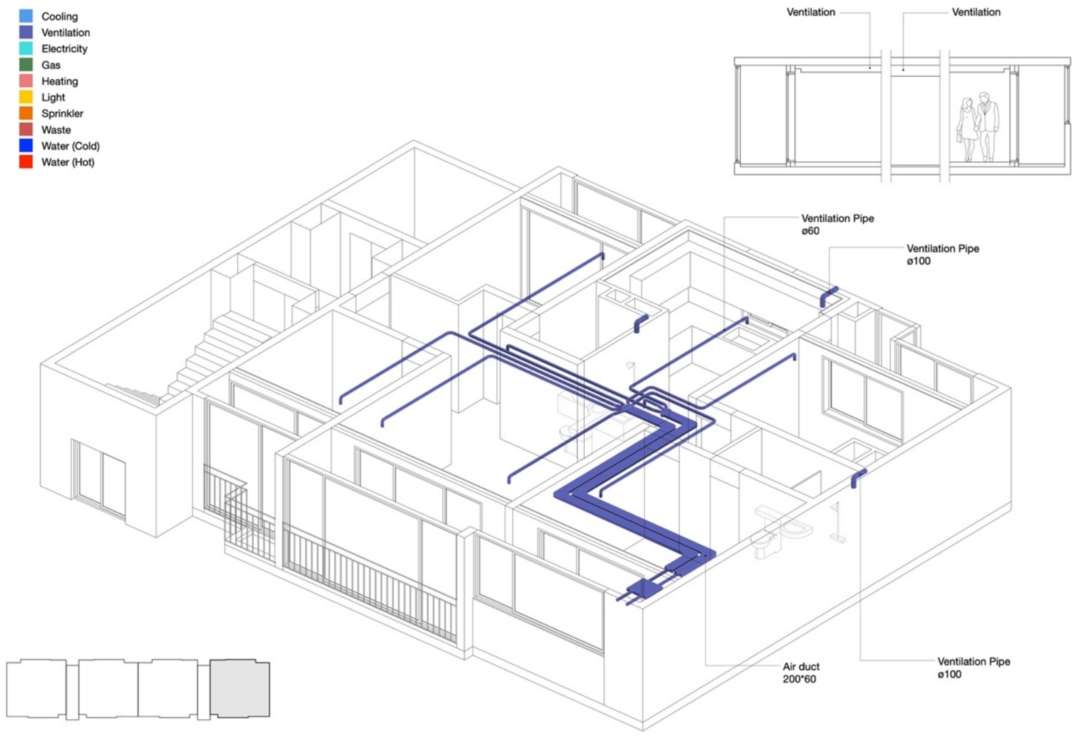
Inside the housing unit, a separate shaft is installed next to spaces requiring drainage installation, such as bathrooms and kitchens. Inside the shaft, there are a drain pipe and a sewage pipe, and each size is 100 mm, respectively. Sewage generated from wash-basin, toilets, bathtubs, shower booths, bathroom floors, sinks, washing machines, etc., goes down the drain pipe, passes through the inside of the ceiling finish of the bathroom downstairs, and is connected to a vertical pipe in the shaft. The sewage pipe connected to the toilet is 100 mm in diameter, and the rest of the sewage pipes are 50 mm.

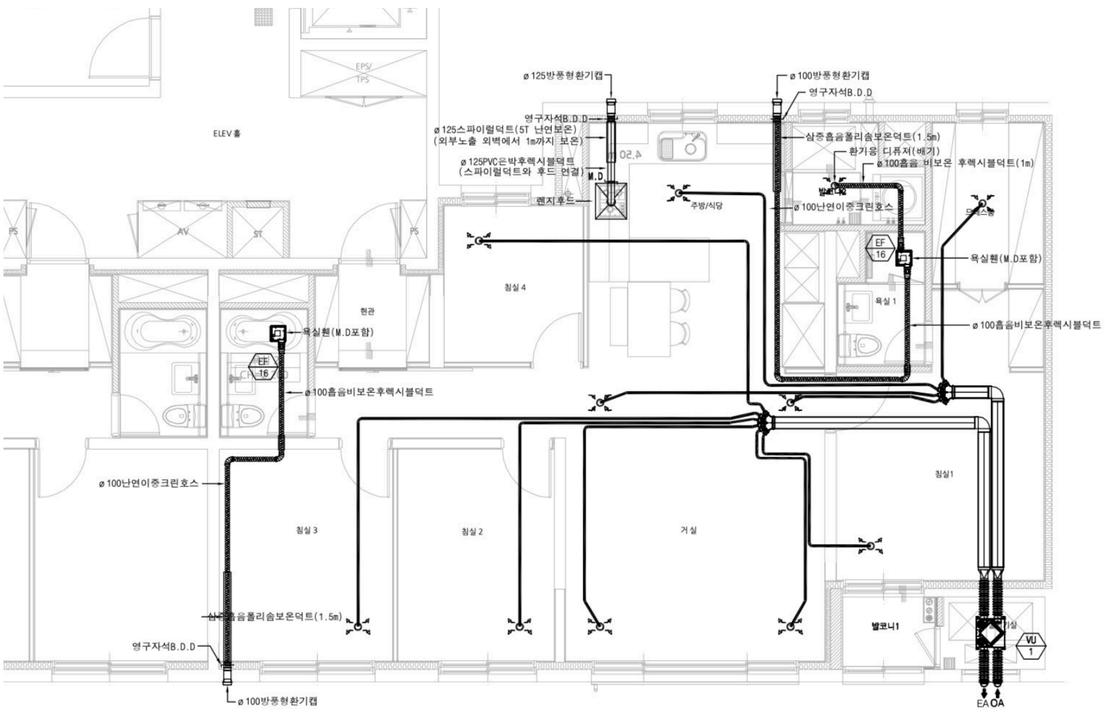




1.6. Ventilation

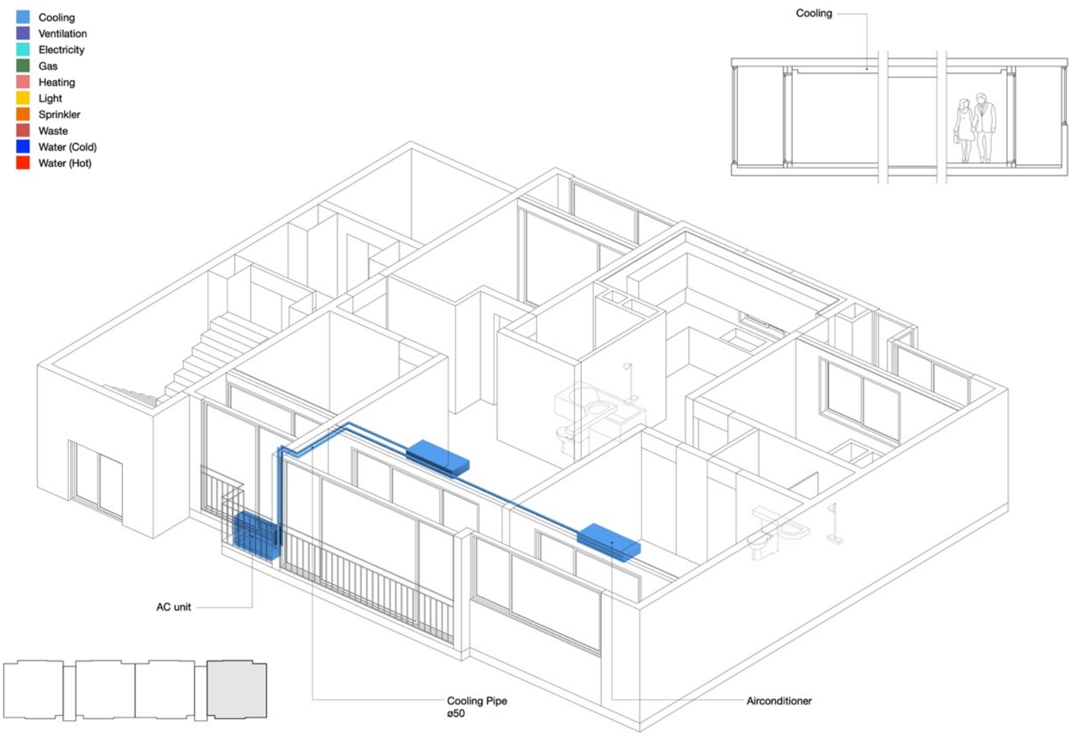
Ventilation in the bathroom is also done through adjacent shafts. Exhaust air from each bathroom is collected to the shaft through a ventilation duct (100 mm diameter) inside the ceiling finish and sent to the roof of the Apatu. In addition, the air supply and exhaust required for each room are operated through the air ducts (60mm diameter) in the ceiling finish, and all ducts are gathered in the main duct (200mm*60mm) and sent to the facade. A ventilation pipe (100 mm diameter) connected to the kitchen hood is also connected to the opposite facade.

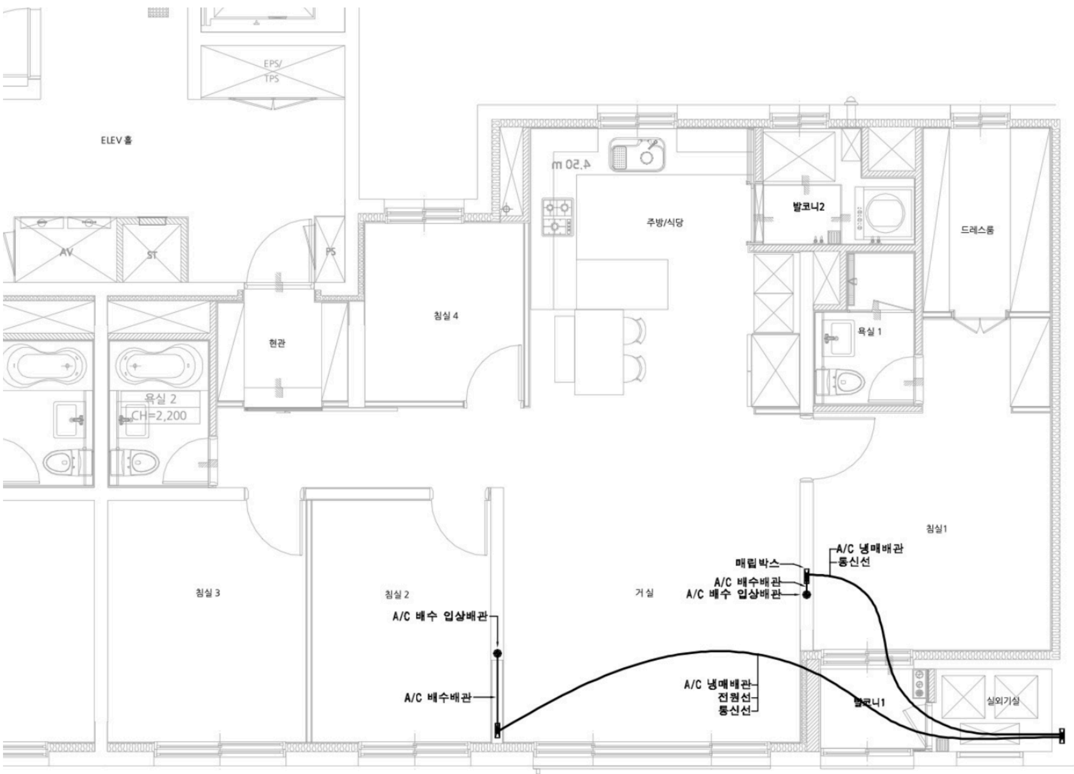




1.7. Cooling

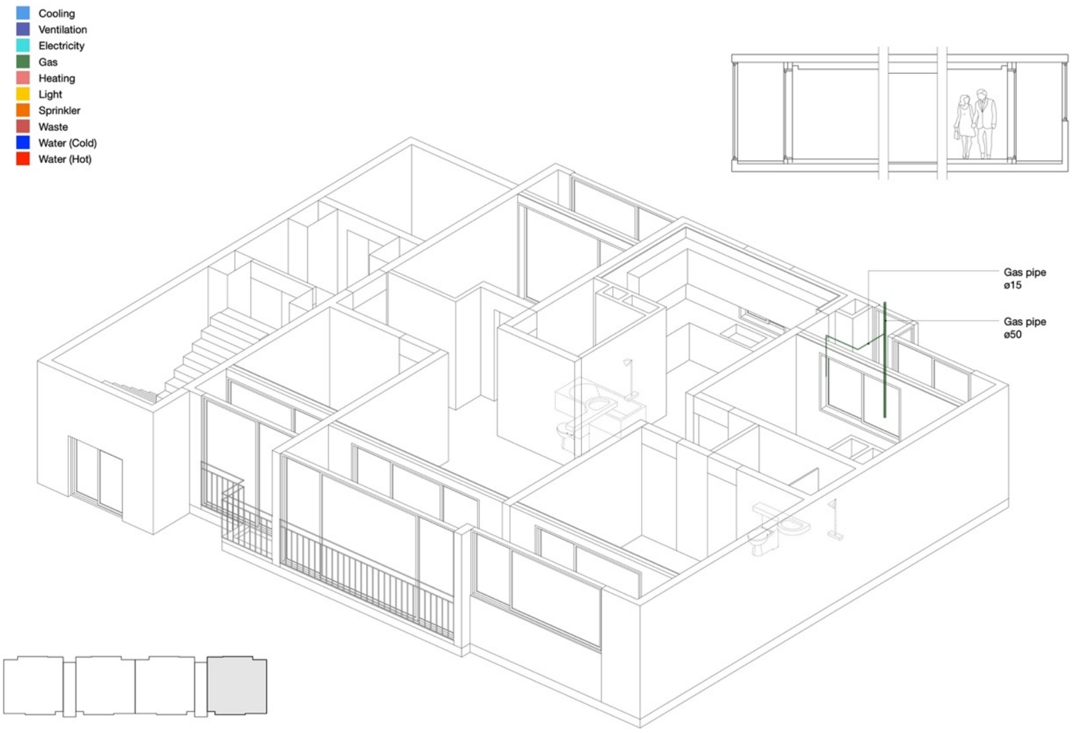
It can be said that air conditioning and cooling facilities are essential in Korea's climate. The air conditioner consists of an indoor ceiling air conditioner (1200mm*500mm*200mm), an outdoor air conditioner unit, and a cooling pipe (50mm in diameter) that connects the two installations.

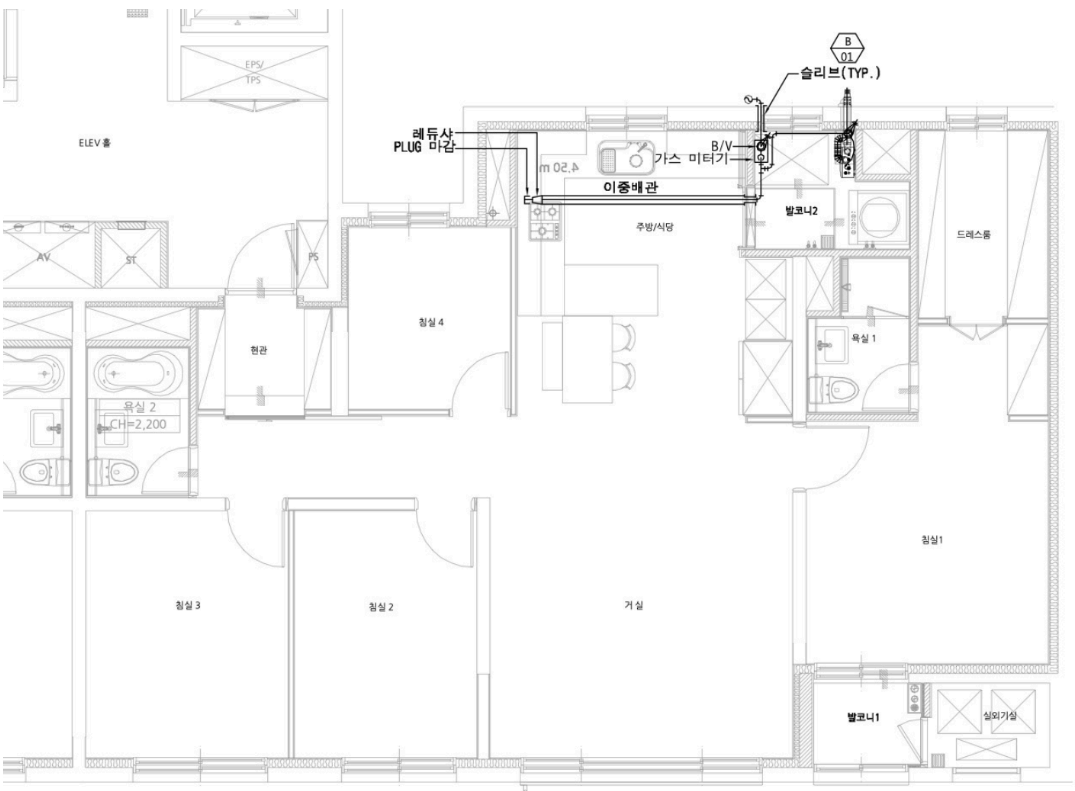




1.8. Gas

Finally, a gas pipe (50 mm diameter) used in a kitchen gas stove is located in a facade on the kitchen side and is connected indoors through a 15 mm gas pipe.





Appendix 2 (The Earth, Wind, and Fire Concept)

2.1. Ventilation Requirement in Korea

Since one housing unit of Apatu set as the context has an area of 130.29m^2 and a height of 2.3m, it can be confirmed that the total volume is 299.66 m^3. According to Korea's ventilation regulations (Article 11 Paragraph 1 of Regulations on Facility Standards for Buildings), more than half of the air per hour must be ventilated, so an amount of 149.83 m^3 must be circulated.

2.2. Size of Climate Cascade

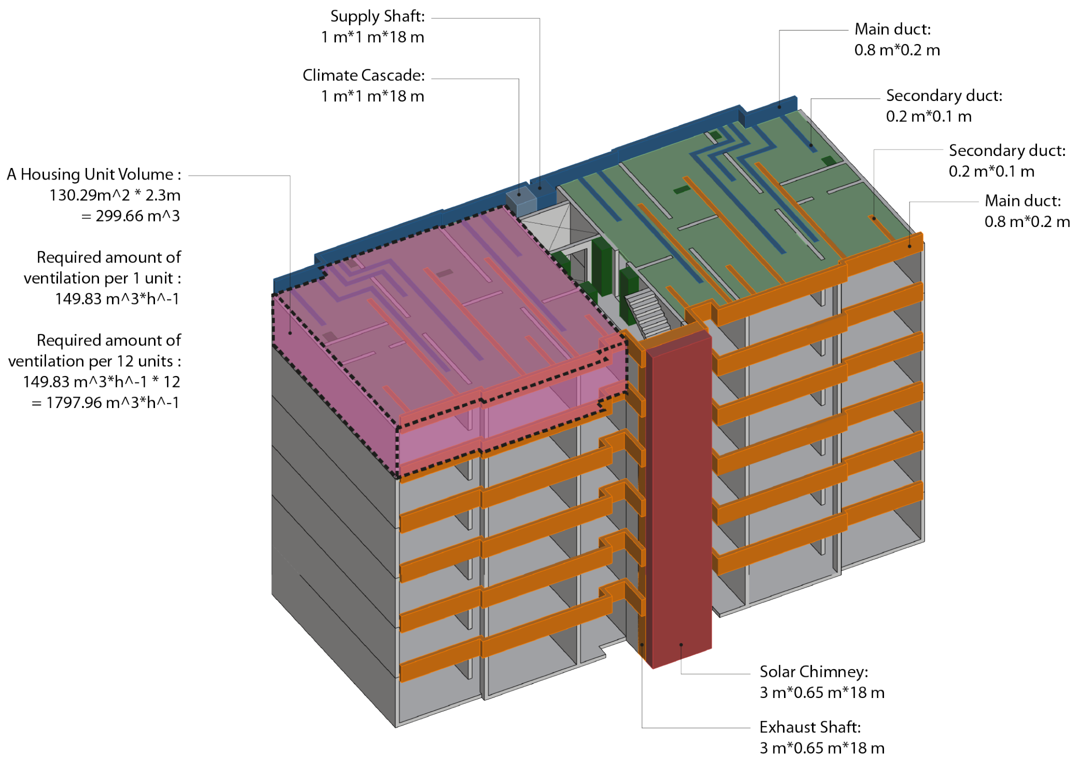
According to the research of Bronsema (2013), the amount of air supplied by the Climate Cascade 1m×1m×6m module is 1800 m^3h^{-1}. So, that means that one studied module can accommodate approximately 12 housing units. The supply shaft connected to the Climate Cascade is also applied the same size to cover the same amount of air.

2.3. Size of Solar Chimney

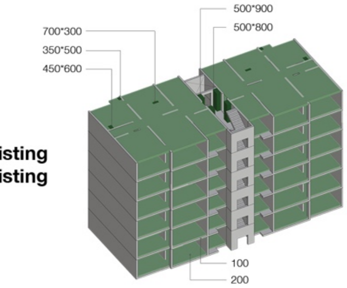
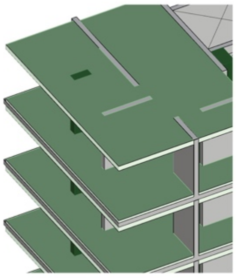
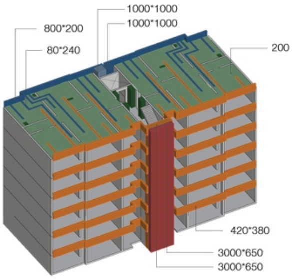
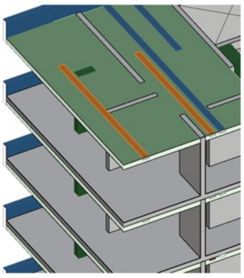
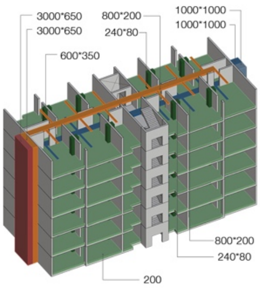
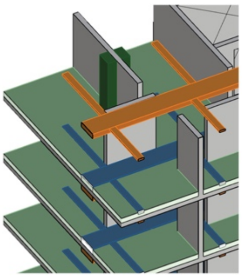
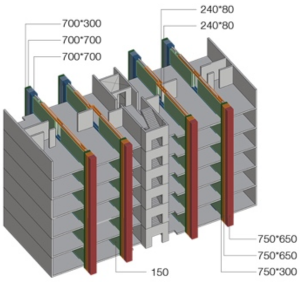
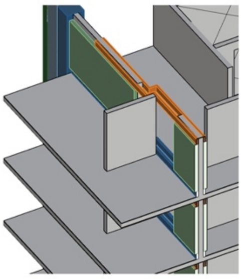
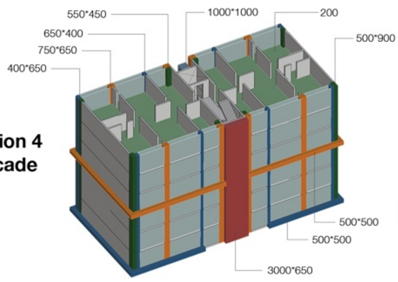
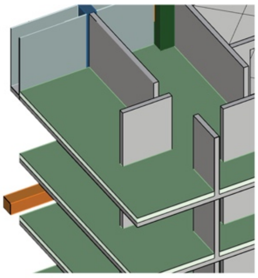
Solar Chimney is also a standard that accommodates an amount of 1800 m^3h^{-1} corresponding to the capacity of Climate Cascade, and sets 3 m*0.65 m*18 m as the basic module according to the research and context conditions of Yamini Patidal (2021). The exhaust Shaft is also set to the same size as Solar Chimney.

2.4. Size of Duct

The size of the duct connecting the supply shaft to the interior and the exhaust shaft should be considerably more significant than that of the conventional mechanical system due to low air speed and pressure loss (Peter Swier, 2016). In consideration of Yamini Patidal's research (2021) and the context conditions, main duct size is set to 0.8m*0.2m, and the secondary duct is set to 0.2m*0.1m.



APPENDIX 3 (LAYOUT OPTION)

	Application	Section	EWF vertical Shaft	EWF horizontal Shaft	EWF Duct	Service Shaft	Installation
Existing Existing			-	-	-	Core, Interior	Ceiling, Floor
Option 1 De-centralized			Façade (Core)	Façade (Apartment)	Ceiling	Existing	Ceiling
Option 2 Centralized			Façade (Side)	Floor, Ceiling	Floor, Ceiling	Interior	Ceiling, Floor
Option 3 Wall			Façade	Wall	-	Façade	Wall
Option 4 Facade			Façade (Core)	Façade (New)	-	Façade (New)	Floor

APPENDIX 4 (FLEXIBILITY MEASUREMENT METHOD)

Kiaee et al., 2019	Measure the flexibility of the housing spatial system, using the space syntax in different patterns in Qazvin.
Idrissi, 2006	Quantitative study about flexible housing on chosen case studies in Morocco includes an index based on the functional area of the cases after the alterations made by users.
Rajan et al., 2003	Clear ranking system to evaluate flexibility in their paper "Design for flexibility- measures and guidelines", which suggests design guidelines for the flexible design in Swedish society.
Nal & Ünlü, 2009	Research about flexibility provided by an open plan system focusing on constructional features of permanent houses in Düzce.
Koman & Eren, 2010	Study aiming for a decision-making process in housing based on the preferences of the tenants, which is based on different usage of space related with the dimensions of the dwelling units and number of occupants.
Hasgül & Özsoy, 2016	A design matrix, which is more a qualitative discussion on different housing typologies about flexibility, provided a comparison of the selected projects hierarchically and defined three levels of flexibility degree.
Altaş & Özsoy, 1998	An assessment based on the frequency of responses of tenant's adaptability which doesn't include a multifactorial analysis.
Hatipoğlu & Ismail (2020)	Focusing on more specific category, holistic approach, and consideration of cultural aspect regarding flexibility

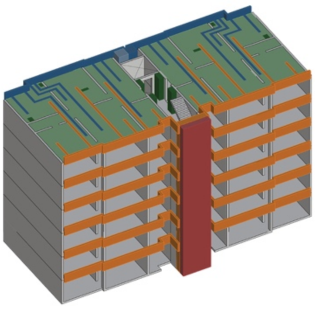
(Hatipoğlu & Ismail, 2020)

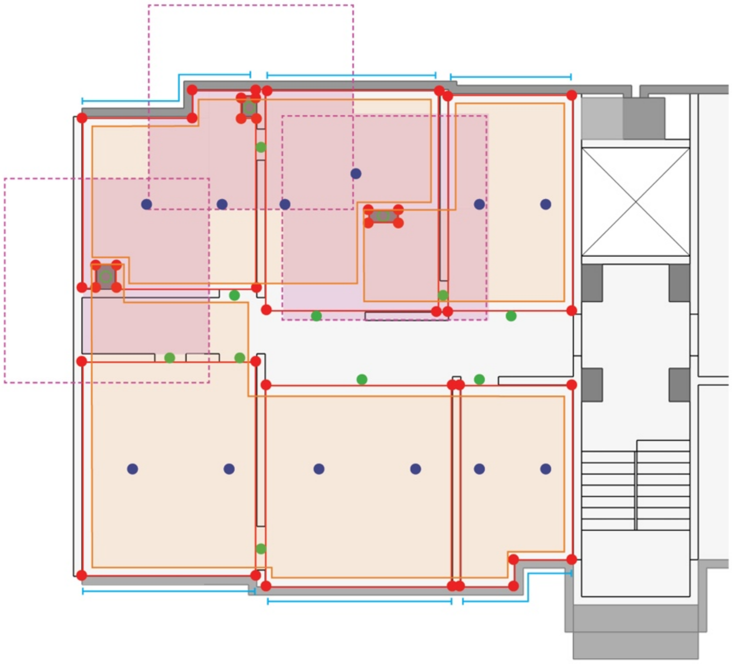
APPENDIX 5 (WEIGHTING CRITERIA)

	Circulation	Form Neutrality	Ceiling Height	Floor Area	Opening Size	Unit Separation	Wet Space Area	Maintenance	Amount of Material	Diversity of Infill Method	Surface Area of Service	Climate Performance	Total	**Weight**
Circulation		0	0	1	0	0	0	0	1	0	0	1	4	**1**
Form Neutrality	1		0	1	0	0	0	1	1	1	1	1	8	**2**
Ceiling Height	1	1		1	1	0	0	1	1	1	1	1	11	**3**
Floor Area	0	0	0		0	0	0	0	1	0	0	0	2	**1**
Opening Size	1	1	0	1		0	0	0	1	1	1	1	9	**3**
Unit Separation	1	1	1	1	1		0	1	1	1	1	1	12	**3**
Wet Space Area	1	1	1	1	1	1		1	1	1	1	1	13	**3**
Maintenance	1	0	0	1	0	0	0		1	0	0	1	6	**2**
Amount of Material	0	0	0	1	0	0	0	0		0	0	0	2	**1**
Diversity of Infill Method	1	0	0	1	0	0	0	1	1		1	1	7	**2**
Surface Area of Service	1	0	0	1	0	0	0	1	1	0		0	5	**2**
Climate Performance	0	0	0	1	0	0	0	0	1	0	0		3	**1**

Appendix 6 (Evaluation)

Option 1 (De-centralized)





- EWF vertical Shaft : Facade (Core)
- EWF horizontal Shaft : Facade (Apartment)
- EWF Pipe : Ceiling
- Service Shaft : Existing
- Installation : Ceiling

Adaptability

Circulation
Weight 1

: 10 Openings connecting each space, and 3 objects disturbing the connection. Total score is 7.

Form Neutrality
Weight 2

: There are a total of 40 vertices in six spaces.

Ceiling Height
Weight 3

: 2.4m

Surface Area
Weight 1

: 131 m^2

Variability

Opening Size
Weight 3

: 45m^2 (Length 24m * Height 1.8m)

Housing unit
Weight 3

: Maximum 3 units

Wet space area
Weight 3

: Assuming that the appropriate size of kitchen and bathroom is 2m * 2m, wet space area is 35m^2

Maintanance
Weight 2

Installation : easy (ceiling)
Service Shaft : easy (Inside)
EWF Shaft : difficult (outside)
score : 3+3+1 = 7

Construction

Amount of Material
Weight 1

: Sum of the volumes of all installations related to the service per six floors. 235.18 m^3

Diversity of Infill Method
Weight 2

: Horizontal Extension, General Interior renovation with New Facade.

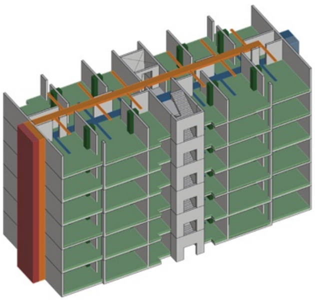
Surface Area of Service
Weight 2

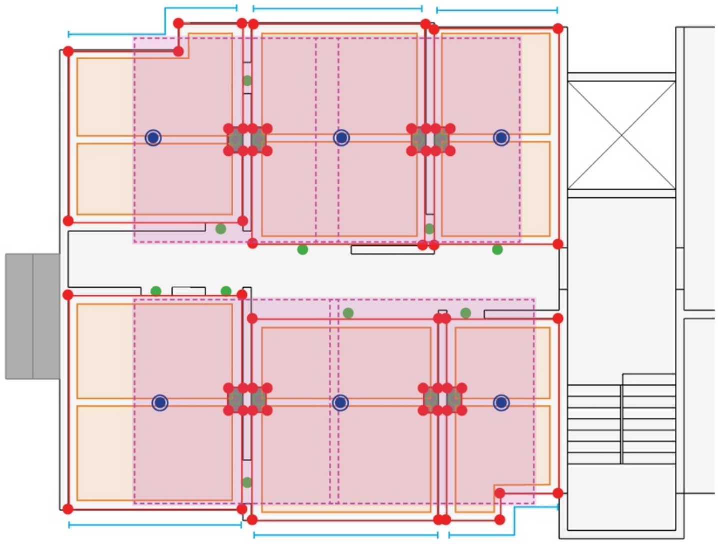
: Ceiling (131 m^2)

Climate Performance
Weight 1

Energy distribution : good (center)
Ventilation performance : bad (supply and exhaust ducts are at the same level)

Option 2 (Centralized)





- EWF vertical Shaft : Facade (Side)
- EWF horizontal Shaft : Floor, Ceiling
- EWF Pipe : Floor, Ceiling
- Service Shaft : Interior
- Installation : Floor, Ceiling

Adaptability

Circulation

Weight 1

●○○○

: 10 Openings connecting each space, and 4 objects disturbing the connection. Total score is 6.

Form Neutrality

Weight 2

●○○○

: There are a total of 60 vertices in six spaces.

Ceiling Height

Weight 3

●○○○

: 2.2m

Surface Area

Weight 1

●●○○

: 129m^2

Variability

Opening Size

Weight 3

●●●○

: 52.8m^2 (Length 24m * Height 2.2m)

Housing unit

Weight 3

●●●○

: Maximum 12 units

Wet space area

Weight 3

●●●○

: Assuming that the appropriate size of kitchen and bathroom is 2m * 2m, wet space area is 84m^2

Maintanance

Weight 2

●●●○

: Installation : normal (floor and ceiling)
Service Shaft : easy (Inside)
EWF Shaft : difficult (outside)
score : 2+3+1 = 6

Construction

Amount of Material

Weight 1

●●●○

: Sum of the volumes of all installations related to the service per six floors.
219.01 m^3

Diversity of Infill Method

Weight 2

●●●●

: Horizontal Extension, General Interior renovation with New Facade, Housing Module Plug-in.

Surface Area of Service

Weight 2

●●●●

: Ceiling (129 m^2)
Floor (129 m^2)
Total (258 m^2)

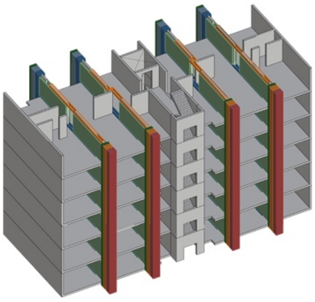
Climate Performance

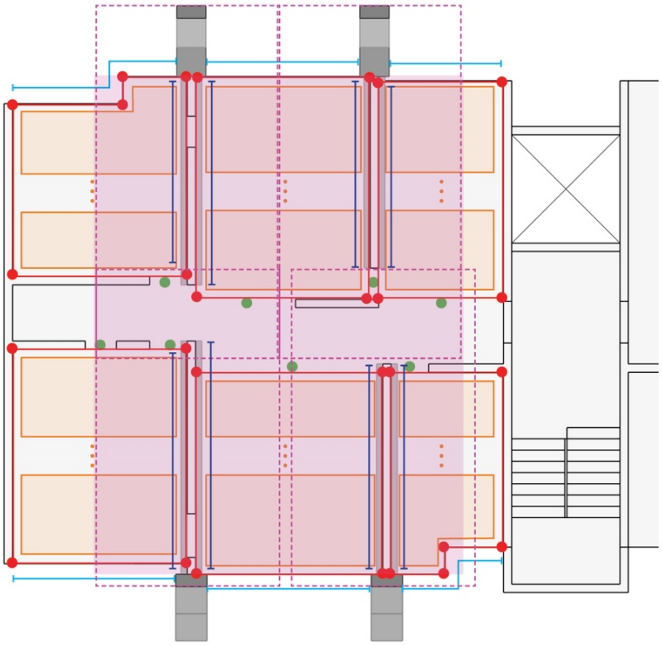
Weight 1

●●●●

Energy distribution : good (center)
Ventilation performance : good (supply and exhaust ducts are at the different level)

Option 3 (Wall)





- EWF vertical Shaft : Facade
- EWF horizontal Shaft : Wall
- EWF Pipe : -
- Service Shaft : Facade
- Installation : Wall

Adaptability

Circulation
Weight 1
●●●○
: 8 Openings connecting each space, and 0 objects disturbing the connection. Total score is 8.

Form Neutrality
Weight 2
●●●●
: There are a total of 28 vertices in six spaces.

Ceiling Height
Weight 3
●●●●
: 2.6m

Surface Area
Weight 1
●○○○
: 125m^2

Variability

Opening Size
Weight 3
●●●●
: 59m^2 (Length 23m * Height 2.6m)

Housing unit
Weight 3
●●●●
: More than 12 units

Wet space area
Weight 3
●●●●
: Assuming that the appropriate size of kitchen and bathroom is 2m * 2m, wet space area is 95m^2

Maintanance
Weight 2
●○○○
Installation : difficult (wall)
Service Shaft : normal (Inside or outside)
EWF Shaft : normal (Inside or outside)
score : 1+2+2 = 5

Construction

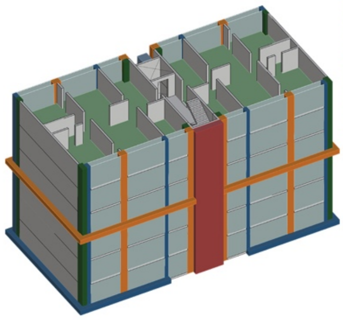
Amount of Material
Weight 1
●●●●
: Sum of the volumes of all installations related to the service per six floors.
179.89 m^3

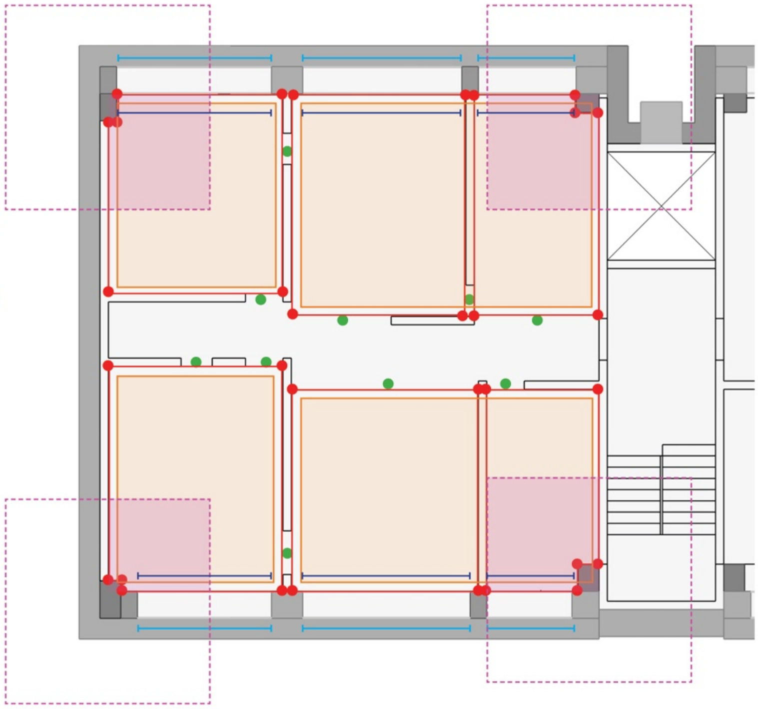
Diversity of Infill Method
Weight 2
●●●●
: Horizontal Extension, General Interior renovation with New Facade, Housing Module Plug-in.

Surface Area of Service
Weight 2
●○○○
: Wall (110 m^2)

Climate Performance
Weight 1
●●●○
Energy distribution : bad (side)
Ventilation performance : good (supply and exhaust ducts are at the different level)

Option 4 (Facade)





- EWF vertical Shaft : Facade (Core)
- EWF horizontal Shaft : Facade (New)
- EWF Pipe : -
- Service Shaft : Facade (New)
- Installation : Floor

Adaptability

Circulation
Weight 1

: 10 Openings connecting each space, and 0 objects disturbing the connection. Total score is 10.

Form Neutrality
Weight 2

: There are a total of 32 vertices in six spaces.

Ceiling Height
Weight 3

: 2.4m

Surface Area
Weight 1

: 134 m^2

Variability

Opening Size
Weight 3

: 46m^2 (Length 19m * Height 2.4m)

Housing unit
Weight 3

: Maximum 4 units

Wet space area
Weight 3

: Assuming that the appropriate size of kitchen and bathroom is 2m * 2m, wet space area is 24m^2

Maintanance
Weight 2

Installation : difficult (floor)
Service Shaft : easy (Inside)
EWF Shaft : difficult (outside)
score : 1+3+1 = 5

Construction

Amount of Material
Weight 1

: Sum of the volumes of all installations related to the service per six floors.
245.73 m^3

Diversity of Infill Method
Weight 2

: Horizontal Extension, General Interior renovation with New Facade.

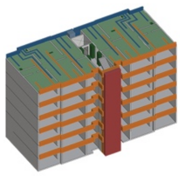
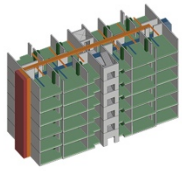
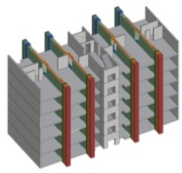
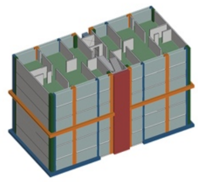
Surface Area of Service
Weight 2

: Floor (134 m^2)

Climate Performance
Weight 1

Energy distribution : bad (side)
Ventilation performance : bad (supply and exhaust ducts are at the same level)

Appendix 7 (Result)

		Option 1		Option 2		Option 3		Option 4	
									
Adaptability	**Circulation** Weight 1	●●○○	2	●○○○	1	●●●○	3	●●●●	4
	Form Neutrality Weight 2	●●○○	4	●○○○	2	●●●●	8	●●●○	6
	Ceiling Height Weight 3	●●●○	9	●○○○	3	●●●●	12	●●●○	9
	Surface Area Weight 1	●●●○	3	●●○○	2	●○○○	1	●●●●	4
Variability	**Opening Size** Weight 3	●○○○	3	●●●○	9	●●●●	12	●●○○	6
	Housing unit Weight 3	●○○○	3	●●●○	9	●●●●	12	●●○○	6
	Wet space area Weight 3	●●○○	6	●●●○	9	●●●●	12	●○○○	3
	Maintanance Weight 2	●●●●	8	●●●○	6	●○○○	2	●○○○	2
Construction	**Amount of Material** Weight 1	●●○○	2	●●●○	3	●●●●	4	●○○○	1
	Diversity of Infill Method Weight 2	●●○○	4	●●●●	8	●●●●	8	●●○○	4
	Surface Area of Service Weight 2	●●○○	4	●●●●	8	●○○○	2	●●●○	6
	Climate Performance Weight 1	●●●○	3	●●●●	4	●●●○	3	●○○○	1
Total Weighted Score		51		64		79		52	