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# Construction in extreme environments: Definition of extremeness and parameter analysis of case projects

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**Abstract.** With an aim to gain a better understanding of human habitats and contribute to the enhancement and sustainability of built environments, this paper focuses on the reciprocal of our living environment and first attempts to define the ‘extremeness’ of environments; an ‘extreme environment’ is defined as an environment unsuitable for human habitation. Factors that determine extremeness are examined, and a matrix to categorize and qualitatively evaluate the extremeness of environments is constructed. The discussion then proceeds to the composition of a framework for case studies on construction projects in extreme environments. Three sets of parameters are given as the constituents of the framework: the project’s scope, environmental conditions, and elemental technologies. By applying the framework to case projects, interdependencies between the parameters are identified.

## 1. Introduction

Through unforeseeable natural disasters and long-term climate change, our current living environments, without exception, could potentially transform into harsh environments where it is difficult for human beings to survive. Therefore, developing technologies that enable the construction of communities in environments conventionally hostile to human habitation is important. It would contribute as a means to enhance our built environments and sustain human society. From this viewpoint, the purpose of this paper is to explore the fundamental conditions of our habitat by focusing on its complementary environments and develop a theoretical foundation for advancing building technologies toward constructing human communities in hostile environments.

Multiple categories of environments are referred to as extreme environments, for example, polar regions, highlands, oceans, and space, and each of these environments has a distinguished history of research and exploration. However, theoretical examination and case studies from a perspective of human habitability in these environments as a whole, and extreme environments in general, allow further consideration and development. Therefore, this paper first examines the preconditions of the environments conventionally described as extreme and attempts to define the constituents of the extremeness of environments.

There are also numerous examples of technical investigations, theoretical examinations, and on-going projects concerning building construction in each type of hostile environment, and conferences and institutions exist where such cases are addressed, such as the Biennial International Conference on Engineering, Science, Construction, and Operations in Challenging Environments (Earth and Space) hosted by the American Society of Civil Engineers (ASCE) [1] or Extreme-Design.eu [2], a Europe-

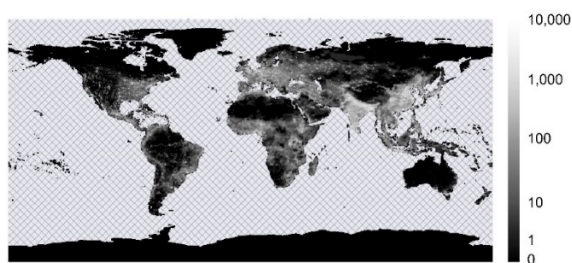


based research project group. Nonetheless, the scope of these cases (i.e., the purpose and scale of building construction and the range of technologies) are widely diversified, and the knowledge acquired through these cases requires further systematization for future utilization. This paper thus seeks to devise a framework for the systematic and transversal analysis of existing cases, with an aim to reveal technologies yet to be developed for constructing built environments in extreme environments in general.

## 2. Definition of Extreme Environments

### 2.1. Human-centric definition

Although the term ‘extreme environment’ is used in several disciplines, such as studies of extremophiles or astrobiology [3], an extreme environment, in this paper, signifies environments that are only extreme concerning human habitation, not living organisms in general. Therefore, an extreme environment in this paper is defined as an environment that poses difficulties for human habitation. With this definition, extreme environments are considered the reciprocal of our living environment. Figure 1 provides an overview of the distribution of extreme environments on the Earth’s surface.



**Figure 1.** Global map of population density (per km<sup>2</sup>) [4]. The dark areas indicate the location of extreme environments on the Earth’s terrain.

### 2.2. Conventional names of environments

Based on the definition provided above, conventional names for describing extreme environments are listed in Table 1 for further examination of the preconditions of the extremeness of environments.

The items of indices A to F were categorized by sequentially negating the following conditions that satisfy the temperate climate zones: (1) on-Earth, (2) on-land, (3) mid-latitude, (4) aboveground, (5) low elevation, and (6) with precipitation. Items G (isolate island) and H (dense forest) are environments that appear dark in Figure 1 but are excluded from A to F. I (disaster area) and J (radiation-contaminated area) are environments generated by temporary events, and items K to M are environments found within a built environment. Conceivable subcategories for each item are also listed.

### 2.3. Environmental-Extremeness Matrix

Having listed the environmental categories conventionally considered ‘extreme’, it is apparent that the factors contributing to the extremeness of each environment are diverse, and differences between extreme environments cannot be discussed without evaluating these factors. Therefore, this paper introduces the environmental-extremeness matrix (EXM) for the qualitative classification of environments by examining which factors determine the extremeness of each environment.

**2.3.1. The constituting parameters of the EXM.** As the major components contributing to environmental extremeness (i.e., the difficulty of human habitation), this paper proposes two qualities of environments: intolerability and resource unavailability. When considering the preconditions of extreme environments, only natural and geographic aspects tend to gain attention, but as Bannova [6] indicated, acknowledging social, political, and economic factors is also crucial.

Intolerability is a parameter that describes the degree of difficulty humans experience in maintaining their physical condition in the environment, and it also represents the static facet of an environment. While various factors contribute to the intolerability of an environment, this paper attempts to represent the parameter in one dimensional axis to focus on survivability, which is a single aspect of an environment. On the other hand, the resource unavailability parameter describes the degree of difficulty

**Table 1.** List of conventional names of extreme environments<sup>a</sup>.

	Name	Name	Name
<b>A</b>	<b>Space</b>	<b>E</b>	<b>Highlands<sup>b</sup></b>
A1	Inner Space	E1	Extreme Altitude
A2	Low Earth Orbit	E2	Very-High Altitude
A3	Moon	E3	High Altitude
A4	Mars	<b>F</b>	<b>Desert</b>
<b>B</b>	<b>Waters</b>	F1	Desert (Center)
B1	Undersea	F2	Desert (Periphery)
B2	Sea Surface	<b>G</b>	<b>Isolated Island</b>
B3	Freshwater	G1	Isolated Island (Remote)
<b>C</b>	<b>Underground</b>	G2	Isolated Island (Vicinity)
C1	Underground (Soil)	<b>H</b>	<b>Dense Forest</b>
C2	Underground (Ice)	H1	Dense Forest (Center)
<b>D</b>	<b>Polar Region</b>	H2	Dense Forest (Periphery)
D1	Arctic		
D2	Antarctica		
		<b>I</b>	<b>Disaster Area</b>
		I1	Storm-Hit Area
		I2	Flooded Area
		I3	Earthquake-Hit Area
		I4	Volcanic Disaster Area
		I5	War-Ravaged Area
		<b>J</b>	<b>Radiation-Contaminated Area</b>
		J1	Radiation-Contaminated (Underground)
		J2	Radiation-Contaminated (Aboveground)
		<b>K</b>	<b>Slum</b>
		<b>L</b>	<b>Polluted Area</b>
		<b>M</b>	<b>Hazardous Facility Neighborhood</b>

<sup>a</sup> Non-exhaustive.<sup>b</sup> This category is based on the International Society of Mountain Medicine's classification [5].**Table 2.** Criteria and scales of the parameters of EXM.

	Intolerability	Resource Unavailability
<b>Criteria</b>	Whether a human being with sufficient provisions can maintain his or her physical condition in the environment without protection.	Whether a human being with physical protection can gain access to natural, human, and social resources in the environment.
<b>Scale</b>	0: Tolerable 1: Deterioration in health conditions (fatal in days) 2: Death (in hours) 3: Immediate death (in minutes)	0: Possible 1: Difficult 2: Impossible

Resource Unavailability	<b>2</b>	G1 Isolated Island (Remote) H1 Dense Forest (Center)	F1 Desert (Center)	B2 Sea Surface D2 Antarctica E1 Extreme Altitude	A Space B1 Undersea C Underground J1 Radiation Contaminated (Underground)
	<b>1</b>	G2 Isolated Island (Vicinity) H2 Dense Forest (Periphery) I Disaster Area	E3 High Altitude F2 Desert (Periphery) I2 Flooded Area I4 Volcanic Disaster Area	B3 Freshwater D1 Arctic E2 Very-High Altitude J2 Radiation Contaminated (Aboveground)	
	<b>0</b>		K Slum L Polluted Area M Hazardous Facility Neighborhood		
		<b>0</b>	<b>1</b>	<b>2</b>	<b>3</b>
		Intolerability			

**Figure 2.** EXM with items from Table 1.

Resource Unavailability	<b>2</b>	<b>3</b>	<b>4</b>	<b>5</b>
	<b>1</b>	<b>2</b>	<b>3</b>	
	<b>0</b>	<b>1</b>		
	<b>0</b>	<b>1</b>		
	Intolerability			

**Figure 3.** Degree of Extremeness (DoX).

encountered in gaining access to resources required for human habitation (e.g., energy, food, water, goods, and information, services), which incorporates the social, political, and economic features. Resource unavailability also represents the dynamic facet of an environment. Table 2 shows the criteria and scale of each parameter, and an example of classifying the environmental categories listed in Table 1 is illustrated in Figure 2.

However, objectivity of the evaluation in the EXM is still insufficient, since objective boundaries between the classified names of environments are yet to be defined. Means to categorize and label a certain environment and distinguish it from other environments require further examination.

**2.3.2. Degree of Extremeness (DoX).** In the EXM, our living environment (i.e., the complement of extreme environments) can be classified in the cell with 0 intolerability and resource unavailability. Using this matrix, a degree of extremeness (DoX) can be defined as the indicator of the comprehensive extremeness of an environment, according to the distance from the cell with the scale of 0 for both parameters (Figure 3). It can be predicted that technical demands are higher for environments with high DoX.

### 3. Analysis Framework

#### 3.1. The parameters of the framework

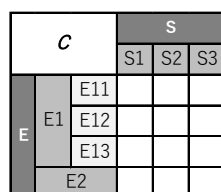
To systematically examine construction projects in extreme environments, this paper describes each case with three sets of parameters: parameters related to the scope of the project, parameters of environmental conditions, and elemental technologies of the project. Given that each set of parameters are represented with  $S$ ,  $E$ , and  $T$  respectively, a case project  $C$  can be illustrated with the formula:

$$C = (S, E, T) \quad (1)$$

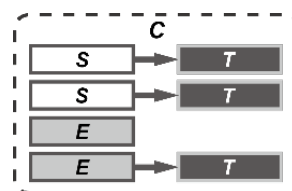
Bannova [7] suggests that human requirements and environmental influences are two factors that should be considered when planning and designing architecture in extreme environments, and the two parameter sets described above (i.e., scope and environment) correspond to these factors. The structure and interrelations of parameters within the sets are examined in the following sections. The component parameters of each set are as follows:

**Table 3.** List of scope ( $S$ ) and environmental ( $E$ ) parameters.

$S$ : Scope parameters		$E$ : Environmental parameters	
<b>S1:</b> Function	Function.	<b>E11:</b> Phase	Physical phase of the environment.
<b>S2:</b> Spatial scale	(a) Size; (b) Capacity.	<b>E12:</b> Geometry	(a) Topography (geometry of solid environment); (b) Meteorology (geometry of gaseous environment).
<b>S3:</b> Temporal scale	(a) Physical duration; (b) Visit duration of individuals.	<b>E13:</b> Quality	(a) Temperature; (b) Desiccation; (c) Radiation; (d) Acidity; (e) Salinity; (f) Pressure; (g) Oxygen pressure; (h) Gravity.
		<b>E2:</b> Resource unavailability	(a) Feasible resources; (b) Time distance to nearest city on land; (c) Barriers to resource usage.



**Figure 4.** Format of an S-E Matrix.



**Figure 5.** Format of a SET Digraph.

*3.1.1. Scope parameters (S).* In this paper, the scope of a case indicates the range or domain of the project, and it consists of three subsets of parameters: function (*S1*), spatial scale (*S2*), and temporal scale (*S3*). The spatial and temporal scales can be decomposed to elemental parameters: the physical size, such as the volume or area, capacity, or physical duration of the building, and the visit duration of individual personnel.

*3.1.2. Environmental parameters (E).* The environmental parameter of a case project is composed of parameters related to intolerability (*E1*) and resource unavailability (*E2*), which are parameters used to construct the EXM. The subsets of intolerability are phase (*E11*), geometry (*E12*), and quality (*E13*). The phase indicates which material phase (i.e., gas, liquid, or solid) the environment is in or whether the environment is between two different material phases, and the geometry of an environment indicates the physical morphology of the environment. The quality of an environment is a set of measurable components of an environment, which includes nine environmental components defined by NASA's Astrobiology Institute [7] (i.e., temperature, desiccation, radiation, acidity, salinity, pressure, and oxygen pressure) and gravity. As for resource unavailability, three factors were employed as its parameters: types of resources feasible in the environment, time distance to nearest city on surface transportation [8], and limitations to resource usage.

*3.1.3. Elemental technologies (T).* Numerous technologies are in use to support each construction case project in extreme environments. This paper focuses on technologies developed to meet the requirements of each scope and environmental parameters and refers to these technologies as elemental technologies.

### *3.2. Composing the frameworks*

Using the three sets of parameters defined in the previous section, three frameworks were composed for case analysis purposes.

*3.2.1. Parameter list.* For each case project *C*, a list of scope and environmental parameters is compiled to make comparisons between different cases. The items of the parameter sets are shown in Table 3.

*3.2.2. S-E Matrix.* To analyze the interrelationships between the scope and environmental parameters within each case, an S-E Matrix (i.e., a matrix with scope parameters as columns and environmental parameters as rows) is constructed (Figure 4).

*3.2.3. SET Digraph.* Relationships between the elemental technologies and the scope and environmental parameters are illustrated in digraphs, the format of which is shown in Figure 5.

## **4. Case Analysis: Built Environment in an eXtreme Environment (BEXE)**

### *4.1. Case projects*

In the extreme environments defined above, various cases of construction projects and built environments (i.e., built environments in an extreme environment (BEXE) exist, and each case is different in its purpose, function, scale, and other factors (Table 4). In this paper, considering the availability of detailed literature, six BEXEs (i.e., the International Space Station (ISS; C1), Super Kamiokande (C4), Syowa Station (C8), Mount Fuji summit observatory (C10), Biosphere 2 (C13), and Chernobyl New Safe Confinement (NSC; C18)) were chosen as case analysis subjects.

### *4.2. Application of the frameworks*

*4.2.1. Decomposing the environmental parameters E.* Parameter lists were compiled for each of the six cases in the study (Table 5). As apparent from the lists, environmental parameters are different in

each case, and because it can be interpreted that the environmental parameters are independently defined by the cases, the environmental parameters can be described as  $E(C)$ .

Furthermore, among the parameters included in  $E$ , some parameters act as strong constraints to the BEXE, such that the environmental parameter, in particular, must be technologically modified for the realization of the scopes, while other parameters do not. When environmental parameters functioning as strong constraints are written as  $X$ , and the other moderate parameters  $M$ ,  $X$  and  $M$  are both subsets of  $E$  with different characteristics, but it is not obvious that these two subsets are independent of each other. Therefore, the parameter set  $E$  can be described as a union allowing duplication:

$$E = X \cup M \quad (2)$$

**Table 4.** Exemplar cases of BEXE.

Index	Name		Located Environment	Reference
<b>C1</b>	<b>International Space Station (ISS)</b>	A2	Low Earth Orbit	<b>[9]</b>
C2	North Atlantic Offshore Wind Turbines	B2	Sea Surface	[10]
C3	Petronius Oil Platform	B2	Sea Surface	[11]
<b>C4</b>	<b>Super Kamiokande</b>	C1	Underground (Soil)	<b>[12]</b>
C5	CERN LEP Collider	C1	Underground (Soil)	[13]
C6	IceCube Neutrino Observatory	C2	Underground (Ice)	[14]
C7	Svalbard Global Seed Vault	D1	Arctic	[15]
<b>C8</b>	<b>Syowa Station</b>	D2	Antarctica	<b>[16]</b>
C9	McMurdo Station	D2	Antarctica	[17]
<b>C10</b>	<b>Mount Fuji Summit Observatory</b>	E2	Very-High Altitude	<b>[18]</b>
C11	Atacama Large Millimeter/submillimeter Array	E2	Very-High Altitude	[19]
C12	Mongolian yurt	F2	Desert (Periphery)	[20]
<b>C13</b>	<b>Biosphere 2</b>	F2	Desert (Periphery)	<b>[21]</b>
C14	Masdar City	F2	Desert (Periphery)	[22]
C15	Mimamitorishima (Marcus Island)	G1	Isolate Island (Remote)	[23]
C16	Canopy Observation System, Sarawak	H2	Dense Forest (Periphery)	[24]
C17	ONKALO Spent Nuclear Fuel Repository	J1	Radiation Contaminated (Underground)	[25]
<b>C18</b>	<b>Chernobyl New Safe Confinement</b>	J2	Radiation Contaminated (Aboveground)	<b>[26]</b>

*4.2.2. Relationships between scope parameters  $S$  and environmental parameters  $E$ .* S-E Matrices were depicted for each case. The matrix for Syowa Station (C8) is shown in Figure 6 as an example. The X marks in the matrix represent the environmental parameters that are especially restrictive to the scope in each column.

Using Syowa Station as an example, while the environmental parameter of ‘uneven flatland’ is highly restrictive to the area of 7,480 m<sup>2</sup>, it is not apparent that the same environmental parameter would similarly be a constraint to BEXEs with different scope parameters, such as a base camp with an area of 10 m<sup>2</sup>. Hence, the distribution of elements in  $X$  and  $M$  can be described as dependant on scope  $S$ :

$$E(C) = X(S) \cup M(S) \quad (3)$$

Moreover, among the parameters in sets  $X(S)$  and  $M(S)$ , it can be supposed that some parameters are unaffected by the scope parameters, independent of whether they function as constraints. For instance, the physical phase of Super Kamiokande (C4), a solid, can be described as a constraint regardless of the scope as long as the case examples are built environments constructed by humans. Therefore,  $X(S)$  and  $M(S)$  can be described as

$$X(S) \cup M(S) = E_s \cup X_c \cup M_c \quad (4)$$

Here,  $E_s$  represents environmental parameters with constraining qualities that are strongly affected by the scope parameters, and  $X_c$  and  $M_c$  represent the constraining and non-constraining environmental

parameters unaffected by the scope parameters. In sum, the set of environmental parameters  $E$  can be now described as the union sum of sets of parameters with different qualities.

$$E = Es \cup Xc \cup Mc \quad (5)$$

**Table 5.** Parameter list of selected cases (C1, C4, C8, C10, C13, C18).

	C1	C4	C8	C10	C13	C18
Name	International Space Station	Super Kamiokande	Syowa Station	Mount Fuji Summit Observatory	Biosphere 2	Chernobyl New Safe Confinement
Located environment	A2 Low Earth Orbit	C Underground (Soil)	D2 Antarctica	E2 Very High Altitude	F2 Desert (Periphery)	J2 Radiation Contaminated (Aboveground)
DoX	5	5	4	3	2	3
Intolerability	3	3	2	2	1	2
Resource Unavailability	2	2	2	1	1	1
Function	Research (experiments/ observations), Habitation	Research (neutrino observation)	Research (Antarctic observation), Habitation	Research (meteorological observation)	Research (experiment)	Environmental protection (confinement of nuclear reactor)
<b>S</b> Size	935 m <sup>3</sup>	78000 m <sup>3</sup>	7480 m <sup>2</sup>	165 m <sup>2</sup>	200,000 m <sup>3</sup>	3,000,000 m <sup>3</sup>
Capacity	6	2	75	N/A	8	N/A
Physical duration	> 20 yrs.	> 20 yrs.	> 60 yrs.	70 yrs.	100 yrs. (plan)	> 100 yrs.
Visit duration of individuals	< 2 yrs.	0.01 yr.	0.5 yr.	0.1 yr.	2 yrs.	0.1 yr.
Physical phase	Gas	Solid	Gas & Solid	Gas & Solid	Gas & Solid	Gas & Solid
Topography	-	-	Uneven flatland	Uneven slope	Flat terrain	Flat terrain
Meteorology	-	-	Snow drift Strong wind pressure	Strong wind pressure Lightning strike	Strong solar radiation	Snowfall
Temperature	-270 ~ 200 °C	40 ~ 50 °C	-20 ~ 0 °C	-20 ~ 10 °C	10 ~ 30 °C	0 ~ 20 °C
<b>E1</b> Desiccation	No water	Groundwater	No precipitation (ice and snow)	No precipitation (ice and snow)	Annual rainfall: 600 mm	Annual rainfall: 350 mm
Radiation	SPE, GCR	Natural radiation	Natural radiation	Natural radiation	Natural radiation	Fatal near reactor
Acidity	-	N/A	-	-	-	-
Salinity	-	N/A	-	-	-	-
<b>E</b> Pressure	0 atm.	200 atm.	1 atm.	0.6 atm.	1 atm.	1 atm.
O <sub>2</sub> pressure	0 atm.	0 atm.	0.2 atm.	0.1 atm.	0.2 atm.	0.2 atm.
Gravity	0 G	1 G	1 G	1 G	1 G	1 G
Feasible resources	Solar energy	Geothermal energy; Minerals	Solar & wind energy; Ice, snow, water; Minerals	Solar & wind energy; Ice, snow, water; Minerals	No major limitations	No major limitations
<b>E2</b> Time to nearest city on land	$\infty$	< 1 d	> 10 d	< 1 d	< 1 d	< 1 d
Barriers to resource usage	Rocket payload; Human operation; No wired communication	Payload of vehicles through haulage drift; No radio communication	Payload of supply vessel (3 per year) and vehicle; Limited professions	Payload of helicopter or human-power	Vehicle or aircraft payload	Vehicle or aircraft payload

4.2.3. *Relationships between the elemental technologies  $T$  and the parameters  $S$  and  $E$ .* Figure 7 shows the SET digraphs of the six examples of BEXEs. As this paper focuses on the elemental technologies derived from each scope and environmental parameters, the set of elemental technologies  $T$  can be expressed as  $T(S, E)$ . Following Equation 6, the elemental technologies  $T(S, E)$  can be also described as

$$T(S, E) = T(S) \cup T(Es) \cup T(Xc) \cup T(Mc) \quad (6)$$



This expression signifies that the technologies constituting cases of BEXEs can be deconstructed into four sets of technologies with different qualities: (1) technologies demanded by the scope of BEXE  $T(S)$ , (2) ones demanded by the environmental parameters that functions as constraints depending on the scope  $T(Es)$ , (3) ones demanded by the constraining environmental parameters regardless of the scope  $T(Xc)$ , and (4) ones demanded by the environmental parameters that are not constraints  $T(Mc)$

C8 Syowa Station		S				
		S1	S2	S3		
		Function	Size	Capacity	Physical duration	Stay duration of individuals
		Research; Habitation	7480 m <sup>2</sup>	75	> 60 yrs.	0.5 yr.
E	E1	Gas & Solid				
		Uneven flatland	X			
		Snow drift	X	X	X	X
		Strong wind pressure in blizzards	X	X	X	X
		-20°C ~ 0°C	X	X	X	X
		No precipitation (ice and snow)	X	X	X	X
		Natural radiation				
		-				
		-				
		1 atm				
		0.2 atm				
		1 G				
	E2	Solar & wind energy; ice, snow, water; Minerals	X	X	X	X
		> 10 d	X	X	X	X
		Payload of supply vessel (3 times per year) and snow vehicle	X	X	X	X

**Figure 6.** S-E Matrix of Case-8: Syowa Station. Each X mark in the cells indicates that the environmental parameter in the corresponding row functions as a restrictive condition on the scope parameter in the corresponding column of the cell.

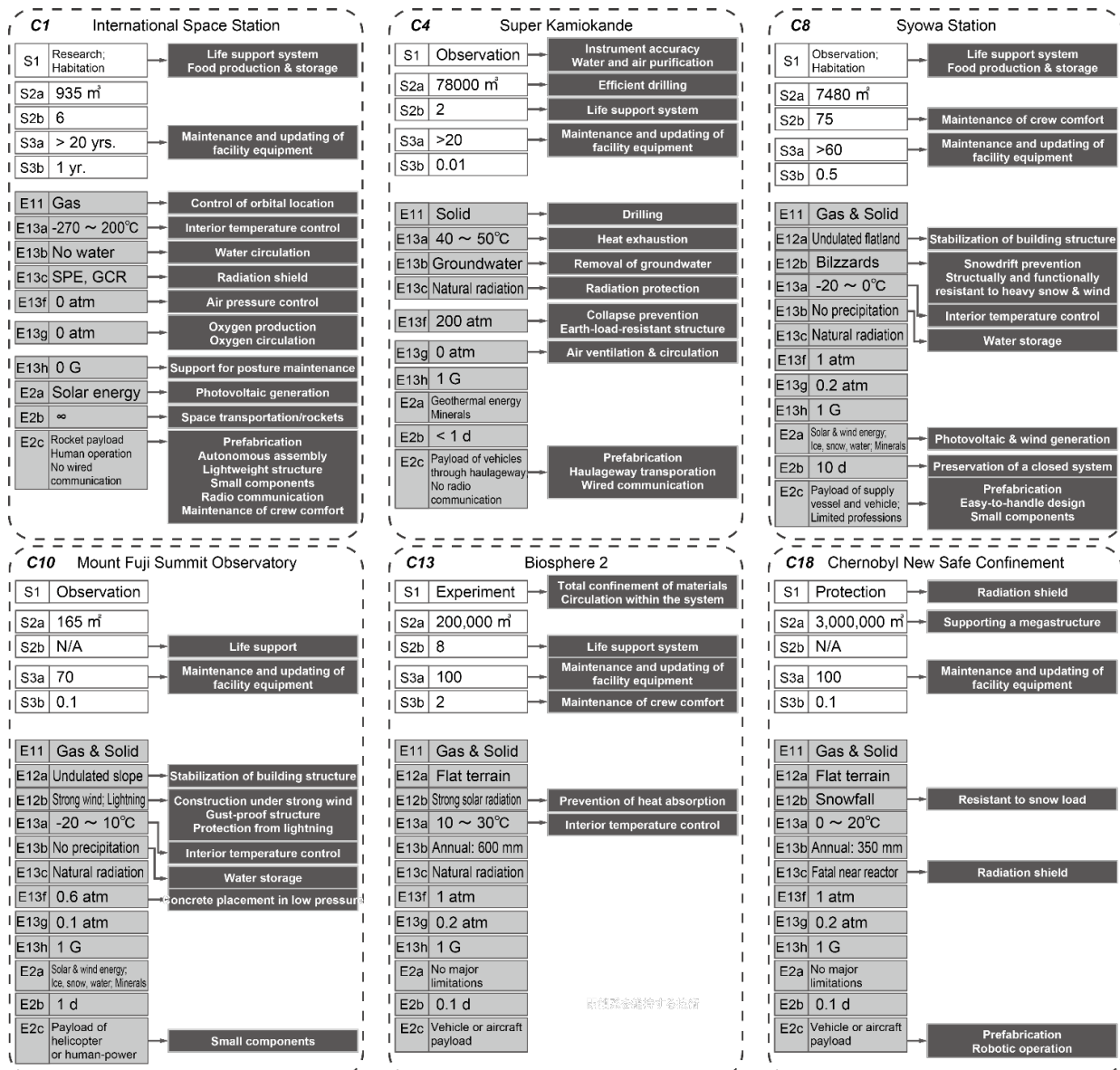
## 5. Concluding Remarks

This paper first attempted to define the concept of an extreme environment and composed frameworks for systematic analyses of cases of BEXE with various scopes and environmental conditions. The elemental technologies composing each BEXE can now be viewed as a union of four different sets of technologies, and as the technologies strongly are related to the dominant environmental parameters in each environment, two sets of technologies— $T(Es)$  and  $T(Xc)$ —were extracted. These sets of technologies correspond to different parameters with different attributes. Therefore, it can be assumed that different approaches and potentials can be conceived for each of these sets. Additionally, extracting the environmental parameters  $Es$  and technologies  $T(Es)$ , which are strongly influenced by the scope  $S$ , can contribute to identifying critical technologies and effective problem-solving to realize given sets of scopes, such as constructing a self-sustaining large-scale community. Further case analyses with additional examples and information are required, and the way technologies related to each BEXE are illustrated must be examined in greater detail.

Through further development, the results of this research can be expected to contribute to the human society preparing for substantial changes in the environment, such as natural and human disasters and climate change. Establishing a framework for analyzing the hostility of an environment enables appropriate evaluation of the effect of environmental changes on human society. Furthermore, understanding the relationships between environmental parameters and the technologies used to construct and maintain built environments could guide planners, designers and engineers to create built environments most adaptable to the given environment.

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**Figure 7.** SET Digraphs of selected cases: C1, C4, C8, C10, C13, C18.

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