Study on the Guiding and Control Index for the Design of Residential Building in the Northwest China Focuses on Generalized Solar Energy Utilization

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Abstract

Guiding and control index (GCI) is recognized as a useful tool to direct architecture design in terms of energy consumption, etc. To promote the development of solar energy technologies, and focusing on the utilization of generalized solar energy (GSE), this paper explores the establishment principle and method of GCI for residential building design in northwest China. Firstly, the meaning of GSE is explained and the Solar and Thermal Engineering Map of Gansu province was created, which form the bases for GCI establishment. Secondly, the classification of indexes from technical standards, policies and evaluation standards of China about GSE utilization are abstracted and presented, which provided a base for classification of GCI. Thirdly, new concepts regarding thermal domain (TD) and auxiliary domain (AD) of residential buildings are put forward, and principles and methods for the establishment of GCI are discussed. Finally, examples of GCI establishment regarding window-wall ratio in Gansu region are introduced.

Keywords: guiding and control index (GCI), generalized solar energy, thermal domain, residential building, China.

1. Introduction

Climate change and the scarcity of energy resources are two of the big challenges the world has to face in the near future, the shortage of fossil fuel energy and the risks of using nuclear energy have indirectly promoted the development of renewable energy (Miljana and Maria, 2012). It has been reported that renewable energy provided about 18.2% of global primary energy consumption in 2017, in which the contribution of modern renewable technologies accounts for 10.4% (REN 21, 2018).

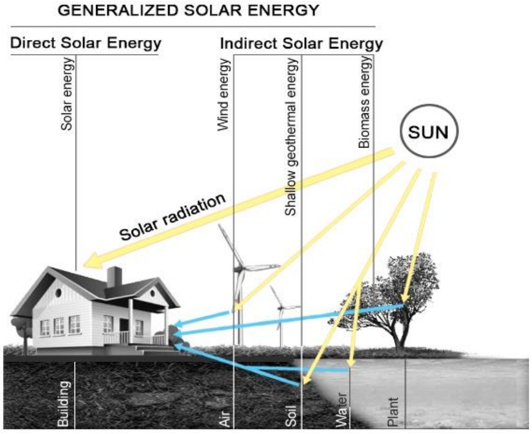

Fig. 1: The meaning of generalized solar energy

Many countries and regions, including the European Union, China, Australia, etc. have established ambitious goals for promoting the development and utilization of renewable energy on a long term (European Community, 2011; NDRC, 2016). Generalized solar energy (GSE) consists of direct solar energy and indirect solar energy

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(solar energy stored in soil, water, air and plants, etc.), which forms the main component of renewable energy (Fig. 1).

GSE can be converted into electricity or heat for human use, and it is abundant in Northwest China area. Gansu province, for example, is located in northwest China. It covers an area of 13085.6km^2 and has narrow terrain and diverse landforms. The global solar radiation (GSR) of Gansu is between 4700~6350 MJ m^{-2} and its geographical distribution is decreased from northwest to southeast. Relevant studies show that solar energy resources in Gansu can be divided into three main regions, they are very rich area (GSR>6100 MJ m^{-2}), rich area (6100>GSR>5400 MJ m^{-2}) and available area (5400>GSR>4700 MJ m^{-2}) (Zhu et al. 2010). Meanwhile, according to the Code for Thermal Design of Civil Building (MOHURD, 2016a), China is divided into five building thermal engineering areas (Sever Cold, Cold, Hot Summer and Cold Winter, Hot Summer and Warm Winter and Warm area), in which Gansu possesses three of them: Severe Cold area ($t_{min\cdot m} \leqslant -10$℃), Cold area (-10℃$< t_{min\cdot m} \leqslant 0$℃) and Hot Summer and Cold Winter area (HSCW) (0℃$< t_{min\cdot m} \leqslant 10$℃, 25℃$< t_{max\cdot m} \leqslant 30$℃)[1]. Because of the complexity of its solar energy resource distribution and climate environment, Gansu region become a typical place for researching the application of GSE. A repartition map is proposed for establishing guiding and control index (GCI) for architectural design in Gansu. It was an overlap of two different maps: the map of solar energy resources distribution and the map of building thermal engineering distribution. The proposed map is called the Solar and Thermal Engineering (STE) map, in which Gansu is divided into 5 areas, they are “very rich and very cold area” (area 1), “rich and cold area”(area 2), “rich and very cold area” (area 3), “available and cold area” (area 4), “available and HSCW area” (area 5). (Fig. 2)

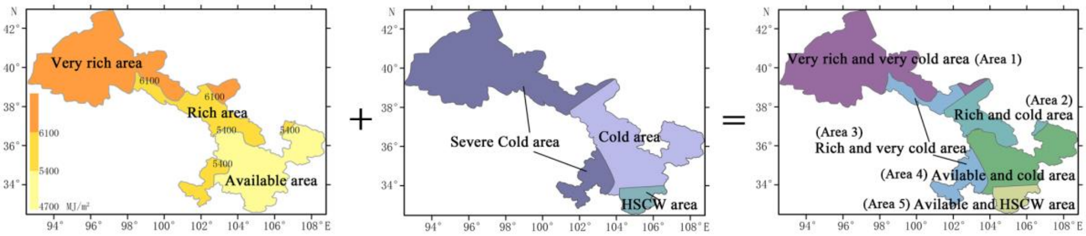

Fig. 2: The formation path of Solar and Thermal Engineering (STE) map

STE map shows information of heat gain and loss that should be considered in building design. The richness of direct solar energy indicates the efficiency level of heat gains; at the same time, the thermal performance information presents heat loss of building. These two main issues are shown at the same time so as toguide architects to make more reasonable decisions when design solar residential buildings. Meanwhile, indirect solar technology can be selected and adjusted based on the intensity of direct solar radiation. This map can also guide the development of GCI for GSE utilization and energy conservation.

It is noted that studies about GCI that is focused on the building scheme design stage are still insufficient, the integration of GSE technologies in the residential buildings are also insufficient (Qi, 2016). This paper explores new indexes based on existing studies and standards, so as to promote the application of solar technologies in China.

2. Literature review

Utilization of GSE can be an effective way to achieve coordination among economic, society and environment. With this background, evaluation standards for solar energy utilization in residential buildings have been developed in many countries. For example, BREEAM (Building Research Establishment Environmental Assessment Method) promotes optimizing building energy efficiency and reduce carbon emission (BRE, 1990); LEED (Leadership in Energy and Environmental Design) encourages the solar energy integrated with building design and provides relevant rewards for it (USGBC, 2014); DGNB (Deutsche Gesellschaft für Nachhaltiges Bauen) emphasizes total primary energy demands and proportion of renewable primary energy in the “Ecological Quality” (GSBC, 2007). ASGB (Assessment Standard for Green Building) focus on the ratio of renewable energy,

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[1] In this paper, “$t_{min\cdot m}$” means average temperature of the coldest month and “$t_{max\cdot m}$” means average temperature of the hottest month.

especially solar energy, to building energy consumption (MOHURD, 2019). These evaluation standards care more about the ultimate energy-saving performance, many indexes of them cannot directly guide architects when designing solar buildings. Because they require a long path (simulation, field test or complex computing) to be translated into direct references for scheme design. In order to help architects to play a more active role in the green building design process, Liu (Liu, 2019) proposed three concepts for the establishment of GCI for the scheme design stage, which are “distance of action”, “processing time” and “position of action”, according to which, all the indexes can be divided into 3 categories: A (short processing time/ can do quick judgment), B (medium length of processing time/require some calculation), C (long processing time/require massive time for calculation or simulation). Based on these the above concepts, indexes relating to GSE utilization in the existing technical standards, policies and evaluation standard of China are studied and categorized (Tab. 1).

Tab. 1: indexes classification from technical standards, policies and evaluation standard of China about GSE utilization

Name of standards/codes	Guiding stages	Categories	Items of index	Numbers
Evaluation standard for solar water heating system of civil buildings (MOHURD, 2011)	Building planning	B	4.2.4, 4.2.5	2
		C	4.2.6, 4.2.7, 4.2.8	3
	Building design	A	4.3.5, 4.3.6, 4.3.7, 4.3.8	4
		B	4.3.3, 4.3.4	2
		C	4.3.2, 4.3.10, 4.3.11	3
Design code for residential buildings (MOHURD, 2012a)	Building planning	C	3.0.4, 3.0.5	2
	Building design	A	7.1.3, 7.1.6, 7.1.7, 7.2.3, 7.2.4	5
		B	7.1.1, 7.1.4, 7.1.8, 7.2.1	4
		C	7.2.2	1
Technical code for passive solar buildings (MOHURD, 2012b)	Building planning	C	1.0.3, 4.1(3), 4.2(3)	7
	Building design	A	4.3.2, 4.3.3, 4.3.5.4, 4.3.6, 5.2.3, 5.2.4, 5.2.5,5.2.6, 5.2.7, 5.2.8, 5.4.4	11
		B	4.3.4, 4.3.5, 5.2.2, 5.4.2, 5.4(4)	8
		C	3.0.1, 3.0.2,3.0.3, 4.4(6), 4.5(7), 4.6(3), 5.2.1, 5.3(2)	22
Standard for daylighting design of buildings (MOHURD, 2013)	Design stage	A	5.0.1, 7.0.2, 7.0.3, 7.0.4	4
		B	5.0.2, 5.0.4, 7.0.5, 7.0.6	4
		C	5.0.3, 5.0.8, 5.0.9, 7.0.1, 3.0.6	5
Technical specification for integration of building and solar photovoltaic system (MOHURD, 2016b)	Building planning	C	1.0.3, 4.2(4)	5
	Building design	A	4.3.7, 4.3.8, 4.3.9, 4.3.10, 4.3.11, 4.3.12, 4.3.13	7
		B	4.3.1,4.3.3, 4.3.4, 4.3.5, 4.3.6	5
		C	4.1(4), 4.3.2	5
Standard for urban residential area planning and design (MOHURD, 2018)	Building planning	B	4.0.9	1
		C	3.0.7, 4.0.8	2
		A	8.2.1, 7.2.11	1

Assessment standard for green building (MOHURD, 2019)	Building planning	B	4.1.3,8.2.3, 8.2.5, 8.2.9	4
		C	7.1.1, 8.1.1, 8.1.2, 8.1.3, 8.1.4, 8.2.2, 8.2.8	7
	Building design	A	7.1.2, 7.1.3, 7.2.7, 7.2.10	5
		B	5.2.10, 5.2.11, 7.2.1, 7.2.2, 7.2.3, 7.2.12, 7.2.13	7
		C	5.2.8, 7.2.4, 7.2.5, 7.2.6, 7.2.8, 7.2.9, 7.2.13	7

Table 1 shows that indexes relating to GSE utilization in the existing standards/codes mostly fall in category C, which are hard to be applied directly by architects. There are also many category B indexes that need to be calculated before application. Take "Assessment Standard for Green Building (GB/T 50378-2019)" as an example, the number of indexes about GSE utilization is 31, including 14 category C indexes (such as 5.2.8, "the proportion of domestic water provided by renewable energy sources $R_{hw} \geqslant 80\%$, which needs simulations)", 11 category B indexes (such as 5.2.10 "the ratio of ventilation opening area to floor area of a room reaches 5% in other region", which needs calculations) and 6 category A indexes (such as 8.2.1 "the original waters, wetlands, vegetation, etc. should be protected", which is easy to judge). However, there is little time for architects to calculate or simulate during the planning and design stage, so the insufficiency of category A indexes for solar building scheme design stage would be a disadvantage for promoting development of solar building, and scheme design stage has great influence on the outlook of building as well as the performance of GSE application (Haider et al. 2019). The more direct guidance that architects can get, the more efficient their design can be; therefore, developments of GCI of category A or B for architects becomes necessary and valuable.

3. Thermal domain and methods for developing GCI

3.1. Thermal domain and auxiliary domain

The source of GSE varies from day to night and from summer to winter, the energy needs of people in residential building also changes with time and seasons. Buildings should adjust themselves appropriately to adapt these changes and needs. The way trees respond to the seasonal change provides a good reference for residential building design. The core of a tree is its trunk. In hot season, leaves provide shade and roots absorb water for cooling; in cold season, trunk exposures to sunlight and decayed leaves provide heat for its core. Referring to the adjustment modes of tree, residential buildings can also have its core area, and in this paper it is defined as a Thermal Domain (TD) (Fig. 2).

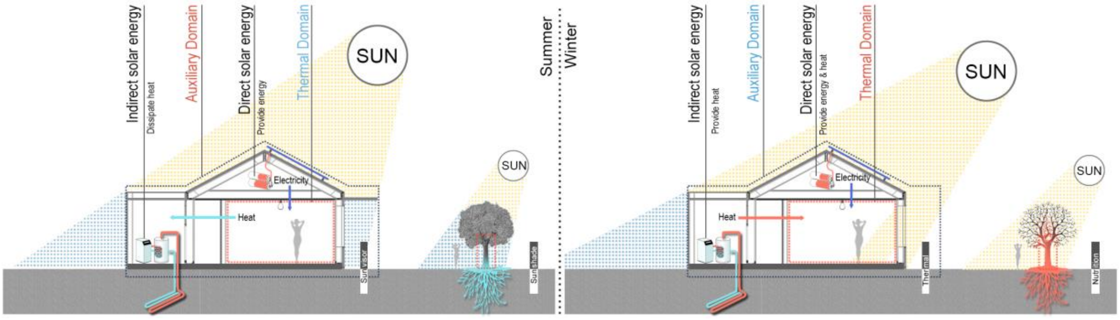

Fig. 2: The function of TD and AD

TD is characterized by heat gain. It is the major active areas of residential building and majority of building energy is consumed here; it also has a higher need for indoor comfort. TD in residential buildings mainly include bedroom, living room etc. Auxiliary Domain (AD) is the region around TD. It includes auxiliary rooms and space near TD. TD and AD have different functions: the former should improve its thermal insulation performance and reduce energy consumption, while the later should captures as much GSE as possible to supply the demand of TD. This concept gives architects a clear building design thought to use GSE and it can help to develop valuable GCI for design. The purpose is to identify the core to be served by GSE and provide appropriate work division for different domain.

3.2. Basic principle of GCI

The GCI of GSE utilization for building design should follow three principles (Liu, 2019):

(1) Target associated: GCI should have a clear target association to the design goal of GSE utilization, which will guide the architects to choose a reasonable technology.

(2) Decision associated: an index should be conductive for guiding architects to choose a GSE utilization methods. Therefore, GCI should be logically related to GSE utilization method that can be adopted in buildings.

(3) Suitable for fast decision-making: if one GCI need long time or a lot of simulation to judge, it will affect the flow of design thinking, so GCI should help architects make fast decisions, especially in the early design stage.

3.3. Methods for the establishment of GCI for GSE utilization

(1) TD as the core of energy conservation.

Setting up a TD and AD for a residential building does not mean to split one building into two parts, its essence is to clarify the core area of one building. In the scheme design stage, the AD should be considered to have relevant installation platforms for energy equipment and provide passive energy-saving technologies support for TD. Firstly, an AD should consider integration of building and solar energy technology. It needs to facilitate installation and maintenance of solar heating system and solar photovoltaic system etc. Secondly, an AD should provide proper sunshade (adjustable sunshade or fixed sunshade) and insulation measures (sunroom, insulation wall, etc.) for the TD. At the same time, a TD should reduce its energy consumption and make use of passive technology to reduce carbon emissions. Firstly, the shape coefficient of thermal domain should be controlled to reduce heat loss. Secondly, energy-efficient appliances such as floor heating should be installed in the TD. Thirdly, passive energy saving device, heat insulating window as an example, should be adopted in this domain. Based on the difference between TD and AD, some GCIs with clear target can be established.

(2) Index for comprehensive utilization of regional generalized solar energy.

The potential of exploration and utilization of GSE varies in different region. GSE include direct solar energy and indirect solar energy (wind energy, shallow geothermal energy and biomass energy). Take Gansu province as an example, China National Renewable Energy Centre (CNREC, 2019) has published the energy distribution of Gansu region, relevant studies also gave available GSE in difference regions of Gansu (Tab.2). It shows that solar energy is available in all regions and it can be the main source of energy utilization, auxiliary energy can be selected based on the geographical and economic environment. This information will help designers to choose appropriate energy utilization strategies.

The objective for energy efficiency in building design needs to be set in the planning stage. However, unlike the appearance and plan of one building, it is very difficult to link the energy saving effect with the scheme design for architects. Because no tool that can give visualized results about the relation between a scheme design and the amount of energy consumption is available yet. However, there have been many researches on design method focus on the goal-oriented green performance, the performance simulation, parametric calculation and genetic algorithms and other aided design tools are adopted. Duan Liangfei (Duan et al, 2015) used eQUEST software to simulate the cold and heat load of a residential building in Shijiazhuang, the influence of single factors such as such as heat transfer coefficient of external wall, heat transfer coefficient of external window and shading coefficient on energy consumption had been analyzed, the influence degree of each factor on residential building energy consumption had been presented. Ren Jiqing (Ren et al, 2019) used genetic algorithms to construct the goal-oriented model of minimizing incremental cost and maximizing incremental benefit of green building schemes, it was concluded that optimal energy saving effect can be achieved through an effective and reasonable combination of technologies. These kinds of researches provide a reference for the establishment of GCI. GCI should provide suggestions for architects about the energy saving methods and technology using, meanwhile, it should have a clear logical relationship with the energy saving target.

Tab. 2. Main energy and auxiliary energy of different regions of Gansu

Main energy	Auxiliary energy	Region
Solar energy	Wind energy	Jiuquan, Jiayuguan, Baiyin, Zhangye, Wuwei, Dingxi, Pingliang (Zhang, 2011)
	Shallow geothermal energy	Dunhuang, Lanzhou, Jinchang, Baiyin (Qiu, 2009)
	Biomass energy	Long Nan Region, Tibetan Autonomy in Gannan

(3) Index can be judged quickly.

If an index can be judged quickly, which means the distance of action and processing time between this index and design decision is short. Liu (Liu, 2019) provides three methods to reduce the “distance of action” and “processing time”. New visualizing design software can be developed to make the judgement results of indexes present in real time with the progress of design. Some indexes can be extracted from existing standards and researches. The purpose is to establish category A indexes that can be referenced directly and category B indexes that need only a short processing time during design.

In order to show the establishment method of GCI, the index about window-wall ratio of Gansu region has been introduced as an example of this establishment process.

4. Index establishment of window-wall ratio for Gansu

Indoor temperature control is one of the main problems for TD. Window-wall ratio is the key factors to control the heat gain and loss of TD. Building south outer window controls the amount of solar radiation enter the room which can increase the indoor temperature. So, the south outer window should be enlarged appropriately. Conversely, the area of north outer window should be suitably reduced to control the indoor heat loss. Gansu region has been divided into 5 areas in solar and thermal engineering map, the window-wall ratio of residential building should be adjusted in different area. The GCI in Gansu should point out differences between these areas and make clear suggestions for residential building design.

Lanzhou (103.88E, 36.5N) is the capital city of Gansu province, and it is in the “available and cold area”. Its elevation is 1517.2m and annual average temperature is 2-5°C. The annual average sunshine hours the city center is 2608h (Li, 2009). This paper analyzes the window-wall ratio of this region by simulation, software EnergyPlus was used. A simplified building model was adopted, the basic construction information of this model is shown in table 3 (Tab. 3), its plan and appearance are shown in figure 3, the weather data of Lanzhou (DOE, 2019) was applied in the simulation.

Tab. 3: construction information of simulation model

Construction	Material	Thickness (m)	Conductivity (W m^{-1} k^{-1})	Density (Kg m^{-3})	Specific heat (J kg^{-1} K^{-1})
Exterior wall	Foam ceramic insulation board	0.02	0.08	200	1126
	Cement mortar	0.01	0.93	1800	1050
	XPS insulation board	0.05	0.03	35	1380
	Shale perforated brick masonry	0.19	0.58	1500	1050
	Cement mortar	0.01	0.93	1800	1050
	Putty	0.005	0.76	1500	1050

Interior wall	Putty		0.005	0.76	1500	1050
	Cement mortar		0.01	0.93	1800	1050
	Shale brick		0.18	0.81	1800	1050
	Cement mortar		0.01	0.93	1800	1050
	Putty		0.005	0.76	1500	1050
Roof	Waterproof coating		0.02	0.71	600	1470
	XPS insulation board		0.02	0.03	35	1380
	Reinforced concrete		0.1	1.74	2500	920
	Putty		0.005	0.76	1500	1050
Floor	Wood floor		0.016	0.15	500	2510
	Reinforced concrete		0.1	1.74	2500	920
Window	**Material**		**Thickness (m)**	**Conductivity ($W\ m^{-1}\ k^{-1}$)**	**Thermal resistance ($m^2\ K\ W^{-1}$)**	**-**
	Double glass	Glazing	0.006	0.9	-	-
		Gas	0.012	-	0.15	-
		Glazing	0.006	0.9	-	-

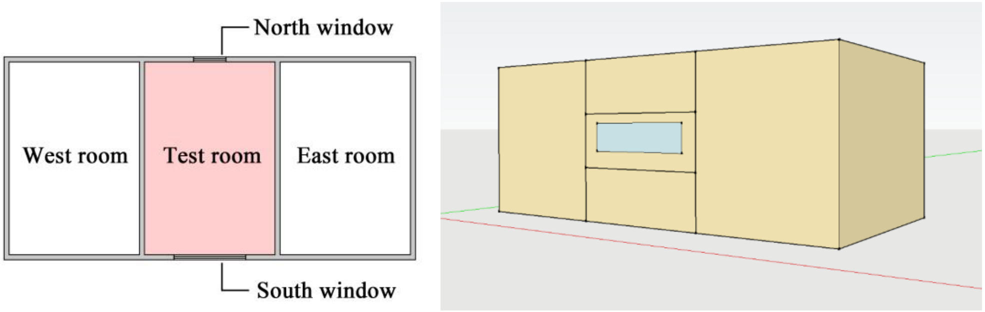

Fig. 3: The plane and appearance of simulation model

This simulation is to analyze the effects of different window-wall ratio on indoor temperature without refrigeration and heating services. The north exterior window does not accept solar radiation, so its function is mainly to meet the requirements of lighting. According to the "Standard for daylighting design of buildings" (MOHURD, 2013), the daylight factor of one light climate region is the standard value of daylight factor multiplied by the daylight climate coefficient value of this light climate region, the daylight climate coefficient value of different light climate region is shown in table 4 (Tab. 4). According to this standard, Lanzhou is located in the III light climate region, the daylight climate coefficient of Lanzhou is 1.00, meanwhile, the standard value of daylight factor of lateral daylighting in this region is 3%. So, the daylight factor of this region is 3%.

Tab. 4: Daylight climate coefficient values

Variable name	Light climate region				
	I	II	III	IV	V
Daylight climate coefficient values (K)	0.85	0.90	1.00	1.10	1.20

Design illumination value of outdoor natural light (E_s/lx)	18,000	16,500	15,000	13,500	12,000

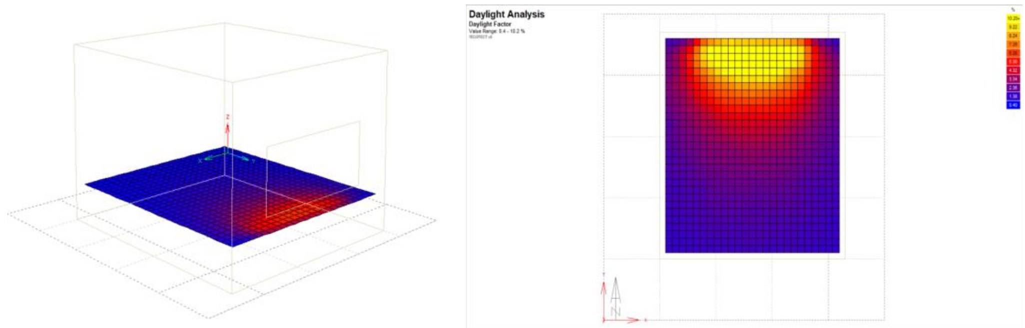

Fig. 4: The simulation model and simulation result for 10% north window-wall ratio

Lighting analysis software Ecotect Analysis 2011 was used to simulate the minimum opening of the north wall, the simulation model and the simulation result is shown in figure 4 (Fig. 4). The result shows that the average daylight factor of the room is 5% when the window-wall ratio in the north wall is 10%, which means that 10% of the window-wall ratio can meet the indoor lighting needs.

In order to analyze the influence of the south window-wall ratio to indoor temperature, this ratio of north window remains at 10% and the ratio of south window changes from 10% to 90%, double glass window (6+12+6) has been adopted to both south and north. The changes of indoor temperature were simulated, the monthly mean temperature and annual mean temperature of the outdoor and indoor are presented in figure 5 (Fig. 5). The results show that, firstly, without refrigeration and heating measures, indoor temperature varies with outdoor environment temperature and the former has no significant temperature increase compared with latter. Secondly, the indoor annual mean temperature increases with the enlargement of the south window-wall ratio, when the ratio over 50%, the former decrease with the enlargement of the latter. The enlargement of the south window-wall ratio makes building receive more solar radiation and then increase the indoor temperature. However, when the area of window comes larger, the heat loss through window in winter become faster, the annual mean temperature decrease. Therefore, the south window-wall ratio of residential building in Lanzhou is recommended at 50%.

Triple glazing window (6+12+6+12+6) was also adopted in the simulation, and the results are shown in figure 6. Because the heat preservation performance of triple glazing glass is better than that of double glass window, the indoor monthly mean temperature has a significant increase compare with outdoor environment temperature. Meanwhile, the indoor annual mean temperature increases with the enlargement of the south window-wall ratio until this value reach 70%, after that, the indoor annual mean temperature gradually falls.

Thus, for residential buildings in Lanzhou, if the heat transfer coefficient (HTC) of exterior wall is between 0.4~0.6 ($\mathrm{W\ m^{-2}\ K^{-1}}$) , when double glass window is adopted, the south window-wall ratio is recommended at 50%, when triple glazing window is adopted, the south window-wall ratio is recommended at 70%.

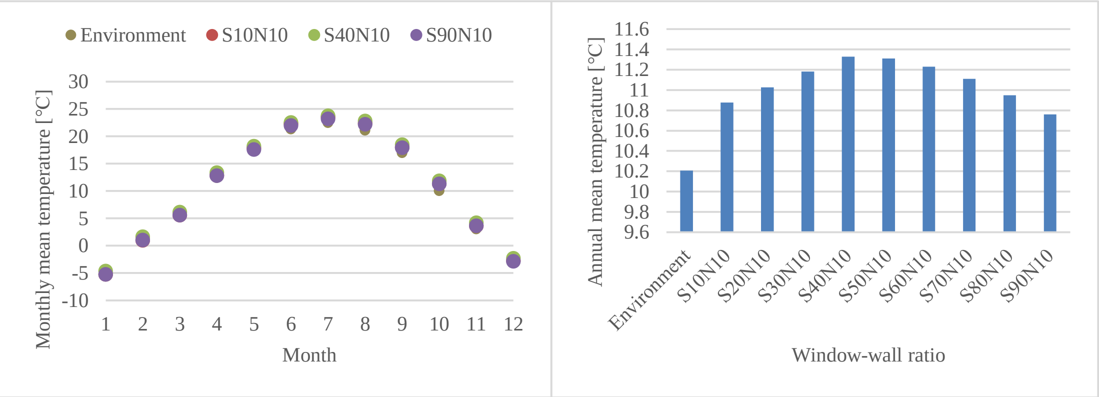

Fig. 5: Monthly mean temperature changes of double glass window with different south window-wall ratio (left) and annual mean temperature changes of double glass window with different south window-wall ratio (right)

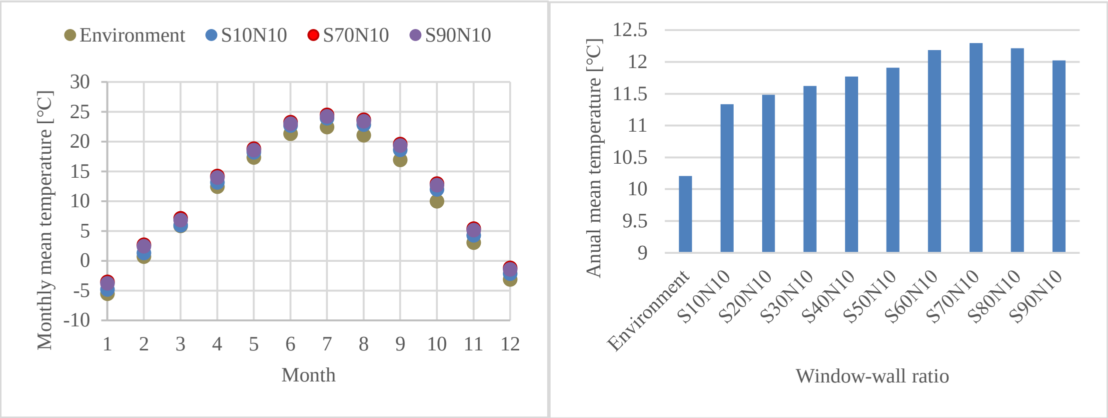

Fig. 6: Monthly mean temperature changes of triple glazing window with different south window-wall ratio (left) and annual mean temperature changes of triple glazing window with different south window-wall ratio (right)

Through this method, the recommended window-wall ratio of other region in Gansu region is achieved through a series of simulation experiments, which are not shown in this paper due to space limitation. The simulation results show that, firstly, when the HTC of exterior window in the Cold area is between 2.5~1.8 (W m^{-2} K^{-1}) and the HTC of exterior window in the Severe cold area is between 2.0~1.5 (W m^{-2} K^{-1}), the window-wall ratio of residential building in Lanzhou is recommended as in Table 4 (Tab. 4). Secondly, when the HTC of exterior window in the Cold area is no more than 1.8 (W m^{-2} K^{-1}) and the HTC of exterior window in the Severe Cold area is no more than 1.5 (W m^{-2} K^{-1}), the window-wall ratio of residential building in Lanzhou is recommended as in Table 5(Tab. 5). The results can be translated into a category B index of GCI.

Tab. 4: The recommendation value for window-wall ration in Lanzhou (a)

Orientation	**Window-wall ratio**				
	Area 1	Area 2	Area 3	Area 4	Area 5
South	0.35~0.5	0.35~0.55	0.3~0.5	0.3~0.5	0.45
North	0.2	0.15	0.2	0.15	0.4
East/West	0.2	0.25	0.2	0.25	0.35

Tab. 5: The recommendation value for window-wall ration in Lanzhou (b)

Orientation	**Window-wall ratio**				
	Area 1	Area 2	Area 3	Area 4	Area 5
South	0.35~0.7	0.4~0.8	0.35~0.7	0.4~0.8	0.6
North	0.2	0.15	0.2	0.15	0.4
East/West	0.2	0.25	0.2	0.25	0.35

5. Conclusion

The establishment principles and methods of GCI for the design of residential building in northwest China focuses on GSE utilization are discussed in this paper. Firstly, in order to establish GCI effectively, the solar and thermal engineering map and the conception of TD and AD are put forward. Secondly, indexes about GSE utilization in China are extracted and classified, the basic principle and establishment method of GCI for GSE utilization are discussed. Thirdly, the index about window-wall ratio of Gansu region is introduced as an example to explain the process of GCI's establishment. The method proposed in this paper is expected to provide reference for related researches.

"How to create a clear map of GSE for architects?", "how to enable GCI to guide different stages of design?" and "how to develop a visualizing design software that can present the judgement results of GCI in real time in corresponding with the progress of architectural design?" are questions that still need to be discussed in further researches.

6. Acknowledgments

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