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Assessment of operative energy optimization in case of haveli-turned-hotels located in composite climate zone of India

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Abstract
In the study area of Rajasthan in India many architectonic picturesque havelis of 200 years age has been converted to heritage hotels to cater to the both national and international tourists visiting this and surrounding places to enable them to experience the charm and vigor of the traditional haveli architecture of Rajasthan, India. According to the Indian Bureau of Energy Efficiency (BEE), the energy consumption due to HVAC and lighting in hospitality industry accounts to almost 62% of the total energy usage and air-conditioners account for the majority of those power demands to maintain indoor comfort conditions in hotels. Considering the above scenario, this research presents the assessment of the impacts of building envelope construction regarding wall, roof, window-wall-ratio (WWR) and glazing type affecting the operative energy consumption of the haveli-turned hotel buildings located in the composite climate of Rajasthan. This study will help in selecting the appropriate construction materials for similar case to achieve reduced optimum operative energy consumption which will also reduce the overall energy footprint of those similar commercial buildings located in the composite climate of India. The paper has analyzed the design specifications and other energy conservation measures that help to mitigate the operational energy demand of a hotel and has proposed a scalable material suggestion and WWR recommendations that can be readily adapted in similar projects in similar climatic zones. The paper has also proposed further scope of research.

Keywords: Building envelope materials selection, Haveli architecture of Rajasthan, operational energy optimization, window-wall-ratio optimization

1. Introduction

In India, as travel is becoming more popular for both business, pleasure and as an international tourist destination, the number of hotels and resorts being built is increasing. Moreover, the hospitality business is no more a seasonal business; they receive normal to heavy traffic throughout the year. As a consequence, power consumption by the hospitality industry is on the rise. Commercial building sector of India accounts for 6.5% of total electricity consumption, and it is growing at a rate of 11-12% over the last few years [1, 2]. Building components such as Heating, Ventilation and Air-Conditioning (HVAC) system, equipment, lighting and envelope affect building energy consumption.

According to the report published by the Indian Bureau of Energy Efficiency (BEE) [3], the energy consumption for HVAC and lighting in hospitality industry accounts to almost 62% of the total energy use. And air conditioners account for the majority of the power requirements as Indian hotels needs round-the-year air conditioning due to the climatic conditions. In fact, power costs account for 8-10 percent of the operating expenses of an average Indian hotel. These costs are only expected to increase in the future. Operational energy demand is the energy required to operate (or generated by operating) the building in terms of energy-transfer processes, such as space cooling, heating, lighting, and other operating appliances. Hotels have different energy requirements than other commercial buildings because of the variety of facilities available and operational schedules. But nowadays the hotel managements are more conscious towards energy efficiency, allowing the hospitality sector to integrate various energy management systems that will help in improving (a) comfort of guests, (b) energy efficiency of the hotels, and (c) overall operating cost of hotel assets.

Considering the above scenario, this research presents the assessment of the impacts of building envelope construction details regarding wall and roof materials including insulation materials, window-wall-ratio (WWR) and glazing type affecting the operative energy consumption of the haveli-turned hotel buildings located in the composite climate of Rajasthan. In the study area of Rajasthan many havelis of 200 years age has been converted to heritage hotels to cater to the both national and international tourists visiting this and surrounding places to enable them to experience the charm and vigor of the traditional haveli architecture of Rajasthan, India. The research further attempts (a) to study the energy usage patterns of a heritage hotel building located in composite climate; (b) to analyze design specifications and other energy conservation measures that help to mitigate the operational energy demand of a hotel; (c) to explore various traditional passive strategies that helps in providing comfortable conditions to the inhabitants; and (d) to propose a scalable material suggestion and window-wall-ratio (WWR) recommendations that can be readily adapted in similar projects in similar climatic zones to result into less energy consumption to maintain indoor thermal comfort.

The scope of this study considers the utilization of passive strategies of traditional architecture of Rajasthan in contemporary context with different material and WWR approach for less operational energy consumption. The study considers composite climate zones and low-rise constructions. The study only focusses on operational energy demand aspect. Due to time constraints the present study will not focus on structural analysis and cost aspect of the project. The study considers only low-rise haveli buildings of Rajasthan and composite climatic conditions, hence applicable for similar conditions.

2. Review of literature

2.1 Energy efficiency

A study [4] was done to analyze the potential impact of implementation of Energy Conservation Building Code of India (ECBC) [5] for different types of buildings located in Jaipur, found that the energy saving potential in commercial buildings can range from 17% to 42% based on the usage patterns. Analyzed buildings show the possibility of higher energy savings by implementing more advanced features of the ECBC such as installation of daylight sensors, occupancy sensors, higher coefficient-of-performance (COP) of air conditioning system, etc. Another study [6] done in composite climate of Jaipur for different categories of hotel buildings shows that the implementation of ECBC guidelines can result energy savings in the hotel buildings ranging 18.42% - 37.2% and with further application of advanced energy efficiency measures the energy saving potential may be ranging between 53.92% - 61.75%. Other researchers [7] have analyzed different materials for wall assembly in different climatic zones of India according the ECBC recommendations for different types of commercial buildings found in India. The study shows that for all other building types wall assemblies up to 0.15 m was found as ECBC compliant only in temperate climate. It was observed that walls having thickness more than 0.25 m was in compliance with respect to the ECBC and ECBC+ prescription; whereas 'ECBC Super compliance' [8] is not possible using the material that has been considered into the study for the walls having thickness up to 0.3 m. A study [9] done to analyze the optimization of building form in hot humid/hot dry climate of Zaria, Nigeria, to enhance heat modulation and reduce cooling loads of hotels considering the thermal performance of the building envelope, types of glazing used and fenestrations using the ECOTECT® software. The study results showed that using the right building form can give an energy saving of up to 40% for a building in the composite hot-humid/ hot-dry climate. Further, the guidebook published by BEE [3] provides various measures that can be taken for energy efficiency in a hotel building in line with the National Building Code of India, 2015 (NBC) [10] and ECBC guidelines [8] in terms of end-uses in buildings like lighting, heating-ventilation-air conditioning (HVAC), building envelope design, etc. From the literature review for this study the effect of the parameters such as the materials of construction available in present day and different WWR criteria are evaluated to assess the potential of reduction of annual energy consumption of the haveli which is being converted to hotel located in Rajasthan.

2.2 Traditional architecture of Rajasthan

Researchers [11] have studied the salient features of the traditional architecture of Rajasthan by analyzing the traditional settlement pattern and *Shekhawati* havelis. They have highlighted the following characteristics of those havelis which has contributed to passive cooling of the interior environment of those buildings to achieve indoor thermal comfort condition for occupants for most part of the years: compact settlement plan, shaded narrow streets with surrounding tall buildings, courtyard planning, heavy structures with high thermal mass, higher ceiling heights, shaded colonnades and semi-open spaces like verandahs, thick walls and thick roofs with high thermal lag, staircase-*Mumty* (head-room) act as wind towers, small openings with thick shutters, *Jaali* screens and *Jharokhas*.

3. Methodology

To fulfill the stated aim and objectives of the paper, the methodology adopted for this study consist of the following steps.

- Identification of study area in Rajasthan, India with composite climate.
- Selection of haveli with traditional architectural style converted to heritage hotel.
- Quantitative and qualitative appraisal of the selected haveli-turned-hotel with respect to the parameters like its form and massing, materials of construction, openings and glazing, shading, and energy performance index (EPI).
- Analysis through iterative study considering different materials for present day wall and roof construction and varying WWR criteria and glazing materials.
- Evaluation of the results and discussion about the significance of the study regarding optimization of the annual energy consumption of the haveli-turned-hotel.

For the analysis carried out through the building simulation tools like Climate Consultant [12], Envi-Met [13], Rhino [14] and Climate studio [15], the climate-data file of Jaipur, Rajasthan [16] is used as per the ASHRAE [17] and ECBC [8] protocol.

3.1 Description of study area: The study area is located in

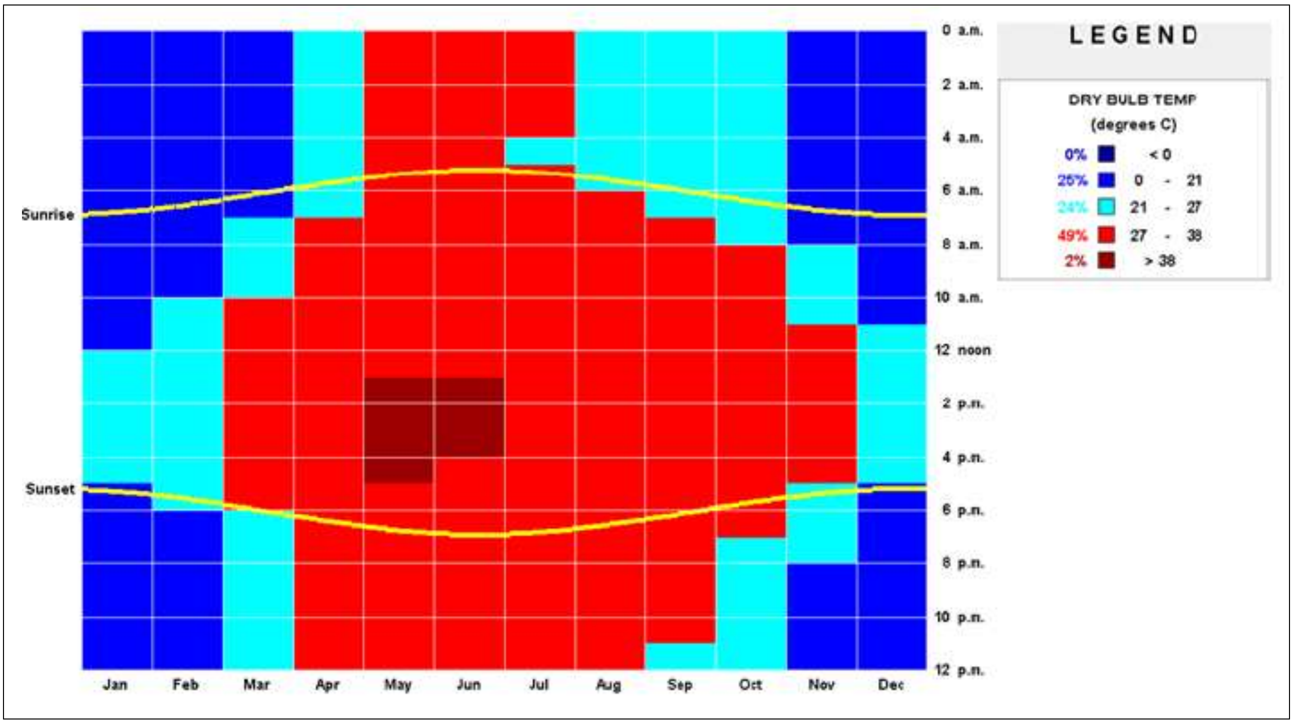
Mandawa town (Latitude 28.05º North, Longitude 75.14º East, and Altitude 390m above MSL), around 169km from Jaipur city in Rajasthan having composite climate. The Mandawa town is also well-known as the open-air art gallery due to the numerous architecturally and artistically beautiful frescos and historical structures found in the town (Fig. 1). Most of the around 160 heritage havelis of Mandawa are famous for their paintings, murals, and various other artifacts and many of these are almost 200 years old construction [18].

(***Source***: Authors)

Fig 1: Views of Havelis of Rajasthan

The town has composite climate with characteristics of hot and dry, warm and humid, and cold climates. The maximum day time temperature crosses above 40 ºC during peak summer months of May and June, and night-time temperature falls below 5 ºC during winter months of December to February. Prevailing wind direction is from west direction during summers and from east during winters. Wind blows from all directions throughout the year and from every direction with wind-speed of 1-3m/s [18]. Fig. 2 shows the timetable plot according to the dry-bulb temperature of the region. It is observed from the graph that may and June are the most extreme months and has highest temperatures.

For physiological cooling and indoor thermal comfort, heat dissipation from the body to the environment is required during summer season and heat retention is needed during winter months as outdoor temperature is much lower. For monsoon months, outdoor breezes passing through the building through openings and body surface will help to provide comfort as humidity in air is higher.



(***Source***: Climate Consultant)

Fig 2: Time Table Chart, Mandawa, Rajasthan

3.2 Description of Case-study Haveli

Hotel Singhasan Haveli, Mandawa has been selected in this study for evaluation which represents the traditional haveli architecture found in this region of Rajasthan, India. The exterior and interior views of the selected haveli are shown in Fig. 3 (a) and (b). The selected haveli-cum-hotel has 16 rooms, oriented towards south-west direction, and is located on a site-area of 658m2 with total built-up area of 628m2 comprising of 2 floors with height of 9.5m. The majestic artistic structure is around 200 years old. Fig. 4(a), (b) and

(b) shows the floor plans and context of the haveli-cum- hotel.

A B

Fig 3(a): Front elevation and (b) Interior view of the *haveli* (Source: Authors)

Fig 4(a): Ground floor plan of the haveli-cum-hotel

Fig 4(b): First floor plan of the haveli-cum-hotel

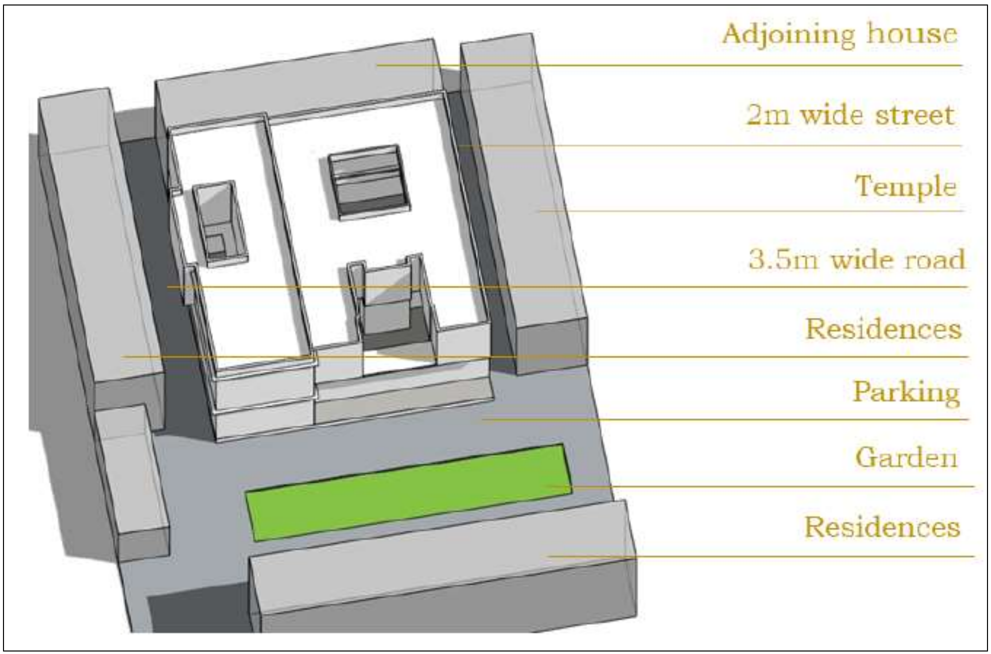


Fig 4(c): Context details of the haveli-cum-hotel

4. Analysis of data

4.1 Architectural features

Orientation

The haveli is oriented to the south-west direction with placement of open-to-sky courtyard behind the entrance facade acting as a buffer space to reduce the exposure to extreme hot or cold winds. South-east side of the haveli is shaded most times of the day as it has a narrow street with 8m high temple across the street, which helps in lowering the ambient air temperature as building envelope is shaded.

4.1.1 Form and massing

Aspect ratio of the haveli is 1:1 as it is a square plan form which is good for reducing heat gain into the structure (Fig. 4). Lesser the surface to volume ratio of a building lesser will be heat gain. Here the surface to volume ratio is calculated as 0.26 because of compact form.

4.1.2 Zoning of Spaces

As per Fig. 4, the external courtyard houses public spaces with reception and waiting planned there. The central part of the haveli is occupied by inner courtyard and surrounding to it, rooms are arranged.

4.2 Shading study

The details of the external courtyard 1 and internal courtyard 2 (Refer Fig. 4) is given in the Table 1 and the findings of their shading analysis during the summer and winter months are shown in Fig, 5(a) and (b) respectively.

Table 1: Details of courtyard 1 and courtyard 2 (Refer Fig. 4)

Parameters	External Courtyard 1	Internal Courtyard 2
Size	7.6 x 6.5 m	7.5 x 7.5 m
Aspect ratio	1:1.16	1:1
Surface to volume ratio	0.67	0.60
Height of the courtyard	8 m	8 m

The internal and external courtyards remain shaded most of the time, thus helping in providing comfortable conditions to the inhabitants and acting as a leisure space to sit and relax (Refer Fig. 6).

Fig 5(a): Courtyard shading analysis during summer

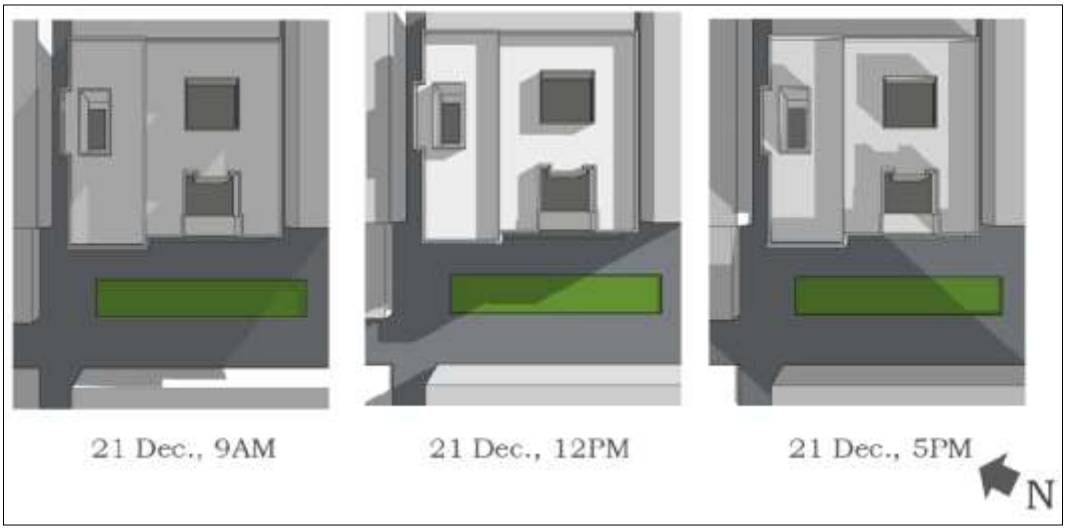


Fig 5(b): Courtyard shading analysis during winter

Fig 6: Shaded external and internal courtyard views

4.3 Fenestration details

The windows are placed in a rhythm and symmetry. Richly carved teak wood panels are used for both doors and windows shutters. More openings (Refer Fig. 7) are provided facing towards the courtyards as compared to the external side to reduce the hot air coming from outside entering the building. As the haveli has high thermal mass construction due to thick 45cm wall, small recessed shaded openings are provided on the external wall. These small windows can be opened at night for night ventilation to the spaces. The details of window-wall-ratio (WWR) as calculated for the external façade of the haveli and the internal façade facing the internal courtyard is given in Table 2.

Table 2: WWR details of external and internal wall façade

Wall orientation	External façade WWR (%)	Internal façade WWR (%)
South-west	22	27
North-west	7	14.7
South-east	0.8	14.7
North-east	-	8

Fig 7: Views of openings on external and internal façade

4.4 Annual energy consumption

The annual energy consumption of the selected haveli cum hotel is calculated considering 70% occupancy of the hotel rooms by using Rhino and Climate Studio software. Summer season prevails for 9 months in a year with highest temperatures occurring in May and June months resulting in more usage of air-conditioning (AC). According to a report [2] the average energy performance index (EPI), which is calculated by dividing the total annual energy consumption of the building by its total floor area, for commercial buildings is around 70 kWh/m2/year. The EPI for the selected haveli cum hotel is calculated as 35 kWh/m2/year which is lower than the benchmark EPI value and the detail is given in Table 3.

Table 3: The EPI details of the selected haveli cum hotel

Month	Weather condition	Energy consumption (kWh)
January	Cold	560
February	Cold	560
March	Hot	1125
April	Hot	2250
May	Hot	3375
June	Hot	3375
July	Hot	2810
August	Hot	2250
September	Hot	2250
October	Hot	1500
November	Hot	1125
December	Cold	560
Total annual energy consumption		21740kWh
Total built-up area		628m^2
EPI		34.62 kWh/m^2/year

4.5 Study of building materials

The walls of the haveli are made of locally available Jhajhariya (limestone) stone sourced from quarries located nearby. These stones were also the source of the coarse lime, used for making mortar. The plastering process apparently includes plastering wall with a centimeter-thick coarse layer called of lime plaster (*chuna* or *lipai*). Then, while the wall is still damp, a two mm layer of a finer version of the mortar is applied by beating it on, which helps in better adhesion and prevents future cracking. The view and cross-section details of the wall is shown in Fig. 8(a) and (b) respectively.

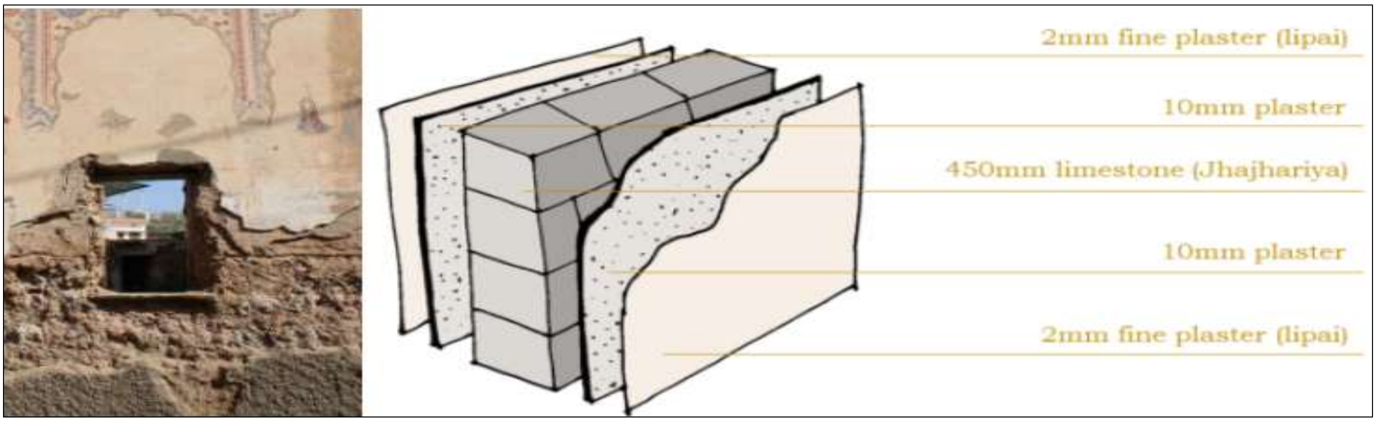


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Fig 8(a): View of wall; (b) Cross-section details of wall

The physical and thermal properties of the construction materials used in the haveli is given in Table 4.

Table 4: Properties of construction materials used in the *haveli* of Rajasthan calculated from [10, 15, 19].

Component		Material	Physical Property		Thermal properties				
			Dimension (m)	Density (Kg/mÂ³)	Specific heat (kJ/kgK)	Conductivity (W/mK)	U-value (W/m2KK)	Time lag (hours)	Reflectance
Foundation		Limestone	-	2420	0.84	1.8	-	-	-
Wall	Masonry	Limestone (jhajhariya)	0,45	2420	0.84	1.8	2.2	11.96	-
	Internal finish	Lime plaster	0.015	1646	0.88	0.73			-
	External finish	Lime plaster	0.015	1646	0.88	0.73			0,6
Roof	Slab	Limestone	0.15	2420	0.84	1.8	3.08	4.86	-
	Internal finish	Lime plaster	0.015	1646	0.88	0.73			-
	External finish	Lime plaster	0.015	1646	0.88	0.73			0.2
Floor	Finish	Kota stone	0.15	3102	2.07	3.02	-	-	-
Window	Shutters	Teak wood	0,04	720	1,68	0.144	4.2	-	-
		Single pane tinted glass	0.06	2500	0.84	1.1	3,97	-	-
Door	Shutters	Teak wood	0,04	720	1.68	0.144	4.2	-	-
Brackets		Limestone	0.05	2420	0,84	-	-	-	-
Projections		Limestone	0.15	2420	0,84	-	-	-	-

5. Results and Discussion

5.1 Thermal performance study of the courtyards

Envi-met software has been used to assess the potential air-temperature condition of the courtyards. The input building area dimension is 21.7m x 21.7m, building height is 11m, courtyard 1 dimension is 7.5m x 6.5m, and courtyard 2 dimension is 7.5m x 7.5m (Refer Fig. 4). Other inputs for the thermal analysis of the courtyards are given in Table 5. For the modelling following contextual conditions are considered: towards north-west - 3.6m wide road, 7m high building across the road; south-east - 2.1m wide street, 7m high building across the road; north-east - other building (15m high); and south-west - parking and road, 7m high building across the road.

Table 5: Inputs for the thermal analysis of the courtyards

Location	Mandawa, Rajasthan
Model area	50x50x34
Day of simulation	21-Jun-22
Simulation start time	10am
Simulation end time	6pm
Total simulation time	8hours
Climatic Data Inputs	
Air temperature min.	35Â°C
Air temperature max.	39Â°C
Relative humidity min.	38%
Relative humidity max.	50%
Wind speed	1.6m/s
Wind direction	90Â°
Roughness length	0.01

Results of the analysis of the air-temperature condition in the courtyards are shown in Fig. 9, which indicates that air-temperature inside the courtyard is increasing till 2.00 pm and it drops after that till 6.00 pm.

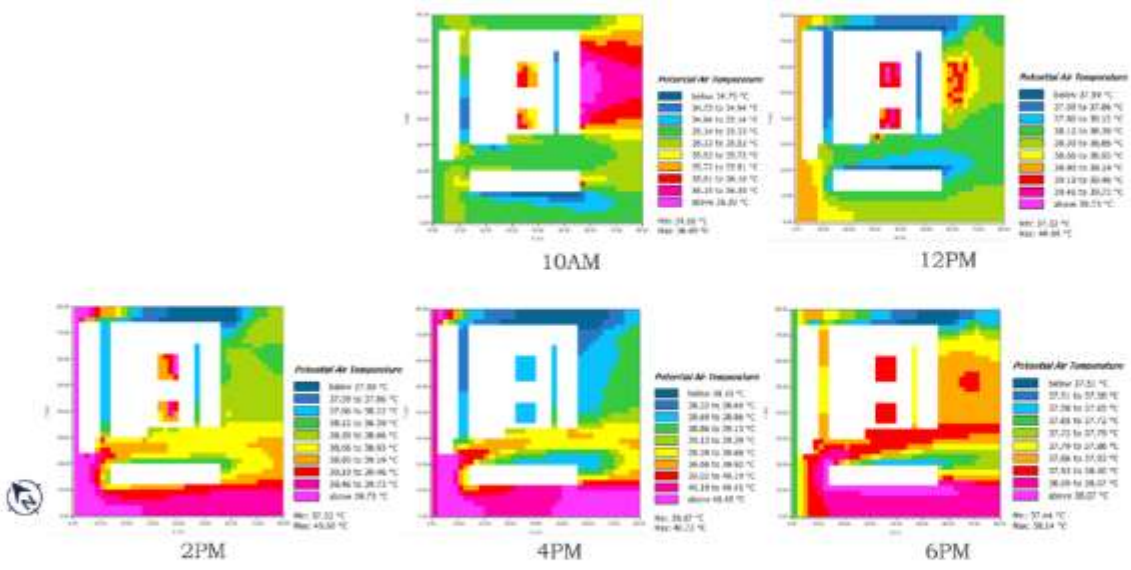

Fig 9: Analysis of air-temperature condition in courtyards

5.2 Thermal performance study of the Haveli

Rhino and Climate Studio simulation software has been used to assess the thermal performance of the haveli. The inputs parameters for the thermal analysis of the haveli are given in Table 6.

Table 6: Inputs for the thermal analysis of the *haveli*

HotelRoom	Program
Hotel	UseType
People (On)	
0.1	People Density [p/m2]
1.2	Metabolic Rate [met]
occHotelRoom	Occupancy Schedule
AirSpeed 0	Airspeed Schedule [m/s]
Dynamic Clothing Model ASHRAE55	Clothing [clo]
Equipment (On)	
5	Equipment Power Density [W/m2]
equipHotelRoom	Equipment Availability Schedule
Lighting (On)	
10	Lighting Power Density [W/m2]
lightsHotelRoom	Lights Availability Schedule
400	Illuminance Target [Lux]
Off	DimmingType

Heating (On)	
22 (Constant)	HeatingSetpoint [C]
occHotelRoom	HeatingSchedule [Schedule name]
30	MaxHeatSupplyAirTemp [C]
NoLimit	HeatingLimitType [enum]
100	MaxHeatingCapacity [W/m2]
100	MaxHeatFlow [m3/s/m2]
1	HeatingCOP
Cooling (On)	
28 (Constant)	CoolingSetpoint [C]
occHotelRoom	CoolingSchedule [Schedule name]
18	MinCoolSupplyAirTemp [C]
NoLimit	CoolingLimitType [enum]
100	MaxCoolingCapacity [W/m2]
100	MaxCoolFlow [m3/s/m2]
1	CoolingCOP

Mechanical Ventilation (On)	
10	MinFreshAirPerson [L/s/p]
1	MinFreshAirArea [L/s/m2]
occHotelRoom	MechVentSchedule [Schedule name]
Sensible	HeatRecoveryType [enum]
0.6	HeatRecoveryEfficiencySensible [0-1]
0.65	HeatRecoveryEfficiencyLatent [0-1]
NoEconomizer	EconomizerType [enum]
☐	EMSFanEnergyIsOn
1000	FanPressureRise [Pa]
Infiltration (On)	
0.5	InfiltrationAch [ACH]
1	InfiltrationConstantCoefficient
0	InfiltrationTemperatureCoefficient
0	InfiltrationWindVelocityCoefficient
0	InfiltrationWindVelocitySquaredCoefficient
0.001	AFN AirMassFlowCoefficient Crack

Constructions
Roof: haveli roof
Facade: haveli wall
Partition: haveli wall
Slab: haveli roof
External Floor: UVal_0.2_Mass
Ground Slab: defaultConstruction
Ground Wall: defaultConstruction

All of the guest rooms are modelled as thermal zones for energy requirement simulation. Thermal zones on ground floor and first floor have been created. Rest all spaces like toilets, common spaces, kitchen, restaurant are modelled as shading. Surrounding buildings are also modelled as shading. The modelled thermal zones are shown in Fig. 10.

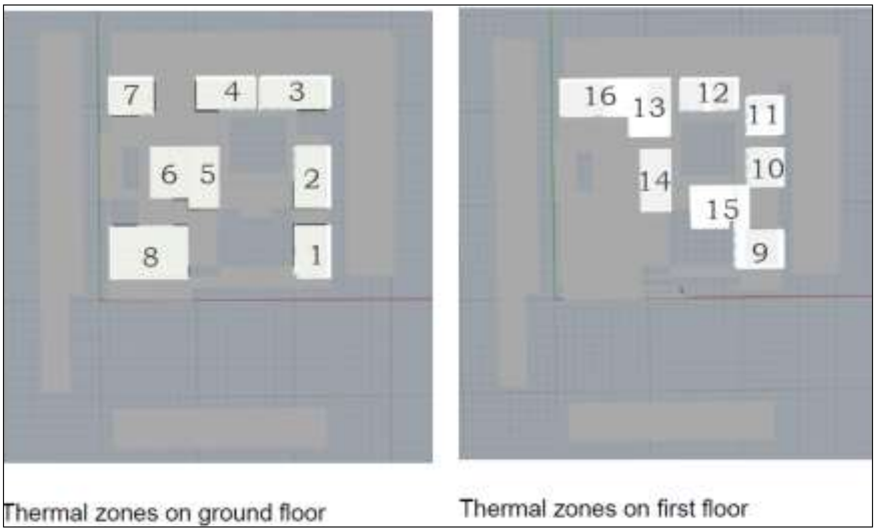

Fig 10: The modelled thermal zones of the *haveli*

The following boundary conditions are considered for the thermal analysis of the haveli: (a) The analysis has been done for yearly period and energy consumption and indoors temperature has been studied; (b) Only guest rooms are considered as thermal zones and rest of the spaces are considered as shading; (c) Occupancy hours are taken from 8pm to 8am in the morning; (d) Strategies like orientation, form, massing, zoning of spaces, courtyards, WWR, shading, surface finishes, materials are considered during modelling; (e) Strategies like *Jaali* walls (perforated walls) are modelled as windows and smaller projections are not considered; (f) All of the fenestrations are considered as air walls, as in the base case they have wooden shutters with no glazing provided.

The result from the simulation analysis of the probable annual energy use regarding various end-usage like equipment, fans, lighting, hot-water, heating, and cooling is given in Fig. 11. Further, Fig. 12 shows the probable annual energy flow regarding different parameters like equipment, fans, people, lighting, window, environment, mechanical ventilation, and systems, etc.

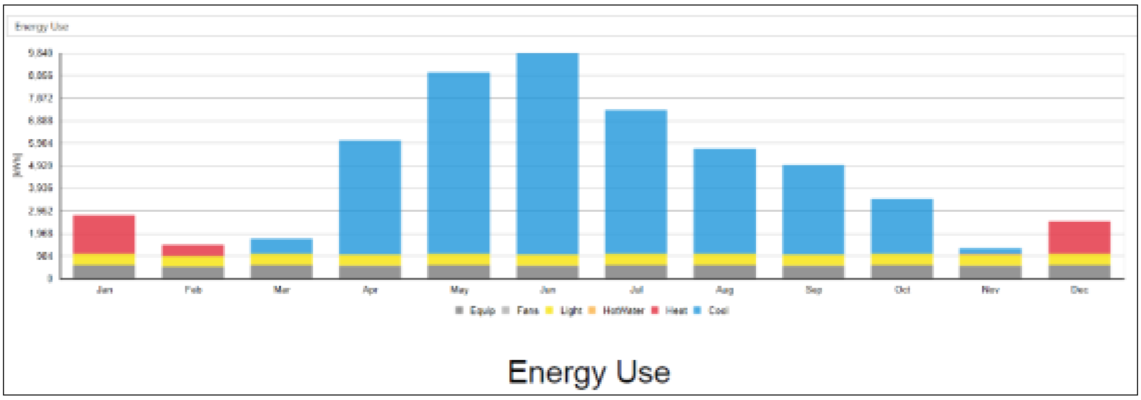

Fig 11: Yearly probable energy use in the haveli regarding various end-usage

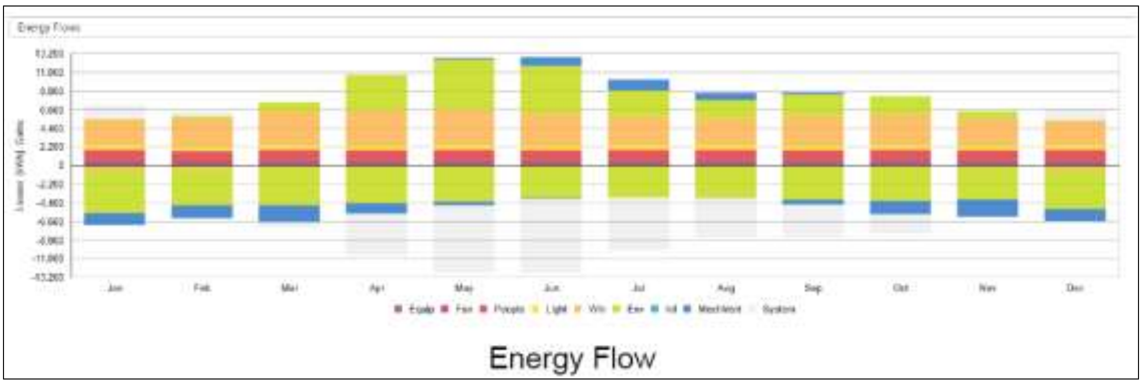

Fig 12: Yearly probable energy flow in the haveli regarding various parameters

The analysis shows that 4105 hours out of total 8760 hours are found comfortable in a year. The cooling load during the June month is maximum as the month experiences the highest temperature. The maximum energy consumption is for cooling and cooling is required from the month of April to October. Whereas heating is required only for the month of December, January, and February. Equipment and other loads are not much here because of the usage of the space. The components which are contributing to energy gain are equipment, people, fan, and mechanical ventilation. The components contributing to energy losses are environment, mechanical ventilation and HVAC.

The results of the annual energy consumption analysis of different thermal zones are given in Table 7. The results show that the rooms located on the ground floor consumes less energy as compared to first floor rooms. Also, the rooms located facing the courtyard has less energy demand followed by the room located in the south-east direction. Further it can be seen that the energy usage of the zones is also dependent on the amount of exposed surface area and less window provision. The results of the daylighting analysis are given in Fig. 13.

Table 7: Results of the annual energy consumption analysis of different thermal zones of the *haveli*

Zones	Orientation	Area (m Â^2	Volume (m Â^2	Heating load (kWh)	Cooling load (kWh)	Lighing load (kWh)	Equipment load (kWh)	Energy use (kWh)	Energy use per mÂ^2 (kWh/mÂ^2)
Zone 1	South	18.01	64.82	118	1209	329	375	2031	112.7707
Zone 2	South-East	20.96	75.47	214	957	383	436	1990	94.94275
Zone 3	East	21.18	76.25	342	1234	387	441	2404	113.5033
Zone 4	North-East	18.04	64,93	381	860	329	375	1946	107.8714
Zone 5	Courtyard (SE)	18.97	68.31	312	415	346	395	1469	77.43806
Zone 6	Internal	19.31	69.52	463	470	352	402	1687	87.36406
Zone 7	North	15.64	56.31	350	1025	285	325	1985	126.9182
Zone 8	West	41.54	149.55	590	1221	758	864	3433	82.64324
Zone 9	South	22.88	82.37	79	5497	418	476	6470	282.7797
Zone 10	South-East	13.22	47.58	66	2903	241	275	3485	263.6157
Zone 11	South-East	12.88	46.36	77	2903	241	275	3676	285.4037
Zone 12	North-East	17.41	62.69	108	3875	318	362	4663	267.8346
Zone 13	North-East	23.62	84.67	111	4195	429	489	5224	221.1685
Zone 14	Courtyard (SE)	18,97	68.31	148	3579	346	395	4468	235.5298
Zone 15	South-West	18.5	66.58	65	4476	338	385	5262	284.4324
Zone 16	North	23.68	85.25	185	4702	432	493	5812	245.4392

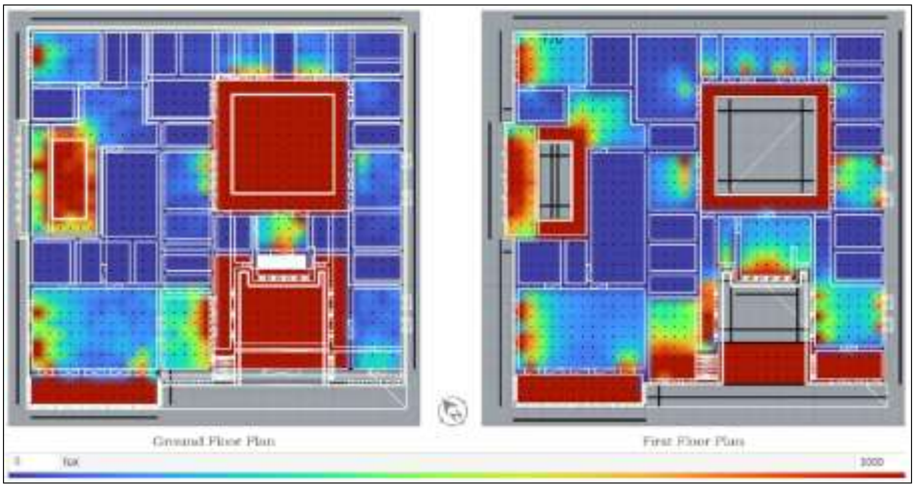

Fig 13: The results of the daylighting analysis of the *haveli*

5.3 Wall and roof optimization study

Comparative analysis has been done among the combination and impact of different wall materials, insulation materials, and roof materials to reduce and optimise the probable annual energy consumption of the haveli cum hotel building. The thermal properties of the different options for the wall and roof construction are given in Table 8 and the combination matrix is shown in Table 9.

Table 8: Thermal properties of iterative materials to be analyzed in thermal analysis of the *haveli*

S. No.	Materials of study	Thermal properties		
	Wall masonry materials	Thermal conductivity W/mK	Specific heat J/kgK	Density Kg/m^3
1.	Burnt Bricks - W1 The base case has been taken with the fire burnt clay bricks.	0.72	800	1700
2.	Autoclaved aerated concrete (AAC) Blocks - W2	0.14	800	1700
3.	CSEB (Hollow Interlocking Blocks) - W3	1.25	1000	2050
4.	Agrocrete Blocks - W4	0.40	-	1400
	Insulation materials			
5.	Expanded Polystyrene - I1	0.14	800	1700

6.	Jute Fibre - I2	0.14	2300	1450
7.	Cork Board - I3	0.044	960	192
Roof materials		Layer thickness meter	Total thickness meter	U-value W/m^{2}K
8.	Reinforced cement concrete (RCC) + EPS insulation - R1	RCC - 0.15 EPS - 0.08	0.23	0.3
9.	Brick-Bat Coba with EPS - R2	RCC - 0.15 Cement mortar-0.03 EPS - 0.1 Brick bat coba - 0.08	0.37	0.31
10.	Mud Phuska - R3	RCC - 0.15 Mud phuska - 0.15	0.3	0.3

Table 9: The combination matrix of materials used in energy analysis of the *haveli*

	WALL & ROOF ASSEMBLIES –	Thickness	U-value
WALL MASONRY – • W1 - Burnt clay brick • W2 - AAC blocks • W3 - Hollow earth blocks • W4 - Agrocrete blocks	• W1I1 – Burnt clay brick + EPS insulation • W1I2 - Burnt clay brick + Jute fibre insulation • W1I3 - Burnt clay brick + Cork board insulation	0.29m 0.36m 0.30m	0.56 W/m²K 0.62W/m²K 0.60W/m²K
	• W2I1 – AAC blocks + EPS insulation • W2I2 – AAC blocks + Jute fibre insulation • W2I3 – AAC blocks + Cork board insulation	0.23m 0.20m 0.20m	0.32W/m²K 0.59W/m²K 0.51W/m²K
INSULATION - • I1 - EPS Insulation • I2 - Jute fibre insulation • I3 - Cork board insulation	• W3I1 – Hollow earth blocks + EPS insulation • W3I2 – Hollow earth blocks + Jute fibre insulation • W3I3 – Hollow earth blocks + Cork board insulation	0.36m 0.47m 0.38m	0.62W/m²K 0.59W/m²K 0.59W/m²K
	• W4I1 – Agrocrete blocks + EPS insulation • W4I2 – Agrocrete blocks + Jute fibre insulation • W4I3 – Agrocrete blocks + Cork board insulation	0.20m 0.30m 0.20m	0.47W/m²K 0.60W/m²K 0.60W/m²K
ROOF - • R1 - RCC • R2 - Brick-Bat Coba with EPS • R3 - Mud Phuska	• R1 - RCC + EPS insulation • R2 - Brick-Bat Coba with EPS • R3 - Mud Phuska	0.26m 0.37m 0.3m	0.30W/m²K 0.31W/m²K 0.30W/m²K

As per the analysis using the simulation tool the energy consumption in different zones of the haveli per unit area is shown in Table 10.

Table 10: Details of energy consumption in different zones studied in the *haveli*

Zones	Orientation	Area (m²)	Volume (m³)	W1I1R1	W1I2R1	W1I3R1	W2I1R1	W2I2R1	W2I3R1	W3I1R1	W3I2R1	W3I3R1	W4I1R1	W4I2R1	W4I3R1
Zone 1	South	18.01	64.82	49.91671	49.9167	50.5274	48.2520	51.74903	49.58356	51.86063	56.71294	50.13881	49.52804	50.19434	52.63742
Zone 2	South-East	20.96	75.47	51.19275	51.1927	51.5744	49.2366	52.14695	50.90649	51.9084	51.76527	51.57443	50.52481	51.35588	52.29008
Zone 3	East	21.18	76.25	54.67422	54.6742	55.3824	50.9915	55.85458	54.01322	55.80737	55.38244	55.24079	53.02172	54.95751	55.85458
Zone 4	North-East	18.04	64.93	54.26829	54.2682	55.0443	107.8714	55.04435	53.15965	55.6541	54.87805	54.93348	52.93792	54.96891	55.0867
Zone 5	Courtyard (SE)	18.97	68.31	56.03585	20.8223	51.9768	49.6674	78.2815	45.75646	52.29309	52.08224	52.02952	157.7754	51.92409	52.18766
Zone 6	Internal	19.31	69.52	55.0492	55.0491	55.4117	53.7027	55.10098	54.53133	55.72242	55.92957	55.61883	53.4956	55.0492	54.53133
Zone 7	North	15.64	56.31	60.99744	60.9974	62.0843	54.0281	62.83166	59.78261	62.72379	61.50895	61.70077	57.41688	60.9335	62.27621
Zone 8	West	41.54	149.55	53.00915	53.0091	53.2258	50.5055	53.34617	52.40732	53.65912	52.67212	53.15359	52.91286	52.88878	54.33317
Zone 9	South	22.88	82.37	225.9615	20.8041	127.3601	223.3391	229.7203	226.9568	226.0927	227.7535	226.3986	212.1941	222.0717	218.4441
Zone 10	South-East	13.22	47.58	215.7357	20.8018	217.0196	263.6157	222.6172	218.9107	214.7504	218.6838	215.9607	191.1498	207.7912	199.2436
Zone 11	South East	12.88	46.36	225	20.8074	225	215.1285	229.8137	226.4752	224.6118	227.0186	225.3106	207.2981	219.7981	214.1304
Zone 12	North-East	17.41	62.69	230.058	20.7926	267.8346	243.9402	243.0213	241.7576	237.3923	240.0345	238.8857	217.2315	229.6381	221.5968
Zone 13	North-East	23.62	84.67	156.5199	20.7027	157.5783	151.0584	158.4074	155.9090	157.663	157.79	157.152	101.0584	156.1369	155.5880
Zone 14	Courtyard (SE)	18.97	68.31	172.8519	20.8223	174.5387	166.1570	51.81866	173.9062	173.5372	175.1715	173.379	157.7754	169.6363	166.5261
Zone 15	South-West	18.5	66.58	269.1892	18.2702	268.2702	279.5675	109.1351	272.4865	266.7568	269.9459	268.6486	261.2973	262.973	258.3243
Zone 16	North	23.68	85.25	193.0743	20.8192	192.5041	245.4392	195.5236	192.9054	194.1301	194.5101	193.8345	165.3885	191.2162	189.9916

Zones	Orientation	Area (m²)	Volume (m³)	W1I1R2	W1I2R2	W1I3R2	W2I1R2	W2I2R2	W2I3R2	W3I1R2	W3I2R2	W3I3R2	W4I1R2	W4I2R2	W4I3R2
Zone 1	South	18.01	64.82	49.69461	50.69406	50.30539	46.14103	51.52693	49.41099	50.63853	49.86119	49.91671	49.08384	49.97224	52.1377
Zone 2	South-East	20.96	75.47	51.14804	52.05153	51.57443	49.23664	52.09924	50.90649	51.81298	51.71756	51.52672	50.52481	51.33588	52.19466
Zone 3	East	21.18	76.25	54.53258	53.99632	55.24079	50.89707	55.71294	53.87138	55.66572	55.24079	55.09915	52.9745	54.91029	55.71294
Zone 4	North-East	18.04	64.93	54.15743	55.70953	54.08891	49.55654	54.93348	53.04878	55.54324	54.82262	54.82262	52.82705	54.93348	55.87583
Zone 5	Courtyard (SE)	18.97	68.31	51.55509	52.39852	51.92409	49.49921	51.66052	50.92251	52.24038	52.02052	51.92400	163.7849	51.87138	170.6378
Zone 6	Internal	19.31	69.52	55.46349	56.29208	55.77421	54.37597	55.826	55.25634	56.29208	56.44744	56.1885	54.32418	55.56706	55.30813
Zone 7	North	15.64	56.31	60.99744	62.85166	62.0844	54.09207	62.9156	59.78261	62.72379	61.50895	61.70077	57.35294	60.86957	62.21228
Zone 8	West	41.54	149.55	51.17959	51.66105	51.51661	48.70005	51.73327	50.74627	51.78142	51.20366	51.30624	50.43332	51.27588	52.07029
Zone 9	South	22.88	82.37	225.5682	227.5787	226.5297	220.9353	227.4913	224.8252	224.7815	226.1801	224.8689	229.7115	223.2517	220.6731
Zone 10	South-East	13.22	47.58	216.1876	219.4402	217.4735	214.2965	221.7852	218.3812	215.8004	210.2133	216.5658	200.9077	211.8003	206.354
Zone 11	South-East	12.88	46.36	224.6118	227.2516	225.854	221.118	228.5714	225.4658	225	226.7857	225.1553	212.0553	221.6615	217.8571
Zone 12	North-East	17.41	62.69	236.5883	237.9093	237.0477	240.3217	240.3791	239.0086	235.4968	238.5411	236.7605	221.9884	230.872	234.4113
Zone 13	North-East	23.62	84.67	156.3082	158.2557	157.3666	150.0847	157.155	154.7841	157.0703	156.9656	156.4775	152.3709	156.6046	156.4352
Zone 14	Courtyard (SE)	18.97	68.31	173.3263	176.3419	174.9077	166.3679	177.6489	173.6426	174.5367	175.593	174.0643	163.7849	172.1666	170.6378
Zone 15	South-West	18.5	66.58	268.5405	267.5676	267.8378	260.0541	272	273.2432	268.1081	271.0811	269.8378	264.1622	264.1081	260.6486
Zone 16	North	23.68	85.25	192.1875	194.1723	193.261	187.7111	194.7635	192.272	193.7022	194.0878	193.4122	188.3598	191.3007	190.5828

Zones	Orientation	Area (m²)	Volume (m³)	W1I1R3	W1I2R3	W1I3R3	W2I1R3	W2I2R3	W2I3R3	W3I1R3	W3I2R3	W3I3R3	W4I1R3	W4I2R3	W4I3R3
Zone 1	South	18.01	64.82	49.75014	50.74958	50.36091	46.19656	51.58245	49.47252	50.69406	49.86119	49.97224	49.19489	50.02776	52.24875
Zone 2	South-East	20.96	75.47	51.24046	52.14695	51.62214	49.27977	52.19466	51.00191	51.9084	51.76527	51.57443	50.66794	51.38359	52.29008
Zone 3	East	21.18	76.25	54.57979	56.04344	55.28801	51.03872	55.76015	52.96601	55.71294	55.28801	55.14636	53.06893	54.95751	55.80737
Zone 4	North-East	18.04	64.93	54.21286	55.76497	54.98891	49.61197	84.3681	53.10421	55.59867	54.87805	54.87805	52.88248	54.93348	55.87583
Zone 5	Courtyard (SE)	18.97	68.31	51.6078	174.3806	172.7464	163.5741	51.81866	171.2177	172.3774	173.3263	171.8503	160.0422	170.0053	168.582
Zone 6	Internal	19.31	69.52	55.77421	56.8026	56.08493	54.47954	55.92957	55.35993	56.34386	56.49922	56.24029	54.73848	55.87778	55.67064
Zone 7	North	15.64	56.31	60.99744	62.9156	62.0844	54.09207	62.85166	59.78261	62.72379	61.50895	61.70077	57.35294	60.86957	62.21228
Zone 8	West	41.54	149.55	51.29005	51.75734	51.6129	48.82041	51.82936	50.84256	51.90178	51.29095	51.49254	50.60183	51.30624	52.21473
Zone 9	South	22.88	82.37	223.208	225.2185	224.2133	219.0678	226.1801	223.5577	223.7762	225	223.7762	118.5752	220.8910	218.4878
Zone 10	South-East	13.22	47.58	214.2209	217.3979	215.5825	212.1029	219.6672	216.3389	213.9939	217.171	214.6747	199.1679	209.9092	204.6899
Zone 11	South-East	12.88	46.36	222.5155	225.1553	223.8354	218.6355	226.3975	223.2143	223.059	224.6118	223.1366	210.6366	219.5652	216.0714
Zone 12	North-East	17.41	62.69	234.5204	235.784	234.9799	237.7944	238.139	236.7003	233.4865	236.3584	234.6927	220.2183	228.6617	222.6881
Zone 13	North-East	23.62	84.67	153.3086	155.6308	154.6994	147.5868	154.0958	152.5626	155.0381	112.5741	154.403	149.492	153.9373	153.8103
Zone 14	Courtyard (SE)	18.97	68.31	171.1123	174.3806	172.7464	163.5741	175.3295	171.2177	172.3774	173.3263	171.8503	160.0422	170.0053	168.582
Zone 15	South-West	18.5	66.58	266.0541	265.027	265.3514	275.1351	267.7838	268.8649	264.1081	266.973	265.7297	251.7297	261.6757	258.3243
Zone 16	North	23.68	85.25	190.076	192.1453	191.1318	184.7128	192.103	189.527	191.3851	191.5541	190.9206	184.2061	189.2736	168.6402

The result of the analysis shows that for the wall and roof assemblies where the ECBC prescription has been followed caused less energy consumption. For external façades W2I1R1 (AAC blocks + EPS insulation + RCC slab with EPS insulation) gives best result as per the assessment. For internal facades facing the courtyard, W1I2R1 (AAC blocks + Jute fibre insulation + RCC slab with EPS insulation) works best.

Ground floor zones requires less energy as compared to the zones located on the first floor. Average energy consumption of the zones located on the ground floor is 45-70Wh/m² and average energy consumption of the zones located on the first floor is 120-170 Wh/m². Also, since the base case wall assemblies were found 300mm thick, the proposed wall assembly is 230 mm, which will eventually provide more usable space.

Based on the above analysis, the recommended wall and roof assembly construction details is proposed in Fig. 14(a) and (b) respectively which may be adopted in present day construction for optimized annual energy consumption in the haveli cum hotel buildings located in the composite climate like Rajasthan.

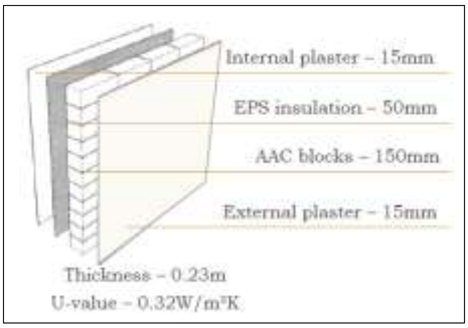

Fig 14(a): Recommended wall details from study

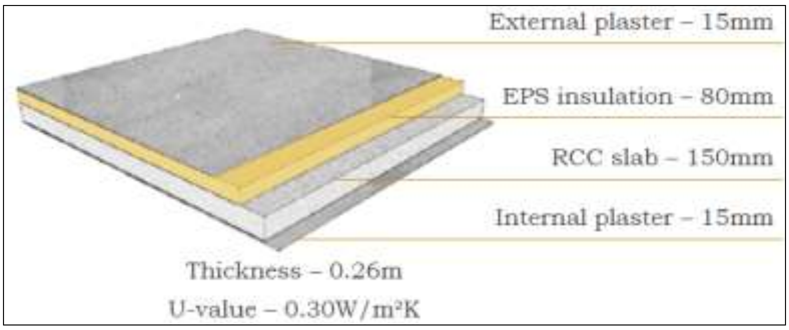

Fig 14(b): Recommended roof details from study

5.4 WWR and glazing optimization

Comparative analysis has been done among the combination and impact of different WWR values and window glazing types on the probable annual energy consumption of the haveli cum hotel building. The combination matrix of different options used in the analysis is given in Table 11. As per the analysis based on different combination of WWR values and glazing types the energy consumption in different zones of the haveli per unit area is calculated and presented in Table 12.

Table 11: The combination matrix of WWR values and different glazing types used in energy analysis of the *haveli*

WWR	G1- Double glazed clear glass	G2- Double Glazed - Low Solar Gain Glass	G3- Planitherm Glass (blue tinted)
EXISTING External façade – • South-west – 22% • North-west – 7% • South-east – 0.8% Internal courtyard - • South-west – 27% • North-west – 14.7% • South-east – 14.7% • North-east – 8% **PROPOSED** Courtyard & external facade - WWR 1 - 20% WWR 2 - 30% WWR 3 - 40%	A typical clear, double-glazed unit has two panes of glass with the inner and outer layers of glass that is completely sealed -forming a transparent insulating barrier between the interior of your space and the outdoors. VLT – 0.5 U-factor – 2.67W/m²K SHGC – 0.7	Low-E Glass Double-glazed window with a low-solar-gain low-E glass with argon gas fill. Compared to most tinted and reflective glazing's, this low-E glass provides a higher level of visible light transmission for a given amount of solar heat reduction. VLT – 0.5 U-value – 2.53W/m²K SHGC – 0.45	Planitherm is thermally insulated glass. It uses the latest advances in glazing technology to coat the surface of the glass with a high performance thermally insulating layer, and this will, of course, lead to savings in heating bills for your home. VLT – 0.5 U-value – 1.8W/m²K SHGC – 0.35

Table 12: Details of energy consumption in different zones studied in the *haveli* due to WWR values and glazing types

Zones	Orientation	Area (m²)	Volume (m³)	G1 + 20% WWR	G2 + 20% WWR	G3 + 20% WWR	G1 + 30% WWR	G2 + 30% WWR	G3 + 30% WWR	G1 + 40% WWR	G2 + 40% WWR	G3 + 40% WWR
Zone 1	South	18.01	64.82	105.9411	104.8862	103.387	107.8845	106.3298	104.1644	119.9889	107.2182	104.3865
Zone 2	South-East	20.96	75.47	90.93511	90.60115	89.55153	91.50763	90.98282	89.64695	97.1374	91.31679	89.59924
Zone 3	East	21.18	76.25	108.3569	108.0264	107.0349	108.8763	108.4514	107.1766	115.9585	108.9235	107.3182
Zone 4	North-East	18.04	64.93	104.6009	104.6563	104.102	104.9889	104.9889	104.2129	107.3823	105.0998	104.1574
Zone 5	Courtyard (SE)	18.97	68.31	75.01318	75.01318	74.32789	74.64418	74.53875	73.80074	80.81181	75.22404	73.95888
Zone 6	Internal	19.31	69.52	86.69083	86.69083	86.06939	86.63905	86.69083	86.01761	98.60176	86.74262	86.06939
Zone 7	North	15.64	56.31	117.1995	116.624	115.4092	118.0307	117.3274	115.7928	129.0921	117.9668	116.1765
Zone 8	West	41.54	149.55	80.25999	80.09148	75.63601	77.78045	77.56379	76.50457	94.22244	77.99711	76.60087
Zone 9	South	22.88	82.37	252.1853	249.1096	249.0385	255.9003	251.6608	251.5297	272.4213	254.7395	254.0647
Zone 10	South-East	13.22	47.58	240.2421	238.1997	238.1241	242.2844	239.4856	239.41	249.1679	240.6959	240.6203
Zone 11	South East	12.88	46.36	275.7764	257.6087	257.3758	262.9658	259.2391	259.0839	272.7484	260.7919	260.6366
Zone 12	North-East	17.41	62.69	234.9225	233.8311	233.5439	237.1051	235.3245	234.9225	252.8986	236.703	236.2435
Zone 13	North East	23.62	84.67	211.939	211.0923	211.05	211.9814	211.05	211.05	223.7087	211.5157	211.4733
Zone 14	Courtyard (SE)	18.97	68.31	223.669	222.7201	222.4038	224.8814	223.4581	223.0364	240.854	224.0907	223.4581
Zone 15	South West	18.5	66.58	236.1622	232.3243	231.8378	240.0541	234.9189	234.3784	253.4054	237.2973	236.8649
Zone 16	North	23.68	85.25	224.7889	222.6351	222.2973	225.3378	223.0574	222.6774	239.9493	224.8733	224.4088

Different WWR values and glazing types has been simulated for the base case and other proposed combinations to study their performances with respect to the orientation of the façade. It has been found that the least the WWR value, the more energy savings can be achieved. The Blue tinted Planitherm Glass has the least U-value (1.8W/m²K), SHGC (0.35) and VLT of 0.5, hence providing good thermal insulation as compared to the other glazing types. WWR of 20% with the Blue tinted 'Planitherm' Glass provides the maximum energy efficiency.

Based on the analysis it has been found that the zones located in the west direction is the least energy consuming as it is mostly shaded. Also, the zones arranged in the courtyard are the least energy consuming as they are mostly shaded. Max. energy consuming zones is located in the South-East direction. Further study will be done regarding assessment of daylighting to support optimization of the WWR values and glazing types.

6. Conclusion

The present study has presented an approach and the findings from the analysis of a haveli-turned-hotel building located in Rajasthan with composite climate regarding the reduction and optimization of its annual energy consumption to maintain indoor thermal comfort with use of air-conditioning. From the study wall and roof assembly, WWR value and glazing type are proposed which may result more energy savings for the buildings in composite climate. Further studies will be taken up to assess the impact of various factors on the daylighting condition as well.

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