FEASIBILITY OF PREFABRICATED BUILDING STRUCTURES IN BHUTAN

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DOI: 10.54417/jaetm.v3i1.103

Abstract— *Studies and research on the arena of prefabrication have prodigiously reported faster project delivery, improved quality and safer working conditions. More prominently, reduction in waste materials at project sites without any implications to environmental aspects has been a major breakthrough. Prefabricated building structures have been progressively recognized as a substitute to the conventional methods of construction at a rapid rate, however, there is a knowledge vacuum and inadequate data on the adoption of prefabrication in Bhutan. Hence, in the current study, the feasibility of Prefabricated Buildings in Bhutan with a case study was carried out. The study focused on the benefits, constraints and way forward of prefabrication works in Bhutan through field survey and questionnaire survey. In addition, economic, environmental assessments and insulation performance were carried on a Pre-Engineered building with prefabricated materials and subsequently compared to a conventional building. From the study, the major benefit found to be ease of construction whereas the constraints pertaining to the design and planning phase of the project were deemed to be the major constraint. In particular for prefabricated construction, the cost was found to be 24.18% higher but the duration of the project can be reduced by 25-31% and the environmental impact was found to be 20.81% less than for the conventional building. Therefore, adopting prefabricated construction will depend on the requirements of a particular project, the availability of funds and environmental standards to be followed. However, the use and acceptance of prefabrication in the construction industry can be improved by better advocacy and public awareness.*

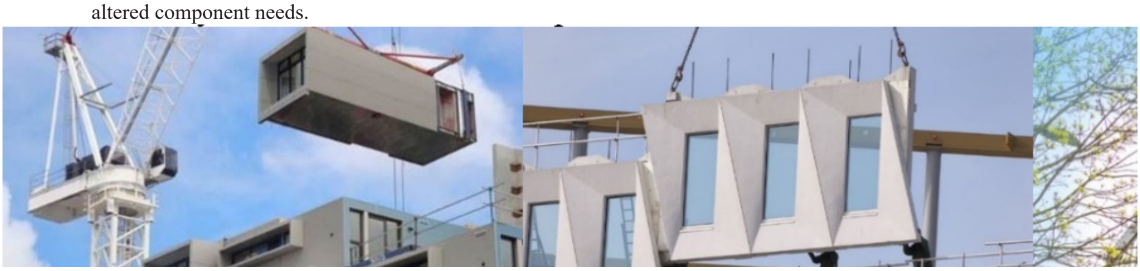
Keywords— prefabrication, prefab, pre-engineered building, conventional building.

1. INTRODUCTION

Prefabrication, also known as offsite manufacturing (OSM) of building components, is a relatively new and creative construction method in which the majority of building components are made offsite. Building components are manufactured in a controlled atmosphere in a specialized factory setting before being transported to and installed at the project site [1]. OSM is a useful technique espoused from manufacturing that can boost productivity rates in construction industries. The concept behind manufactured construction is that if some operations are shifted to a manufacturing facility rather than being conducted on a building site where workers would be exposed to the weather conditions, the amount of effort required to get the same outcome would be significantly less [2]. Prefabrication has several advantages for the construction sector, including increased control over operations, as well as improved safety and component quality. The ability to save construction time on the job site is also a noteworthy benefit for both clients and contractors. A manufacturing plant's regulated environment may boost productivity and save labor expenses. The whole life cycle of a prefabricated building structure is dependent on long-term vulnerabilities and catastrophes, the selection of acceptable materials, and the precision of material connections during assembly.

The three main types of prefabricated buildings, as shown in Figure 1, are [3]:

1. Modular: 3D components that are solely produced in a manufacturing plant setting are supplied to the project site for installation. This is sometimes referred to as sectional PPVC (Prefabricated Prefinished Volumetric Construction) or unitized systems of 3-dimensional structural units that are integrated on-site with other elements to create a full building.
2. Panelized: 2D panel houses are partially constructed in a manufacturing setting before being shipped to the site for assembly and building. Houses made of pre-sized, pre-cut or pre-shaped components that are built or placed on site are also known as flat pack, pre-cut, or kit homes.
3. Hybrid: A combination of 2D panel and 3D modular construction. A hybrid system has advantages for systems with altered component needs.



1(a) 1(b) 1(c)

Fig. 1. (a) Modular, 1(b) Panelized & 1(c) Hybrid [3].

The construction industry of Bhutan states the critical symptoms of failure and poor performance that include irreparable liabilities of time and cost overrun, ignored oddities of safety, dull quality of works etc. [4]. On the other hand, there is an absence of information on what the industry thinks about prefabrication performance. There is a prerequisite to identify specific gaps and the needs in the area of design and decision support systems which are to be addressed. Prefabrication is at its infancy stage in Bhutan and the preferential policies could have only a temporary promotion. There is knowledge gap on prefabrication due to unpublished and inadequate data, concerning rapid urbanization, and the construction industry has to seek innovative materials and technologies which can provide more high-quality housing using less construction time. A lack of awareness on the performance, benefits and affordability design and techniques provided by the prefabricated systems is also a major challenge for the marketing of prefabricated building construction. The conventional construction implicates the casting technology at site, form works and excessive amounts of material wastages. There is a high amount of time and cost invested in the current construction methods which also generates environment impacts during construction and demolition phase, yet few public and private sectors have ventured into prefabrication during the recent years. Consequently, the objectives of this study are:

1. Assess the current trend and uses of prefabricated building structures in Bhutan;
2. Explore the benefits, constraints and prospective of various prefabrication constructions in Bhutan;
3. Conduct an analysis on cost, time, environmental impact and insulation performance;
4. Carry out a comparative analysis between the conventional construction method and prefabrication construction used in the country.

2. DATA AND METHOD

The methodology was divided into two parts: Part A and Part B (Figure 2). Part A adopted a questionnaire-based survey to find out the status of prefabrication in Bhutan implementing a mixed approach of both qualitative and quantitative methods. SPSS version 26.0 was used to analyze the data. The required information for this study was collected through an online questionnaire survey. The questions in the survey form were developed through literature reviews of various papers on the subject and also, in consultation with the field engineers by understanding the ground reality of the prefabrication works at sites. Questions pertaining to benefits and constraints were based on Likert Scale (Strongly Disagree = 1, Disagree = 2, Moderate =3, Agree = 4 and Strongly Agree = 5). Next, Part B uses only the quantitative method for field survey and data analysis using software by considering a case study. A Blower Door Test was carried out to check the air tightness for the insulation performance of a case study building under Part B. The methodology used in this study is as follows:

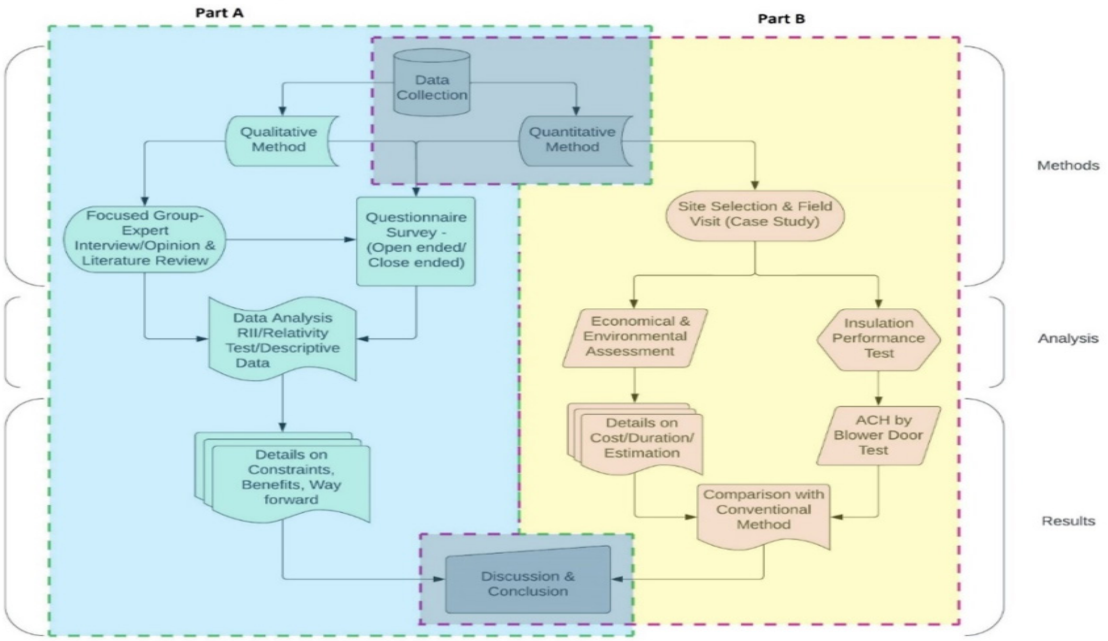


Fig. 2. Methodology adopted for study

3. FINDINGS

The sample size of the questionnaire survey collected was 114 with the respondents from various sectors as listed in Table 1.

Table 1. Background information of respondents.

Total Sample (n) = 114		
Item	Number	Percentage
Experience (years)		
0 – 5	48	42.11
5 – 10	20	17.54
10 – 15	10	8.77
15 – 20	14	12.28
20 – 25	9	7.89
25 – 30	6	5.26
30 – 35	7	6.14
Qualification		
Diploma	21	18.4
Degree	72	63.2
Masters	20	17.5
PhD	1	0.9

Organizations		
Government	29	25.44
Corporates	13	11.4
Privates	56	49.12
Autonomous	9	7.89
Others	7	6.14
Designations		
Designer	20	17.5
Project Manager	17	14.9
Project Engineer	30	26.3
Site Engineer	30	26.3
Architect	8	7.0
Others	9	7.9

3.1. Benefits of prefabrication

Reduced construction time implies the building generates revenue for the customer far sooner than it would in a conventional construction project [5]. Buildings are often completed in approximately 6 to 8 weeks after the drawings have been approved. Pre-Engineered Building will thus at least 30% shorten the project's overall production time. When compared to conventional construction methods, the main advantages of prefabricated building systems are cost and time savings. Other advantages include better manufacturing quality and precision, on-site installation speed, and the ability to deconstruct and reuse [5][6]. This type of prefabricated structure also has environmental benefits, such as lowering construction waste and CO2 emissions, as well as causing less disruption to nearby residents by reducing on-site noise and dust [7]. Prefabrication is touted as a sustainable building technique [8]. A concrete framed buildings use more energy consumption and environmental impact than steel structural-frame buildings [9]. Construction waste generated by conventional homes is 2.5 times more than that of modular homes [10]. Prefabrication has a low operating and maintenance cost as well as a low total cost of ownership, but it has a high capital cost [6]. Despite these advantages, however, the technology's application in the building sector has not received the attention it deserves. This is due to the anecdotal nature of the stated benefits [1]. The list of benefits retrieved through various references against their mean and standard deviation based on the questionnaire survey are tabulated as follows.

Table 2. List of benefits of prefabrication in Bhutan.

Stages	Benefits	Source	Mean	Standard Deviation
Planning and Design	Lower construction cost	[11]	3.46	1.070
	Durable and weather resistant	[12]	3.56	0.679
	Quality controlled	[13]	3.92	0.693
	High-efficiency building	[14]	3.61	0.770
Construction	Easy assembling	[3]	4.32	0.733
	Shortens overall project time	[13]	4.33	0.687
	Relieves labour shortages	[15] [16]	4.11	0.670
	Waste Management/ reduction	[7]	3.99	0.804
	Improve safety for construction workers	[16]	3.79	0.722
Operation and Maintenance	Lower maintenance cost	[17]	3.46	0.884
	Enhances environmental protection	[18]	3.81	0.851
Demolition	Disassembled and reusable	[6]	4.11	0.784

3.2. Constraints of prefabrication

Prefabricated housing is not considered for mortgage financing until it is permanently erected. People sometimes consider prefabricated dwellings as objects rather than real estate, and as a result, prefabricated homes depreciate more rapidly than regular residences [19]. Regardless how customizable prefabricated designs promise to be, they are limited in terms of flexibility and diversity [19]. The higher capital cost is the most significant barrier to the development of prefabrication [20][21]. [22] indicated that the capital cost of the prefabricated building was 10–20% higher than the traditional on-site construction. [20] argued that the higher cost of project cost consisted of material cost, labour cost, machinery cost, factory cost, land cost and management cost. Even though there is less labour on the construction site, prefabricated modules must still be manufactured, which drives up the cost of the construction [23]. According to [24], when accounting for long-distance transport brought on by offshore manufacturing, the cost of transportation might rise to more than 18% of the entire cost. The logistics of prefabrications demand a rigorous load-unload control procedure, extra protection, and fixation in contrast to the conventional material transportation method to prevent potential damage during transit. Apart from that, the weight and dimensions of modules are other constraints, which not only restrict the transportation route but also elevate the expenditure resulting from the specific requirement for vehicles [25][26]. Prefabricated modules are installed during on-site assembly using a significant quantity of equipment, particularly cranes, which results in an increase in the overall cost [20][27]. Furthermore, [28] showed that a significant problem with the installation of modules is the numerous intricate connections of modular buildings. The constraints based on various references against their mean and standard deviation as per the questionnaire survey are listed below.

Table 3. List of constraints of prefabrication in Bhutan.

Stages	Constraints	Source	Mean	Standard Deviation
Planning and Design	Lack of experience and expertise	[29]	4.41	0.762
	Lack of government support	[30]	3.48	0.914
	Poor market and society acceptance	[31]	3.89	0.835
	Lack of Research & Development input	[32]	4.35	0.728
	Lack of policies, building codes and standards	[30]	4.04	0.856
	Poor design flexibility	[33]	3.54	0.952
Construction	Higher capital cost	[20]	3.73	0.980
	Higher construction cost	[34]	3.31	0.942
	Lack of coordination among stakeholders	[35]	3.82	0.790
	Difficult to blend with Bhutanese architecture	Based on Experts' Views	3.70	1.113
	Lack of technical support (in-house fabrication)	[29] & Based on Experts' Views	4.25	0.759
	Inadequate skilled workers	[27]	4.18	0.833
	Hired workers from other countries	Based on Experts' Views	4.15	0.844
	Inaccurate estimation of quantities of work	Based on Experts' Views	3.12	0.942
	Complexity of connection	[31]	3.09	0.992
	Accidents during construction	[16]	3.01	0.907
Transportation	Higher transportation charges	[27][36]	4.04	0.954
	Materials damage during transportation	[37]	3.61	0.973
	Potential delay during transportation	[38]	3.70	1.004
	Requires intensive material handling	[34]	3.61	1.009
	Additional lifting machines cost	[20]	3.83	0.911
Assembly	Materials unavailable readily	Based on Experts' Views	4.18	0.87
	Limitations of weight/dimensions of materials	[39]	3.65	0.922
	Lack of durability, leakage, and cracks	[40]	3.25	0.878
	Lack of quality inspection standard	[37]	3.60	0.993

3.3. Case Study

In order to supplement the questionnaire survey, the case study was selected of 96 Bedded Hostel Construction for Gedu College of Business Studies (GCBS) under the Royal University of Bhutan (RUB). The hostel is a Pre-Engineered Building (PEB) with Prefabricated Structural Insulated Panels (SIP). The structural insulated panels used are Polyurethane panels for walls. The details of the building project are given in Table 4.

Table 4. General information of the case study building.

Particulars	Description
Location	Gedu, Chukha, Bhutan
Latitude	26°55'07.3"N
Longitude	89°31'19.1"E
Building Type	Hostel
Total Area	17500 sq.ft.
No. of Floor	2
Structural System	Pre-Engineered Building (Steel)
Floor Height	3.3 m
No. of Occupants	96
Life Span	50 years
Year of Study	2022

3.3.1. Integration of Economic Assessment and Environmental Assessment

The economic and environmental impacts of various construction technologies used to construct hostel building were carried out by combining Life Cycle Cost (LCC) and Life Cycle Assessment (LCA) as shown in Figure 3. The optimal building system was determined in the final stage using the developed LCA-LCC model, which took into consideration both economic and environmental impacts. This LCA was then integrated with the LCC evaluation to determine the total cost of constructing a project using a certain construction modality as well as the cost of operating such a facility over a 50-year period.

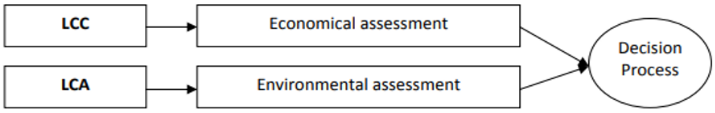
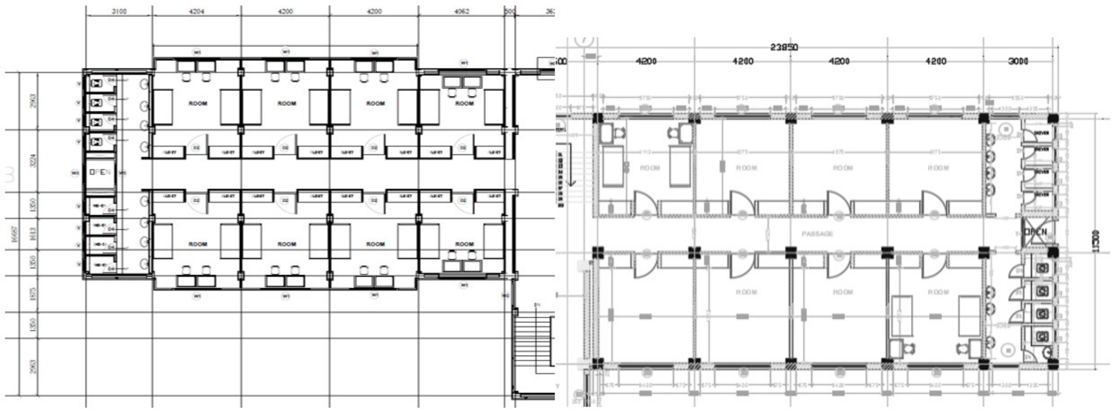


Fig. 3. The use of LCA/LCC as tool for decision making process [41].

A comparison study has been accomplished between the PEB case study Building and a hypothetical Conventional Building Structure considering a Reinforced Cement Concrete (RCC) Building of the same size with Aerated Autoclaved Concrete (AAC) Block and Burnt Brick walls. The comparison study comprises only the structural frame and the walls as per the drawings in Figure 4. Other components of the buildings are considered to be the same.



(a) (b)

Fig. 4. 2D drawing of (a) PEB Structure and (b) Conventional Structure.

The duration was calculated using the deterministic approach of the Critical Path Method (CPM) as well as the probabilistic approach of time estimate as per PERT (Program Evaluation and Review Technique) of Project Management. The LCC was used as a method to calculate the total costs during the building's lifecycle from cradle-to-grave. LCC steps include stages A0–C4 (from pre-construction and construction costs, followed by the maintenance, replacement, operational, and end-of-life costs). The LCC was performed by using One Click LCA software [42] that is in compliance with ISO 15686-5 standard [43] and follows the structure of EN 16627 standard [44]. The analysis cover costs were computed over the lifespan of the building from the pre-construction stage until the end-of-life stage. The included LCC modules are presented in Table 5.

Table 5. LCC modules according to EN 16627 standard.

Pre-construction stage	Costs of purchase/rent the land	A0
Production stage	Raw material supply	A1
	Transport	A2
	Manufacturing	A3
Construction process stage	Transport to the building site	A4
	Installation into the building	A5
Use stage	Use/application	B1
	Maintenance	B2
	Repair	B3
	Replacement	B4
	Refurbishment	B5
	Operational energy use	B6
	Operational water use	B7
End-of-life stage	Deconstruction/Demolition	C1
	Transport	C2
	Water processing	C3
	Disposal	C4

In this LCC calculation, the present value (PV) formula was used for discounting future cash flows to present values [45].

$$PV = Ft \times 1 \ (1 + d)t \qquad (i)$$

PV = Present value
t = Time in unit of year
Ft = Future cash amount that occurs in year t
d = Discount rate used for discounting future cash amounts to the present value.

For calculating all costs that appear through the building lifetime, the present value formula was applied. The general LCC formula for buildings was used for summarizing all costs that occur from cradle-to-grave.

$$LCC = I + Repl + E + W + EOL \qquad (ii)$$

I = Investment costs
Repl = Replacement costs
E = Operational energy costs
W = Operational water costs
EOL = End-of-life costs

Table 6 shows the parameters fetched from various sources which were used for measuring LCC and LCC in the software.

Table 6. Parameters used in calculations for LCC and LCA.

Parameters	Input	Description
Life span of the building	50	Calculation period considered
Electricity price	Nu. 2.68/kWh	(Bhutan Power Corporation Limited, 2021)
Water price	-	No charges on water for the case study
General inflation rate	7.3%	(National Statistics Bureau, 2021)
Discount rate	8%	(Bank of Bhutan, 2020)
Regional material cost index	1.92%	(National Statistics Bureau, 2021)
Hourly labour rate of craftsman	Nu. 75	(Bhutan Schedule of Rates, 2020)
Hourly labour rate of worker	Nu. 56.25	(Bhutan Schedule of Rates, 2020)
Energy/water inflation rate	5.6	Data provided by software (default)
EOL as % of capital costs	2.5%	Data provided by software (default)

The carbon emission factors of the materials database in accordance with the International Standardization Organization (ISO) for Life Cycle Assessment are used in this study. The following equation (iii) is used to calculate the total embodied carbon of materials used in the designed buildings [46].

$$E_M = \sum M_j^M \cdot f_j^M / 1000 \qquad (iii)$$

E_M is the total embodied carbon of all building materials (in tons CO2-e) (CO2-e: CO2- equivalent)
M_j^M is the amount of building material j (in kg) obtained from quantity take-offs tables from estimates
f_j^M is the carbon emission factor for building material j (in kg CO2-e/kg)

Additionally, other factors for all impact categories are calculated by using equation (iv) [47].

Inventory x Impacts = Total Environment Impact of the Building (iv)

Inventory = Estimate of quantities of materials and processes in building
Impacts = Estimate of Environmental Impacts for each material and process

3.3.2. Insulation Performance

In order to assess the air tightness or the insulation performance of the case study building, blower door test is one of the tests adapted [48]. The insulation performance of the building was done using Blower Door Test Equipment as shown in Figure 5. All of the air blown out of the building by the blower is replaced by air coming in through all of the leaks. The measured value was then converted to an air change rate. A cubic foot of air leaks for every cubic foot of air blown out by the fan. The structures were depressurized to a continuous differential pressure of 50 Pascal (Pa) in order to detect the air leaks. At 50 Pa, the blower test findings were standardized according to the testing equipment. At a reference pressure of 50 Pa, the air leakage (m^{-3}. h^{-1}. m^{-2}) between the interior and exterior of the building envelope was measured as (m^{-3}. h^{-1}. m^{-2} @ 50 P). The blower door test result was used for comparing the air tightness of PEB in comparison with Conventional Building structures.

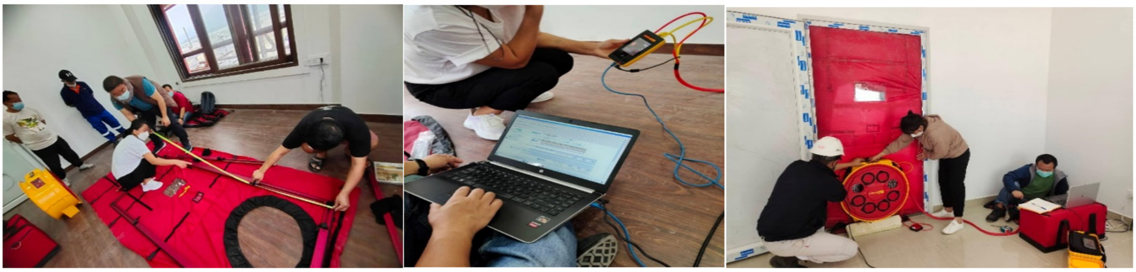


Fig. 5. Blower Door test is being conducted in the case study building.

4. RESULTS AND DISCUSSION

4.1. Status of prefabrication in Bhutan

The factors as per Figure 6 based on the questionnaire survey shows the highest RII for benefits such as 'Simplifies work process/ shortens project', 'Easy assembling', 'Disassembling and reusable' and 'Relieves labour shortages' whereas benefits like 'Waste management/ reduction', 'Quality controlled', 'Enhances environment protection' and 'Improve safety for construction workers' have RII of mid-range. The top five ranked RII of benefits shows that the maximum benefits of prefabrication are there during the construction phase. However, the survey shows the lowest RII for 'High energy efficiency building', 'Lower construction cost', Durable and weather resistant', and 'Lower maintenance cost'.

The factors as per Figure 7 based on the questionnaire survey shows the highest RII for constraints such as 'Lack of experience and expertise', 'Lack of Research and Development input', 'Lack of technical support', 'Materials unavailable readily', 'Inadequate skilled workers' and 'Hired workers from other countries'. Lowest ranked RII of constraints include 'Poor design flexibility', 'Lack of Government support', 'Higher construction cost', 'Lack of durability, leakage and cracks', 'Inaccurate estimation of quantities of materials', 'Complexity of connection', and 'Accidents during construction'. Rest constraints show a mid-range of RII. The top five ranked RII of constraints shows that the top two ranked constraints are during the planning and design phase and the next three top ranked RII were during the construction phase.

There is also a contradicting factor as per the Relative Importance Index ranked factors of Benefits and Constraints that the 'Lower construction cost' is amongst the lowest RII ranked of benefits as well as 'Higher construction cost' is also amongst the lower RII ranked of Constraints. This clearly indicates that there are opposing responses in terms of construction cost. This may be attributed to the fact that the prefabricated structures are relatively new in Bhutan and are yet to make any pronounced impact largely on the cost of construction. Subsequently, to supplement this incongruity by considering the questionnaire survey based on the 16 prefabricated building projects details executed across the country (Figure 8), it does conclude that 50% of the executed prefabricated building projects have acquired a lower construction cost than the conventional method while 31% i.e., 5 projects disagreed. Rest, 13% i.e., 2 projects are not sure as of now while 6% i.e., 1 project says it is at par as these are ongoing projects. Hence, the construction cost of prefabricated buildings could be higher or lower than that of conventional buildings, nonetheless, the cost can be reduced leading to competitive market with improved awareness on prefabricated structures in the country.

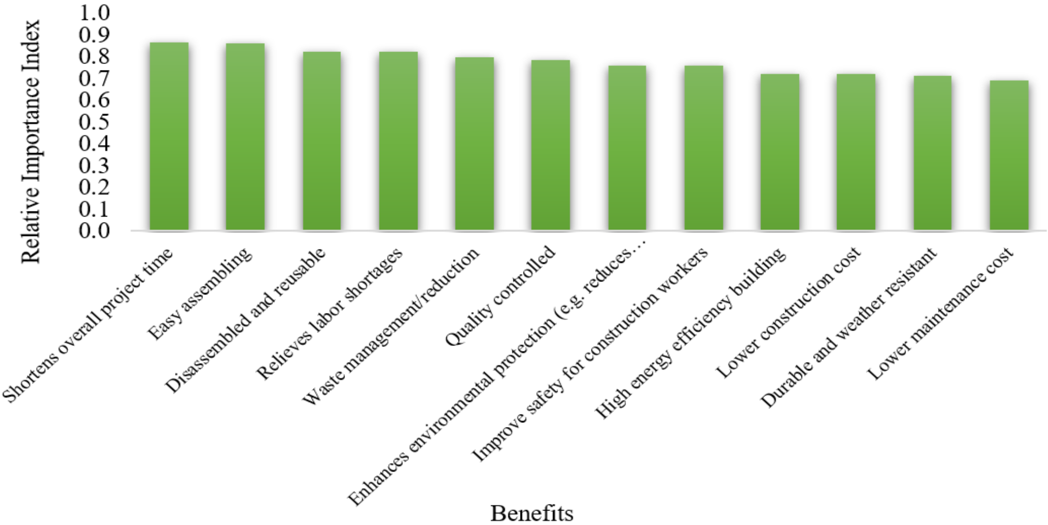


Fig. 6. Graphical illustration of Benefits and Relative Importance Index (RII).

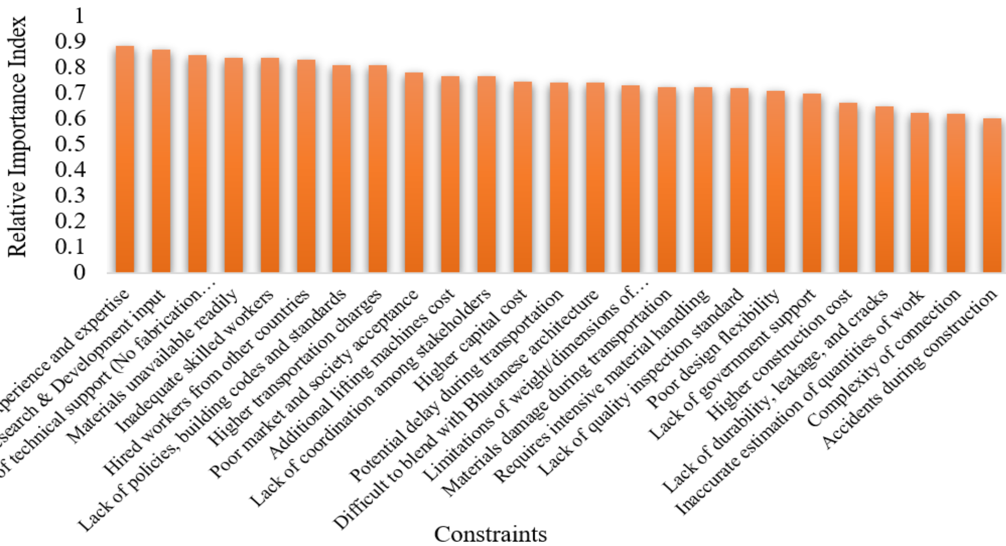


Fig. 7. Graphical illustration of Constraints and Relative Importance Index (RII).

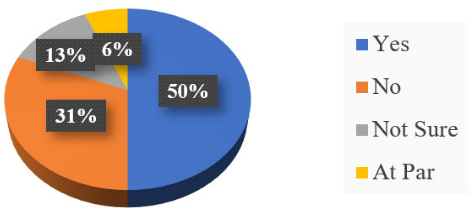


Figure 8. Pie Diagram showing whether prefab projects executed are more expensive than conventional in Bhutan.

Out of 114 respondents, 107 agreed the current dominancy of conventional method over prefabricated building structures. The main reasons were such as prefab structures are new, not familiar or unaware. The conventional method being predominant and prevalent till date due to its advantages of constructability, stability and durability. There is a confidence on the availability of skilled workers and materials in the market. Lack of prefab factories and expertise were the main concern with regard to prefab structures. Almost 77% of the respondents are willing to live in a prefabricated house due to its nature to construct faster and cost saving. Their preferences meant something new to try based on low rents to pay cheaper house provided the quality and designs were met. Rest 17% favored conventional while 6% weren't sure of. The constraints presently are relatively higher than the benefits met where the focus is to reduce the constraints in meeting the ground demands.

4.1.1. Prospective of prefabrication in Bhutan

The survey encompassed the open-ended questionnaire seeking ways of improvements or increase in the use of prefabrication works in Bhutan. The followings were results and are listed pertaining to the number of frequencies on the respondents' answers:

1. Awareness - Respondents suggested on promoting the use of prefabricated building structures. More advertisement and marketing are essential to be carried out so that everyone understands the benefits of this method. The concept of prefabrication buildings is to be heightened.
2. Policies and guidelines – Government is to encourage on the prefab usage. Policies and guidelines to be refined in favour of prefabrication.
3.Training/demonstration – This is needed to build inhouse capacity through trainings or workshops and developing skills to enhance domestic expertise by demonstrating which shall lead in building confidence amongst the users at the same time.
4. Standards/Quality/durability – The required specifications are to be made without comprise in design at par or better than conventional method.
5. Encourage manufacturing industries – There should be inhouse production facility to reduce the cost and facilitate to accelerate the project time by availing quicker access of materials. Hence, the transportation cost of the materials shall not be a huge burden to the projects.
7. Competent market price – This is vibrantly desired to meet the local requirements.
8. Research/analysis – Investing in Research and Development is crucial in for future learning. It should be an alternative under material crises.
9. Tax exemption/reduction when importing – Until now, most of the materials are imported. In order to retain capital, production facilities are essential in country or else there should be nominal taxes to be paid to the government. The materials should be transported with improved transportation system.
10. An alternative to conventional method - Under material crises, it should be a compliment to conventional method rather than replacement.
11. Should be energy efficient in addition with maintenance should be available and the product to be enhanced during temporary settlement.

4.2. Economical Assessment

The total duration estimated for construction (Table 7 and Table 8) of the case study building for PEB is 487 days (approximately 16 months) whereas it takes 709 days (approximately 23 months) to construct the conventional building of the same size. On the other hand, as per the critical path method, it takes 434 days and 576 days to construct PEB and conventional buildings respectively (Figure 9 and Figure 10Error! Reference source not found.).

Table 7. Estimated time for construction of PEB.

Description	Activity (Code)	Predecessor Activity	Optimistic Time (To)	Most likely Time (Tm)	Pessimistic Time (Tp)	Meantime (Te)	Variance of each task
Preparatory Works	A	-	7	12	15	12	1.78
Excavation Works	B	A	10	12	15	12	0.69
Foundation Works	C	B	30	35	37	35	1.36
Frame Erection	D	C	60	65	70	65	2.78
Staircase Steel installation	E	D	14	18	22	18	1.78
Steel beams	F	D	45	50	55	50	2.78
Roofing works	G	E, F	30	35	45	36	6.25
Floor works	H	F	45	50	55	50	2.78
Wall panel installation	I	G, H	60	65	70	65	2.78
Installation Works (Doors & Windows)	J	I	65	75	85	75	11.11
Finishing Works	K	J	65	70	73	70	1.78
Total Days			431	487	542	487	

The duration for constructing PEB is 31.35% lesser than the conventional building calculated using probabilistic approach of PERT while considering the deterministic approach of CPM, the duration is shortened by 24.65%. As a result, it can be concluded that the construction period of PEB is 25-31% less than the conventional building. Although the cost involved in PEB construction is higher for now, the time is reduced notably and the project is delivered earlier than conventional construction method. Time is crucial when building conventional structures; after pouring concrete in one area, we cannot move on to the next since it needs 28 day curing period before it can reach its full strength [12]. In this prefabricated construction there is no delay in time because most of the materials are fabricated in the factory only.

The total initial cost calculated for PEB is Nu. 514.65 per sq.ft. higher than that of conventional building for the case study building of 17500 sq.ft. Thus, the construction cost of PEB is higher than the conventional building for the case study as shown in Error! Reference source not found. although the operational cost will be the same.

Consequently, the life cycle cost is higher for PEB buildings over the life span of 50 years than conventional buildings with a cost of around Nu. 99Million after discount and inflation as shown in Figure 11. As a result, the nominal LCC i.e., undiscounted with inflation is Nu. 830Million which is also higher than the conventional ones. LCC (discounted with inflation) for conventional buildings with block and brick walls are Nu. 90Million and Nu. 89Million respectively. Also, the nominal LCC for conventional block building is Nu. 811Million and conventional brick building is Nu. 808Million (Figure 12).

Table 8. Estimated time for construction of conventional building.

Description	Activity (Code)	Predecessor Activity	Optimistic Time (To)	Most likely Time (Tm)	Pessimistic Time (Tp)	Meantime (Te)	Variance of each task
Preparatory Works	A	-	7	12	15	12	1.78
Excavation Works	B	A	10	12	15	12	0.69
Foundation Works	C	B	30	35	37	35	1.36
Column Structure Works	D	C	80	83	85	83	0.69
Beam work	E	D	75	80	85	80	2.78
Slab Works	F	E	60	65	70	65	2.78
Staircase Work	G	F	45	48	55	49	2.78
Wall and Frame Works	H	F, G	90	95	100	95	2.78
Roof Trust Works	I	G	30	35	40	35	2.78
Roof (Ceilings and sheet) Works	J	I	30	35	40	35	2.78
Plaster Works	K	H	60	65	68	65	1.78
Installation Works (Doors & Windows)	L	H	65	75	85	75	11.11
Finishing Works	M	K, J, L	65	70	73	70	1.78
Total Days			647	710	768	709	

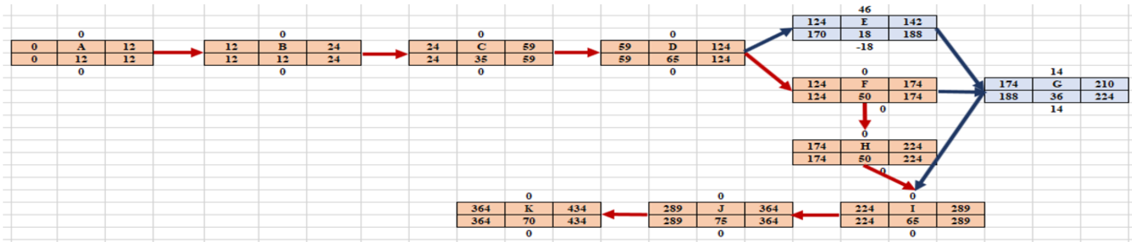


Fig. 9. Duration of PEB using Critical Path Method (CPM).

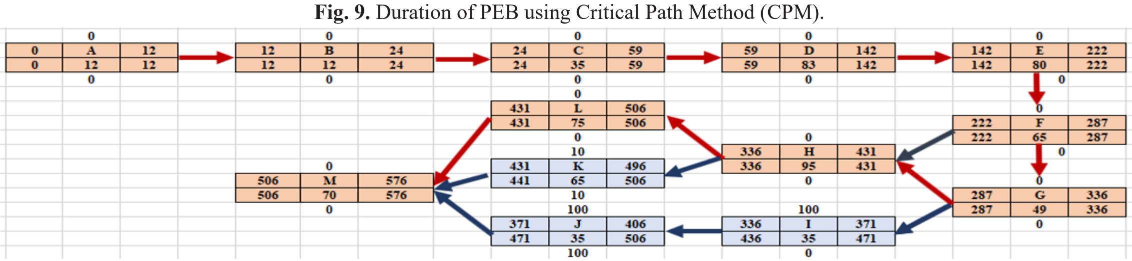


Fig. 10. Duration of Conventional Building using Critical Path Method (CPM).

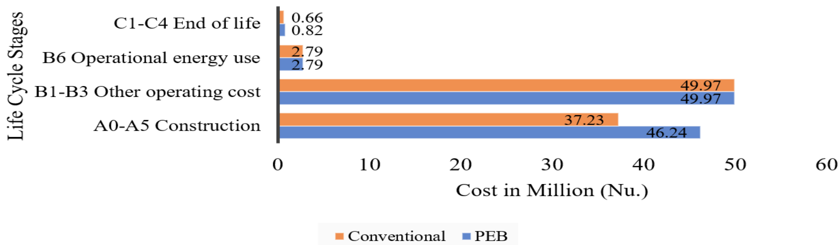


Fig. 11. LCC comparison between PEB and Conventional as per life cycle stages.

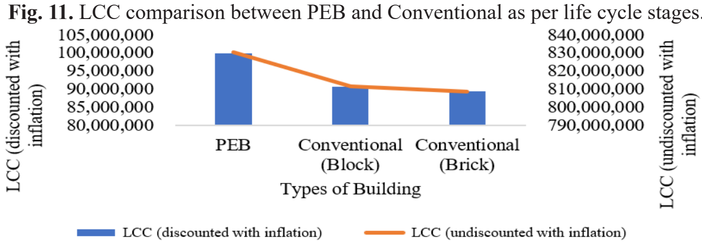


Fig. 12. LCC (discounted with inflation) and LCC (undiscounted with inflation) of different building types as per life cycle stages for 50 years.

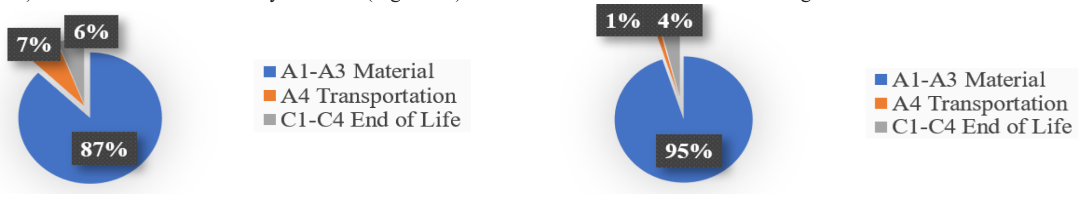
The difference in the mass of the structures of PEB and Conventional Building in Table 9 depicts that the overall mass of the conventional building is higher than the PEB.

Table 9. Mass of structures of PEB and Conventional Building.

	PEB		Conventional	
Item	Mass (Kg)	Percentage (%)	Mass (Kg)	Percentage (%)
Floor slabs, ceilings, roofing decks, beams and roofs	690,000	50.39	1,500,000	43.21
Foundation, sub-surface, basement and retaining walls	360,000	26.04	1,000,000	28.13
Internal walls and non-bearing structures	130,000	9.66	490,000	13.95
Columns and load bearing vertical structures	100,000	7.56	390,000	11.04
External walls and facade	87,000	6.35	130,000	3.67

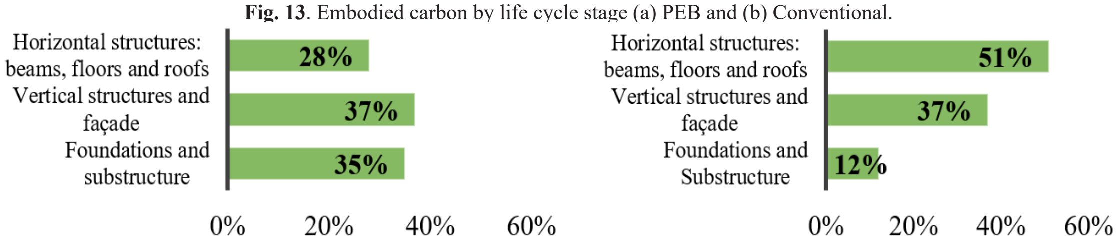
4.3 Environmental Assessment

Life Cycle Assessment was done to check the environmental impact along with the cost involved to compare the PEB with prefabricated structures and conventional building structures. The following figures show the difference between the embodied carbon by stages (Figure 13) and the embodied carbon by structure (Figure 14) between PEB and conventional buildings.



(a) (b)

Fig. 13. Embodied carbon by life cycle stage (a) PEB and (b) Conventional.



(a) (b)

Fig. 14. Embodied carbon by structure (a) PEB and (b) Conventional.

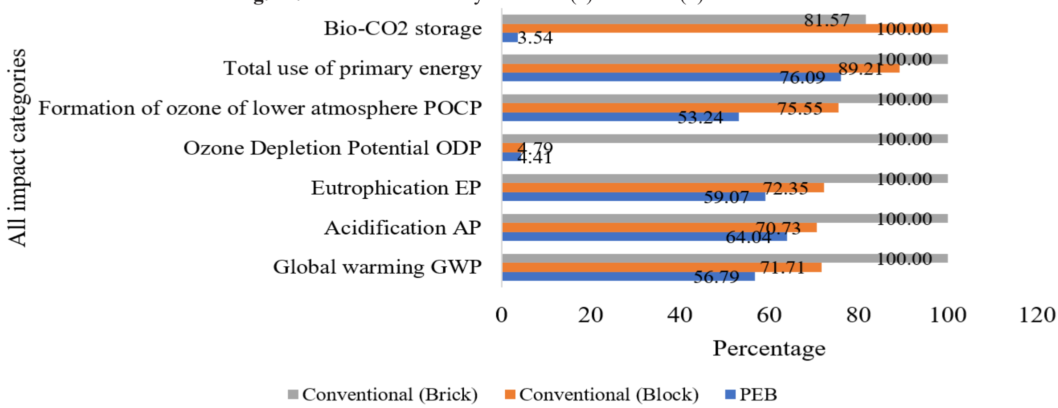


Fig. 15. Life-cycle assessment, EN-15978 of all impact categories.

The Life Cycle Assessment concludes PEB has 20.81% less environmental impact than Conventional (Figure 15). Although, the PEB being at its infant stage now in Bhutan, however, the Global Warming Potential (GWP) results of PEB worked out is 14.92% less than Conventional Building. The component elements of PEB are manufactured in a factory, it can be done in inclement weather, saving time and resources. Additionally, on-site equipment like scaffolding and formwork can be largely eliminated. Prefabricated materials assure the safety of the people as these structures are lightweight, earthquake resistant, and aesthetic. PEB is 61% lighter than the conventional building for this case study.

The graph (Figure 16) shows that environmental impact for PEB during transportation is higher than the conventional building while construction materials of PEB has least impact than the rest. The transportation of PEB impacts 3 times greater than the conventional building. Yet, construction waste and water consumption of conventional building are extensively higher than the PEB (Figure 17). The construction waste is 4.3 times higher in conventional building construction and 98% more water consumption than in PEB. Water usage can be lowered during PEB construction, thus, saving water too.

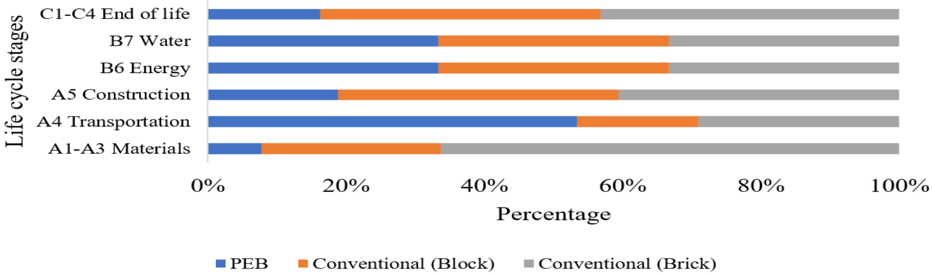


Fig 16. Global warming, kg CO2e of all Life-cycle stages.

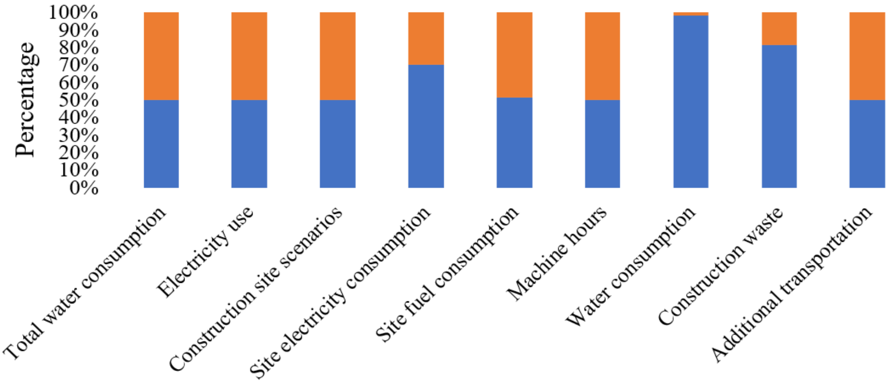


Fig. 17. Global warming, kg CO2e of all elements.

Regarding the insulation performance, the measured Air Changes per Hour (ACH) is 4.62 while measuring a laboratory of RCC building, the ACH is 5.21 (Table 10). There is a difference of 0.59, however, both the buildings' ACH qualify as moderately tight in accordance with the ACH ranges. The ACH of PEB being less than the conventional, this can in long run save energy costs in future during operational stage. According to [49], the replacement of windows, airtightness, and wall and roof insulation have the most effects on energy savings and have helped to reduce 45 percent of the total yearly energy consumed. By lowering the natural gas use, these changes can prevent the emissions of more than 70 tons of CO2-eq annually.

Table 10. Comparison of Blower Door Test Results between PEB and Conventional Building.

Building and Test Information	PEB Hostel, Gedu College of Business Studies	RCC Laboratory, College of Science and Technology
Test file name:	EN13829-SE 2022-04-16 1133	EN13829-EU 2022-03-12 1536
Building volume [m³]:	53.3	320
Envelope Area [m²]:	87.3	308
Floor Area [m²]:	19.5	80
Building Height (from ground to top) [m]:	3.3	7
Building Exposure to wind:	Highly exposed building	Partially protected building
Accuracy of measurements:	10%	10%
Air changes at 50 Pa, n50 [/h]	4.62	5.21

This study shows that PEB is environmentally feasible, however, it is economically unfeasible at present. PEB structure can be a compliment to the conventional building provided that the manufacturing units or suppliers are within the nearby vicinity which can reduce the material cost and the transportation cost. In-house material production and in-house PEB labour skill development are certain areas which can enhance PEB in Bhutan. Prefabricated construction could have a potential gain to Bhutan through educating the local industry, and employment opportunities for the local individuals by providing necessary training thereby developing skilled personnel required to be associated with prefabricated construction. Depending on the distance between the manufacturer and the building site, the delivery of a PEB would require more energy than a conventional building. The further prefab structures must be transported, more energy is used and more greenhouse gases are released in the transportation due to which keeping a better environmental performance than a conventional building will depend heavily on minimizing the distance a PEB is delivered. Accordingly, the PEB may successfully satisfy the requirements for both economic and environmental sustainability.

5. CONCLUSION

The concept has dwelled and the influences and the impressions of prefabrication that have left is incredible. The key focus is on the mechanization of project works by reducing cost, time and enhancing the quality at a greater height. This research was carried out to understand the building method of using prefabricated materials through a case study of Pre-Engineered Building in order to assess its usefulness in a rapidly urbanizing Bhutan. As the prefabrication, work has picked up as one of the largest sectors, a profound evolution in construction sectors is assured to encounter. The manufacturing industries have equally greater responsibilities in the production of leading the business. Several activities can be carried out simultaneously with no hindrances in the work in progress with continuous supplies from the manufacturing units to working sites. The main stream construction work flow is incessant. The involvement requires the procedure which should be highly planned to result in higher productivity. The prefabricated construction advances quality, labor efficiency, safety, productivity, construction time frame, construction water, noise, dust and energy usages. Bhutan needs to grow in order to sustain the rapid growing of the construction industries. It has to develop the infrastructures at an extraordinary benchmark. Prefabrication performs better in terms of sustainable construction when it comes to waste production, aesthetic options, site disruption, water use, and pollution generation. Environmental risks are reduced and workers are assured of their safety. By using these modern technologies and techniques, buildings may be made lightweight, earthquake resistant and weather resistant, with little on-site construction and minimal usage of aggregates, bricks, rebars, cement, and excessive water. The exploration is necessity to move beyond the conventional time-consuming methods of constructions. On a longer run, with in house production amenities and skilled labor can boom the construction sectors of Bhutan. The economic can have a greater impact and ecofriendly benefit is the key impression in maintaining the country's environment.

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