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PROMOTING SUSTAINABILITY IN EMERGING ECONOMIES VIA LIFE CYCLE THINKING

Comparative life cycle assessment and life cycle costing of lodging in the Himalaya

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Abstract
Purpose The main aim of the study is to assess the environmental and economic impacts of the lodging sector located in the Himalayan region of Nepal, from a life cycle perspective. The assessment should support decision making in technology and material selection for minimal environmental and economic burden in future construction projects.
Methods The study consists of the life cycle assessment and life cycle costing of lodging in three building types: traditional, semi-modern and modern. The life cycle stages under analysis include raw material acquisition, manufacturing, construction, use, maintenance and material replacement. The study includes a sensitivity analysis focusing on the lifespan of buildings, occupancy rate and discount and inflation rates. The functional unit was formulated as the '*Lodging of one additional guest per night*', and the time horizon is 50 years of building lifespan. Both primary and secondary data were used in the life cycle inventory.
Results and discussion The modern building has the highest global warming potential (kg $CO_{2\text{-eq}}$) as well as higher costs over 50 years of building lifespan. The results show that the use stage is responsible for the largest share of environmental impacts and costs, which are related to energy use for different household activities. The use of commercial materials in the modern building, which have to be transported mostly from the capital in the buildings, makes the higher GWP in the construction and replacement stages. Furthermore, a breakdown of the building components shows that the roof and wall of the building are the largest contributors to the production-related environmental impact.
Conclusions The findings suggest that the main improvement opportunities in the lodging sector lie in the reduction of impacts on the use stage and in the choice of materials for wall and roof.

Keywords Construction materials · Economic impact · Energy demand · Environmental impact · Global warming potential · Net present value

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1 Introduction

The building sector makes a considerable contribution to global environmental impacts (Scheuer et al. 2003). For instance, the building sector is responsible for 30 % of global annual greenhouse gas emissions and consumes up to 40 % of all energy (UNEP 2009). To assess the sustainability of long-term investments like buildings, it is important to consider their entire life cycle and to evaluate the environmental impacts associated with the raw material extraction, the production, transport stages involved, etc., as well as the final disposal of the materials (Raymond and Cole 2000; Sonnemann et al. 2003; Pittet et al. 2012; Ferreira et al. 2015). Although the choice of the building materials mainly depends on their cost, availability and appearance, the environmental suitability of materials is becoming increasingly an important choice element (Asif et al. 2007). A comprehensive evaluation of a building's life cycle should include a quantification of both their environmental and economic performance (Gu et al. 2008). Previous authors have stressed how combining environmental and economic aspects can strengthen sustainability assessment of buildings (Rathcliffe and Stubbs 2005). In this context, the use of decision support tools such as life cycle assessment (LCA) and life cycle costing (LCC) for sustainability assessment is particularly appropriate.

Ristimäki et al. (2013) describe how implementing LCC and LCA analysis in an early building design stage allows identifying the best economic and environmental design alternatives to develop sustainable urban areas. In particular, the use of LCC in the early design stage allows decision makers to obtain a deeper understanding of long-term design strategies (Ristimäki et al. 2013) and to optimize product efficiency and lifetime cost of ownership (Gluch and Baumann 2003). Moschetti et al. (2015) develop an overall methodology regarding buildings' environmental impacts, energy output and global costs for a complete building sustainability evaluation. Brown et al. (2011) show how life cycle management approaches, where LCA and LCC are integrated, help in establishing sustainability in the design of resorts. Other studies have also tried to combine LCA with LCC to support environmentally concerned decision making in the building sector (Sterner 2002; Gu et al. 2008; Brown et al. 2011). Despite the many studies on LCA of buildings, little is known about the impact of building in developing countries, where modern construction methods are slowly replacing traditional ones.

In the Himalayan touristic region of the Sagarmatha National Park (SNP), the construction of modern buildings is growing fast, due to the increasing tourist flow. To satisfy the needs of the increasing tourist population, traditional building design is modified and concrete structure is reinforced, replacing traditional wood and stone masonry. The modern building is built by using imported construction materials which have to be transported from the capital city, Kathmandu, by air due to the complex terrain orography that makes road transport difficult. Commercial materials are likely to have a larger environmental burden from a life cycle perspective than the traditional materials. On top of this large amount of energy supply is the need to satisfy the demand of this increased tourist population; where possible, the energy is supplied from the combination of traditional energy sources (firewood and animal dung) and commercial sources (kerosene, LPG and electricity). In this context, the assessment of environmental and economic impacts of different building types is of great importance.

This paper reports on double assessment method combining LCA with LCC within the lodging in different building types, in particular by looking at the unique situation of buildings in the Himalayan region. Information about the environmental impact of building materials is currently very limited in developing countries and especially in the Himalayan region, one among the most vulnerable areas in the world with regard to the hazards associated with climate change (Pouliotte et al. 2009; Gentle and Maraseni 2012; Pandit 2013). This paper aims at filling this gap by providing new information on Himalayan buildings and their life cycle impacts. The scope of the study is limited to examining the environmental and economic performance of lodging in three different types of buildings in the Himalayan region of the Sagarmatha National Park Buffer Zone (SNPBZ). Based on this assessment, the study aims to support the selection of technologies and materials to minimize the environmental and economic burden of future construction projects in this region.

This study aims to address the following questions:

1. Which building type is more environmental friendly and cost-effective to satisfy additional lodging demand?
2. Which life cycle stage comprises a high GWP and cost in studied lodges?
3. What are the characteristics of buildings in the Park?
4. How does the study help in selecting technologies and materials to minimize the environmental and economic burden of future construction projects?

2 Materials and methods

2.1 Building types in the Himalayas

As a consequence of higher altitude and cold weather, the buildings in the Himalayas are constructed and designed to meet the human demands in a cold environment (Little and Hanna 1978). Due to the cold climate in the region, houses are built facing south-east to receive the early morning sun and to continue receiving it until late in the afternoon (Pokharel and Parajuli 2000). Due to the difficult terrain, movement of people and materials over long distances is rather difficult, therefore, mainly local materials and skills are used (Pokharel and Parajuli 2000). The materials adopted in the construction of the traditional building are mainly wood, stone and mud, which are locally available and used for e.g. roof and wall construction.

The modern and semi-modern buildings are built by using mainly imported construction materials i.e. cement and insulation materials like glass wool and polystyrene which have to be transported from the capital city, Kathmandu, by air freight. Such materials are likely to have a larger environmental burden from a life cycle perspective from production till its end use. However, locally available materials like stone and wood are also used for the construction of this kind of building. The Park authority has legalized a regulation to the local people that allows the use of 30 m^3 of wood timbers per construction of one new building. Additional wood timbers are brought from Jiri, also called Gateway to Mount Everest, which is located at a 51-km aerial distance from the Park. These materials are mostly transported by helicopter from Jiri to the Sagarmatha National Park.

2.2 Building types addressed in the study

In the context of the tourist presence in this region, the study focused on the commercial building types present in the area. More specifically, the study focused on buildings that have the commercial purpose of both the accommodation of tourists and the provision of food for them. Three different existing building types, typical of current Himalayan Sherpa architecture and building typologies, were chosen as a case study for this analysis as described below:

1. *Modern type*: to enhance the tourism in the national park area, the modern cemented houses (Fig. 1) are designed using imported construction materials for insulation like glass wool and polystyrene. Interestingly, nowadays all the modern houses (latest built) are being equipped with the latest efficient lighting arrangement with sensors.
2. *Semi-modern type*: this type of building is a combination of local and modern technologies with limited insulation (Fig. 2). It is the modification of traditional houses into modern ones.
3. *Traditional type*: these follow the ancestral house design typically known as 'Sherpa House'. In the construction of these types of houses, locally available materials are abundantly used, particularly on the roof and the wall construction. For example, locally available wood is used as beams in the roofs whereas locally available wooden planks, dry stones and mud plasters are used in walls (Fig. 3).

Fig. 1 Modern building

Fig. 2 Semi-modern building (Bhochhibhoya and Cavalli 2016)

Primary data on building size, building materials and energy consumption of three commercial buildings were collected through questionnaires in SNP during the month of March/April, in 2014. Three buildings were selected with three different patterns based on material used and architecture design: traditional, semi-modern and modern that are representative to all the existing buildings in the Park.

As the commercial materials were imported from Kathmandu, the questionnaires on the source of materials, type of vehicle used from the manufacturer to the retailer and transportation distance covered were undertaken from the retailers of building materials in Kathmandu. General features of the three building types are summarized in Table 1.

2.3 Life cycle assessment

In this study, a cradle-to-gate LCA from construction till replacement stage was performed. Additionally, a sensitivity analysis focusing on specific parameters was performed. The ecoinvent v.3 with the consequential model assumption was used to model the background system. The SimaPro 8 software was used for the calculations.

Fig. 3 Traditional building

Table 1 Characteristics of the three buildings types considered in the study

Type	Traditional	Semi-modern	Modern
Location	Namche	Namche	Namche
Elevation (m)	3800	3800	3800
Operational season	7 months	7 months	7 months
Net area (m^2)	210	244	301
Gross volume (m^3)	1953	2868	3897
Construction method	Load bearing	Load bearing	Reinforced concrete
No. of floor	3	4	3
No. of beds	17	33	34
Occupancy assumption (in % of rooms occupied)	80	80	80
Guests per night stay	14	26	27
External walls	Mud plaster inner and outer side of dry stone, with wooden plank in internal wall	Cement pointing in dry stone, with wooden plank in internal wall	Cement pointing in dry stone, with insulating materials in space, wooden plank in internal wall
Insulation	Mud plaster	Polystyrenes	Glass wool/polystyrenes
Windows	Wooden frame with single glazed glass	Wooden frame with single glazed glass	Wooden frame with double-glazed glass, 4 mm thick each, and air space of 6 mm
Roofing	Galvanized sheets	Galvanized sheets	Galvanized sheets
Floor	Wooden plank	Wooden plank	Wooden plank
Door	Wooden	Wooden	Wooden
Heating system	Metal heating chimney	Metal heating chimney	Metal heating chimney + electric heater

2.3.1 Goal and scope definition

The goal of the study was to evaluate the life cycle environmental impacts of the lodging in three building types: traditional, semi-modern and modern. Detailed study on the LCA was carried out for three representative lodges based on type and structure of the building. The scope of the study included the following life cycle stages: raw material acquisition and manufacture, building construction, building use, building maintenance and material replacement (Fig. 4). The end of life of the building was not taken into account due to the limited information on building demolition, waste transportation and different waste treatment processes. The functional unit (FU) was considered as the increase in demand for lodging and formulated as the '*Lodging of one additional guest per night*'. This allows comparing environmental and economic aspects of lodging in three different types of buildings in SNPBZ. The building lifetime was set to 50 years as this is the average age of buildings in SNPBZ.

2.3.2 Life cycle inventory

Both primary and secondary data were used in the life cycle inventory. Primary data on the quantity of material used in each type of buildings, transportation distances and the used means of transport, energy consumption for different household activities were collected in the field. Data on energy consumption during building use were collected through questionnaires with the owners of selected three lodges. Direct measurements of the building size and dimensions were also carried out to quantify the volumes of different building components (e.g. wall, doors) and then calculate the amount of building materials used. Measurement of room dimensions (height, length, width), wall thickness and type of material used; measurement of doors and windows and its numbers and measurement of the whole building (length and breadth) were undertaken. This study is the first of its kind in Nepal and is primarily based on field data collected using a structured questionnaire from sampled areas to avoid error due to assumptions. The process from the consequential version of ecoinvent database v.3 (Frischknecht et al. 2004; Frischknecht et al. 2007; Weidema et al. 2013) has been utilized to model the manufacturing process of the material used and their associated emissions.

Construction stage The construction stage in this study includes the collection of raw materials by resource extraction, processing of the raw materials to building products and

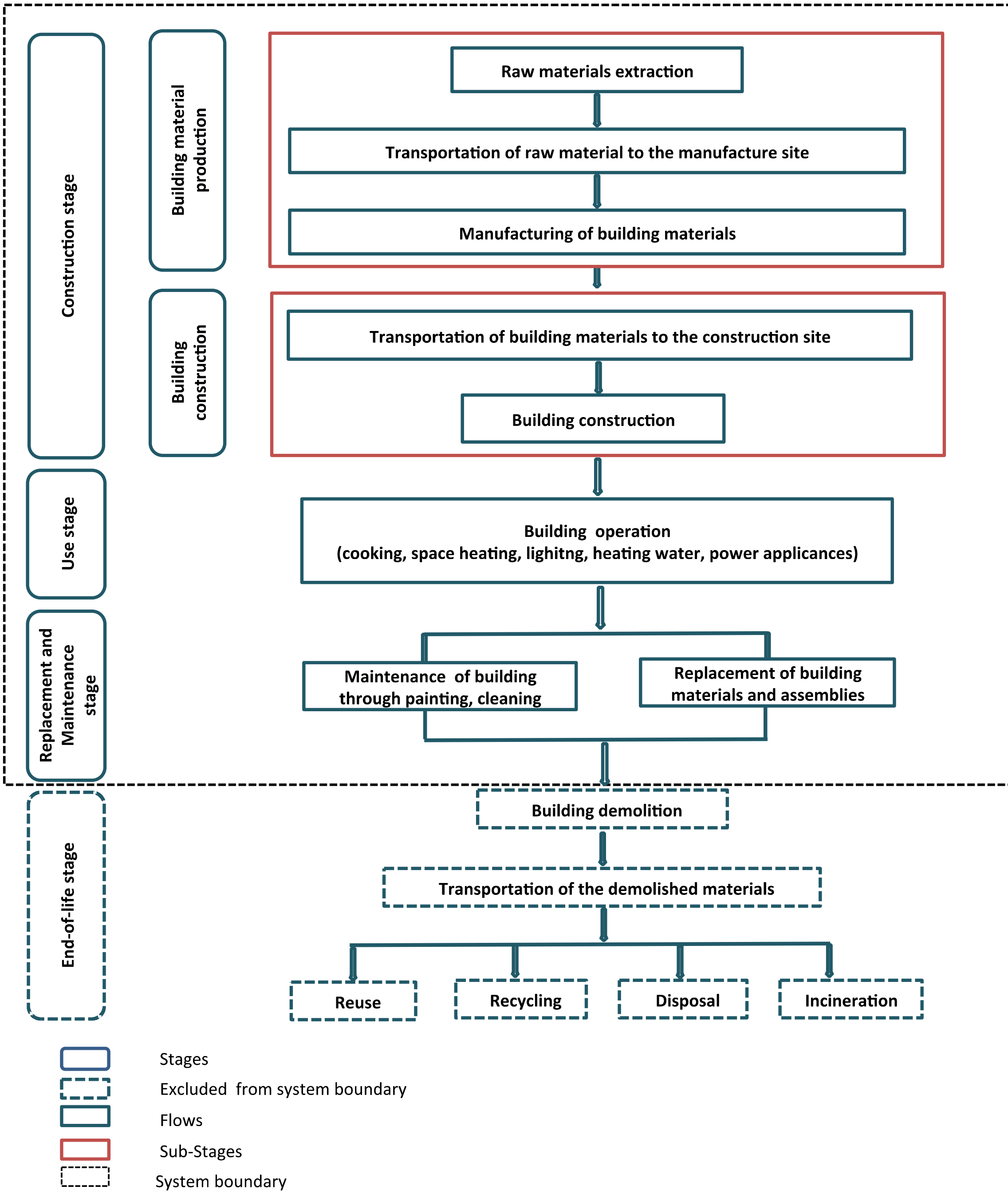

Fig. 4 LCA system boundaries

transportation of the products to the construction site till the assembly of the products on a construction site. The type and quantities of material used for the construction of three lodges are given in Table 2, and detailed information is given in Appendix 1 (Electronic Supplementary Material). The data were collected from the fieldwork. Measurements of the buildings on site, direct observations and interview of concerned people like an expert, contractor and local people were done. The weight is calculated based on the measured volume of the materials in the buildings and on their density.

In addition, transportation means and distance covered from the manufacturing site to the construction site were estimated for each construction material. To obtain the environmental impact from transportation, the total weight (tonnes) of construction materials was multiplied by the total distance covered (km).

Use stage The use stage is included to account for the impact generated by the energy consumption of different household activities such as cooking, space heating, water heating,

Table 2 Life cycle inventory of the lodges

Enclosure	Materials	Weight (kg) Modern	Semi-modern	Traditional
Wall	Wooden plank	1842.80	1394.46	752.76
	Plywood	116.23	79.43	30.86
	Glass wool	176.03	0.00	0.00
	Mud	8095.16	4963.00	8408.28
	Stone	443,407.32	271,845.07	115,145.29
	Polystyrene	204.98	0.00	0.00
	Enamel	46.05	36.26	14.93
	Ordinary nails	8.53	6.72	2.77
	Cement	328.03	194.84	72.50
Roof	Wooden joist	6567.48	2226.29	2230.01
	Corrugated galvanized iron	834.91	282.35	281.41
	Roofing nails	9.84	3.33	3.32
Window	Wooden frame	371.28	227.91	81.11
	Glass	1221.68	432.51	204.53
Door	Wooden door	98.54	84.65	102.04
	Plywood door	4.76	4.53	1.76
Floor	Wooden joist	5661.65	3500.52	1410.44
	Wooden plank	7045.70	4356.27	1755.23
Ceiling	Wooden joist	5661.65	3500.52	1410.44
	Plywood	36.43	22.53	9.08
Ladder	Wood	56.26	72.34	56.26
Corridor	Wooden plank	1677.47	737.35	823.76
	Wooden joist	460.03	170.61	201.63
Pillar	Cement	251.94	0	0
	Sand	1084.75	0	0
	Iron rod	256.00	0	0

lighting and the use of other electrical appliances during the building lifetime. The energy consumption of the lodge has significant seasonal variation. The tourist season was taken into consideration since higher amounts of energy are consumed in this period.

The energy consumption for different household activities was estimated with questionnaires administered to the lodge owner in these three lodges of three building types. The emission factor for the different fuel types was taken from literature (Bhattacharya and Salam 2002) mentioned in Appendix 2 (Electronic Supplementary Material).

The use of traditional fuels (fuel wood and cow dung), commercial fuels (kerosene and LPG) and electricity was quantified. Table 3 reports the amount of energy used for different household activities in the three selected lodges. The environmental impact from the transportation of commercial fuels is also included with the total emission. The emission arising from the production of the stoves is excluded from this study.

Maintenance and replacement stage This stage accounts for the impact associated with the replacement of building materials and the building maintenance during the 50-year building lifespan. The rate of maintenance was estimated based on the questionnaire responses given by the lodge owner, whereas the rate of replacement of building materials was calculated based on the expected material lifetime. Maintenance activities include enamelling every 10 years; for the replacements of plywood wall and polystyrene, twice in 50 years; and for plywood door, ceiling, glass wool, mud, wooden plank for the wall and corrugated galvanised iron (CGI) sheet, once in 50 years (ATD Home Inspection 2015). Details are given in Appendix 3 (Electronic Supplementary Material).

2.3.3 Impact assessment and interpretation

The two impact assessment methods IPCC 2013 and ReCiPe were chosen for the impact assessment of the lodging in three building types. Five impact categories were included in the analysis: global warming potential (kg $CO_{2\text{-eq}}$), ozone

Table 3 Energy consumption pattern in three lodges

Building type	Building activities	Fuelwood (kWh * guest night^{-1})	Kerosene (kWh * guest night^{-1})	LPG (kWh * guest night^{-1})	Electricity (kWh * guest night^{-1})	Solar PV (kWh * guest night^{-1})	Total (kWh * guest night^{-1})
Modern	Cooking	–	8.09	0.67	0.27	–	9.03
	Lighting	–	–	–	0.09	–	0.09
	Space heating	2.36	–	–	0.73	–	3.09
	Heating water	–	–	–	0.08	–	0.08
	Electrical appl.	–	–	–	0.003	–	0.003
	Total						12.29
Semi modern	Cooking	2.59	1.92	0.73	0.15	–	5.39
	Lighting	–	–	–	0.06	0.45	0.51
	Space heating	3.24	–	–	–	–	3.24
	Heating water	–	–	–	0.06	–	0.06
	Electrical appl.	–	–	–	0.01	–	0.01
	Total						9.21
Traditional	Cooking	9.43	–	0.48	0.31	–	10.22
	Lighting	–	–	–	0.02	–	0.02
	Space heating	9.42	–	–	–	–	9.42
	Heating water	–	–	–	0.11	–	0.11
	Electrical appl.	–	–	–	0.01	–	0.01
	Total						19.78

depletion ptential (kg CFC_{-11eq}), eutrophication potential (kg PO_{4eq}), acidification potential (kg SO_{2eq}) and photochemical ozone creation potential (kg C_2H_{4eq}). These are the most important and common environmental indicators applied in the building sectors at global (global warming potential, ozone depletion potential), regional (acidification potential, photochemical ozone creation potential) and local scales (eutrophication potential) as indicated by Khasreen et al. (2009). Global warming potential (GWP) impact category, which is without biogenic $CO_{2,}$ has been chosen to express and compare the impact of three buildings. GWP is generally regarded as a major indicator in LCA studies (Knauf 2015). Furthermore, GWP or 'greenhouse effect' leads to climate change, which is currently one of the significant global environmental issues. Moreover, the situation of mountains is certainly perilous due to global warming, thus the prime importance has been given to mitigate the impact due to climate change by reducing greenhouse gas emissions. Improving building sector and restraining carbon emission have a significant impact on energy conservation and global climate change (Chen et al. 2011; Ristimäki et al. 2013).

2.4 Life cycle costing

Life cycle costing was applied to compare different building designs in terms of both initial costs and expected future operational costs (Ristimäki et al. 2013).

In this study, initial costs are all the costs incurred in the construction of the building, whereas future costs are costs for the building's operation and maintenance and replacement over the 50-year lifespan. In order to accurately combine initial expenses with future expenses, the present value of all expenses was determined (Mearig et al. 1999). The LCC analysis approach developed by the SMART SPP consortium (Seebach et al. 2011) was used in this study (Eq. (1)). The present value of all the costs, including construction costs, use costs and maintenance and replacement costs, in the 50-year building lifespan has been studied.

$$\mathrm{LCC} = \mathrm{Co} + \sum\nolimits_{t=0}^{T} \frac{\mathrm{Ct}}{(1+i-j)t} \tag{1}$$

where C_0 is the initial cost; C_t is the present value of all recurring costs (use costs, maintenance and replacement costs) at year t; t is the year of cash flow; i is the discount rate and j is the inflation rate.

The discount rate and inflation rate were chosen in order to actualize the future price in the initial price. It is used to discount and transform future cash flows (such as future operation, replacement, disposal costs) into present value costs. The Central Bank discount rate of Nepal is 6 %, and the inflation rate is 10 % in the fiscal year 2013.

An escalation rate was also taken into account to indicate the relative price changes over time (Kirk and Dell'Isola

1995). This rate accounts for the increase in future costs over time. The escalation rate was applied on energy cost and material cost, labour cost for maintenance and replacement costs. We used escalation rates obtained from the interviews with the retailers as well as web search. The escalation rate for kerosene is 4 and 2 % for LPG (Nepal Oil Corporation Limited 2015). From the interview with retailers, it was found that the escalation rate of enamel is 6 %, wooden plank 3 %, glass wool 1 %, polystyrene 1 %, plywood 9 %, CGI 8 % and nail 2 %. However, the labour cost for transportation is increased by 5 % every year.

Construction costs are the sum of the costs for building construction materials, transportation of materials from the retailer to the building site by vehicles and labour. Construction costs are evaluated based on the cost of each material in the retail shop, including VAT, in addition to transportation costs from the retail shop, which is mainly based on a flight from Kathmandu to Lukla. Further, the materials are transported to the construction site from the Lukla airport manually, which is counted as labour cost for transportation.

Use costs include the energy cost associated with building operation activities such as cooking, space heating, lighting, heating water and use of other electrical appliances. The costs of energy were estimated by an interview in the retail shop in SNPBZ. Costs associated with building operation are discounted to present value.

3 Results

3.1 Global warming potential of Himalayan buildings

Results for the GWP impact produced by lodging of one additional guest per night in the three building types are reported in Table 4. Among the three building types, the stay of one additional guest per night in the modern building shows the highest GWP impact (10.53 $CO_{2\text{-eq}}$ * guest night^{-1}). GWP of a modern building is almost the double of the semi-modern GWP (5.32 $CO_{2\text{-eq}}$ * guest night^{-1}) and 18 % higher than the GWP produced by a guest in the traditional building (8.93 $CO_{2\text{-eq}}$ * guest night^{-1}). The use stage is the largest contributor to the GWP in the three building types (98 %), whereas both the building construction and the replacement stage represent about 1 % of the total impact. Since these three buildings are hotels and lodges, a high amount of energy is consumed for different household activities to fulfil the needs of the tourist. Thus, the GWP associated with energy consumption in the use stage is higher compared to construction and replacement stages during the period of 50 years. Thus, the variation of the results is due to the energy performance in different household activities in the three buildings.

The GWP of the modern building in the construction stage is remarkable than that of the traditional and semi-modern building. It is important to note that the modern building is constructed mostly with commercial materials such as cement, plywood, glass wool, polystyrene and glass which are brought to the Park through various means of transportation. Moreover, the net area of the modern building is usually bigger than the rest of the building types.

3.1.1 Construction stage

Figure 5 shows the result of the GWP impact associated with the main building components: wall, roof, window, door, ceiling, floor, ladder and columns. The wall and roof construction produces the highest amount of $CO_{2\text{-eq}}$ * guest night^{-1}, followed by the ceiling, the floor and the window construction. The total GWP of roof and wall for the modern building is approximately 0.08 kg $CO_{2\text{-eq}}$ * guest night^{-1}, 0.03 kg $CO_{2\text{-eq}}$ * guest night^{-1} for semi-modern and 0.05 kg $CO_{2\text{-eq}}$ * guest night^{-1} for traditional buildings.

These results are acceptable as the building component that covers a larger area, as wall and roof, uses more materials and ultimately has a larger environmental impact.

3.1.2 Use stage

The GWP emission from lodging one additional guest per night in the modern building is higher than in the other types of buildings (Fig. 6). The GWP of cooking in a modern building is 8.67 kg $CO_{2\text{-eq}}$ * guest night^{-1} while the space heating is responsible for 1.50 kg $CO_{2\text{-eq}}$ * guest night^{-1}. The variation of the results depends on the type and quantity of the energy source (Table 3). Kerosene and LPG, used for cooking activities, have the highest emission factor per unit of energy, with the consumption of 8.09 kWh and 0.67 kWh * guest night^{-1} respectively.

The semi-modern building has the best environmental performance during the use stage, with approximately half the impact of the modern buildings. This may be due to the equal use of both traditional (firewood) and commercial (Kerosene and LPG) fuel types in the use stage. The semi-modern building uses an equal amount of wood and kerosene as energy sources (Table 3): 48 % of firewood, 36 % of kerosene and 16 % of LPG and electricity.

In the traditional building, GWP emissions produced during the use stage are 74 % higher than those of the semi-modern building. Firewood is the major energy source in traditional building and is used for producing 90 % of total energy, whereas in the semi-modern building the use of firewood covers the 63 % of energy demand with 3.3 times less wood than in the traditional building (Table 3). The lower energy needs are tied to a more efficient insulation material of the semi-modern building (polystyrene) compared to the traditional one (mud plaster) (Table 1).

Table 4 GWP of three building types

Building types/ phases	Construction (GWP kg $CO_{2\text{-}eq}$ * guest night^{-1})	Operation (GWP kg $CO_{2\text{-}eq}$ * guest night^{-1})	Replacement (GWP kg $CO_{2\text{-}eq}$ * guest night^{-1})	Total (GWP kg $CO_{2\text{-}eq}$ * guest night^{-1})
Modern	0.12	10.28	0.14	10.53
Semi-modern	0.04	5.20	0.08	5.32
Traditional	0.07	8.73	0.13	8.93

3.1.3 Replacement stage

Similar to the construction stage, the main contributors to the total environmental impact of the replacement stage are the walls and roof components of the building (Fig. 7). Walls contribute 48 % of the total GWP while the roof contributes 40 % in the modern building. On the other hand, the roof contributes the major environmental impacts in the semi-modern and traditional buildings by 53 and 59 % respectively.

3.2 Results for other impact categories than climate change

ReCiPe method has also been used to calculate the system burden in other impact categories. The results are reported in Table 5. The results on other impact categories show that the modern building has the highest environmental impacts. The variation of the results is mainly based on energy performance and construction technique. The use stage in all the building types has the highest environmental impact due to the highest amount of energy needed.

The results for eutrophication psotential (EP) are dominated by the use stage and the construction phase for all building types. The EP value of the modern building is ten times higher than that of the semi-modern building and similar to that of the traditional building.

The calculated acidification potential (AP) value of the modern building is still higher than those of semi-modern and traditional buildings, but the less emissive building in terms of AP is the traditional one with 0.01 kg $SO_{2\text{-}eq}$. The emissions are mainly from the use stage and the production of construction materials. Also, for the impact categories photochemical ozone creation potential (POCP) and ozone depletion potential (ODP), the construction and operation stages are the most important.

3.3 LCC analysis results

The cost of lodging in three building types during its lifespan is shown in Table 6. As in the case of LCA results, the LCC results show that the modern building contributes the highest life cycle cost (19.91 € * guest night $^{-1}$) over a period of 50 years of lifespan of the building. In this case, the semi-modern building with 6.33 € * guest night^{-1} comes second with three times lower cost than the modern building. Traditional building (4.28 € * guest night^{-1}) has the least LCC which is almost five times lesser than that of modern buildings since the traditional building relies on the local products in terms of building product as well as energy, which is comparably less costly than that of a commercial product.

The construction cost concurred with the relatively small percentage of global cost in all building types that contribute only 1 % because the cost is associated with the use of the building by a guest. While the use cost contributes around 90 % in modern and semi-modern buildings and 79 % in the traditional building. Replacement cost, on the other hand,

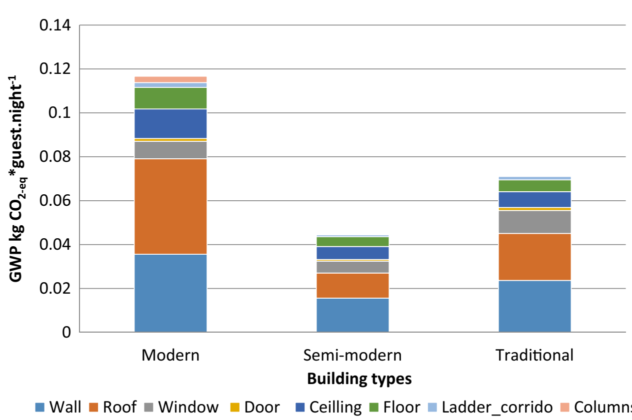

Fig. 5 GWP ($CO_{2\text{-}eq}$ * guest night^{-1}) of construction stages for the three different building types

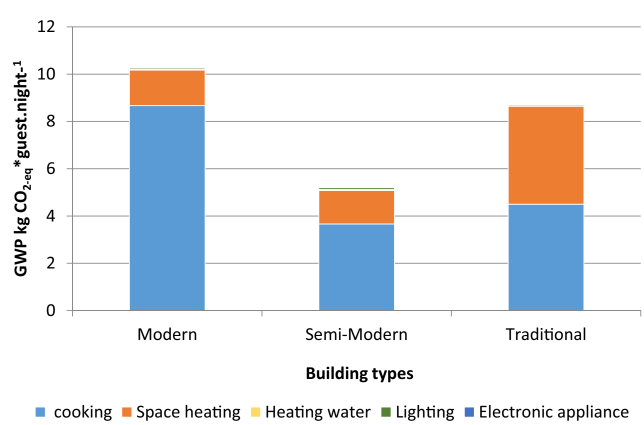

Fig. 6 GWP ($CO_{2\text{-}eq}$ * guest night^{-1}) of the use stages for the three different building types

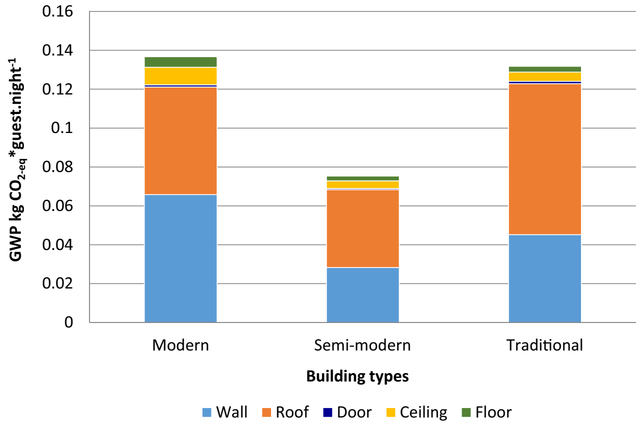

Fig. 7 GWP ($CO_{2\text{-eq}}$ * guest $night^{-1}$) of the replacement stages for three building types

contributes around 8 % of the total cost in modern and semi-modern buildings and 19 % in the traditional building.

3.4 Sensitivity analysis

The LCA and LCC modelling in the study is based on multiple assumptions that may have an effect on the results. Therefore, a sensitivity analysis was undertaken to address modelling uncertainties. The lifetime of the buildings, the percentage of occupancy of a room in the buildings and the discount and inflation rates were considered as key parameters in terms of uncertainty. The sensitivity of LCA and LCC results with respect to these parameters was then investigated. Figure 8 summarizes the results of the sensitivity analysis, and details are given in Appendix 4 (Electronic Supplementary Material).

Discount and inflation rates are continually changing, depending on the interest rate set by the commercial bank of Nepal (Adhikari 1987) and fluctuation in the overall price levels of goods and services of the country (World Bank 2015). The sensitivity analysis evaluated a change of discount and inflation rate from 6 and 10 to 3 and 5 % respectively. The results show that the economic impacts decrease in the construction and replacement stages of all building types.

The lifetime of the building was initially estimated to be 50 years. However, this may vary depending on the degree of use and maintenance. Thus, results were calculated for a lifetime of 25 and 100 years respectively. The changes in a lifetime have a substantial overall effect on the GWP and economic impact. The sensitivity analysis of 25 years of building lifetime shows that all the potential impacts, both GWP and economic, increase in the construction and replacement stages of different building types. Concerning the replacement stage, the economic impact of modern and semi-modern buildings is higher than that GWP; conversely, the replacement phase in the traditional building shows a lower economic impact

Table 5 Life cycle impact categories indicators of the buildings calculated by ReCipe method

Impact category*		Modern			Semi-modern			Traditional		
		construction	operation	replacement	construction	operation	replacement	construction	operation	replacement
ODP	kg $CFC_{-11\ eq}$ * guest $night^{-1}$	9.9E−09	6.2E−06	9.7E−09	3.8E−09	1.9E−06	5.6E−09	6.0E−09	5.2E−07	9.8E−09
POCP	kg $C_2H_{4\ eq}$ * guest $night^{-1}$	7.9E−05	3.7E−03	9.0E−05	3.6E−05	1.4E−03	4.8E−05	5.0E−05	9.6E−04	8.1E−05
AP	kg $SO_{2\ eq}$ * guest $night^{-1}$	8.4E−04	5.9E−02	9.7E−04	3.4E−04	2.0E−02	5.1E−04	5.4E−04	1.0E−02	8.9E−04
EP	kg PO_{4e} * guest $night^{-1}$	1.7E−03	1.5E−02	2.0E−03	4.7E−04	5.7E−03	1.4E−03	8.5E−04	5.0E−03	2.6E−03
PM	kg PM_{10eq} * guest $night^{-1}$	6.1E−04	1.7E−02	7.0E−04	2.2E−04	5.7E−03	4.0E−04	3.5E−04	4.0E−03	7.2E−04

ODP ozone depletion potential, *EP* eutrophication potential, *AP* acidification potential, *POCP* photochemical ozone creation potential, *PM* particulate matter formation

Table 6 Life cycle costing of different building types during its lifespan

Building types/phases	Construction (€ * guest night^{-1})	Operation (€ * guest night^{-1})	Replacement (€ * guest night^{-1})	Total (€ * guest night^{-1})
Modern	0.15	18.46	1.30	19.91
Semi-modern	0.05	5.73	0.55	6.33
Traditional	0.08	3.38	0.82	4.28

compared to the GWP. In the use stage, no change was observed in all three building types as energy consumption in building operation remains the same per guest in a night stay.

All the potential GWP and economic costs decrease with the increase of lifespan of the building in 100 years. There is no change in the use stage in this case also, as energy consumption in building operation remains the same per guest in a night stay. Furthermore, the increase in lifetime causes a decrease in the differences between the impacts of both economic and GWP between the different types of buildings.

The change in the percentage of room occupancy in the buildings from 80 to 50 % shows all the impact categories on the environment and economic increases in the three buildings. The share of impacts increases per guest as the occupancy of the building decreases.

4 Discussion

The aim of this study was to evaluate both the environmental and economic life cycle impacts of lodging in three existing building types in the Himalaya in order to give a valuable overview for decision making in future building construction projects. From the study, it was concluded that the highest environmental and economic impacts during the building life cycle took place during the use stage. Thus, the pattern of the consumption habits, use of renewable energy, increasing the efficiency of the stoves and proper insulation in the building could be appropriate measures to reduce the environmental impacts of buildings.

The study showed that the use stage is the hot spot (approximately 98 % of total GWP). This value confirms the results of other studies showing the impact of the use stage to be in the range of 80–90 % (Asdrubali et al. 2013). The study done by Cuéllar-Franca and Azapagic (2012) shows that the use stage contributes to 90 % of GWP in the UK residential buildings. Comparably, the study done by Ortiz et al. (2009) concluded that the highest environmental impact in a dwelling located in Sweden is the operation stage with 85 % of GWP. However, the results of these case studies vary according to the assumptions made. Results may also depend on which household activities are included in the analysis and on the functional unit chosen. The study done by Ristimäki et al. (2013) accounted for heating and cooling of the buildings, plus

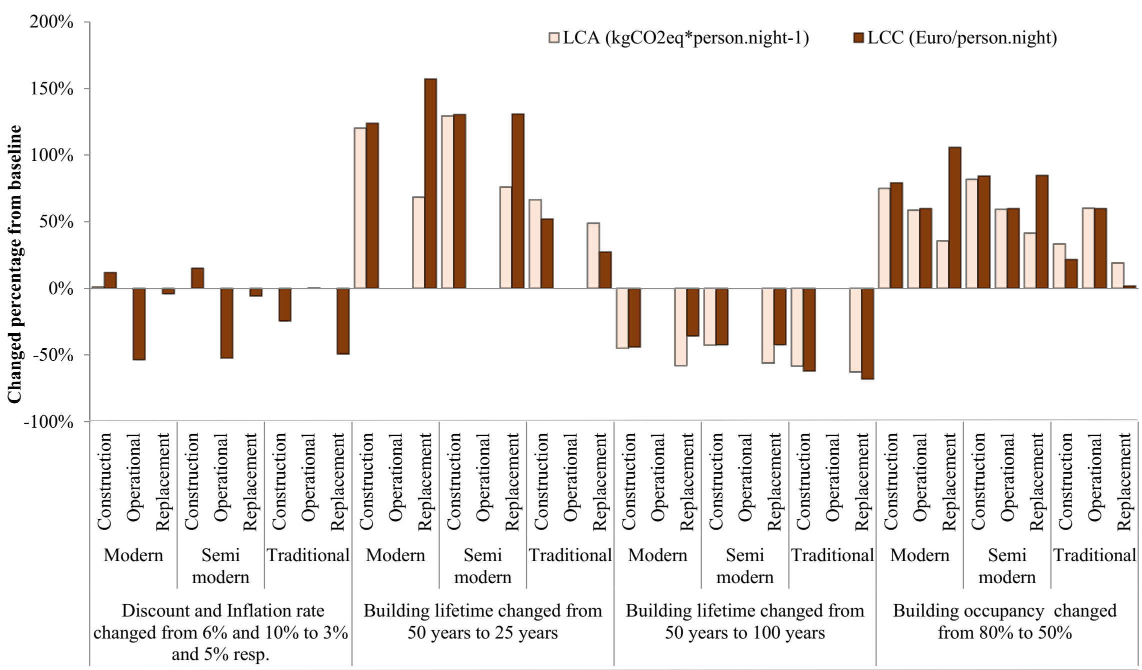

Fig. 8 Sensitivity analysis of the building system

heating water and lighting in the use stage, whereas other studies (Asdrubali et al. 2013; Cuéllar-Franca and Azapagic 2012) included all the household activities such as cooking, space heating, lighting, water heating and electrical appliances.

The study done by Filimonau et al. (2011) on two hotels in Poole, Dorset, UK, shows that the emission on hotel 1 that has 3300 m^2 area has 7.50 kg $CO_{2\text{-eq}}$ * guest $night^{-1}$. Hotel 2 that has 2000 m^2 area contributes 4.50 kg $CO_{2\text{-eq}}$ * guest $night^{-1}$. These hotels have a high electricity consumption, thus the GWP might be similar to our results, though these hotels are bigger in size than our selected lodges. A previous study reports an estimate of 34.32 kg $CO_{2\text{-eq}}$ for GHG emission 'per room night' in hotels (Chenoweth 2009). Similarly, the study on GHG emission 'guest per night stay' by (Becken et al. 2001) shows that the hotel in New Zealand contributes 24.60 kg $CO_{2\text{-eq}}$ * guest $night^{-1}$. The results of these studies are higher compared to our results which might be due to the hotel size and differences in the occupancy rate.

The result in the breakdown of the building components signifies that the wall and roof are responsible for the largest share of the total environmental impact of the construction stage. The study done by Zhang et al. (2014) also gives a similar overview with the highest environmental impact on the wall and roof.

The LCA study requires a significant amount of data, and the outcome depends on the quality, accessibility and accuracy of this input data (Ristimäki et al. 2013). However, there is the lack of data on the building sector for developing countries. The primary data collected on the site, as well as the ecoinvent database, were used to assess the result. The buildings are chosen as representative, but there may be variations across the various buildings in the Park. The result on LCA and LCC of three buildings might not give a comprehensive picture of the whole Park. Thus, buildings from different elevation, the village and villagers had to be randomly chosen for the analysis for the overall picture of the whole Park.

Three representative lodges were studied to give a detailed insight of building in terms of LCA and LCC, but even with these results, it is difficult to generalize the findings of the study to the buildings for the whole Park, and this should be the focus of further research.

Estimated long-term energy consumption and cost for 50 years is a questionable matter. As the efficiency of the stove, type of energy source and its cost have been changing, it is difficult to predict the type and amount of energy source and its cost for the future. For future price estimation, the escalation rate of energy price has been used for the long-term price increment. It should be noted that these future price estimations are influenced by the political situation of the country.

5 Conclusions

LCA and LCC were performed to assess the environmental and economic impacts of lodging in three existing buildings in the Himalayas. Results show that modern building accounts the highest GWP and cost over the period of 50 years as commercial materials and fuels are mostly used which accounts the highest environmental impact and high material cost.

The obtained results show that the use stage is responsible for high GWP and high use cost, which relate to energy use for different household activities. The main improvement opportunities in the lodging perspective to the Himalayan region lie in the reduction of impacts on the use stage. Building with local materials is a more environmentally friendly option than building with other equivalent commercial materials because of the low impact associated with the production of this material and the lower need for transportation.

On the basis of LCA and LCC results, it is concluded that energy-efficient building with the use of local materials with proper insulation and renewable energy is the recommended option for sustainable building design in the Himalayan region. Well-insulated energy-efficient building construction method could reduce GWP and improve the quality of the lives of local people as this helps to reduce the heating needs through firewood, dung and other burnable fuels. Energy-efficient technologies, including cooking stoves, heating stove, light bulb and use of renewable energy should be encouraged in the Park. Sustainable building with low energy consumption, high efficiency and innovation in building construction (Zabalza et al. 2009), such as passive house, should be promoted. It is recommended that the government and environmental agencies should improve the construction codes and relevant environmental policies for incentive sustainable building construction practices in the country.

Further study on LCA and LCC of lodging in different building types in all three Village Development Committee (VDC) of the Park is needed to give a more comprehensive picture on a life cycle prospective both in environmental and economic aspects, which would accomplish building sustainability and promote the use of sustainable construction practices.

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