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Comprehensive Evaluation of Carbon Emissions for the Development of High-Rise Residential Building

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Abstract: Despite the fact that many novel initiatives have been put forward to reduce the carbon emissions of buildings, there is still a lack of comprehensive investigation in analyzing a buildings' life cycle greenhouse gas (GHG) emissions, especially in high-density cities. In addition, no studies have made attempt to evaluate GHG emissions by considering the whole life cycle of buildings in Hong Kong. Knowledge of localized emission at different stages is critical, as the emission varies greatly in different regions. Without a reliable emission level of buildings, it is difficult to determine which aspects can reduce the life cycle GHG emissions. Therefore, this study aims to evaluate the life cycle GHG emissions of buildings by considering "cradle-to-grave" system boundary, with a case-specific high-rise residential housing block as a representative public housing development in Hong Kong. The results demonstrated that the life cycle GHG emission of the case residential building was 4980 kg CO_2e/m^2. The analysis showed that the majority (over 86%) of the emission resulted from the use phase of the building including renovation. The results and analysis presented in this study can help the relevant parties in designing low carbon and sustainable residential development in the future.

Keywords: greenhouse gases; residential building; life cycle assessment

1. Introduction

Climate change has become an unprecedented challenge for humanity. The annual greenhouse gas (GHG) emissions grew on average by 1.0 giga ton carbon dioxide equivalent ($GtCO_2e$) per year from 2000 to 2010 compared to 0.4 $GtCO_2e$ per year from 1970 to 2000, and total anthropogenic GHG emissions were the highest in human history reaching 49.0 $GtCO_2e/y$ in 2010 [1]. These phenomena are primarily due to various human activities, in particular the use of fossil fuels, deforestation, and change in land use [2]. Any delay in stabilizing and reducing the atmospheric CO_2e concentration would only exacerbate the global warming crisis and increase the difficulty to tackle the disastrous consequences in the future [3].

Currently, the building sector represents the single largest contributor to GHG emissions [4,5]. To help reduce GHG emissions, the building sector has an undeniable role to play as buildings worldwide account for up to one-third of the GHG emissions [6]. For subtropical countries and cities like Hong Kong, buildings can contribute to almost 60% of final energy consumption [7]. Of this, residential buildings take up a significant portion of total energy consumption and hence the GHG emissions, resulting from energy used for construction, operation, and demolition of buildings.

With a continuous growth in population, a preference for smaller family sizes, and the desire for a more comfortable living environment, the energy demands and GHG emitted from residential buildings in Hong Kong are expected to escalate even further [8].

Establishing pragmatic policy to encourage the building sector to cut down on GHG emissions is clearly an important goal for governments around the world. This is particularly the case for high-density cities not only because there are lots of high-rise buildings but also due to the rather limited opportunities to adopt emerging renewable energy solutions like photovoltaic panels or wind turbines. For Hong Kong, having committed to reducing the energy intensity by at least 25% by 2030 compared with the 2005 levels, its government has begun to examine the overall life cycle environmental burdens of buildings under their jurisdiction, and the public housing developments would be an ideal starting point as they share around one-third of the entire residential stock in Hong Kong, which is equivalent to 700,000 flats [9]. In 2008, public housing in Hong Kong consumed 6988 million kWh of electricity or five million tons (Mt) of CO_2e [7].

Various studies have been conducted to gauge the environmental impacts of buildings. For example, Chen and Ng [10] proposed factoring in the embodied GHG emissions when assessing the environmental performance of buildings. De Wolf et al. [11] investigated the GHG emissions from 200 recently completed buildings based on the quantities of structural materials (data were based on different design firms) in the United States, without considering the whole life cycle of buildings. A life cycle assessment model was developed to evaluate the environmental impacts of building construction [12]. Peuportier [13] compared the environmental performance of three types of houses located in France, and a sensitivity analysis was performed based on the choice of alternative construction materials, types of heating energy, and transportation using an EQUER tool. Similar studies were conducted in France [14], the Netherlands [15], Japan [16], the United Kingdom [17], and China [18]. Some of the reviews were conducted in assessment of GHG emissions, energy consumption, and other environmental impacts of buildings [19–22].

Focusing on the assessment of GHG emissions generated from the building sector, Suzuki and Oka [23] proposed quantifying the energy consumed and carbon emitted due to the construction, operation, and renovation of office buildings in Japan using input/output tables. On the other hand, Seo and Hwang [24] estimated the life cycle CO_2 emissions of different types of residential buildings. Similarly, Bastosa et al. [25] presented a life cycle energy and GHG analysis of three residential building types in Lisbon. Some studies have also focused on the specific stage of the buildings, such as the material level [26,27], building construction [28,29], renovation [30,31], demolition, and end-of-life treatment [32]. The collection of a large variety of data to model a comprehensive assessment is not only time consuming but also, is often impossible. However, a few studies focused on assessing the GHG emissions of the whole building by considering different stages, but excluding the renovation and end-of-life waste treatment [33–37]. Recent reviews also concluded that the occupancy and end-of-life phases are overlooked in most of the life cycle assessment (LCA) studies of building assessment [19,38–40].

In addition, environmental impacts of buildings can significantly vary among the studies depending upon the regions or countries [38,39]. A few studies were conducted on environmental assessment, including GHG emissions of buildings in Hong Kong [12,41,42]. However, these studies have excluded some important aspects in their assessment, e.g., considerations of use, renovation, and end-of-life phases of the building. The aim of this research therefore, is to evaluate the life cycle GHG emissions of high-rise residential building comprehensively by including the construction, use and renovation, and end-of-life phases as a case in Hong Kong. The results of the study can be used as a benchmark for comparing and setting up mitigation measures for new building construction.

2. Methodology

The life cycle assessment (LCA) method has been used for assessing the GHG emissions of high-rise public housing blocks in this study. LCA enables the quantification and evaluation of environmental impacts of a building [41]. Governed by the ISO 14040 standard [43], an analytical skeleton is applied in this study which consists of four main phases; goal and scope definition, life cycle inventory analysis, life cycle impact assessment, and interpretation.

2.1. Goal and Scope of Study

This study aimed to evaluate the GHG emissions (in terms of CO_2e) from cradle-to-grave of a public housing block as shown in Figure 1. The GHG emissions are calculated by assessing the GHGs as defined in the Kyoto Protocol of the United Nations Framework Convention on Climate Change (UNFCC), including carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydro fluorocarbons (HFCs), perfluorocarbons (PFCs), and sulphurhexafluoride (SF_6) [44,45]. These GHG emissions are converted into kg or tCO_2e emissions using the Intergovernmental Panel on Climate Change (IPCC) 100-year global warming potential (GWP) coefficients [46]. In this study, the functional unit was the unit of flat and gross floor area (GFA) of the building, i.e., m^2.

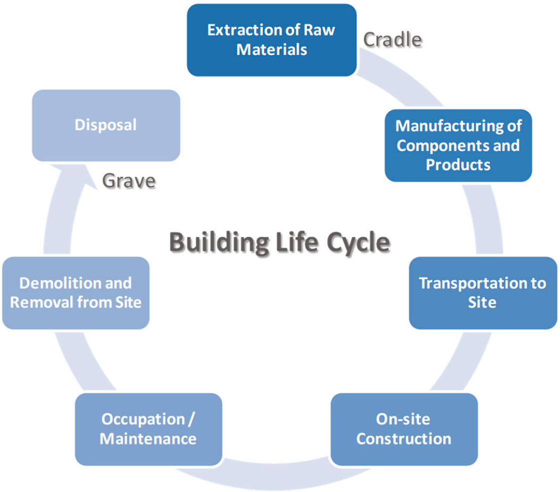

Figure 1. Life cycle process of a building.

A standard housing block design named "New Harmony One" (NH1)—Option 6, as shown in Figure 2, was selected for the analysis and used for setting a benchmark for the life cycle GHG emissions of public residential buildings. The Housing Authority adopted a site specific design approach and the internal floor area since 2004, by applying micro-climate studies at the early planning stage [47]. NH1 is selected as a basis of this study, as such a design can be applied to various sites in Hong Kong on a repetitive basis. Typically, a NH1 block is a reinforced concrete tower of 40 domestic levels which contains 799 flats with a gross floor area of 33,078 m^2. The ground floor is used for non-domestic purpose to accommodate the necessary ancillary facilities. There are 16–20 modular flats per floor which are arranged in four groups in a cruciform configuration attached to the central core where building services, lifts, and staircases are located. The compact form of NH1 makes it suitable for use in smaller urban area sites in Hong Kong.

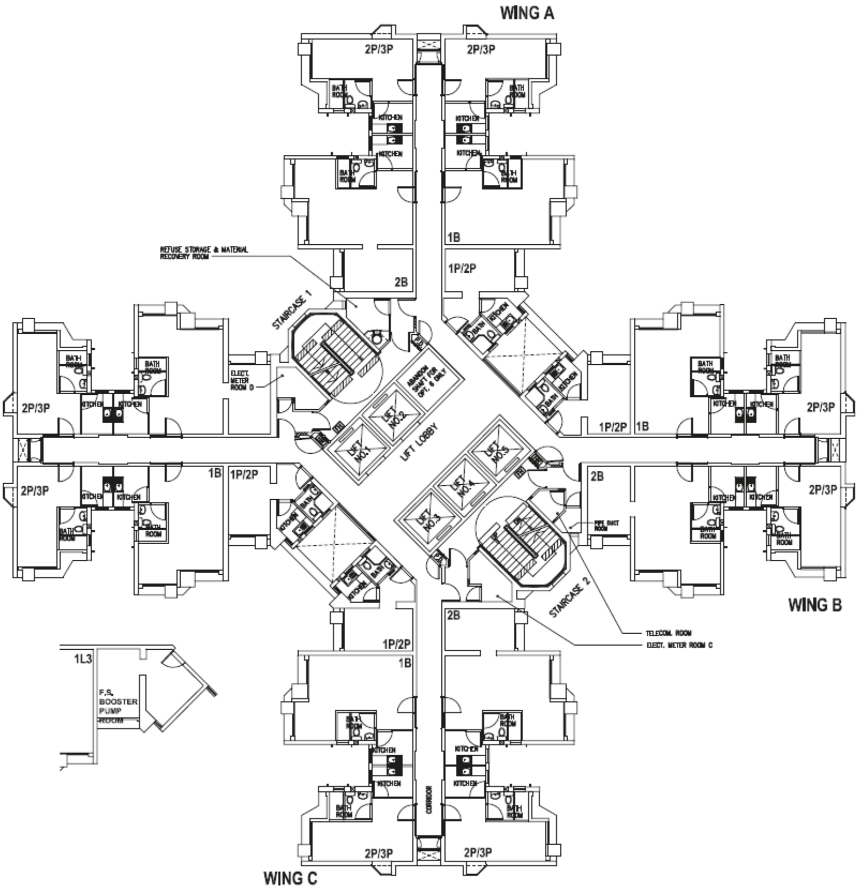

Figure 2. New Harmony One (NH1) residential building design.

The GHG emissions over the building's life cycle are assessed based on their sources and components, so as to evaluate the carbon footprint of the building meaningfully. Based on ISO 21931-1 [48] "Sustainability in Building Construction—Framework for Methods of Assessment of the Environmental Performance of Construction Works—Part 1: Buildings", the scope of a carbon audit study includes eight aspects associated with the following three distinct but interlinked stages: (i) production and construction; (ii) occupation (both energy consumed by tenants and communal installations) and renovation; and (iii) demolition as shown in Table 1. The guidelines provided by this ISO standard were used to derive the equations (Equations (1)–(7)) in this study. In addition, the said method aligns well with the carbon emission estimation model developed by the Hong Kong Housing Department [9], and Equations (1)–(7) were therefore used for the assessment of each individual stage accordingly. These aspects cover the major sources of GHG emissions of a building's life cycle as suggested by Seo and Hwang [24] and Fieldson et al. [49] which form the system boundary of this study. As a result, a "cradle-to-grave" system boundary with the functional unit of 1 m^2 of building floor area was considered in this study. The system boundary covers the production and transportation of principal construction materials; the use stage of buildings including the energy consumed by building services equipment and utilities; renovations including the material's production and transportation; waste transportation and disposal; and the end-of-life stage of buildings including the dismantling of buildings, and transportation of waste materials to the disposal sites (Table 1). However, the energy and fuel used on site during construction were excluded, as their emissions are minimal compared with the emissions of the entire building's life cycle. For example, the construction processes contribute to only about 2–5% of the total emissions (except refurbishments, demolition, and waste treatment) [28,50]. Taking into account the quantity and environmental profile, this study initially focused on three major materials, namely concrete, steel, and timber as they are the dominant contributors of embodied carbon of a housing block [51]. An inventory of materials and energy consumed over the sampled building's life cycle is assessed to calculate the associated GHG emissions. However, the inventory given in Table 1 omits non-structural materials and associated emissions over the building's life cycle.

Table 1. Study scope and system boundary of the greenhouse gas (GHG) evaluation.

Stage	Aspect	Sources of GHG Emissions	
Production and Construction stage	I	Materials consumed during construction	Steel formwork for superstructure Timber formwork for superstructure Steel formwork for substructure Timber formwork for substructure
	II	Materials for structure	Steel for superstructure Concrete for superstructure Steel for substructure Concrete for substructure
	III	Transportation of materials (in Aspects I and II)—from factory gate to site	-
Occupation stage	IV	Energy consumption by communal building services	Lighting Lift Security TV A/C and ventilation Fire services Water supply Electrical distribution
	V	Energy consumption by tenants	Cooking Space conditioning Hot water Lighting Refrigeration Others (laundry, audiovisual and miscellaneous equipment)
	VI	GHG removals	Planting trees (taller than 5 m)
-	VII	Renovation	Materials replacement (production and transport) Waste transport and disposal
Demolition stage	VIII	Disposal	Dismantling of building Transportation of building debris from site to disposal sites

2.2. *Inventory Analysis and Analytical Framework*

2.2.1. Emissions in the Construction Stage (Aspects I, II, and III)

The construction process of building follows the NH1 design of construction. As indicated, the GHG emissions of the construction process is excluded from this study, as it contributes to a negligible amount of emissions compared to the total emission associated with building. While the energy used and the consequential GHG emissions over the occupation of a building contribute to the majority of its carbon footprint, a considerable amount of GHG is emitted during the manufacturing and transportation of building materials [6]. Equation (1) calculates the embodied GHG emissions of key building materials consumed during construction and for structure (i.e., Aspects I and II, respectively), including concrete, steel, and formwork. This accounts for 84–95% of the total materials (structural and non-structural) related GHG emissions for a reinforced concrete framed building [26,52].

This measures the GHG emitted from the extraction, processing and manufacturing of building materials [53].

$$GHG_m = \sum_{i=0}^{n} Q_i \times F_i^m, \tag{1}$$

where GHG_m is the total embodied GHG emissions of concrete, steel, and formwork (in kg CO_2e); Q_i is the amount of building material i (in m^3); and F_i^m is the GHG emission factor for building material i (in kg CO_2e/m^3).

The quantities of concrete, steel, and timber employed during the construction of the NH1 housing block were obtained from the tender documents as well as the drawings. Local, regional, and international sources and databases were used to retrieve the GHG emission factors for the selected building materials (Table 2). For example, the GHG emission factor for steel production was extracted from the Inventory of Carbon and Energy (ICE) compiled by Hammond and Jones [54], which is within the range of steel production in China [55]; local concrete production was according to Zhang et al. [56]; and regional (Southern China) timber production was from Zhang [57]. The use of local or regional GHG emission factors for the principal building materials is important for achieving representative results. Therefore, local or regional GHG emission factors for such materials were used in this study.

Table 2. Embodied carbon of materials (unit: kg CO_2e/m^3).

References	Timber	Steel	Concrete
Hammond and Jones [54]	468	15,210 [b]	317
Morris [58]	450	14,287	326
Eaton and Amato [59]	-	15,313	-
Zhang et al. [56]	-	-	426 [c]
Zhang [57]	962 [a]	-	-
Alcorn [60]	-	10,441	376

Note: [a] plywood, embodied carbon: 1.78 kg CO_2e/kg in China with the density as of 540 kg/m^3 [57]; [b] steel bar and rod, embodied carbon: 1.95 kg CO_2e/kg which is within the range of steel production in China (1.72–1.96 kg CO_2e/kg steel) according to Jing et al. [55]; non-EU average recycled content: 35.5%; density is assumed as 7800 kg/m^3 [61]; [c] concrete grade is assumed as 32/40 MPa, embodied carbon: 0.177 kg CO_2e/kg, density is assumed as 2400 kg/m^3 [61].

Transportation emissions are also an integral part of the LCA study, generated from the transportation of construction materials from cradle-to-gate and from gate-to-site. Aspect III focuses on the latter stage, i.e., the transportation distances from the manufacturing plant to the construction site. The former stage has already been included in the embodied carbon emission factors as shown in Table 2, which embraces all energy required for extraction, manufacturing, and transportation until the materials leave the factory gate. In the case of the NH1 block, 95% of the building materials can be sourced from Hong Kong or South China, they are therefore transported through the land routes using diesel trucks and by sea [51]. Equation (2) calculates the GHG emissions generated from the transportation of building materials.

$$GHG_t = \sum_{i=0}^{n} \frac{(Q_i^l \times E_l \times D_i^l \times F_l^t)}{5}, \tag{2}$$

where GHG_t is the total GHG emissions from fuel combustion of transportation of the key building materials (in kg CO_2e); Q_i^l is the amount of building material i transported by land (in m^3), assuming the loading limit per truck is 5 m^3; E_l is the diesel consumption (in liter/km/truck), which is 0.325 L/km; D_i^l is the total distances of transporting building materials i by land (in km), and the distances between the site and the manufacturing plant in Hong Kong and South China are assumed as 20 km [52] and 250 km [62], respectively; and F_l^t is the emission factors of transporting by diesel truck, which is 2.62 kg CO_2e/liter [52].

2.2.2. Emissions in the Occupation Stage (Aspects IV, V, VI and VII)

During the occupation phase, heating and electricity account for the major portion of GHG emissions [63]. For this study, the GHG emissions at the occupation stage are quantified and classified into three aspects, namely: Aspect IV—Energy consumption by communal building services; Aspect V—Energy consumption by tenants; Aspect VI—GHG removals; and Aspect VII—Renovation. Equation (3) is used to simulate the GHG emissions from the energy consumption by communal building services and tenants.

$$GHG_o = \sum_{i=0}^{n}\left(E_i^e \times F_e + E_i^g \times F_g\right) \times 50, \tag{3}$$

where GHG_o is the total GHG emissions due to the energy used over the 50-year building life cycle (in kg CO_2e); E_i^e and E_i^g are the annual quantity of electricity and gas consumption for building services system i, in kWh or in gas unit (i.e., 1 unit as registered by the gas meter = 48 mega joules consumed), respectively; F_e and F_g are the emission factors of the energy consumed by electricity and gas, respectively, with the territory-wide default values of F_e and F_g being 0.7 kg CO_2e/kWh and 0.59 kg CO_2e/unit of gas purchased, respectively [64].

The electricity consumption data for communal building services installations was calculated from the sampled NH1 housing block. However, the energy consumed by tenants of the sampled housing block was not accessible. Therefore, the energy end-use data of the public housing group (in terajoules) as published by the Electrical and Mechanical Services Department [7] was used for the energy use estimation in this study. It was assumed that 80% of the tenants used electric water heaters while the rest used gas water heaters [65] and 90% of tenants used gas for cooking [66].

GHG removals are calculated by assessing the respective GHG absorption by the assimilation of CO_2 by plants as shown in Equation (4). According to EPD [64], 23 kg CO_2 can be removed by each tree based on Hong Kong's location, woodland types, and estimated density of trees. The figure is applicable to all trees commonly found in Hong Kong which are able to reach at least 5 m in height. Since this figure is derived as an annual average based on an extended period of time corresponding to the life cycle of the trees, the figure is applicable to trees at all ages.

$$GHG_r = (T \times F_t) \times 50, \tag{4}$$

where GHG_r is the total GHG absorption over the 50-year building life cycle by tree planting (in kg CO_2e); T is the number of newly planted trees within the building's physical boundary (e.g., within building premises, associated with the surroundings that are used for multipurpose activities including planting trees for a particular housing estate) after the beginning stage of construction which are able to reach at least 5 m in height; and F_t is the GHG removal factor, which is taken as 23 kg CO_2/tree per annum [64].

In this study, a 50-year service life of a residential block in Hong Kong was considered. As a complex system, buildings would often undergo various changes by means of renovation. Considering the building's service life, typical replacement of principal elements with their number of replacements over the entire life of a building in Hong Kong are shown in Table 3 (adjusted based on Chiang et al. [67]). The production and transport of these materials/elements were included in the LCA. Ecoinvent databases were used for collecting their upstream data, for instance, ceramic tile, emulsion paint, sealing materials, and hardwood doors production. Based on the renovation of typical flats, average per unit (m^2) was calculated according to Chiang et al. [67]. In addition, the transportation and disposal (in landfills) of materials generated during renovation were also considered in this assessment.

Table 3. Typical replacement of building elements during renovation in Hong Kong.

Element/Material	Service Life (years)	Number of Replacements over the Service Life of Building
Ceramic tiles	20	2
Emulsion paint	5	9
Silicone seal	10	4
Hardwood solid-core doors	20	2

Therefore, the total GHG emissions due to the renovation of the building during its service life can be estimated by Equation (5).

$$GHG_R = \sum\nolimits_{service\ life=50} (M_R \times N_R) + T_M + D_L, \tag{5}$$

where GHG_R is the total GHG emissions over the 50-year service life of building (in kg CO_2e); M_R is the materials/elements replacement during renovation; N_R is the number of replacements of the respective elements/materials; T_M is the transport of the materials; and D_L is the disposal into landfill.

2.2.3. Emissions in the Demolition Stage (Aspects VIII)

According to ISO [68], recycling of steel and concrete should be assessed in the subsequent loop of a building life cycle. Typically, inert wastes generated from buildings are disposed at public fill sites, whereas non-inert waste are dumped into landfills, in Hong Kong. After transporting to off-site sorting facilities, inert materials are crushed and screened to recycle materials. In addition, a certain amount of concrete is recycled [69]. After screening, the remaining inert materials are sent to public fills, while the non-inert materials are disposed at landfills. However, the impacts of recycling and disposal were excluded due to the complexity of different management strategies and the lack of data in Hong Kong. In this study, the GHG emitted during the demolition stage is mainly due to the energy consumption for the machinery operation at the demolition site and the transportation of building debris from the site to disposal sites [23]. It is also assumed that the saving of GHG emissions due to steel and concrete recovery, and the induced GHG emissions of other materials' disposal (whether to public fills or landfills) would be similar, and thus they were excluded from this analysis. Equation (6) serves as the basis to assess the emissions.

$$GHG_d = Q_d \times F_d + \frac{Q_d \times E_d \times D_i^l \times F_l^t}{5}, \tag{6}$$

where GHG_d is the total GHG emissions in the demolition stage; Q_d is the amount of building materials to be dismantled or building debris (in m^3), for transportation of building debris, 5 m^3 load per truck is assumed; F_d is the emission factor for dismantling a building, which is 17 kg CO_2e/m^3 according to Nielsen [70]; E_d is the diesel consumption (in liter/km/truck), which is 0.325 L/km [71]; D_i^l is the total distance for transporting building materials i by land (in km) and the distance is taken as 26 km [52]; and F_l^t is the emission factors for transportation by diesel truck, which is 2.62 kg CO_2e/liter [52].

Therefore, the total GHG emissions over the NH1's building life cycle can be estimated by Equation (7):

$$GHG_{NH1} = GHG_m + GHG_t + (GHG_o + GHG_r + GHG_R) + GHG_d, \tag{7}$$

2.3. Limitations

Conducting an environmental assessment of the whole building is complicated due to the differences in materials, associated transportation, diverse considerations at the use stage, lifespan of the building, and different considerations of the end-of-life of the building. Although this study has attempted to include all these in the assessment, several limitations cannot be avoided. For example, this study did not consider the contributions of non-structural materials. Waste material (generated during the construction and end-of-life stages) treatments were not considered in this assessment. During the use stage of building, actual energy consumed by tenants is not accessible. Thus, average energy consumption data was collected from the relevant department [7]. Due to the lack of local/regional data, Ecoinvent databases were used for carbon emissions of the replacement materials for the renovation of building. This study only focused on carbon assessment and excluded other impact categories. However, some of the limitations were further discussed and justified in the Discussion section.

3. Results

The result of GHG emissions throughout the life cycle of the standard NH1 public housing block, based on Equation (7), is presented in Table 4. Using the data collected and assumptions, the estimated total life cycle GHG emissions of the block are 186,150 tCO_2e for the NH1 2000 Edition. The GHG emissions intensity of the sampled building is 232.98 tCO_2e/flat or 5.38 tCO_2e/m^2 of GFA. Figure 3 shows the distribution of the emissions in various life cycle phases. The operating energy consumption by communal building services and tenants is clearly impacting the environment the most, accounting for about 85.82% of the emissions. The materials consumed during construction, though emit considerably less GHGs than that in the operation stage, are taking up about 12.69% of the life cycle emissions. The remaining aspects, including the renovation, transportation of materials, and the disposal of the block are accounted to 1.14%, 0.07%, and 0.28%, respectively, of the building's carbon footprint.

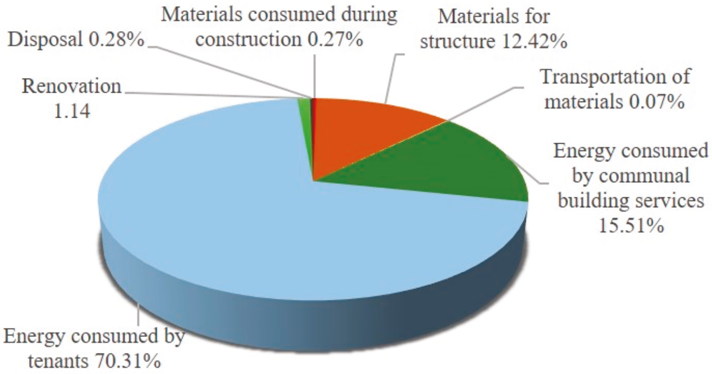

Figure 3. Contribution to the GHG emissions of the sampled housing block.

Hotspots for GHG emissions of building have been highlighted in Figure 3 (i.e., the contribution to GHG emissions). It can be seen that over 85% of the total GHG emissions is associated with energy consumption of tenants and building services equipment. This supports the results from previous studies [16,24,72]. The elements emitting the most significant amount of GHGs are found to be communal lighting and lifts, as well as the energy consumed by tenants for hot water, space conditioning, and refrigeration. This reflects that GHG emitted from a public housing block are strongly dependent not only on the building and occupancy factors such as ventilation and efficiency of appliances, but also on the source of energy. Therefore, it is important to install energy efficient building service equipment, and encourage tenants to use energy efficient appliances to reduce energy consumption and GHG emissions. Apart from reducing the energy consumption and embodied energy in buildings, switching to low carbon fuels and utilizing renewable energy are considered effective in tackling the climate change problem [46]. Materials (including their production and transportation) emit about 13% of the total emissions. However, it is possible to reduce GHG emissions by sourcing sustainable materials and using low carbon materials.

During the construction stage, concrete is the dominant building material for the NH1 housing block, not only in terms of quantities but also the embodied carbon. The NH1 housing block studied consumed over 28,600 m^3 of concrete, producing over 12 million kg of CO_2e. Reducing the carbon content of concrete through the manufacturing process is therefore influential. A saving in embodied carbon can be achieved by increasing the proportion of off-site manufacturing of components and/or adopting recycled materials or materials with lower environmental impact [6,52]. For instance, by replacing cement with alternative binding materials (e.g., pulverized fuel ash, ground granulated blast furnace slag, and silica fume) in the concrete mixes can save significant amount of cement and the associated CO_2 emissions [51,73]. In addition, the use of alternative or low carbon cement, i.e., eco-glass cement or Portland fly-ash cement, can also considerably reduce the carbon footprint of concrete [74].

The study also estimated the GHG emissions of the residential block according to the latest "Model Client Brief 2010" as presented in Table 4. According to the Hong Kong Energy End-Use Data 2010 provided by the Electrical and Mechanical Services Department of Hong Kong SAR [7], this brief has incorporated the latest development of various communal building services installations. These include the employment of electronic ballasts and two illumination levels in the lighting system, adjusting the capacity and weight of lifts, adopting a variable speed drive system in booster pumps, as well as using more energy efficient motors. As a result, a significant reduction in annual electricity consumption is achieved from 1032 kWh/flat in the Client Brief January 2000 Edition to 596 kWh/flat in 2008 [7]. In addition, the brief requires the planting of one tree for every 15 flats in a newly built public housing estate. Consequently, the annual GHG emissions caused by electricity consumption of communal building services installations have decreased from 577 tCO_2e to 337 tCO_2e (Table 4).

According to the "Model Client Brief 2010", the GHG emissions of the NH1 housing block were 215.69 tCO_2e/flat and 4.98 tCO_2e/m^2 per flat and per GFA, respectively. While the energy consumption of tenant areas is beyond the management's control, with Aspect V—"Energy consumption by tenants" being excluded, the GHG emissions were 51.88 tCO_2e/flat and 1.20 tCO_2e/m^2 per flat and per GFA, respectively (Table 4).

Table 4. Evaluation of GHG emissions of the studied case in Hong Kong.

Stage Aspect	**Category**	**Category**	**Benchmarking Block NH1 Standard Block (2000 Edition)**			**Benchmarking Block NH1 Standard Block (Model Client Brief 2010)**		
		Type	Quantity (m^3)	Per Unit CO_2e Emission (kg/m^3)	Total Emission (kg CO_2e)	Quantity (m^3)	Per Unit CO_2e Emission (kg/m^3)	Total Emission (kg CO_2e)
Production and Construction stage	I	Materials consumed during construction (GHG_m)	Steel formwork for superstructure	23.3	15,210	354,393	22.5	15,210	342,073
			Timber formwork for superstructure	149.8	962	144,108	144.6	962	139,105
			Steel formwork for substructure	0.0	15,210	0	0.0	15,210	0
			Timber formwork for substructure	3.4	962	3271	3.4	962	3271
			Sub Total	-	-	501,772	-	-	484,449
	II	Materials for structure (GHG_m)	Steel for superstructure	548.2	15,210	8,338,122	433.0	15,210	6,585,930
			Concrete for superstructure	20,419.0	426	8,698,494	20,460.4	426	8,716,130
			Steel for substructure	170.0	15,210	2,585,700	170.0	15,210	2,585,700
			Concrete for substructure	8212.0	426	3,498,312	8212.0	426	3,498,312
			Sub Total	-	-	23,120,628	-	-	21,386,072
	III	Transportation of materials (GHG_t)	Type	Quantity (m^3)	Distance from site (km)	Total Emission (kg CO_2e)	Quantity (m^3)	Distance from site (km)	Total Emission (kg CO_2e)
			Steel	741.5	250	31,531	625.5	250	26,598
			Timber	153.2	250	6515	148.0	250	6291
			Concrete	28,631.0	20	97,398	28,672.4	20	97,539
	-	-	Sub Total	-	-	135,443	-	-	130,428

Table 4. *Cont.*

Stage Aspect	Category	Category	Benchmarking Block NH1 Standard Block (2000 Edition)			Benchmarking Block NH1 Standard Block (Model Client Brief 2010)		
Operation stage	IV	Energy consumption by communal building services (GHG$_o$)	System	Yearly Energy Consumption (kWh)	Annual Emission (kg CO$_2$e)	Total Emission in 50 Years (kg CO$_2$e)	Yearly Energy Consumption (kWh)	Annual Emission (kg CO$_2$e)	Total Emission in 50 Years (kg CO$_2$e)
			Lighting	538,188	376,732	18,836,580	264,799	185,359	9,267,965
			Lift	165,783	116,048	5,802,405	103,175	72,223	3,611,125
			Security	3793	2655	132,755	3793	2655	132,755
			TV	4205	2944	147,175	4205	2944	147,175
			A/C and ventilation	17,800	12,460	623,000	17,800	12,460	623,000
			Fire services	1764	1235	61,740	1764	1235	61,740
			Water supply	76,972	53,880	2,694,020	76,972	53,880	2,694,020
			Electrical distribution (2% of above items)	16,170	11,319	565,954	9450	6615	330,756
	-	-	Sub Total	824,675	577,273	28,863,629	481,958	337,371	16,868,536
	V	Energy consumption by tenants (GHG$_o$)	Energy End Use	Yearly Energy Consumption (Tera joule)	Annual Emission (kg CO$_2$e)	Total Emission in 50 Years (kg CO$_2$e)	Yearly Energy Consumption (Tera joule)	Annual Emission (kg CO$_2$e)	Total Emission in 50 Years (kg CO$_2$e)
			Cooking (90% gas; 10% electricity)	4.2	158,997	7,949,854	4.2	158,997	7,949,854
			Space conditioning	2.8	551,754	27,587,695	2.8	551,754	27,587,695
			Hot water (20% gas; 80% electricity)	4	634,835	31,741,738	4	634,835	31,741,738
			Lighting	1.1	219,947	10,997,347	1.1	219,947	10,997,347
			Refrigeration	2.2	421,694	21,084,722	2.2	421,694	21,084,722
			Others (laundry, audiovisual and miscellaneous equipment)	3.2	630,544	31,527,209	3.2	630,544	31,527,209
	-	-	Sub Total	17.5	2,617,771	130,888,564	17.5	2,617,771	130,888,564

Table 4. *Cont.*

Stage Aspect		Category	Category	Benchmarking Block NH1 Standard Block (2000 Edition)			Benchmarking Block NH1 Standard Block (Model Client Brief 2010)		
Operation stage	VI	Renovation	-	-	-	Total Emission in 50 Years	-	-	Total Emission in 50 Years
	-	-	Materials/components replacement and transport	-	-	2,127,938	-	-	2,127,938
	-	-	Sub Total	-	-	2,127,938	-	-	2,127,938
	VII	GHG removals (GHG_r)	Tree	Quantity	Annual Emission Absorption (kg CO_2e)	Total Absorption in 50 Years (kg CO_2e)	Quantity	Annual Emission Absorption (kg CO_2e)	Total Absorption in 50 Years (kg CO_2e)
			Tree (Taller than 5 m)	0	0	0	53	1219	60,950
	-	-	Sub Total	-	-	0	-	-	−60,950
Demolition stage	VIII	Disposal (GHG_d)	Demolition	Quantity (m^3)	Per Unit CO_2e Emission (kg/m^3)	Total Emission (kg CO_2e)	Quantity (m^3)	Per Unit CO_2e Emission (kg/m^3)	Total Emission (kg CO_2e)
			Dismantling of building	23,919	17	406,623	23,960	17	407,320
			Transportation	Quantity (m^3)	Distance from site (km)	Total Emission (kg CO_2e)	Quantity (m^3)	Distance from site (km)	Total Emission (kg CO_2e)
			Transportation of building debris from site to disposal sites	23,919	26	105,779	23,960	26	105,961
	-	-	Sub Total	-	-	512,402	-	-	513,281
Overall results				-	Total GHG Emissions		-	Total GHG Emissions	
-				-	(tons CO_2e)	(kg CO_2e)	-	(tons CO_2e)	(kg CO_2e)
Sum of above	Grand total (I + II + III + IV + V + VI + VII + VIII)			-	186,150	186,150,376	-	172,338	172,338,318
	Grand total discounting tenant areas (I + II + III + IV + VI + VII + VIII)			-	55,262	55,261,812	-	41,450	41,449,754
Project data	Total no. of flat			-	799	-	-	799	-
	Gross floor area (GFA) (m^2)			-	34,609	-	-	33,078	-
Results	CO_2e emission per flat = a/c			-	232.98	232,979	-	215.69	215,693
–	CO_2e emission per flat (discounting tenant areas) = b/c			-	69.16	69,164	-	51.88	51,877
-	CO_2e emission per GFA (m^2) = a/d			-	5.38	5379	-	4.98	4980
-	CO_2e emission per GFA (m^2) (discounting tenant areas) = b/d			-	1.60	1597	-	1.20	1198

4. Discussion

This study has comprehensively evaluated the GHG emissions of a concrete reinforced high-rise residential building in Hong Kong. In addition to the structural materials, the study also considered the carbon emitted from communal building services, tenants due to energy end use, renovation, building demolition, and transportation of waste materials. It can be seen that the GHG emissions of the studied case ranged from 4980 kg CO_2e/m^2 to 5379 kg CO_2e/m^2 (based on design). The comparison of GHG emissions among different studies in different regions per functional unit is given in Figure 4. The variation of GHG emissions is relatively high (which ranges from 1657–6276 kg CO_2e/m^2) among different studies due to the use of different structural materials (concrete, steel, wood, composite, and so forth), heating and cooling requirements for different regions based on the climate, as well as other considerations. However, the GHG evaluated in this study is in the upper range of the emissions (Figure 4). This may be due to the higher GHG emission factors for different structural materials used in Hong Kong including the long transport distance, as Hong Kong has sourced most of the construction materials from China, which have higher emission factors (Table 2) which is also supported by the previous studies. For instance, De Wolf et al. [11] estimated the GHG emissions of 200 completed buildings based on structural materials quantities in the US, and calculated the GHG emissions range from 150–600 kg CO_2e/m^2. However, the GHG emissions are even higher than the upper range (for structural materials) found in this study (about 686 kg CO_2e/m^2, Table 4).

Based on the collected data and assumptions for renovation works in Hong Kong, it is estimated that renovation contributes to 61.50 kg CO_2e/m^2 of the building during its considered service life (e.g., 5 years). The value is considerably higher than 45 kg CO_2e/m^2 estimated by Ortiz-Rodríguez et al. [75] and 38 CO_2e/m^2 by Kumanayake and Luo [76]. However, energy efficient and low carbon refurbishments and replacement of building services can significantly help reduce the total embodied CO_2 emissions of buildings [30,77].

Although the evaluation of GHG emissions was based on a single case study in this study, the sampled building is a typical design of housing blocks in Hong Kong. Comparison on the emissions of new housing development can be conducted by making references at different building life cycle stages [36]. GHG emissions can also be minimized by using environmentally-friendly materials or energy efficient appliances, lighting, heating, and cooling equipment [78]. While the tenants of public rental housing estates represent almost 28% of Hong Kong population, their behavior might have a substantial impact on energy use, especially when the building services equipment is controlled manually. Reducing material use as well as specifying the use of localized materials, recycled materials, and/or alternative low carbon material are the options available for implementation during the design stage for reducing the embodied carbon of buildings [79–86].

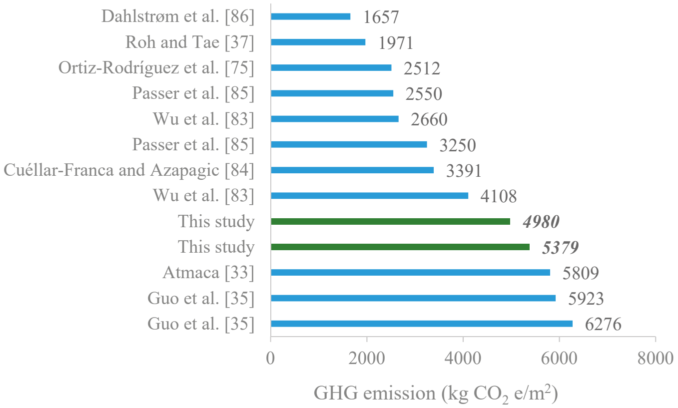

Figure 4. Comparison of GHG emissions of residential buildings.

The contribution of cladding and other non-structural materials, including windows, doors and roof coverings, internal partitions, and internal cladding was not considered in this study. Although some of the materials used during the construction process are negligible in terms of weight, their impacts can be significant to the total impacts. For example, polyamide safety nets and aluminum are used <0.1% by weight, but would contribute 2–3% towards the total GHG emissions [28]. These aspects were also not considered due to data unavailability despite the fact they can affect the emission inventory. In addition, carbon emissions can be expected with an anticipated growth in building activity and higher performance of buildings due to greater material use [80].

Although demolition and waste transportation were included in this study, the assessment of waste material treatments was not considered due to the different end-of-life considerations and the lack of available data. The demolition phase of buildings including demolition, waste transportation, and waste treatment contributed to about 2–5% of the total GHG emissions depending on the types of waste treatment [34,36]. However, according to Coelho and de Brito [32], GHG emissions of waste disposal could be about 65–283 kg CO_2e/m^2 of building (depending on the types of waste treatment). Therefore, the amount is insignificant compared to the total emissions estimated in this study (4980 kg CO_2e/m^2). More comprehensive investigations on the overall environmental performance of buildings by including other impact categories are desirable.

5. Conclusions

Environmental impacts associated with building construction, use, and end-of-life are greatly dependent on the region, climate, and type of buildings. Therefore, a case-specific assessment is important to benchmark the evaluation, as well as to reduce and mitigate the impacts from buildings. In this study, the GHG emissions from a typical high-rise residential building in Hong Kong was comprehensively evaluated using a case-specific analysis with a “cradle-to-grave” system boundary. Through this analytical regime, the GHG emissions were estimated to about 213.03 tCO_2e/flat and 4980 kg CO_2e/m^2, respectively. Considering the GHG emissions over the service life of the sampled residential building, the operating energy causes over 85.82% of the emissions, whereas 12.69% for materials, 1.14% for renovation, 0.28% for end-of-life of the building, and 0.07% for other factors. Therefore, various carbon reduction measures should be attempted and evaluated such as the use of energy efficient equipment, renewable energy, recycled/recyclable materials, and eco-design by utilizing natural lighting and ventilation. Policy and decision makers should explore different low carbon construction initiatives to maximize the opportunity for emission reduction. For future work, the residential buildings including all kinds of public and private buildings should be assessed by considering the limitations of this study on their carbon emissions as well as other environmental impact indicators. Tremendous effort is required to advocate low carbon construction at various levels including building materials, building components, and the entire building through effective incentive and reward schemes. For a more sustainable future, there is an urgent call for immediate, community-wide actions to reduce GHG emissions to help combat climate change.

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