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Carbon Footprint Assessment of A Green Building

Case study: Intel Corporation fitness centre in Ho Chi Minh City, Vietnam

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In this thesis, a carbon footprint (CFP) assessment is performed on a building during the design phase. The building is planned to be located in Ho Chi Minh City and to function as a fitness center. The goal of the assessment was to determine which building materials and life-cycle stages contributed the most to the environmental impacts. The functional unit (FU) is set as 60 years of 1m^2 floor area.

The building environmental impacts were calculated in One Click LCA – a building life cycle metrics software with integrated database from Gabi and Ecoinvent. The building data was taken from Bill of Quantities and Architecture design provided by Intel Corporation – the building owner and Greenviet Consultancy Co., Ltd – the consultant of this project.

The total global warming potential (GWP) throughout the building's life cycle is $9.32*10^5$ $kgCO_2eq/FU$. Speaking of life cycle stages, energy consumption in the use phase generates the highest amount of emissions, accounting for 56.2% of the total amount, followed by the production phase, with 40.6%. Speaking of building materials, the largest environmental impact is caused by concrete with $2.44*10^5$ $kgCO_2eq/FU$, which is 60% of the total emissions from the life cycle of the building.

In conclusion, the major contributors are the concrete production processes and energy consumption, particularly electricity, during the use phase. The CFP assessment consists of limitations and assumptions; therefore, an uncertainty analysis was carried out for transparent results and possible improvements in future assessment.

Keywords	carbon footprint (CFP), life cycle assessment (LCA), building, greenhouse gas, climate change

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Contents

1 Introduction

In recent years, the environment has deteriorated as a result of irresponsible human activities in various fields such as energy production, material production, and transportation. Among the modern industries, the construction sector is one of the main contributors of environmental pollution. It consumes an enormous amount of energy while emitting a considerable amount of greenhouse gases. Common Carbon Metrics (UNEP, 2015) states that “the environmental footprint of the building sector includes 40% of energy use, 30% of raw material uses, 25% of solid waste, 25% of water use, and 12% of land use" [1]. This excessive amount is due to the complex nature of building operations, including the production of raw materials, extracting, manufacturing and transporting to the building site. For example, the production of one tonne Portland cement - the most used building material in the world - is estimated to release approximately one ton of carbon dioxide. Worldwide, the cement industry alone accounts for 7% of all CO_2 generated [2]. Therefore, it is necessary to take notice of the building sector in order to achieve sustainable development.

On the other hand, the society growing concern over climate change created carbon footprint assessment – “a measure of the exclusive total amount of carbon dioxide emissions that is directly and indirectly caused by an activity or is accumulated over the life stages of a product." [3]. Compared to other products, building poses a relatively larger challenge when it comes to environmental assessment, since it involves complex processes occurring throughout its long lifetime. It mainly consists of the extraction of raw materials phase, the construction phase, the use and maintenance phase, and finishes at the end-of-life phase [4]. Therefore, a holistic methodology is needed in order to provide an overview of a building’s performance in terms of sustainability. This involves generating a succinct report that makes sense to the stakeholders. From an engineer’s viewpoint, such methods help selecting sustainable materials and technology for the construction that satisfy the safety requirements as well as the user’s needs, without causing adverse environmental impacts. From a stakeholder’s viewpoint, a life cycle carbon footprint provides a comprehensive view with the understandable numbers and data assisting them choosing better design without unnecessary changes.

In Vietnam, the focus of the government is currently on economic growth and industrialization; as a result, environmental issues are often overlooked. This is the crucial moment that decides the turning point not only for the building industry but also for other industries, changing the quality of life and positively affecting the environment. The building studied in this thesis is one of the first buildings whose carbon footprint was calculated in Vietnam.

During this thesis project, a carbon footprint assessment was conducted on a fitness center of 1624m^2, owned by Intel Cooperation and located in Ho Chi Minh City, Vietnam. The assessment followed the framework of LCA and specifically focused on the building materials in order to find the least sustainable materials and phases in a building construction process as well as to provide alternative solutions to further reduce its negative impact on the environment. Please note that this thesis contains unavoidable limitations and errors such as uncertainty during the data collection process, necessary general assumptions, or the inconsistency between on-site measurements and playbook design.

The structure of this thesis includes 3 parts. Part one defines the theoretical background including the background of carbon footprint (CFP), the global warming potential (GWP), and the building information. Part two is case study with the Intel fitness center, including following steps: goal and scope definition, product footprint calculation, results, and interpretation of the results. Finally, part three discusses the results; draws conclusions and makes recommendations.

2 Theoretical Background

This chapter briefly introduces the concept of carbon footprint, the calculation of global warming potential and description of the study building.

2.1 Introduction of carbon footprint

Carbon footprint is the total amount of greenhouse gas emissions caused by an organization or individuals' activity, product and service [5]. Greenhouse gases (GHGs) absorb infrared radiation in the atmosphere; thus creating a "greenhouse effect" and contributing to global warming; therefore, the carbon footprint can also be equivalent to global warming potential (GWP). Some common GHGs are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) [6].

Life cycle assessment (LCA) is one of the tools developed to measure carbon footprint, in which the emission of GHGs is assessed at different stages of the product's life cycle.

LCA is a holistic method to evaluate the environmental impacts of a product system throughout its life cycle, or from-cradle-to-grave [4]. In summary, a carbon footprint assessment focused on one environmental impact category: greenhouse gas emissions, while an LCA considers more impact categories, such as acidification, eutrophication or ozone depletion. This thesis followed the standard ISO 14044:2006 and PAS 2050 when assessing product life cycle GHG emission.

According to PAS 2050, a life cycle carbon footprint calculation can be divided into following steps [7]:

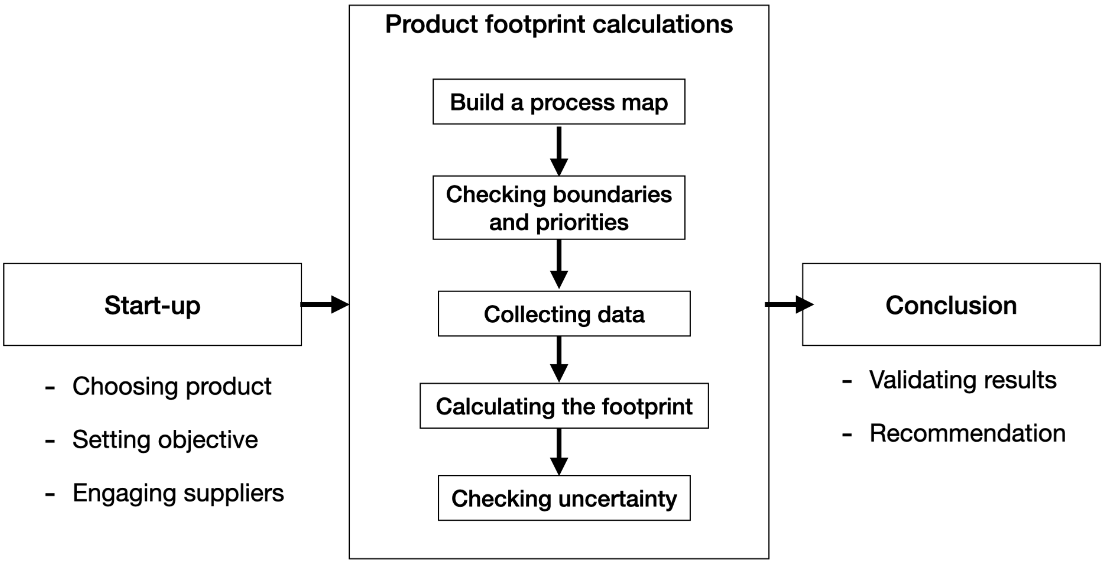

Figure 1: Process of a life cycle carbon footprint calculation

The first step is defining products and objectives of the carbon footprint assessment. The next step handles product footprint calculations, starting with building a process map which comprises the elementary flows and product flows. Although it is ideal to include all of them, it is more important to evaluate the available data and the goal of the study, which results in the next step: checking boundaries and priorities. At this phase, the product system, functional unit, system boundaries, limitations, and assumptions must be determined thoroughly. The functional unit is used as a reference unit by defining a quantification of the product's performance [4]. Setting an appropriate functional unit is important for future comparisons. The system boundary defines which unit processes to be included in or excluded from the assessment. In the third step of calculation, data are collected, including the activity data and emission factors. Next, the footprint is calculated. The final step within the footprint calculation stage is to identify and reduce uncertainty. Lastly, the conclusion stage examines and summarizes the result from the calculation to draw a meaningful conclusion within the established goal and scope. The interpretation must be precise in order to assist the users in the decision-making process. [5]

2.2 Global warming potential

The global warming potential (GWP) estimates the amount of energy that the emission of 1 ton of a gas will absorb for a given period of time, usually 100 years, compared to the emissions of 1 ton of carbon dioxide (CO_2) [9]. GWP can be expressed as the equation below [10]:

$$GWP_{T,i=} \int a_i \, . \, c_i \, . \, (t) \, dt \, / \int a_{CO2} \, . \, c_{CO2} \, . \, (t) \, dt \, ,$$

where a_i [W/m^{2}kg] is the radiative forcing per unit concentration increase of GHG I,
c_i [kg/m^3] is the concentration of greenhouse gas i at time T after release,
t [year] is the time over which the integration is performed.

Table 1 presents some common GHGs and their characterization factors relative to CO_2 for a time horizon of 100 years (GWP100) [11]

Table 1: Common greenhouse gases and their GWP value

Type of gas	Chemical formula	GWP
Carbon dioxide	CO_2	1
Methane	CH_4	25
Nitrous oxide	N_2O	298
Hydrochlorofluorocarbons	HCFCs	124 – 14,800
Chlorofluorcarbons	CFCs	4,750 – 14,400

In other words, GWP uses a common unit to compare the global warming impacts of different gases, hence enabling the identification of the emission source and reducing the negative impacts.

2.3 Case study

2.3.1 Intel building

The building in this study is a fitness center of 1624m^2 situated in the South of Ho Chi Minh City, an urban city in the Southern Vietnam. Specifically, the address of the building is Lot 12, D1 Road, Sai Gon Hi-Tech Park (SHTP), District 9, Ho Chi Minh City. Although it is located in the uptown area, the housing situation as well as the infrastructure is adequate. The construction is planned to start in 2022 and targeted to employ approximately 3000 employees. The intended service life of the building in this study is 60 years.

The Intel building is a fitness centre of one floor. The components of the building include two main parts: main building and the pedestrian area. In the main building, there are cardio equipment, strength circuit, dumbbell, barbell workout area and stretch area (600m^2), group fitness room with storages (150m^2), and accessory fitness equipment. Reception and lobby area (40m^2) include reception desk, waiting coaches, lockable storage and a counter kiosk with computers. In addition, restroom, locker, and shower areas with 300m^2 are required.

A detailed floor plan can be found in Appendix 1.

2.3.2 One-click LCA

One Click LCA was chosen as the calculation tool in this study. One Click LCA is a building life cycle assessment software that utilizes automated data import to optimize the process of life cycle assessment. One Click LCA complies with the following LCA standards: EN 15978, ISO 21931-1 and ISO 21929, and data requirements of ISO 14040 and EN 15804 [17].

3 Goal and Scope

In this chapter, the goal and scope of the study are defined. This is an important phase because the analysis and assessment will only be valid for the specific conditions stated in this phase.

3.1 Goal

The goal of this assessment was to calculate the carbon footprint resulting from structural and envelope building materials during the life cycle of a fitness center with 1624m^2 gross floor area. Subsequently, the building system was studied in order to determine the materials and the stages in the life cycle with the greatest environmental impacts.

The target customer of this study is Intel Cooperation, which is the owner of the building. The study was intended to aid them in improving the design and material selection in order to attain the LEED Platinum certification for their building.

3.2 Scope

The scope defines the spectrum of the study. According to the ISO 14040 standard, the scope should include a functional unit, product systems, system boundaries, allocation, impact categories, data requirements, assumptions, limitations and cut-off criteria [4].

3.2.1 Functional unit

The chosen functional unit for this LCA was 60 years of 1m^2 floor area. 60 years was assumed to be the lifetime of the building, which is common for an average building.

3.2.2 Product system

The product system in this thesis was a fitness center situated in Ho Chi Minh City, Vietnam named Recreation & Wellness Center (RWC). The building has one floor plus a greenhouse on top. Including the pedestrian walking area, it has altogether 1624m^2 of gross floor area.

This assessment followed the EN 15978 structural and envelope scope, which includes the following building elements [12]:

- Foundations and substructure: Foundation, sub-surface, basement, retaining walls
- Vertical structures and facade: external walls, wall finishes, columns
- Horizontal structures: floor, beams, ceilings, roofs

Figure 2 presents the product system of the studied building. Generally, material is the main input for all phases, along with energy. However, due to the incomplete dataset, energy data is only available for the use stage. Outputs of the product system are categorized as material waste and emissions.

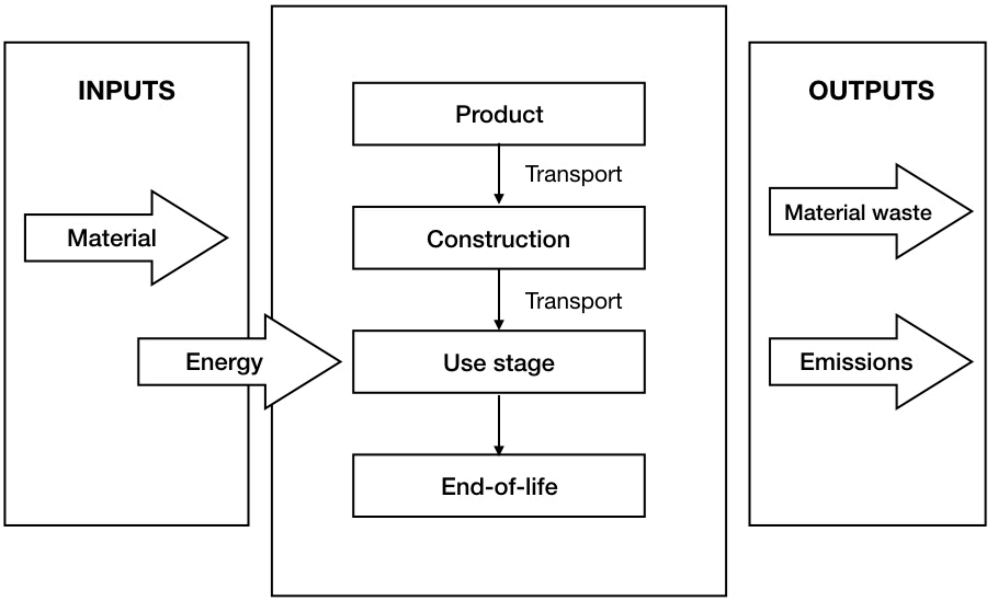

Figure 2: Product system of the study building

3.2.3 System boundaries

According to EN 15978 [12] and EN 15804:2012 [13] standards followed in the assessment, the whole life cycle of a building is divided in four phases:

- Product: raw material extraction and processing (A1), transport of raw materials to the manufacturer (A2), manufacturing of the products and packaging (A3).
- Construction: transport of materials from the manufacture to the building site(A4), installation into the building and wastage from the installation (A5).
- Use stage: B1-B5 related to building fabric while B6-B7 related to the operation of the building (energy and water use).
- End-of-life: demolition (C1), transport to waste processing (C2), waste processing for reuse, recycling, and energy recovery (C3), disposal and the associated processes (C4)

In the building level calculation, the concept is to take into account all the relevant impacts over the building's life cycle. However, the numbers of modules can be constrained depending on different certifications and calculation systems [12]. For the concrete building studied in this thesis, the system boundary included A1-A3, A4, B1-B5, B6, C1-C4 (Table 2).

Table 2: Building life cycle (EN 15978)

Building assessment information																
Building life cycle																Supplementary information
Product			Construction		Use stage							End-of-life				Benefits and loads beyond the system boundary
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
Raw materials supply	Transport	Manufacturing	Transport	Construction	Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	De-construction Demolition	Transport	Waste processing	Disposal	Re-use-Recovery-Recycling-potential
X			X		X					X		X				

3.2.4 Data requirements

The building's environmental impacts were calculated in One Click LCA based on the design and bill of quantities provided by the owner Intel Cooperation and GreenViet Consultancy – the consultant of this project, responsible for implementing LCA and gaining LEED credits. Materials data was taken from the database provided by One Click LCA software.

Table 3 presents a full list of the data sources used in the building assessment:

Table 3: Data sources

Area of analysis	Data sources
Material quantities (A1-A3)	Building information model (BIM), architectural drawings, bill of quantities provided by Intel Cooperation
Building material transport distances (A4)	The case specific transporting distances were used when available. Otherwise, transporting distances were estimated based on typical average transport distances and material type provided by the calculation tool.

Construction and installation process (A5)	Not included in the study due to lack of energy, water, waste management data during construction stage
Material service life (B1-B5)	Concrete and steel were assumed to have a service life of 60 years, same as the building. Ceramic and acrylic emulsion paint were assumed to last 30 years and 10 years, respectively.
Building use phase energy consumption (B6)	Energy consumption was estimated based on design stage energy simulation utilizing VE PRM 2010 Navigator (accordance with ASHRAE Standard 140) with project specific use scenarios.
Building use phase water consumption (B7)	Not included in the study
End-of-life (C1-C3)	Building material waste used default values from One Click LCA database, water and energy recovery are not included.

3.2.5 Assumptions

During the LCA analysis, it was necessary to assume these following conditions:

- The lifetime of the building is 60 years.
- Transportation distance of concrete and steel from the manufacturer to the building site are 20km, since the manufacturers are located in the city.
- Concrete mixer trucks of $8m^3$ are used to transport concrete and trailers combination 40tonnes for other materials (steel, bricks, ...) transportation. All are assumed to have 100% fill rate.

3.2.6 Limitation and cut-off criteria

This thesis contains the following limitations:

- This building's material scope was structure and envelope; therefore, some elements which do not belong to the scope were excluded: windows and doors, stairs, balcony, elevators, parking lots, pipeline, ventilation, building automation system…
- In horizontal and vertical structures, there are more elements such as plating, insulation. These types of materials were also excluded from the report, since they have low quantities and little impact on emissions. Concrete, steel, brick and ceramic tile were primary considerations.

- The renovation of roof (hollow core concrete slabs) and external walls (ceramic tile, aluminum panel, paint) were not included.
- Water consumption was not considered in the calculations.
- Only the consumption of grid electricity was included during the assessment of energy consumption during use phase. District heating and district cooling is not available in Vietnam.
- Waste management from the construction stage is excluded.
- The end-of-life phase only covered building material waste. Water and energy waste and recovery were excluded due to restrictions in data collection.
- The assessment was performed based on site-specific data such as commuting and grid electricity in Vietnam. Therefore, the results are valid only within Vietnam territory.

4 Carbon Footprint Calculation

In this chapter, the inventory of materials in categorized building components, and energy consumption in the use phase are further described and calculations are performed.

4.1 Data collection

4.1.1 Building materials

Table 4 presents details of material included in this thesis divided into 3 main systems: foundation, vertical structures and horizontal structures.

Because there was no information regarding the construction equipment, tools and workers, energy used, waste and transportation during the construction phase are not included in the table.

Table 4: Bill of quantities short version

Building System	Material	Quantities	Unit
1. Foundation			
Foundation	Ready-mix concrete C20/25	109	m^3
	Reinforcement steel (rebar)	15000	kg
	Ready-mix concrete, lightweight, C8/10	10	m^3

2. Vertical structures			
External walls	Hollow bricks, for walls, 126.3 kg/m2	267	m^2
	Hollow bricks, for walls, 126.3 kg/m2	671	m^2
	Acrylic emulsion paint	481	m^2
	Ceramic tile	1096	m^2
	Aluminum composite panel	99	m^2
Columns	Ready-mix concrete C20/25	4.3	m^3
Internal walls	Structural hollow steel sections	4000	kg
3. Horizontal structures			
Floor slabs	Ready-mix concrete C20/25	81	m^3
	Ready-mix concrete, lightweight, C8/10	243	m^3
	Reinforcement steel (rebar)	10000	kg
Ceiling	Heat insulation polyolefin	550	m^2
Beams	Ready-mix concrete, lightweight, C8/10	5.6	m^3
	Ready-mix concrete C20/25	31.6	m^3
	Reinforcement steel (rebar)	10000	kg
Roof	Hollow core concrete slabs	285.3	m^3
	Reinforcement steel (rebar)	15000	kg
	Hollow core concrete slabs	101.3	m^3
	Reinforcement steel (rebar)	18000	kg
	Pre-painted galvanized corrugated roofing sheet	69	m^2

A full version with detailed specifications and usage of each material can be found in Appendix 2.

4.1.2 Energy in Use stage

Table 5 shows the estimation of annual electricity consumption of the building, broken down to each utility and its corresponding share of usage. The calculation process used VE PRM 2010 Navigator – an automation tool for energy modelling. According to the data, total annual energy consumption during the usage stage of the building is 454525.55 kWh, or 454.53 MWh. Electricity used for fitness equipment accounts for almost half of total consumption, followed by space cooling, which takes up 31% of the sum. Ho Chi Minh City is located in a tropical climate area where the average temperature is 27.4 Celsius degrees; thus space heating is unnecessary while space cooling is necessary through the whole year (climate-data.org). Other utilities are relatively small.

Table 5: Electricity consumption in use stage

End use	Electricity use (kWh)	Percentage (%)
Internal Lighting	3038.87	0.67
Exterior Lighting	1985.6	0.44
Space Heating	0	0.00
Space Cooling	141483.8	31.13
Pumps	9384.86	2.06
Heat Rejection	33375.31	7.34
Fans Interior	38923.62	8.56
Fitness equipments	221827.42	48.80
Data Centre Equipment	4506.07	0.99
Cooking	0	0.00
Elevator/Escalators	0	0.00
Other Processes	0	0.00
SUM	**454525.55**	**100**

As can be seen from Table 5, total annual energy consumption during the usage stage of the building is 454525.55 kWh or 454.53 MWh. Therefore, the total energy consumption of the building on one functional unit (1m^2 floor area x 60 years) can be calculated using the following equation:

$$\frac{454.53\ MWh}{1624\ m^2} x60\ year = 16.79\ \left(\frac{MWh}{m^2}.year\right)$$

4.2 Emission factors

The emission factors for different materials and electricity were collected from the database of One Click LCA and used specifically for the Vietnam region. The material was sorted into bricks, ceramic, aluminium, concrete and steel which are the main contributing materials to the emission. The energy related products included in this carbon footprint assessment was electricity from Vietnam's national electricity grid. The detail are given in Table 6 below:

Table 6: Emission factors for different materials and electricity in this study

Energy	Emission factor	Unit
Electricity	0.52	$kgCO_2e/kWh$
Material		
Concrete C40/50	0.16	$kgCO_2e/kg$
Concrete C20/25	0.0998	$kgCO_2e/kg$
Concrete C8	0.12	$kgCO_2e/kg$
Steel	0.67	$kgCO_2e/kg$
Brick	0.15	$kgCO_2e/kg$
Ceramic	0.73	$kgCO_2e/kg$

4.3 Calculation methods

The GHG calculations within the building sector are more challenging as the building involves several processes and products during its life cycle. However, the calculation formulas are approximately the same using emission factors. The calculation process is demonstrated in the figure:

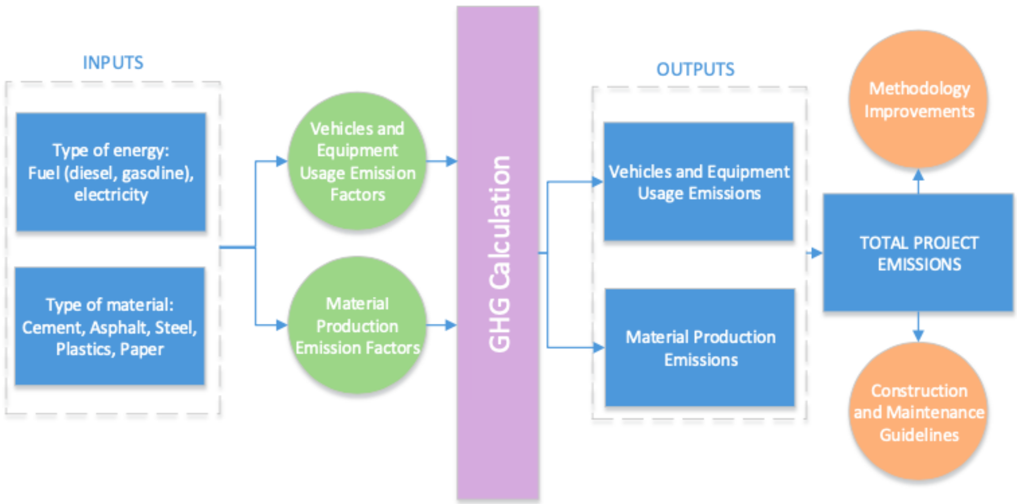

Figure 3: Steps to conduct a carbon footprint assessment for construction projects [31]

The inputs including the materials and energy used in the construction are collected and classified into different categories. The emissions factors are correspondingly collected as in 4.2 section and are then multiplied with each category. Correct unit handling is crucial in the completion of GHG calculations. The emissions from the outputs are added together and result in the total carbon footprint of the building in the life cycle perspective.

In other words, the calculation is merely the sum of collected data times its corresponding emission factor. The equation below further clarifies the carbon footprint calculation process:

$$Carbon\ footprint = Activity\ data\ x\ Emission\ factor,$$

where the activity data is the amount of used materials, energy or service in a product, the unit can be in mass, volume, kWh or m^2; the emission factor converts the activity data into GHG emissions [8].

The total emission helps in drawing conclusions and making suggestions for improvement. Nevertheless, one should keep in mind that emission calculations contain assumptions and limitations that need to be taken into account in the conclusion with an uncertainty analysis.

In One Click LCA, the input of energy consumption and building materials, including their quantities, transportation information, and service life, are manually input. These values are then calculated with the corresponding local emission factors integrated in One Click LCA.

5 Result

The purpose of this chapter is to present the results of the previous calculations into a more comprehensible form from an environmental perspective. Impacts were calculated from the inventory.

5.1 Impact characterisation result

The impact categories were calculated using One Click LCA software tool. The result is summarized in Table 7, which presents the total life cycle impact of the building during its 60-year service lifespan.

Table 7: Life cycle assessment results of the study building

	Global warming	**Acidification**	**Eutrophication**	**Ozone depletion potential**	**Formation of ozone of lower atmosphere**
	kg CO_2e	kg SO_2e	kg PO_4e	kg CFC11e	kg Ethenee

A1-A3	Construction Materials	3.78E+05	1.09E+03	2.05E+02	1.73E-02	8.17E+01
A4	Transportation to site	3.57E+03	7.67E+00	1.61E+00	6.24E-04	4.63E-01
A5	Construction/installation process					
B1-B5	Maintenance and material replacement	1.14E+04	4.21E+01	4.14E+00	3.04E-05	3.86E+00
B6	Energy use	5.24E+05	2.36E+03	3.29E+02	3.59E-02	1.17E+02
B7	Water use					
C1-C4	Deconstruction	1.47E+04	5.56E+01	1.32E+01	2.31E-03	2.76E+00
	Total	**9.32E+05**	**3.56E+03**	**5.53E+02**	**5.62E-02**	**2.06E+02**
	Emission/m^2 Floor Area	**5.74E+02**	**2.19E0**	**3.4E-01**	**3.46E-05**	**1.27E-01**

Table 7 shows that the Intel Fitness Center contributes to 574 $kgCO_2eq/m^2$ in 60 years, which is about: $\frac{574}{60} = 9.57$ $kgCO_2eq/a*m^2$.

Figure 4 gives a comparative overview of the impact categories. According to the graphs, the majority of the emissions are from energy consumption in Use Stage B6 and material production phase A1-A3. Specifically, energy consumption during the use phase contributes to more than half of the emissions in all impact categories, while the material production phase's emissions typically accounts for 30 to 40 percent of the emissions of all impact categories. On the other hand, the other three stages contribute a relatively insignificant amount of emission compared to the Energy and Materials stage.

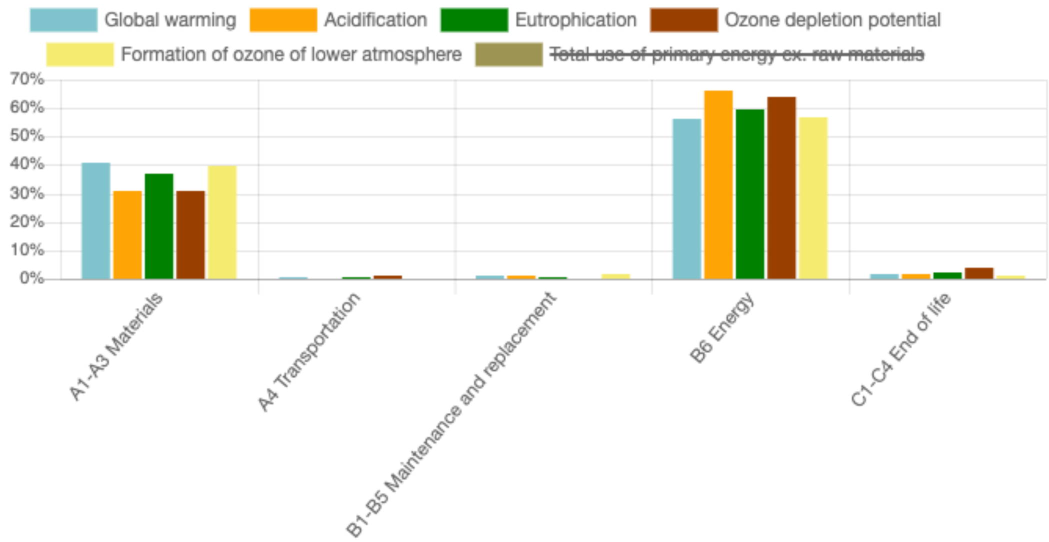

Figure 4: Impacts categories by life-cycle stage

A breakdown of the impact of each materials in each stage can be found in Appendix 3.

5.2 Contribution of life-cycle phases and building elements to GWP

5.2.1 Life-cycle phases

Figure 5 shows that the energy phase in use stage B6 is responsible for a largest portion with 56.2% of the total impacts. Production of material also accounts for a significant amount with 40.6%. The percentages of the end-of-life phase and the maintenance and replacement are relatively small with 1.6% and 1.2%, respectively. The transportation phase accounts for less than 0.5% which is the minimal contribution of all phases.

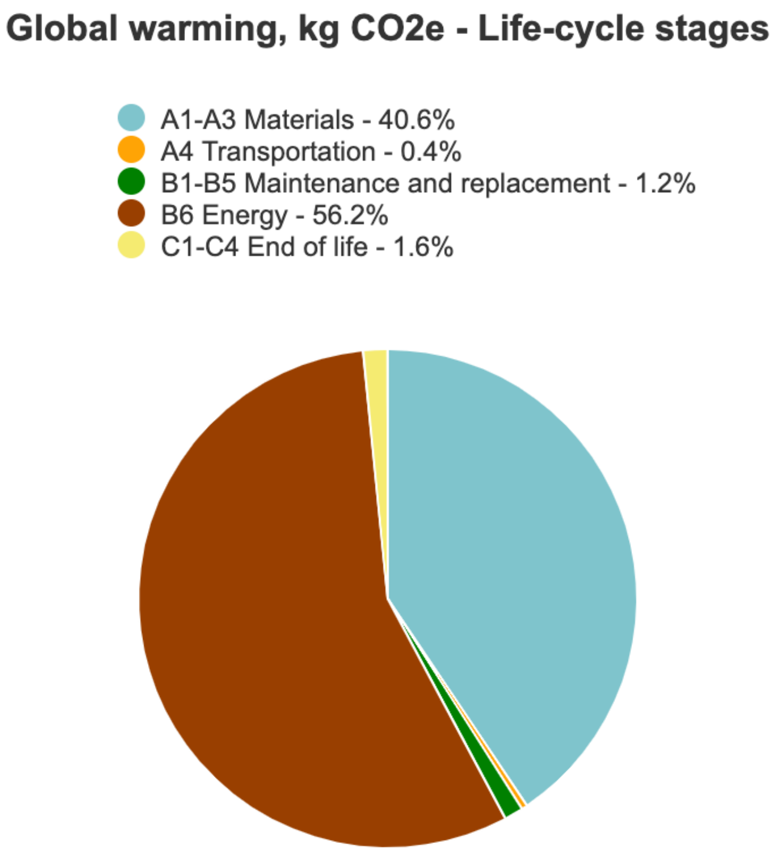

Figure 5: GWP contribution categorized by life-cycle stages

Table 8 illustrates how much GWP emission each life cycle stage emits in kgCO2-eq.

Table 8: GWP contribution categorized by life-cycle stages

Category	**Global warming, kg CO2e - Life-cycle stages**	**Percentage**
A1-A3 Materials	378008.79	40.58
A4 Transportation	3569.55	0.38
B1-B5 Maintenance and replacement	11425.81	1.23
B6 Energy	523774.77	56.23
C1-C4 End of life	14721.47	1.58
Total	**931500.40**	**100**

5.2.2 Building elements

Figure 6 presents the contribution of each material type in global warming potential. The major contributors for GWP emissions were concrete with 59.9%, followed by bricks and ceramics with 23.5% and metals such as steel, aluminium with 14.47%. The figures for Insulation and Coating & pastes are minute with 1.8% and 0.1%, respectively.

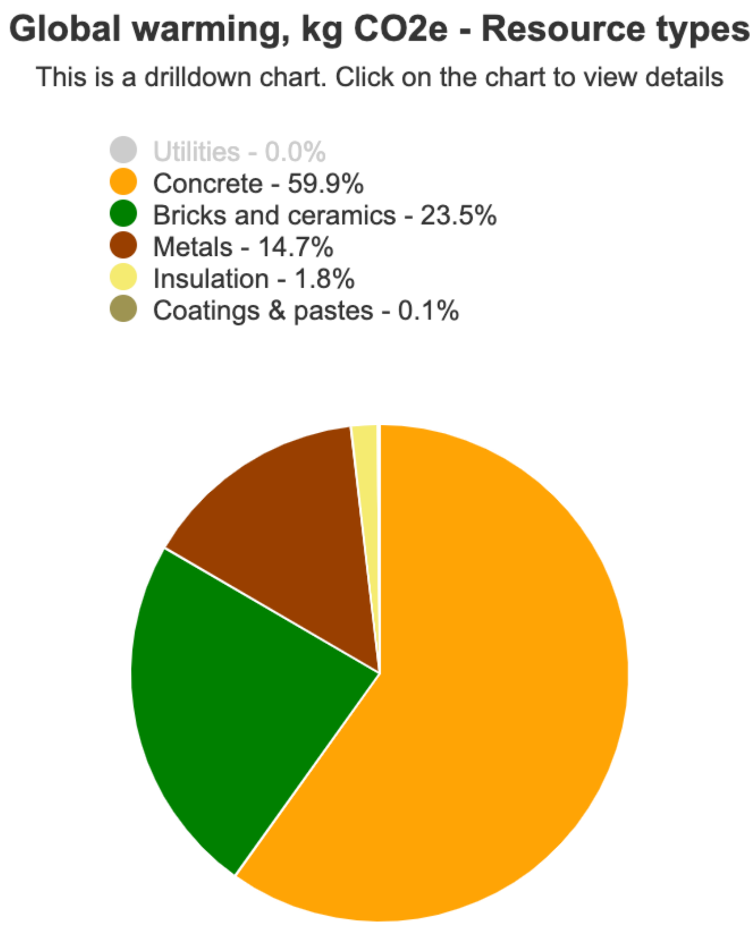

Figure 6: GWP contribution categorized by building material

Table 9 gives further insight into the categories in terms of emission quantity. It estimates that the building will emit 408 tonnes of CO_2-eq throughout its lifetime, with 244 tonnes resulting from using concrete.

Table 9: GWP contribution categorized by building materials

Category	**Global warming, kg CO2e - Resource types**	**Percent-age (%)**
Concrete	244138.06	59.88
Bricks and ceramics	96011.16	23.55
Metals	60000.63	14.72
Insulation	7169.22	1.76
Coatings & pastes	406.56	0.10
Total	**407725.62**	**100.00**

6 Interpretation

6.1 Life-cycle stages

Energy consumption is one of the main sources of emission in the building's life cycle. In this study, electricity consumption in the use phase has the highest impact of GWP (56.2%). Figure 7 shows that Vietnam's electricity is mainly generated by fossil fuels, about 60% in 2017 [29], which explains the huge contribution of energy consumption in the GWP of the building. BAU scenario predicted that until 2050, fossil fuels remains the dominent energy source, accounting for 68.2% of total energy consumption. Additionally, Vietnam's energy demand is expected to rise in which coal, oil products and gas consumption will be 3, 2, and 1.5 times higher, respectively, between 2018 and 2050 [33]. It should be noted that different countries with different means of share in their electricity grid will produce different environmental impacts. Therefore, this study is limited to Vietnam.

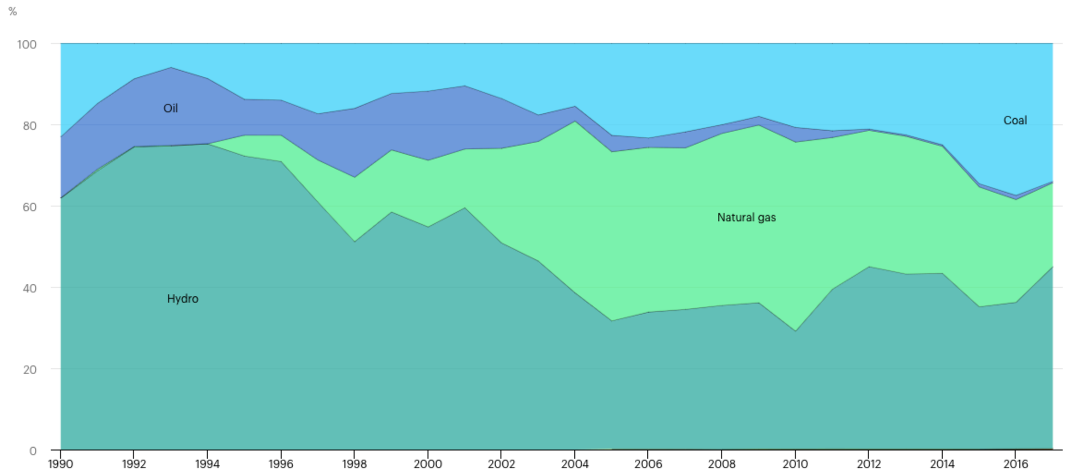

Figure 7: Electricity generation by source of Vietnam 1990 – 2017 (IEA)

Product phase has the second highest impact on GWP. This is due to the raw materials production process and transportation to the manufacturer, especially from the cement production step within the concrete production process. On the other hand, the maintenance and end-of-life phase has a low overall environmental impact due to either the inadequacy of data availability during these phases or the low quantity of materials needed to be replaced.

6.2 Materials

Among main construction materials, concrete and steel are the major sources of emissions. Specifically, concrete alone generates 60% of the total GHG emissions, while steel accounts for about 15% of the total pollution. Globally, the production of cement, which is the main ingredient of concrete, is the third ranking contributor of anthropogenic CO_2, after transportation and energy production [30]. In the process of making cement, CO_2 is produced in two phases. The first occurrence is as a by-product of burning fossil fuels, primarily coal, to generate the required heat to drive the whole process. The second one is during cement clinker production stage, specifically from the thermal decomposition of calcium carbonate. Therefore, the production of one tonne of cement results in 780 kg of CO_2, in which 30% from the use of energy and 70% from decarbonation.

On the other hand, concrete produces higher emission compared to other construction materials involved in the building such as ceramic tiles and bricks, due to the fact that concrete is used in a tremendous quantity. Hence, it is reasonable that concrete is responsible for a large share of the building's environmental impacts. Figure 8 illustrates the contribution of each material to GWP and compares them with electricity consumption in the use phase.

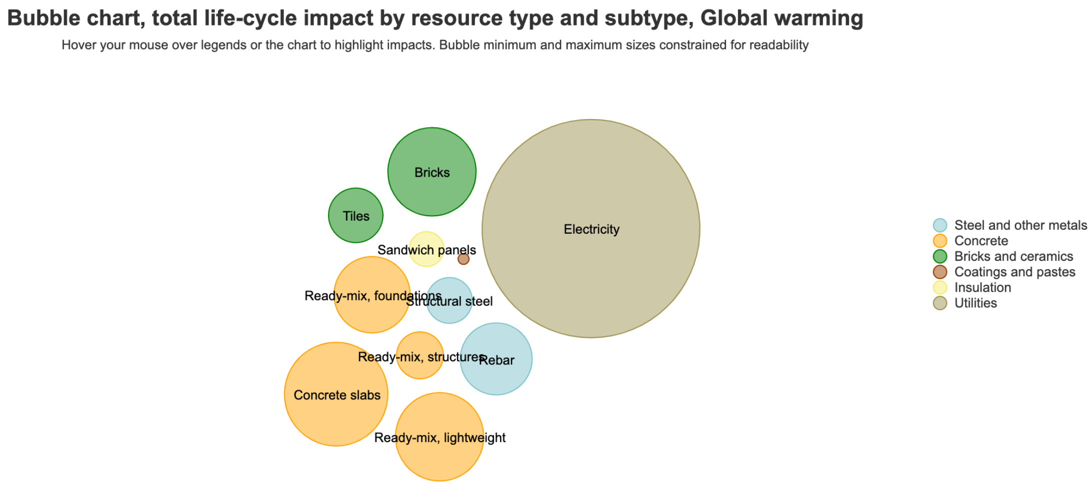

Figure 8: Total life-cycle impact on Global warming categorized by resource type and subtype

6.3 Uncertainty

This part discusses the data of the building used to calculate its environmental impacts and possible uncertainty.

The first uncertainty came from the building envelope data collection. Since the project is still in the design phase, the bill of quantities has not been completed and the materials in the study were chosen based on typical materials used in the other constructions in Vietnam. Moreover, some building elements are neglected such as insulation and cladding due to unavailable information. Consequently, there is a considerable amount of uncertainty in the accounting of the building envelope, which affects the real design.

Secondly, the energy used to calculate in this study is fairly certain. As mentioned, the project design phase has not finished, only the electricity consumption during use stage is estimated throughout the building life-cycle. A significant amount of energy used in production, construction, maintenance and EOL phase are omitted, resulting in uncertainty in energy impact assessment.

Another aspect that contributes to the systematic uncertainty is transportation. Transport distances were either estimated from the most popular concrete and steel manufacturers in the city, which is approximately 20km to the building site, or from the given information from One Click LCA database. Although an effort has been made to choose suitable manufacturer locations, a significant level of uncertainty remains.

The last type of uncertainty comes from assuming the lifetime of the building is 60 years. In the next 60 years, the components of Vietnam's electrical grid may change drastically, as the government is already planning to shift electric power production towards more sustainable methods. The climate is another factor that affects the building's lifetime, especially in the current time, when climate change impacts various aspects of the environment in unforeseeable ways. Additionally, users' behaviours in the future are difficult to predict; therefore, it is best to not make any assumption about this matter.

In conclusion, there are uncertainty factors associated with the LCA of the building, which is a significant drawback to a comprehensive interpretation.

6.4 Literature review

As mentioned earlier, this is one of the first buildings for which an LCA-based design is attempted in Vietnam. Therefore, it is difficult to find an equivalent building to compare the environmental impacts due to different factors in geographical and technical properties. Alternatively, some other relevant researches in Asia have been done that can be used as references and benchmarks for this thesis:

1) Rashid A et.al [22] evaluated LCA cradle-to-grave of a semi-detached residential building in Malaysia with 4 impact categories in CML 2001 including GWP. The result is the building operation or the use phase contributes the highest GWP and concrete is the material having the most significant overall impact in pre-use phase. This LCA produces a similar result with this thesis.

2) Kofoworola & Gheewala [23] conducted an LCA for a 38 stories office building in Thailand. The building floor area is 60,000m^2 and building lifetime is set to 50 years. Similar to this thesis scope, only the structure and the envelope were analysed. The impact categories selected were global warming potential (GWP), acidification potential (AP) and photo-oxidant formation potential (POCP). The results proved concrete and steel represent the highest quantities used and also for their associated environmental impacts with 47% and 24%, compared to the ones of this thesis being 60% and 15% respectively. In addition, the operational stage (equivalent to use stage B1-B7 in this study) has the largest environmental impact: 52% of total GWP, 66% of total AP. In comparison, the present study produces a result of approximately 58% and 67% for each respective category.

7 Conclusions and Recommendations

The carbon footprint assessment is a straightforward method that when combined with LCA, becomes an effective tool to measure environmental impact. With a systematic approach, it shows a great suitability toward the building industry, where its complex architecture and inherently long lifespan tend to hinder the predictive ability of environmental models. The objective of this thesis was to quantify and compare the environmental impacts caused by a fitness center building of 1624m^2 during its lifetime. The study determined the life cycle phases and elements which contributed the most to the building's lifetime environmental impact.

With the functional unit set as 60 years of 1m^2 floor area, the result is that the energy use phase produced the highest GWP (5.24 x 10^5 kgCO_2eq), even though only the electricity consumption is covered in this stage. Material-wise, concrete has been identified as the largest contributor to GWP (2.44 x 10^5 kgCO_2eq).

In terms of life-cycle stages, the use stage of building has the highest environmental impacts, followed by the product phase. In order to decrease emissions, reduction in energy usage should be considered. In terms of building material, concrete is highly likely to be the most significant source of emission. A proposed design has been recommended to the stakeholders by changing the current concrete type with a 10% recycled content, which is typical in a Vietnam building, into the new one with a 55% recycled content which is predicted to result in a 10% reduction in GWP.

CFP and LCA are sophisticated assessment methods applicable to a complex product, in this case, a building. Even though there are limitations and uncertainties that might affect the validity and reliability of the result, the findings of this thesis prove that it is possible to execute a carbon footprint calculation or further, an LCA on a building with current technology. As the environmental awareness of the society grows, CFP and LCA are likely to be even more accurate, and the data is likely to be more abundant.

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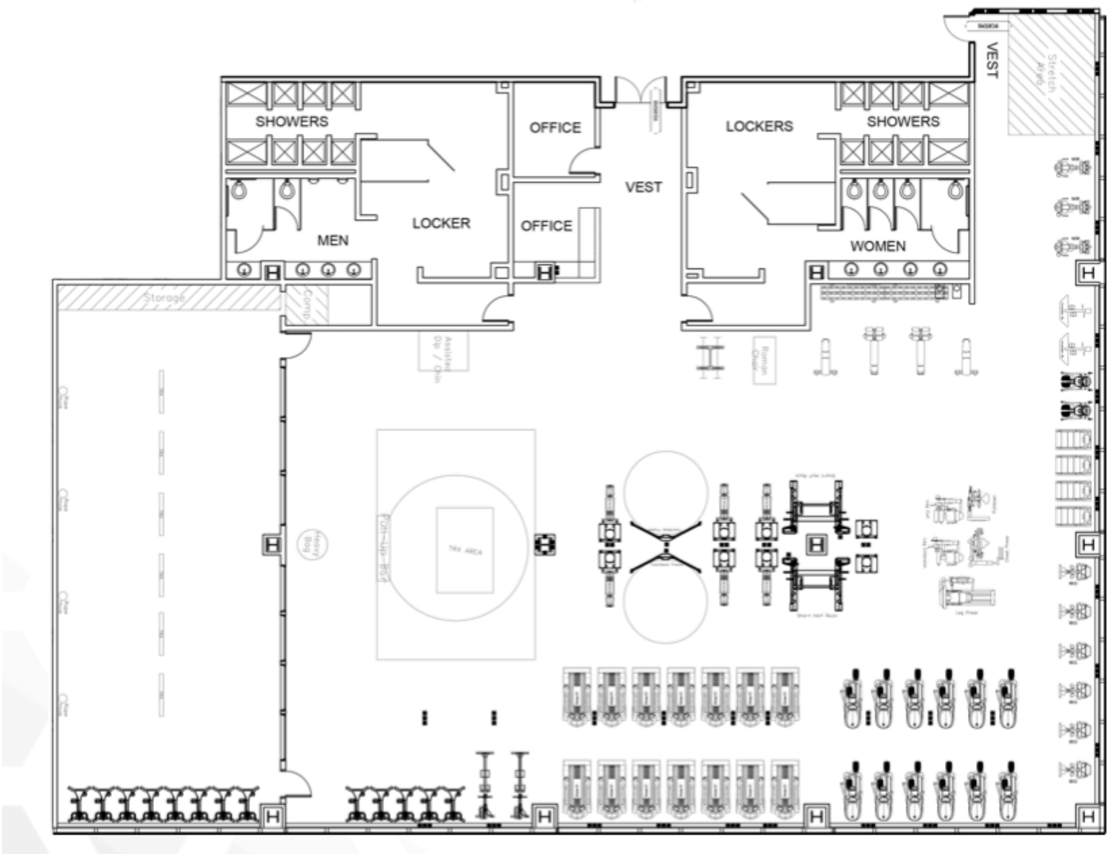
Appendix 1: Floor plan of Intel building



Appendix 2: Building materials list with details on specification and usage

Class	Material	Quantity	Unit	Thickness (mm)	Comment
Foundations and substructure (Materials in the foundations will never be replaced, no matter assessment period length)					
Foundation	Ready-mix concrete, normal-strength, generic, C20/25 (2900/3600 PSI)	109	m^3		
	Reinforcement steel (rebar)	15000	kg		
	Ready-mix concrete, lightweight, C8/10	10	m^3		
Sub-surface					
Basement					
Retaining walls					
Vertical structures and façade (Include finishings, if relevant)					
External walls	Hollow bricks, for walls, 126.3 kg/m2	267	m^2	5	1 side plaster, 1 side tiling
	Hollow bricks, for walls, 126.3 kg/m2	671	m^2	5	Both side plaster & 1 side tiling
	Acrylic emulsion paint, for exterior application, 1.22 - 1.31 g/cm3, 39% solids/volume, dry/wet film thickness 30 - 40 / 77 - 103 µm, 13 - 9.8 m2/l, Jotashield Chống Phai Màu (Mới) (Jotun)	481	m^2	0.05	Exterior paint
	Ceramic tile, US average, 0.287-0.433in, 0.5x0.5in - 24x24in, planks max. 36in, 3.5-7.0 lb/ft2	1096	m^2	7	Wall finishes
	Aluminum composite panel, curtain walling/facade, mineral filled, 4	99	m^2	3	Wall finishes

	mm, 7.1 kg/m2, B1 (Saray)				
Façade					
Columns	Ready-mix concrete, normal-strength, generic, C20/25 (2900/3600 PSI)	4.3	m^3		Pedestal of main building
Internal walls	Structural hollow steel sections (HSS), cold rolled, generic, 10 % recycled content, circular, square and rectangular profiles	4000	kg		
Horizontal structures (Include finishings, if relevant)					
Floor slabs	Ready-mix concrete, normal-strength, generic, C20/25 (2900/3600 PSI)	81	m^3		Ground slab of main building
	Ready-mix concrete, lightweight, C8/10	243	m^3		Ground slab of main building
	Reinforcement steel (rebar), generic, 90% recycled content	10000	kg		Pedestrian of main building
Ceilings	Heat insulation polyolefin foam ixpe, with aluminum coating	550	m^2	8	Ceiling insulation
Roofing decks					
Beams	Ready-mix concrete, lightweight, C8/10	5.6	m^3		Ground beam of main building
	Ready-mix concrete, normal-strength, generic, C20/25 (2900/3600 PSI)	31.6	m^3		Ground beam of main building
	Reinforcement steel (rebar), generic, 90% recycled content	10000	kg		Ground beam of main building
Roof	Hollow core concrete slabs, generic, C40/50	285.3	m^3		Roof slab of main building

	(5800/7300 PSI), 0% (typical) recycled binders in cement (400 kg/m3 / 24.97 lbs/ft3), incl. reinforcement				
	Reinforcement steel (rebar), generic, 90% recycled content	15000	kg		Roof slab of main building
	Hollow core concrete slabs, generic, C40/50 (5800/7300 PSI), 0% (typical) recycled binders in cement (400 kg/m3 / 24.97 lbs/ft3), incl. reinforcement	101.3	m^3		Roof beam of main building
	Reinforcement steel (rebar), generic, 90% recycled content	18000	kg		Roof beam of main building
	Pre-painted galvanized corrugated roofing sheet, AZ150 Klip lok system, light blue, 0.48mm thk	69	m^2	1	Roof finishes

Appendix 3: Impact assessment of each material categorized by building system and life-cycle stages

Foundation

Section	Resource	User input	Unit	GWP	AP	EP	ODP	Formation of ozone of lower atmosphere
A1-A3	Ready-mix concrete C40/50	4,30E0	m3	1,85E3	4,19E0	5,50E−1	4,70E−5	1,80E−1
A1-A3	Structural hollow steel	4,00E3	kg	1,48E4	6,25E1	1,00E1	9,40E−4	8,31E0
A4	Ready-mix concrete C40/50	4,30E0	m3	2,68E1	3,90E−2	8,00E−3	4,50E−6	4,00E−3
A4	Structural hollow steel	4,00E3	kg	8,88E1	4,10E−1	8,90E−2	1,80E−5	5,00E−3
C1-C4	Ready-mix concrete C40/50	4,30E0	m3	1,14E2	3,70E−1	8,90E−2	2,10E−5	1,00E−2
C1-C4	Structural hollow steel	4,00E3	kg	3,10E1	1,20E−1	2,60E−2	6,00E−6	4,20E−3
	TOTAL			**1,69E4**	**6,77E1**	**1,08E1**	**1,00E−3**	**8,51E0**

Vertical structures - External walls and façade

Section	Resource	User input	Unit	GWP	AP	EP	ODP	Formation of ozone of lower atmosphere
A1-A3	Aluminum composite panel	9,90E1	m2	7,16E3	2,54E0	4,21E1	2,20E−4	9,78E0
A1-A3	Acrylic emulsion paint	4,81E2	m2	6,73E1	4,00E−1	8,70E−2	6,00E−6	3,50E−2
A1-A3	Hollow bricks	9,38E2	m2	7,26E4	2,65E2	2,94E1	1,10E−3	1,64E1
A1-A3	Ceramic tile	1,10E3	m2	1,11E4	4,02E1	3,71E0	4,30E−7	3,68E0
A4	Aluminum composite panel	9,90E1	m2	9,42E0	4,30E−2	9,50E−3	1,90E−6	5,30E−4
A4	Acrylic emulsion paint	4,81E2	m2	2,26E0	9,10E−3	2,00E−3	4,40E−7	1,90E−4
A4	Hollow bricks	9,38E2	m2	9,12E1	4,20E−1	9,20E−2	1,80E−5	5,10E−3
A4	Ceramic tile	1,10E3	m2	1,21E2	5,60E−1	1,20E−1	2,40E−5	6,80E−3
B1-B5	Acrylic emulsion paint	4,81E2	m2	3,37E2	1,99E0	4,40E−1	3,00E−5	1,80E−1
B1-B5	Ceramic tile	1,10E3	m2	1,11E4	4,02E1	3,71E0	4,30E−7	3,68E0
C1-C4	Aluminum composite panel	9,90E1	m2	1,92E0	1,50E−2	3,10E−3	1,50E−12	1,50E−3
C1-C4	Acrylic emulsion paint	4,81E2	m2	4,10E−1	2,50E−3	3,70E−4	6,40E−12	2,50E−4
C1-C4	Hollow bricks	9,38E2	m2	3,25E2	2,55E0	5,30E−1	2,60E−10	2,50E−1
C1-C4	Ceramic tile	1,10E3	m2	6,90E2	1,32E0	6,60E−1	4,20E−5	1,90E−1
	TOTAL			**1,04E5**	**3,55E2**	**8,09E1**	**1,50E−3**	**3,42E1**

Vertical Structures - Columns and load-bearing structures

Section	Resource	User input	Unit	GWP	AP	EP	ODP	Formation of ozone of lower atmosphere
A1-A3	Ready-mix concrete C8/10	1,00E1	m3	2,69E3	7,17E0	1,75E0	2,70E−4	3,10E−1
A1-A3	Ready-mix concrete C20/25	1,09E2	m3	2,63E4	6,18E1	8,21E0	7,20E−4	2,66E0
A1-A3	Reinforcement steel (rebar)	1,50E4	kg	1,06E4	4,06E1	6,26E0	8,20E−4	4,71E0
A4	Ready-mix concrete C8/10	1,00E1	m3	5,72E1	8,40E−2	1,70E−2	9,60E−6	8,60E−3
A4	Ready-mix concrete C20/25	1,09E2	m3	6,23E2	9,10E−1	1,90E−1	1,10E−4	9,40E−2
A4	Reinforcement steel (rebar)	1,50E4	kg	1,15E1	5,30E−2	1,20E−2	2,30E−6	6,50E−4
C1-C4	Ready-mix concrete C8/10	1,00E1	m3	6,00E1	4,70E−1	9,80E−2	4,80E−11	4,70E−2
C1-C4	Ready-mix concrete C20/25	1,09E2	m3	2,66E3	8,57E0	2,06E0	5,00E−4	2,40E−1
C1-C4	Reinforcement steel (rebar)	1,50E4	kg	1,16E2	4,60E−1	9,60E−2	2,30E−5	1,60E−2
	TOTAL			**4,31E4**	**1,20E2**	**1,87E1**	**2,50E−3**	**8,08E0**

Horizontal structures: beams, floors and roof

Section	Resource	User input	Unit	GWP	AP	EP	ODP	Formation of ozone of lower atmosphere
A1-A3	Ready-mix concrete C8/10	5,60E0	m3	1,51E3	4,01E0	9,80E−1	1,50E−4	1,70E−1
A1-A3	Ready-mix concrete C40/50	3,16E1	m3	1,26E4	2,89E1	3,79E0	3,30E−4	1,23E0
A1-A3	Ready-mix concrete C20/25	8,10E1	m3	1,95E4	4,59E1	6,10E0	5,40E−4	1,98E0
A1-A3	Hollow core concrete slabs C40/50	1,01E2	m3	2,56E4	5,92E1	7,85E0	7,30E−4	2,71E0
A1-A3	Ready-mix concrete C8/10	2,43E2	m3	6,54E4	1,74E2	4,25E1	6,70E−3	7,59E0
A1-A3	Hollow core concrete slabs, generic C40/50	2,85E2	m3	7,22E4	1,67E2	2,21E1	2,00E−3	7,64E0
A1-A3	Reinforcement steel (rebar)	1,00E4	kg	5,32E3	1,98E1	2,82E0	4,60E−4	1,99E0
A1-A3	Reinforcement steel (rebar)	1,00E4	kg	5,32E3	1,98E1	2,82E0	4,60E−4	1,99E0
A1-A3	Reinforcement steel (rebar)	1,50E4	kg	1,06E4	4,06E1	6,26E0	8,20E−4	4,71E0
A1-A3	Reinforcement steel (rebar)	1,80E4	kg	1,27E4	4,87E1	7,51E0	9,90E−4	5,65E0
A4	Ready-mix concrete C8/10	5,60E0	m3	3,20E1	4,70E−2	9,60E−3	5,40E−6	4,80E−3
A4	Ready-mix concrete C40/50	3,16E1	m3	1,97E2	2,90E−1	5,90E−2	3,30E−5	3,00E−2
A4	Ready-mix concrete C20/25	8,10E1	m3	4,63E2	6,80E−1	1,40E−1	7,80E−5	6,90E−2
A4	Hollow core concrete slabs C40/50	1,01E2	m3	1,09E2	5,00E−1	1,10E−1	2,10E−5	6,10E−3
A4	Ready-mix concrete C8/10	2,43E2	m3	1,39E3	2,03E0	4,10E−1	2,30E−4	2,10E−1
A4	Ready-mix concrete C40/50	2,85E2	m3	3,06E2	1,41E0	3,10E−1	6,00E−5	1,70E−2
A4	Reinforcement steel (rebar)	1,00E4	kg	7,66E0	3,50E−2	7,70E−3	1,50E−6	4,30E−4
A4	Reinforcement steel (rebar)	1,00E4	kg	7,66E0	3,50E−2	7,70E−3	1,50E−6	4,30E−4
A4	Reinforcement steel (rebar)	1,50E4	kg	1,15E1	5,30E−2	1,20E−2	2,30E−6	6,50E−4
A4	Reinforcement steel (rebar)	1,80E4	kg	1,38E1	6,30E−2	1,40E−2	2,70E−6	7,80E−4
C1-C4	Ready-mix concrete C8/10	5,60E0	m3	3,36E1	2,60E−1	5,50E−2	2,70E−11	2,60E−2
C1-C4	Ready-mix concrete C40/50	3,16E1	m3	8,41E2	2,71E0	6,50E−1	1,60E−4	7,60E−2
C1-C4	Ready-mix concrete C20/25	8,10E1	m3	1,98E3	6,37E0	1,53E0	3,70E−4	1,80E−1
C1-C4	Hollow core concrete slabs C40/50	1,01E2	m3	1,57E3	5,07E0	1,22E0	2,90E−4	1,40E−1
C1-C4	Ready-mix concrete C8/10	2,43E2	m3	1,46E3	1,14E1	2,37E0	1,20E−9	1,13E0
C1-C4	Hollow core concrete slabs, generic C40/50	2,85E2	m3	4,43E3	1,43E1	3,43E0	8,20E−4	4,00E−1
C1-C4	Reinforcement steel (rebar)	1,00E4	kg	7,75E1	3,10E−1	6,40E−2	1,50E−5	1,00E−2
C1-C4	Reinforcement steel (rebar)	1,00E4	kg	7,75E1	3,10E−1	6,40E−2	1,50E−5	1,00E−2
C1-C4	Reinforcement steel (rebar)	1,50E4	kg	1,16E2	4,60E−1	9,60E−2	2,30E−5	1,60E−2
C1-C4	Reinforcement steel (rebar)	1,80E4	kg	1,40E2	5,50E−1	1,20E−1	2,70E−5	1,90E−2
	TOTAL			**2,44E5**	**6,55E2**	**1,13E2**	**1,50E−2**	**3,80E1**

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