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Upcycling Shipping Containers as Building Components

An environmental impact assessment

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Abstract

The introduction of shipping containers in the trading system has increased world economic growth exponentially. The drawback of this linear economy consists in the accumulation of empty containers in import-based countries.
Sustainable and green architecture should consider not only recycling but also upcycling and reuse of material. Therefore designers troughout the world are working with intermodal containers for environmental purposes.

Moving from ethical considerations, it is possibile to determine whether container architecture is actually sustainable?

The aim of this study is to quantify the impact of the use of shipping containers as building components from an environmetal point of view. A comparative life cycle analysis has been undertaken. Two benchmark technologies have been selected for this comparative analysis: a steel frame and an X-Lam structure.
Three different scenarios have been developed in order to understand how climate can affect results of the study: hot-tropical, temperate and cold.
A Life cycle Assessment has been used to evaluate 4 impact categories: Global Warming Potential, Ozone Depletion Potential, Acidification Potential and Eutrophication Potential.

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I

ISO Containers as Building Components

1.1 General background

The introduction of standardized shipping containers in the middile of the twentieth century into the transportation system increased world economic growth. However, this revolution also brought unlikely consequences due to trade imbalances in many countries troughout the world. Usually countries are divided into export-based or import-based economies. The trade industry can be modelled as a linear economy where goods move from export-oriented countries to import-oriented ones. The core of the transportation system can be individuated in shipping containers. This system has created a double dilemma: while it is too expensive to retreive empty containers, leaving them in depots occupies a large amount of space and requires a great deal of effort for their repositioning. The surplus of containers worldwide has drawn attention of designers focused on minimizing resource extraction. Moreover designers found in containers a suitable method of construction: they are modular in shape, structurally strong and widely avilable.

The history of transportation system is divided by the introduction of intermodal containers. In 1956 Malcolm P. McLean, a trucking entrepreneur from North Carolina, had the idea that a metal frame could be lifted by a crane and put into a vessel, reducing time of intermodal exchange of goods. The "ideal-X", was the first ship to be delivered with goods collected into metal boxes rather than in bulk cargo. This could potentially reduce loading and unloading time and therefore trading costs. In April, the ideal-X, filled with fifty eight container-like structures, sailed from the port of Newark, in New Jersey, to Houston. This first experiment was embraced by the whole trading industry promoting the optimization and standardization of what we call now shipping containers: since then these steel boxes have made world smaller and economy bigger *[1]*.
The first trip of the ideal-X marked the birth of freight containers, the core of an intermodal transport system which replaced the traditional bulk cargo, where every item was loaded and unloaded individually *[2]*.

The idea that moved McLean was to collect break bulk cargo into and object which could be hooked, lifted and stucked into different transportation systems. This allowed goods to be trasported by sea, and then rapidly loaded into trails and trucks for continental trade. However, the technology for this intermodal challenge was not available at the ports when McLean experimented the first container trip. With the introduction of containers, slowly all the infrastructure of the transportation system started to change, moving towards the highly automated system we know today.

Shipping containers have changed over time, evolving into standardized ISO cargo-containers of 20 and 40 foot lenght - about 6 and 12 meters.
What is of such fundamental relevance regarding intermodal containers is surely not the object itself: "a soulless steel box held together with welds and rivets, with a wooden floor and two enormous doors at the end" *[1]*. The value of this utilitarian object lies in how it is used, rather than what it is. Shipping containers are highly standardized objects which are enginnered to fit with intermodal constrains. It is a steel box that can be carried by different modes of transport such as railways, roads and maritime shipping to facilitate trade flows.
The revolution introduced by containers into the trading and transportaation system was lately called as Containerisation.
It was the process of modernisation of the transport industry from the worn-out break bulk system to a system using standard sized steel boxes specially designed to carry goods and to easy interchange from ships to trucks and trains *[2]*.

During its early stages, the use of shipping containers became common in docks and railways troughout North America, but it was not yet massive worldwide. The main difficulty was that each region had its own shipping containers, with different sizes and properties. Therefore the real problem was the diversity of containers in the world which led to difficulties in the development of intermodal automation *[1]*.
The main step of the actual development was the engineering process that led to standardisation. It is easy to imagine how difficult was for engineers and authorities to get consensus about hich would be the best size for shipping containers. Large ones where hard to fill for small companies, and small ones required too much effort in handling *[41]*.

The standardisation process slowly converged in 1961, when 10-20-30-40-foot boxes were declared to be the only standard containers. A truck equipped to handle a 40-foot container could equally pick up two 20-foot or four 10-footers.
The key to automation was the existence of a standardized product. This process made possible that costs of freight cargo decreased radically. At the very beginning, containers were returned across the ocean empty, and that cost had to be reflected in the rates of shipping freight *[1]*.
To reduce freight costs, transportation companies needed to send more containers to the sea, and therefore requirements of space became evident. This was true not only for a new kind of ships but even for docks, depots and cranes.
Containerisation and standardisation were fundamental steps of Modernisation as whole *[2]*.

Slowly, with the development of technologies and the reduction of manufacturing charges, costs for massive production of shipping containers dropped drastically. That was the point when retrieval of containers was no longer required by export-based countries, leading to the actual container repositioning issue.

1.2 Standardisation

Slowly companies agreed on the best dimensions of each containers according to their necessities. Than they agreed that each container should be able to carry the weight of five fully loaded containers above, with the weight to be carried on the container posts, rather than walls. All containers were then designed to be lifted by spreader bars or hooks engaging the corners *[1]*.
Those decisions gave engineers the basic criteria to use for providing standard requirements of new shipping containers.

The International Standard Organization developed a series of pubblications which classifies intermodal freight shipping containers:

- ISO 830 - Freight containers: Vocabulary;
- ISO 668 - Series 1 freight containers: classification, dimensions and ratings;
- ISO 1496 - Series freight containers: specification and testing;
- ISO 6346 - Ccoding, identification and marking of intermodal containers;
- ISO 1161 - Corner Fittings Specification;
- ISO 874 - Series 1 freight containers: handling and securing.

A freight container is defined by ISO 668 as “an article of transport equipment of a permanent character and accordingly strong enough to be suitable for repeated use […] fitted with devices permitting its ready handling, particularly its transfer from one mode of transport to another” .
The best world that represents the complex structure behind what can appear as a simple steel-box is “system”.
In fact, containers are highly standardized objects made by a combination of elements forming a complex unitary whole. The strenght of containers lies in the arithmetic relationship of its parts *[2]*.

Containers are usually made of weathering steel, Cor-ten steel, were wall and roof panels are usually 2mm thick. The floor base is generally of plywood timber, supported by steel joists.
Follows a table of ISO dimensional requirements for general purpose freight container (Dry Container).

The most important terms used in ISO standards are: Payload (P) which is the maximum permitted mass in a container. Rating value (R) defined as “the gross mass of a container which is both the maximum mass for operation and the minimum mass for testing”, and Tare mass (T) which is the mass of an empty container [ISO 830]. In particular, Payload (P) is the difference between Rating (R) and Tare values (T). *[P = R - T]*

Container	**External dimensions**			**Internal dimensions**			**Volume**	**Empty weight**	**Net load**
	Lenght	*Width*	*Height*	*Lenght*	*Width*	*Height*			
20-foot	6,096 m	2,438 m	2,591 m	5,758 m	2,352 m	2,385 m	33,1 m^3	2 200 kg	28 200 kg
40-foot	12,192 m	2,438 m	2,591 m	12,032 m	2,352 m	2,385 m	67,5 m^3	3 800 kg	26 600 kg
40’ high cube	12,192 m	2,438 m	2,896 m	12,00 m	2,311 m	2,650 m	75,3 m^3	3 900 kg	26 580 kg

FIGURE 1.1 - ISO requirements for freight containers

From the comparison of dimensional standards of shipping containers, it is evident that high cubes are the only suitable container-kind for building purposes due to their internal height.
Moreover in terms of empty weight, 20-foot weights 2 200 kg while 40-foot 3 800 kg. This represents an increment of 72,7% of mass cosidering that a 40’ corresponds to twice over the space. Nevertheless the maximum load, also known as Payload (P) of a 40’ is 26 600 kg which corresponds to a decline of 5,67 % of a 20’ load capacity.

In the cargo-trade industry is widely used a unit of measurement defined as T.E.U. (Twenty-foot Equivalent Unit). This allows to express the cargo capacity of vessels, trains or trucks in relation to the volume of a 20-foot ISO container. It is evident that a TEU is not a measure of mass itself, since containers can be partially loaded, but some conclusions can be directly drawn about the maximum mass that a TEU can represent *[41]* : 1 TEU is equivalent to approximately 26 000 kg.

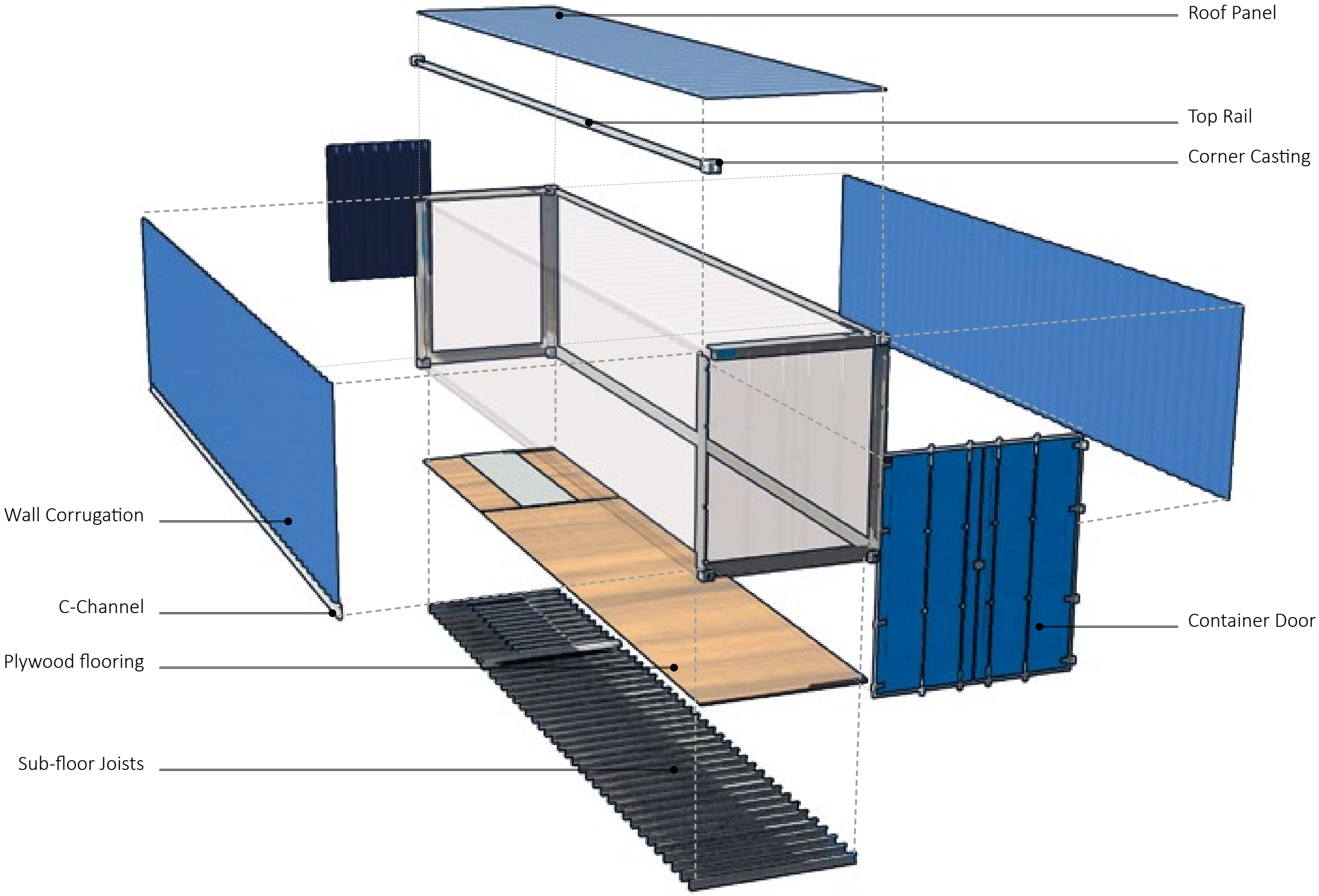


FIGURE 1.2 - Container make-up

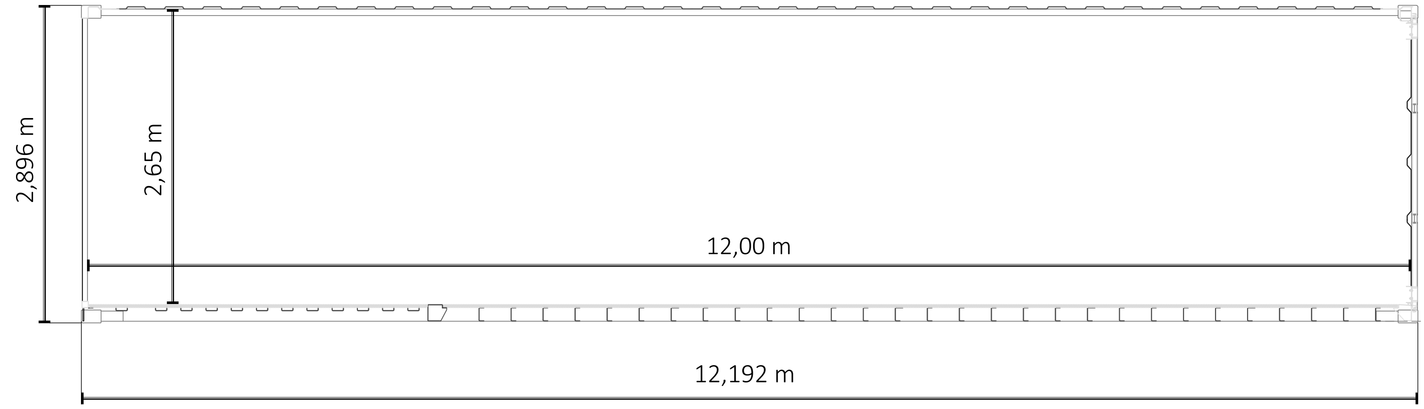


FIGURE 1.3 - 40’ high cube longitudinal section

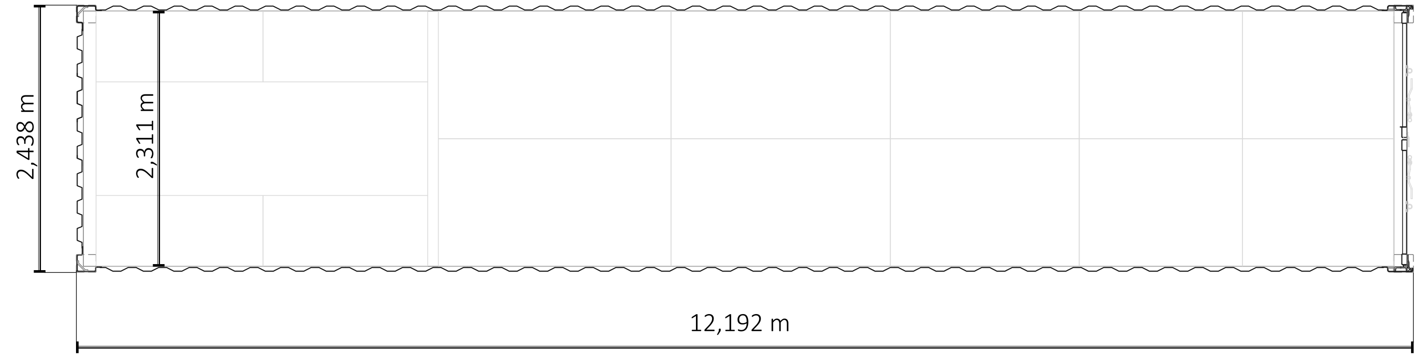


FIGURE 1.4 - 40’ high cube plan

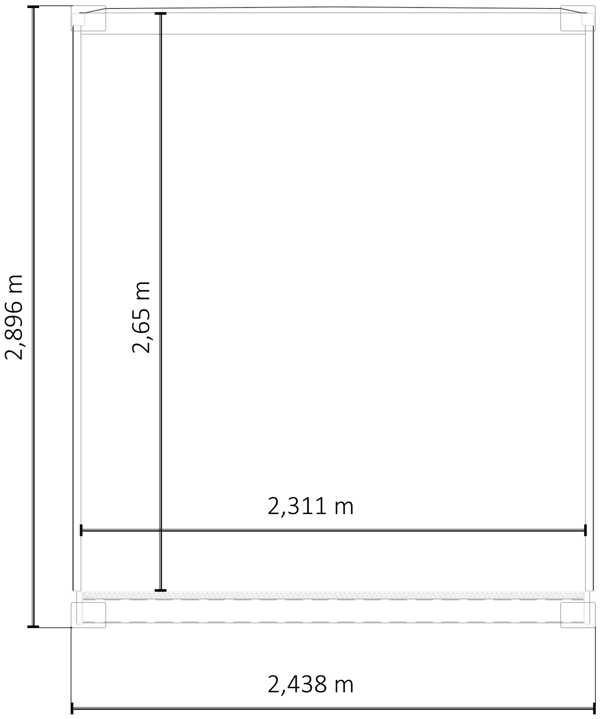


FIGURE 1.5 - 40’ high cube transversal section

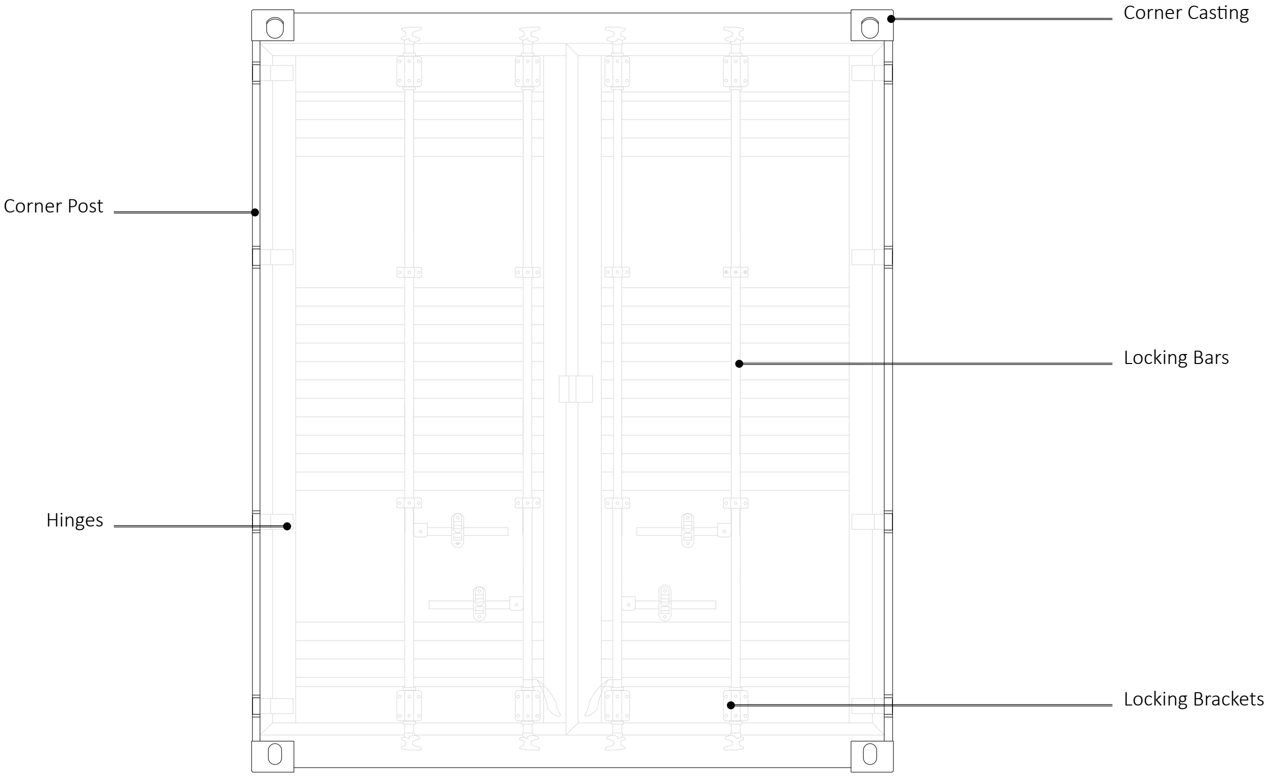


FIGURE 1.6 - 40’ high cube glossary - Rear End

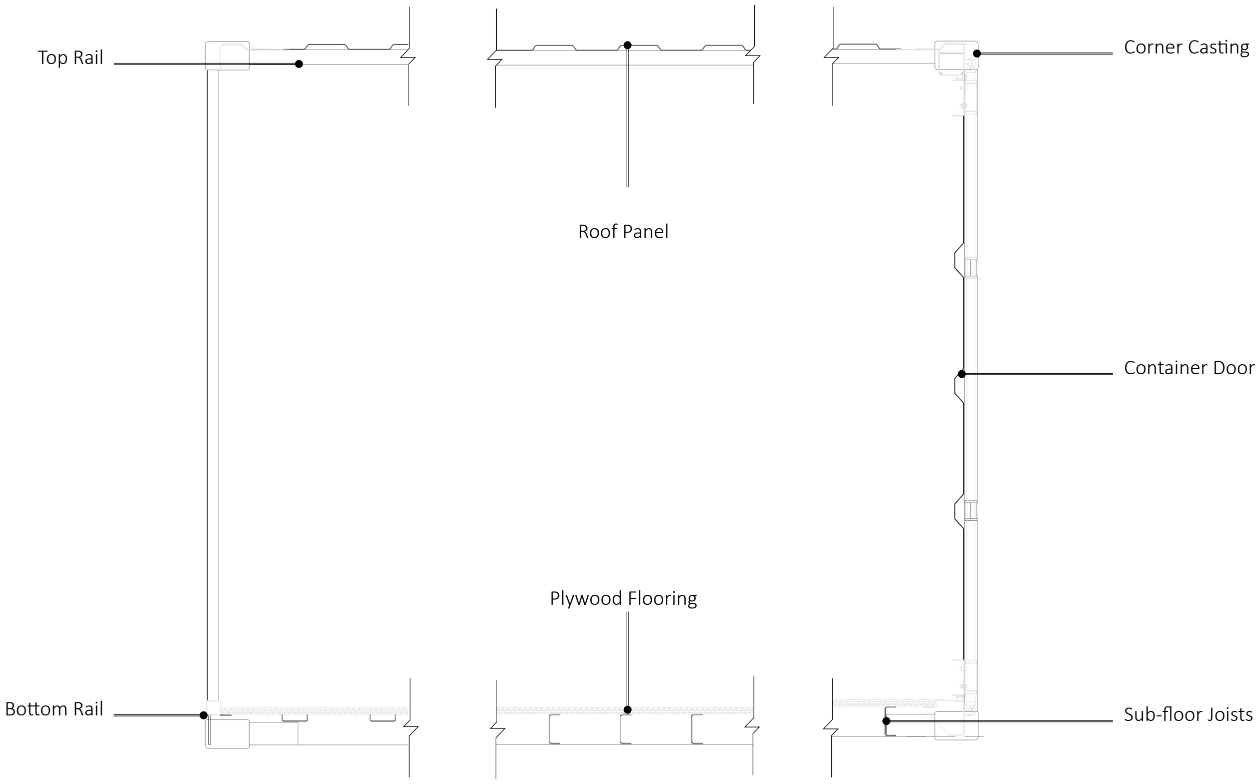


FIGURE 1.7 - 40’ high cube glossary - Longitudinal section

1.3 Trade imbalances

In economics, the balance of trade is the difference between the monetary value of import-export in an economy during a certain period of time [O'Sullivan, Sheffrin (2006)]. This balance can be positive or negative, depending on trade surplus or deficit. World trade is generally unbalaced and movements of goods of the northern hemisphere, compared to southern countries, are overwhelmingly high.
According to the 2008 United Nations report "since 1990, container trade in TEUs is estimated to have increased five times, which is equivalent to an average annual growth of 9,8%". This means that actual empty container accumulation, with the present growth rate, is likely to be much more piercing in the future. Each year about 2 to 2,5 milion TEUs of containers are manufactured. The great majotiy of them in China, taking advantage of its export surplus. China accounts for more than 90% of the global production of containers which is the outcome of several factors, mainly its export-oriented economy and low labour costs *[3]*.

Containers are defined within the trading system as both transport and production unit. They can be moved as an export, import or repositioning flow. Once a container has been unloaded, it has to be moved empty, back to its origin, because cargo cannot be found for the next destination. This collateral transport stage is almost as costly as moving a fully loaded container.
Empty container repositioning is one of the long-standing and ongoing issues in containerized maritime trade. This problem is underlined by the fact that about 2,5 milion TEU of containers are being stored empty, which is also about the same amount of newly manufactured containers, waiting for their handling. Empties account for about 10% of existing container units and 20,5% of global port handling *[3]*.

Trade imbalances are probably the most important cause of accumulation of empty containers. Import-oriented regions will systematically face an accumulation of empties.
Repositioning costs are another source of container accumulation. They include a combination of inland and international transport costs.
The case of United States is particularly eloquent. For 100 containers unloaded, half will be repositioned empty to fulfill an export demand. Of the 50 that remain, most return empty to port terminals, awaiting for export cargo to become available. Only 5 among them will be actually loaded with export cargo shortly after *[3]*.

As reported by ShippingWatch journal, every year Maersk Line, which has the 16% of the global container market, has to spend around 1 billion dollars on managing empty containers.
A solution for the problem does not seem to be around the corner ,even though the considerable amount of research on the subject.

1.4 Structural behaviour

As defined previously, containers are a complex system rather than a simple object. Each element contributes to the overall stability and functionality of the system in order to guarantee the structural requirements of ISO standards.

When any single element is removed, the structural integrity of a container decreases. Therefore, for each modification produced to the original structure, it fundamental to restore its structural properties by strenghtening the container.
Currently, guidelines for safely using shipping containers for building applications do not exist. Shipping container's structural integrity, modification properties, foundation limits, building code regulations, and reinforcing limits are mostly unknown *[4]*.

Firstly it is important to note that the most effective way to use shipping containers as building components is to design assemblies consistent with their load bearing capacity. Containers are engineered to be stucked upon their corner castings. Loads are transferred trough the posts to the corner castings. Therefore it is evident that each operation that leads to a mismatch of corner castings has to be corrected with additional structural material.

ISO 1496 contains five parts which describe a series of structural tests that any ISO container must pass in order to be in operation. The required tests are the only source of information regarding container's structural strength characteristics. Unfortunately, manufacturers' test data is not available. Without container manufacturers disclosing their test data, it is impossible to verify an ISO shipping container's structural strength consistently and accurately. Nevertheless container's failure is a rare occurence indeed *[4]*.

The procedure of construction for a shipping container building is strictly related to the inherent properties of containers themselves.
Foundations can be made with the same technology of traditional structures. Ground floor's corner castings, which carry all structural loads, have to be supported by foundations. It is also important to note that the four lower corner castings are the only elements of a container which are directly in contact with the ground.
A common connection method attaches a container to an appropriately designed steel base plate. Anchor bolts are welded to the underside of the plate and cast into the concrete foundations while it is still wet. Once the concrete is hardened, the base plate is anchored into the foundations. Connections between containers, and foundations, can be made in several ways.
A common procedure consists in the use of the same technology from intermodal transportation. Connection devices lock the containers together by attaching through the top or bottom openings on the corner fittings. Twist locks are connection devices securing two containers at the corner fittings during stacking, transporting, or lifting situations. Twist locks are devices used to secure containers vertically *[4]*.

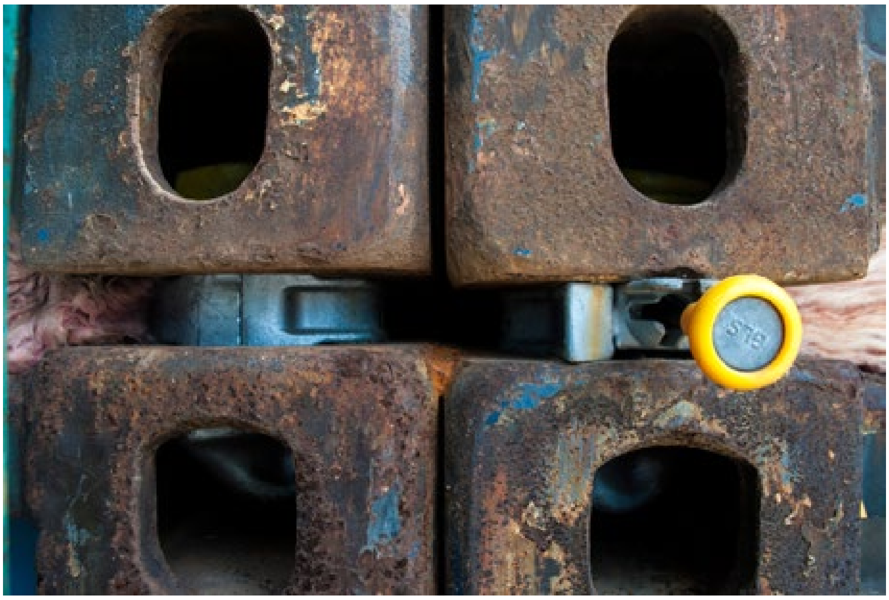


FIGURE 1.8 - Twistlock connection of corner castings - Drivelines Studios

A reinforcement procedure has to follow any modification of the container structure. When some lateral bracing disappears, so does a significant amount of its ability to carry vertical loads. *Figure 1.14* briefly shows the impact of main modifications on the original structure of a container *[K.A.Giriunas - 2012].* This is the main dilemma when designing a container structure. One the one hand, openings must be provided in order to upgrade the empty, dark unventilated nature of containers. On the other hand, cutting walls means diminishing the strenght of the system as a whole. When this happens, the container itself does not have real strenght after being cut and additional steel must be welded to the structure in order to restore its load bearing capacity. Usually reinforcements are steel hollow sections, which dimensions are related to the entity of container loads. Steel hollow sections are then welded to the edge of the container opening.
Structural performances of containers and reinforcement's requirements are not the aim of this study. Therefore, in order to design a single familiy house with shipping containers as core structure, it will be used practical information from the experience in a residential building discussed in the next chapter: Drivelines Studios.

FIGURE 1.9 - Cut and reiforcements for window opening - Drivelines Studios

FIGURE 1.10 - Reinforcements for window's openings - Drivelines Studios

There are three main approaches to shipping container construction. On the one hand, containers can be prefabricated in factory. This method consists in manufacturing modifications in factory and transport modified containers directly to the construction site. Then containers have to be stacked and joined together.
On the other hand, containers can be modified directly on the construction site. They can be placed and then modified when stacked and secured together. Another option is to modify each container individually on site and then place and secure them.

FIGURE 1.11 - On site container manufacturing - Drivelines Studios

The structural strength for 20-foot and 40-foot containers from ISO 1496-1 is resumed in the following table, where

R: rating, maximum wheight of a fully loaded container. For general purpose 20’ and 40’ container is assumed as 30480 kg
T: tare mass, mass of an empty container. 2255 kg for 20’ and 3920 kg for 40’
P: payload, maximum permitted mass in a container. Is the difference between rating (R) and tare values (T)

Although manufacturers’ testing data is not available, information for minimum requirements of load bearing capacity can be desumed from ISO 1496-1 and used as guideline for structural purposes.

Test type	(1) Stacking	(3) Lifting from Top Corner Bottom	(2) Lifting from Top Corner Fittings	(4) Longitudinal Restraint	(5) Front & Door strenght	(6) Side Wall strenght	(8) Floor strenght	(9) Transverse Rigidity	(7) Roof strenght	(10) Longitudinal Rigidity	(11) Lifting from Fork Pocket
Internal Load	1,8 R- T	2 R- T	2R- T	2 R	-	-	-	-	-	-	1,6 R - T
Testing Load	96 000 kg/post	2 R- T	-	-	0,4 P	0,6 P	0,6 P	300 kg	7 260 kg	15 240 kg	-

Schemes of loading tests, which any container has to pass before being shipped, follows.

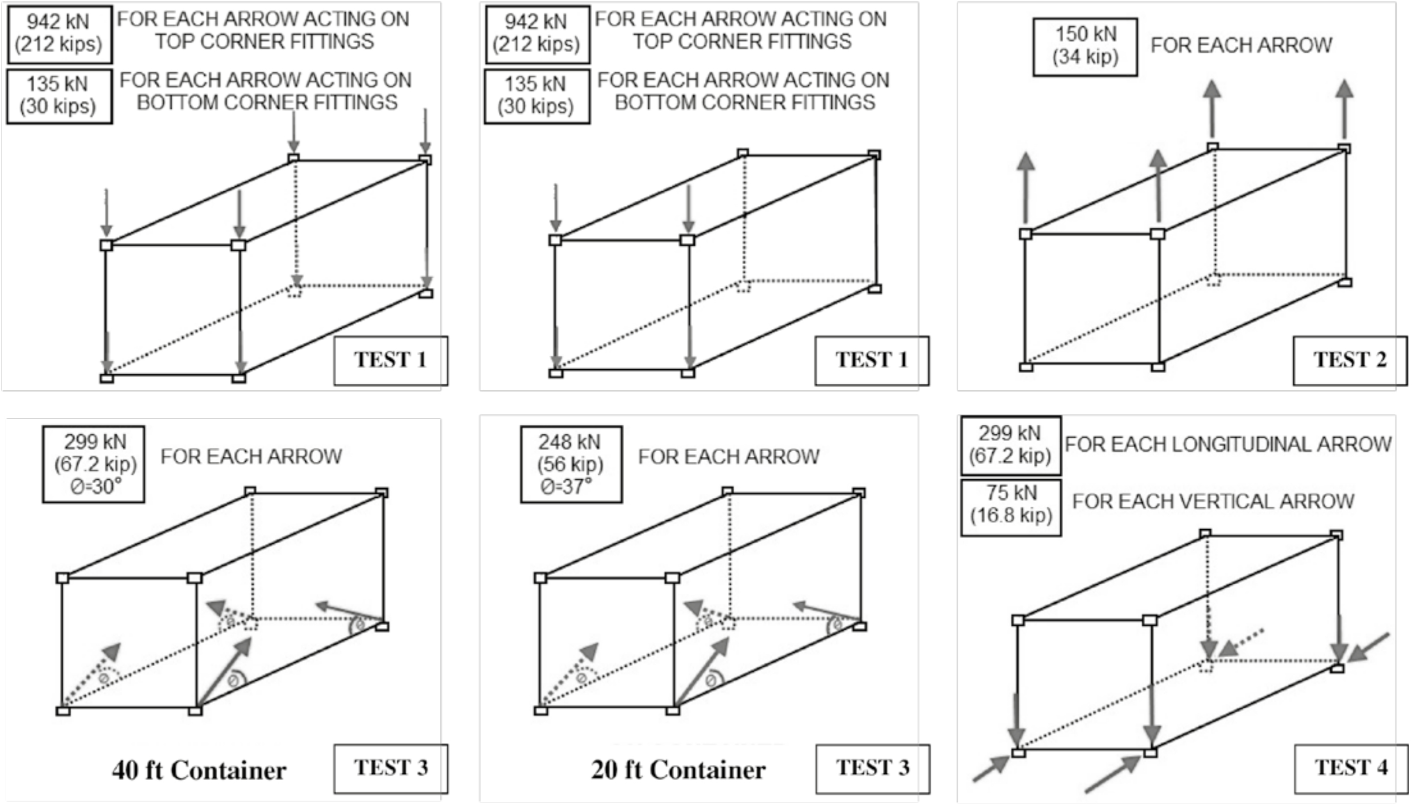


FIGURE 1.12 - Structural tests for ISO shipping containers from ISO 1496-1
- source K.A.Giriunas (2012) - [105]

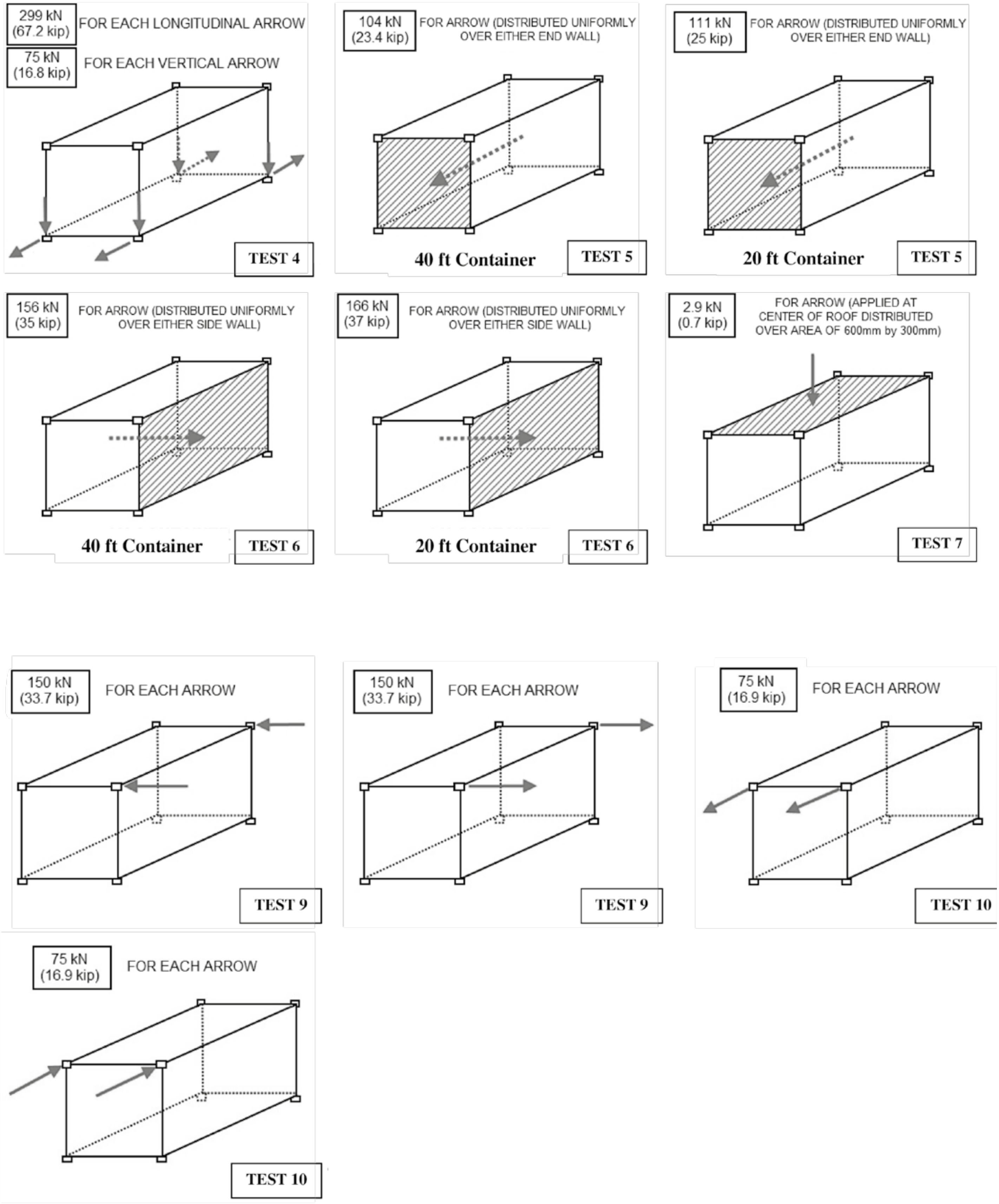


FIGURE 1.13 - Structural tests for ISO shipping containers from ISO 1496-1

- source K.A.Giriunas (2012) - [105]

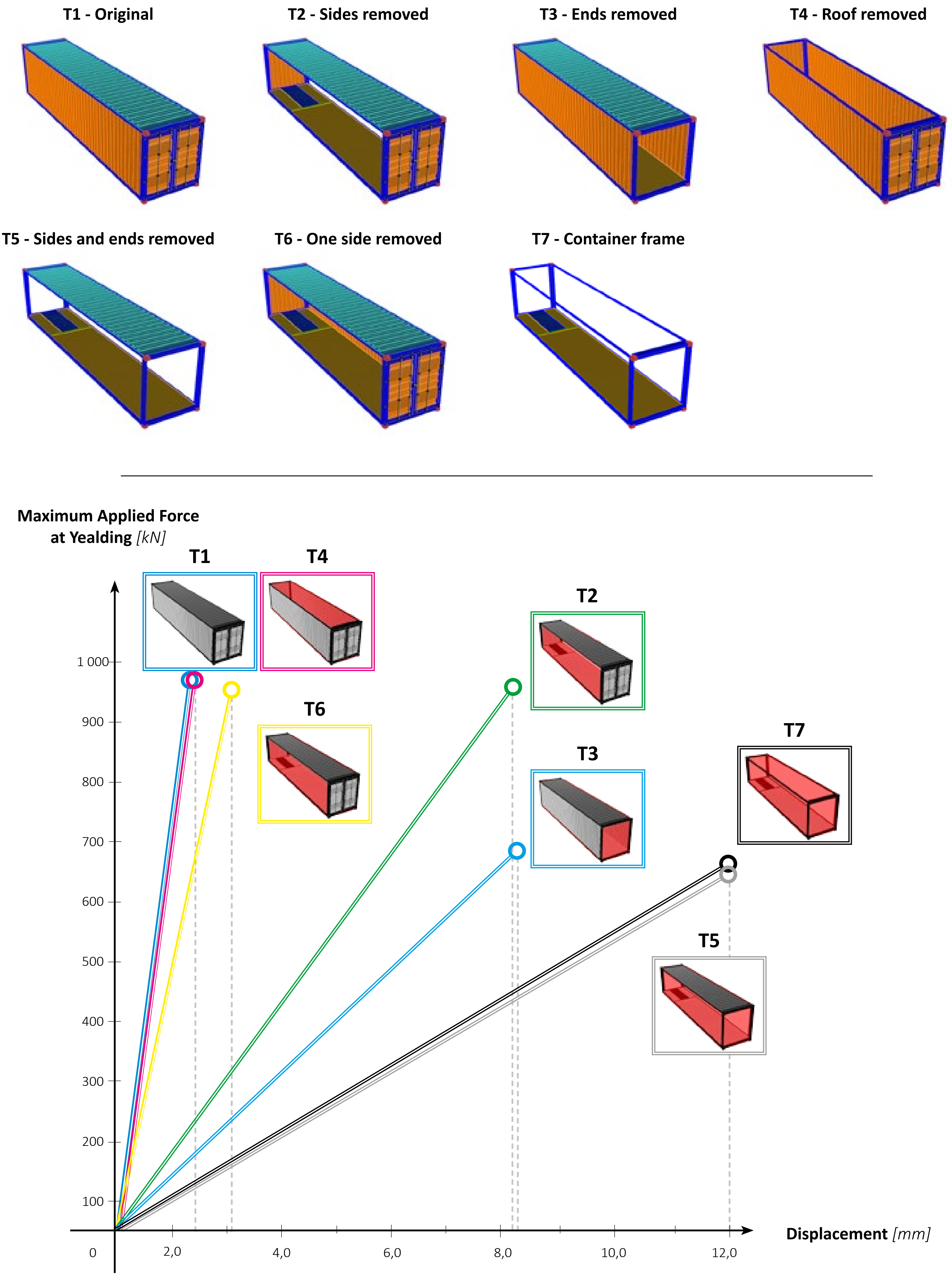


FIGURE 1.14 - Structural behaviour of modified containers

- source K.A.Giriunas (2012) - [105]

1.5 Container architecture: Drivelines Studios

It is not clearly defined when containers have been used for building purposes for the first time. The reuse of freight containers has rised almost naturally from their gradual accumulation in depots around the world. Container architecture might be preliminarly defined as "all of those projects that use intermodal containers as an instrument of construction" *[2]*.
Containers are designed to protect goods from weather conditions and carry them safely and rapidly. Dwellings have many different functions and one among them is exactly to protect people from external weather conditions. This can be seen as the direct link which caught the attention of designers. Moreover containers are attractive for architects because they are: prefabricated, compact, sturdy, weather-resistant, and potentially mobile.

"Container Architecture" by Jure Kotnik (2009) can be seen as the main source of examples of the use of shipping containers. Follows an overview of some high cube-container dwellings around the world, organized by number of modules:

Drivelines Studios by ***LOT-EK.*** 2017 Johannesburg. **120** Containers 40'

Container City I-II-III by ***Urban Space Management***. 2001-2005 London. **73** Containers 40'

31 Shipping Container Home by ***ZieglerBuild***. Birsbane, Australia. **31** Containers 40'

Carroll House by ***LOT-EK***. 2016 New York. **21** Containers 40'

Caterpillar House by ***Sebastian Irarrazaval***. Santiago de Chile. **12** Containers 20'-40'

Container House by ***Adam Kalkin***. 2003 Blue Hill (Maine). **12** Containers 40'

Old Lady House by ***Adam Kalkin***. Califon (NJ). **9** Containers 40'

Maison Container by Patrik Partouche. 2010, Lille. **8** Containers 40'

Casa Incubo by ***Maria Jose Trejos***. Costa Rica . **8** Container 40'

Green Frame House by ***Studio Astori De Ponti***. **6** Contianer

Casa El Tiamblo by ***James & Mau Arquitectura***. Spain. **4** Containers 40'

Eco-Friendly Crossbox House by ***CG Architects***. **4** Containers 40'

Week End House 2+ by ***Jure Kotnik Arhitekt***. Trebnie, Slovenia. **4** Container designed for housing

Six Oaks Residence by ***Modulus***. Santa Cruz (California). **3,5** Containers 40'

Containerlove by ***LHVH Architekten***. Eifel (Germany). **3** Containers 40'

WFH by ***Arcgency***. 2012 China. **3** Containers 40'

Containers of Hope by ***Benjamin Garcia Saxe***. 2011 San Jose, Costa Rica. **2** Containers 40'

Shipping CO House by S***tudio H:T*** . 2010 Nederland (Colorado) . **2** Containers 40'

Upcyce House by ***Lendager Arkitekter***. 2013 Nyborg (Denmark). **2** Containers 40'

Co House by ***Leger Wanaselja Architects***. Richmond, California. **2** Container

Two-Tree House by ***Golany Architects***. **1** Container

Nomad Living by S***tudio ArTe***. 2013 Algarve, Portugal .**1** Container 40'

Container Guest Houses by ***Poteet Architects***. **1** Container 40'

Usually dwellings made up from the reuse of shipping containers require 2 or 3 units in order to design a suitable living space. This underlines that container architecture can't be the only solution to the whole empty container repositioning issue. Nevertheless, up to date, have been developed a few examples of high raised buildings. Among them the Drivelines Studios by LOT-EK stands out for the large amount of shipping containers used: 120 in total.

Drivelines Studios is defined by LOT-EK as *"a live-work building with ground floor retail in the Maboneng Precinct in Johannesburg. As a leader in urban regeneration, over the past few years Propertuity has single-handedly transformed the heart of the Maboneng precinct into a vital hub of leisure, cultural and commercial life. Our building introduces also housing in this urban mix.*
The massing - entirely made of upcycled ISO shipping containers - is organized in a V generating a triangular open yard with swimming pool and sundeck. All residential units are studio apartments varying in size between 40 and 60 square meters and include a private outdoor space along the walkways that look into the yard on all floors".

One of the first problems that this study had to face was the fact that the usage of containers in buildings is something relatively new in the building sector. Hence there is a lack of empirical information regarding the environmental impact of intermodal container in the building sector. The Life Cycle Assessment performed in the present thesis was developed with the direct support of empirical information from the Drivelines Studios construction site: time schedules, operations, bills of quantities, details, reinforcements and requirements.

FIGURE 1.15 - Drivelines Studios - Aerial view

- source LOT-EK studio

FIGURE 1.16- Drivelines Studios - Courtyard view
- source LOT-EK studio

FIGURE 1.17 - Drivelines Studios - Walkway view
- source LOT-EK studio

The building is subdivided into units composed by three 40-foot containers each. Every unit presents two apartments.
Despite the great amount of containers used into the building, the subdivision in units enabled the reduction of data within the range of a 6-container dwelling developed in this study.

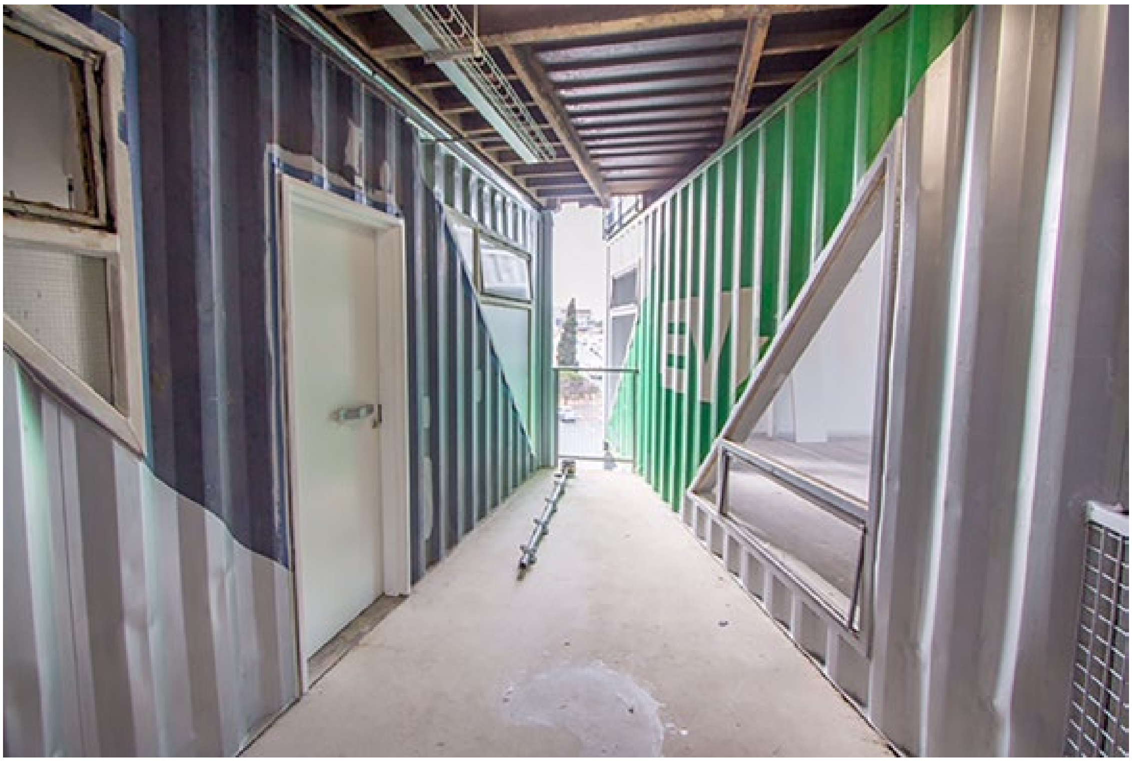


FIGURE 1.18 - Drivelines Studios - Apartments entrance

- source LOT-EK studio

FIGURE 1.19 - Drivelines Studios - Apartment rendering

- source LOT-EK studio

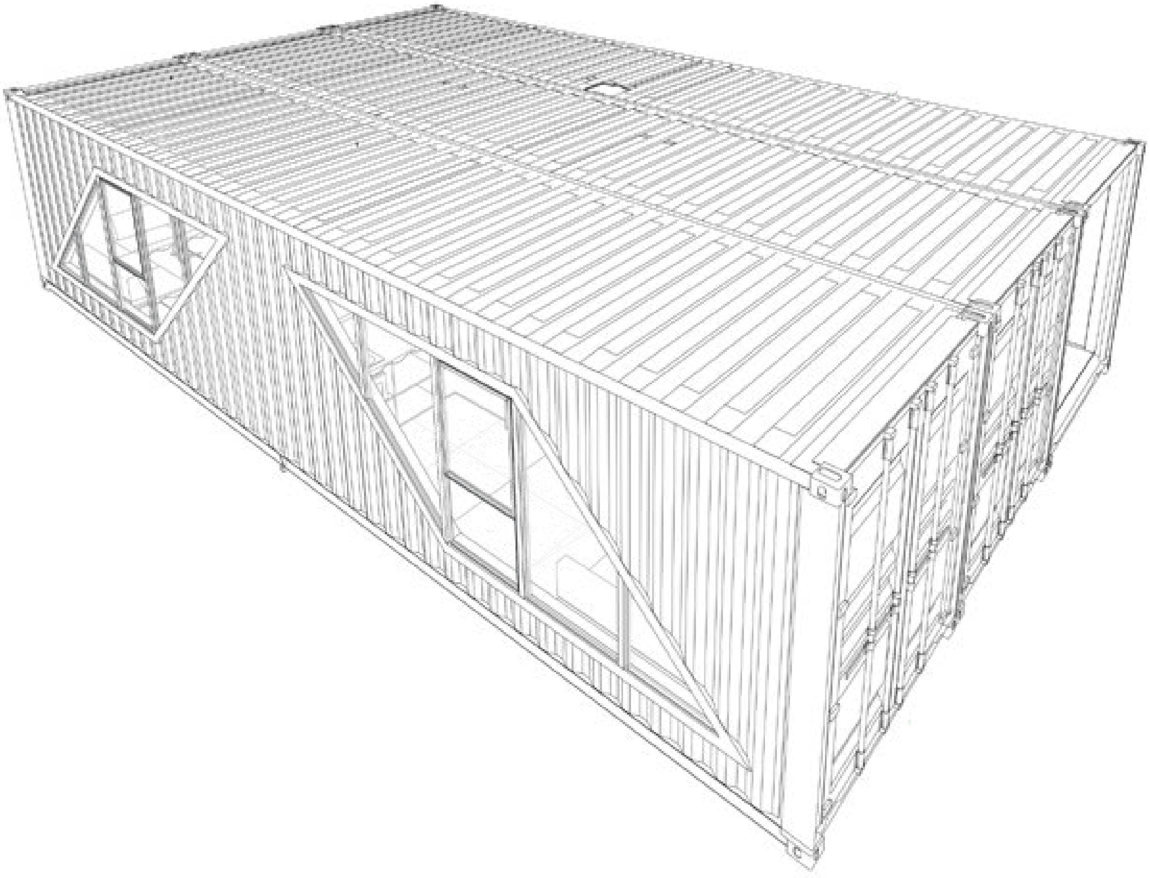


FIGURE 1.20 - Drivelines Studios - Tyipical building unit

- source LOT-EK studio

FIGURE 1.21 - Drivelines Studios - Typical building unit

- source LOT-EK studio

CHAPTER

II

Environmental Assessment

.1 The Role of a Life Cycle Assessment

.2 LCA framework

.3 Impact categories

.4 LCA and ISO containers: literature review

2.1 The Role of a Life Cycle Assessment

Sustainable development has been defined by the World Commission on Environment and Development (1987) as “a development that meets the needs of the present without compromising the ability of future generations to meet their own needs”. Therefore it is clear that sustainability is a broad term covering economic, social and environmental issues.

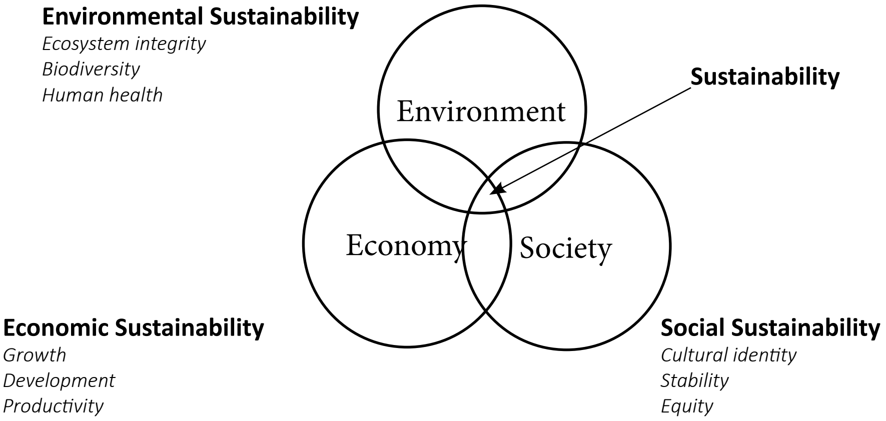


FIGURE 2.1 - Model of sustainable development

Human activities such as construction are having a huge impact on our environment. The building sector is responsible of an average 40% of the waste production for country. The building sector is also responsible for the use of 40% of the total energy consumed worldwide, which in western countries is prevalently related to the building use stage *[14]*.
The awarness of the impact caused by human activities is growing and many instruments to address sustainability have been developed in recent years. Many governments are setting targets to reduce the release of harmful gases (CO2, SOx, NOx) into the atmosphere. Therefore it is important that the building industry adopts the environmental performance as one of its leading principles at the same level of economic and efficiency principles.

Buildings account for one-sixth of the world’s freshwater withdrawals, one-quarter of its wood harverst and two-fifths of its material and energy flows *[Roodman,Lessen. 1995]*. Nearly one-quarter of all ozone-depleting chlorofluorocarbons are emitted by building air conditioners and the processes used to manufacture building materials *[energy Resource Center. 1995]*. Construction and demolition waste in 1997 amounted to the equivalent of 65% of all Municipal Solid Waste in the US *[Franklin Associates, 1999]*.

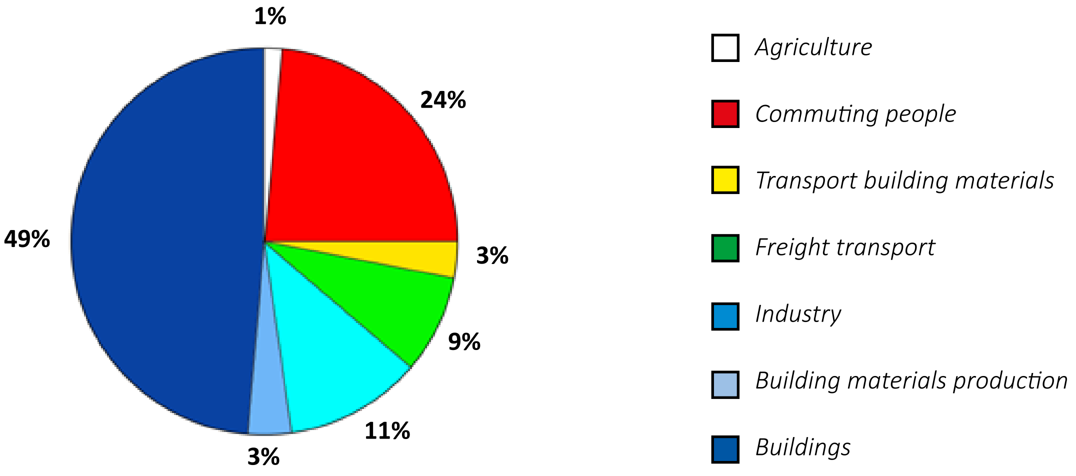


FIGURE 2.2 - Average energy consumption in western countries

The international community effort has come up with standards developed by the International Organization for Standards - ISO. In September 1996 has been published a set of standards called ISO 14000.
Although many practitioners claim their design decisions are sustainable, unless it is carried out an objective quantification of the environmental impacts that a building has on its surroundings, it is nearly impossible to determine their effective sustaibaility.
As the operational impacts of buildings decrease through regulation of newly built and retrofit construction, the impact of materials and construction processes become more important to assess *[14]*.
Furthermore, building's manufacturing processes are less standardized than most of man made activities due to their complexity and their uniqueness. It is evident the necessity to assess the impacts and contributions of a building's life cycle, instead of focusing on the environental properties of just one stage, giving a wider perception of sustainability.

Life Cycle Assessmet - LCA - represents a comprehensive methodology for the analysis of environmental impacts of products, also defined as systems, at all steges of their life cycle, from cradle to grave, and later, including recycling, from cradle to cradle. Therefore the LCA involve the evaluation of environmental impacts of a product (in this case a whole building), by looking at its entire life cycle, from raw materials extraction through disposal, and recycling.
LCA is essential to evaluate how a building's key design systems (materials, structure, walls, roofs, etc) will influence its environmental performance.

2.2 LCA framework

Life Cycle Analysis of a whole building referes to the following phases: extraction of raw materials, transport to factory, manufacture of building materials, transport to site, construction of the building, occupancy, renovation, maintenance, demolition, waste processing, landfilling and recycling-reuse-recovery.

The series of standards ISO 14000 provides principles, framework and methodological standards for conducting LCA studies. These include the four steps of LCA which are: goal and scope definition, inventory analysis, impact assessment and interpretation. This thesis work strictly follows the scheme reported by international standards.

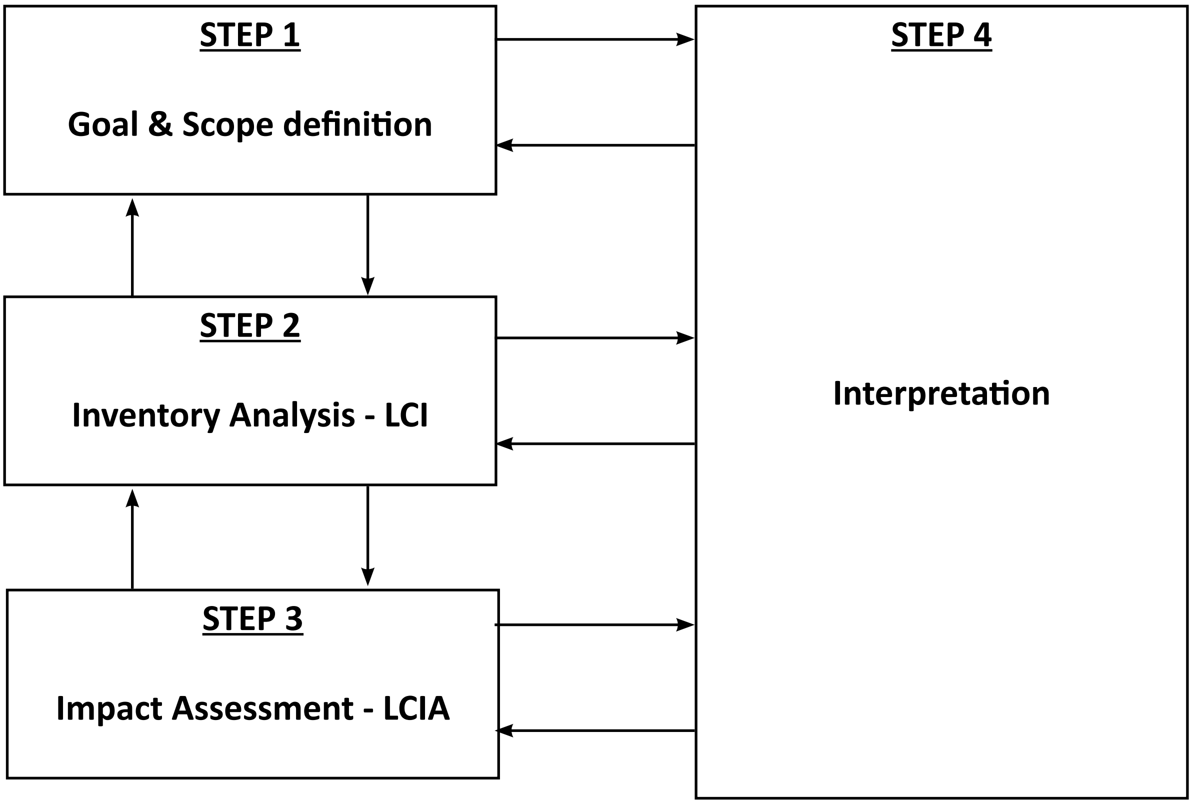


FIGURE 2.3 - Life Cycle Assessment Framework (ISO 14040)

The first stage of an LCA consist in clearly defining and describing the goal of the study and its scope. This phase has to include reasons for carrying out the study as well as the intended application and audience: this will later allow interpretantion and future confrontation of results showed.
This phase also establishes the function of the system, functional unit, system boundaries, data quality, type of impact categories considered and assumptions-limitations. All of these items have to be consistent with the scope and goal of the research. They are partially based on subjective choices.
The functional unit is a mesure of the function of the studied system, representative of its inputs and outputs. This enables a fair comparison between different systems and sub-systems.
System boundaries determine which unit processes are to be included in the LCA study.

The second step, Life Cyle Inventory - LCI, deals with data retrieval from databases, providing emissions related to every unit processes that composes the system. These emissions are connected to the Impact Categories considered in the study.
This phase involves calculations to quantify material and energy inputs and outputs of the building system.
The data collection stage is the most resource consuming part and can affect significantly the results of the entire LCA.
It is possibile to reuse data from other studies, it is yet essential to verify that boundaries and assumptions of the studies are consistent with the LCA.

The third step, Life Cycle Impact Assessment or LCIA, evaluates the impact of the LCI results on each stage of the life cycle. It involves the selection of impact categories, indicators and characterization models.
Impact categories are selected and defined accordingly to the goal and scope. They are expressed in relation to a standard, usually based on the most important emission that causes the effect. All other pollutants and emissions are expressed as an equivaent amount of the reference emissions: for instance Global Warming Potential is caused mainly by CO_2 and therefore expressed in tons of CO_2-equivalent. each ton of Methane (CH_4) corresponds to 84 Kg of CO_2e (equivalent).
Further description of impact categories will be provided in the next paragraph.
International standards provide optional steps which consinst in grouping and sorting impact categories. The last, optional, step is Weighting, which consists in expressing the subjective importance of each impact category providing a unique index.

The aim of the interpretation phase is to evaluate findings and reach conclusions, providing recommendations in accordance with the goal and scope of the study.

For a whole building assessment information steps 2,3 and 4 have to be applied to each stage of the building's life cycle. Standards and literature define each stage with a module in order to clearly identify systems' inputs and outputs *[31]*.

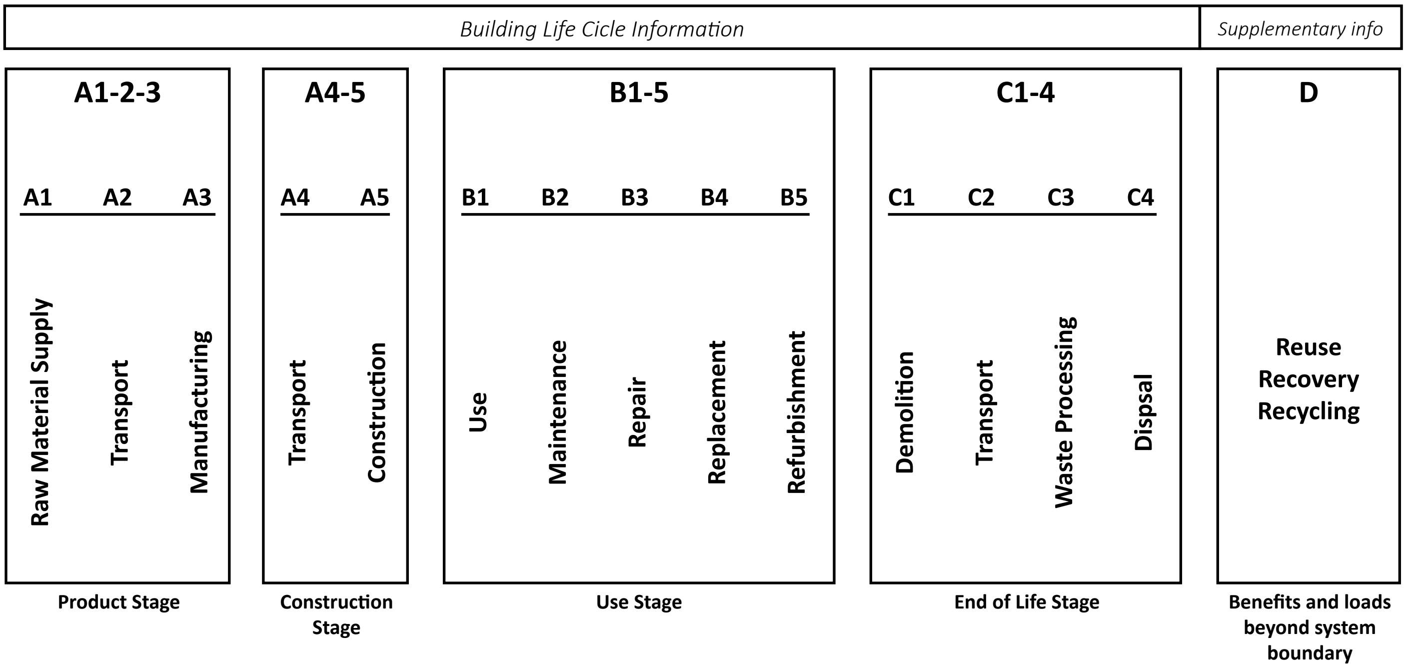


FIGURE 2.4 - Modules of the life cycle stages of a building

- source UNI EN 15978

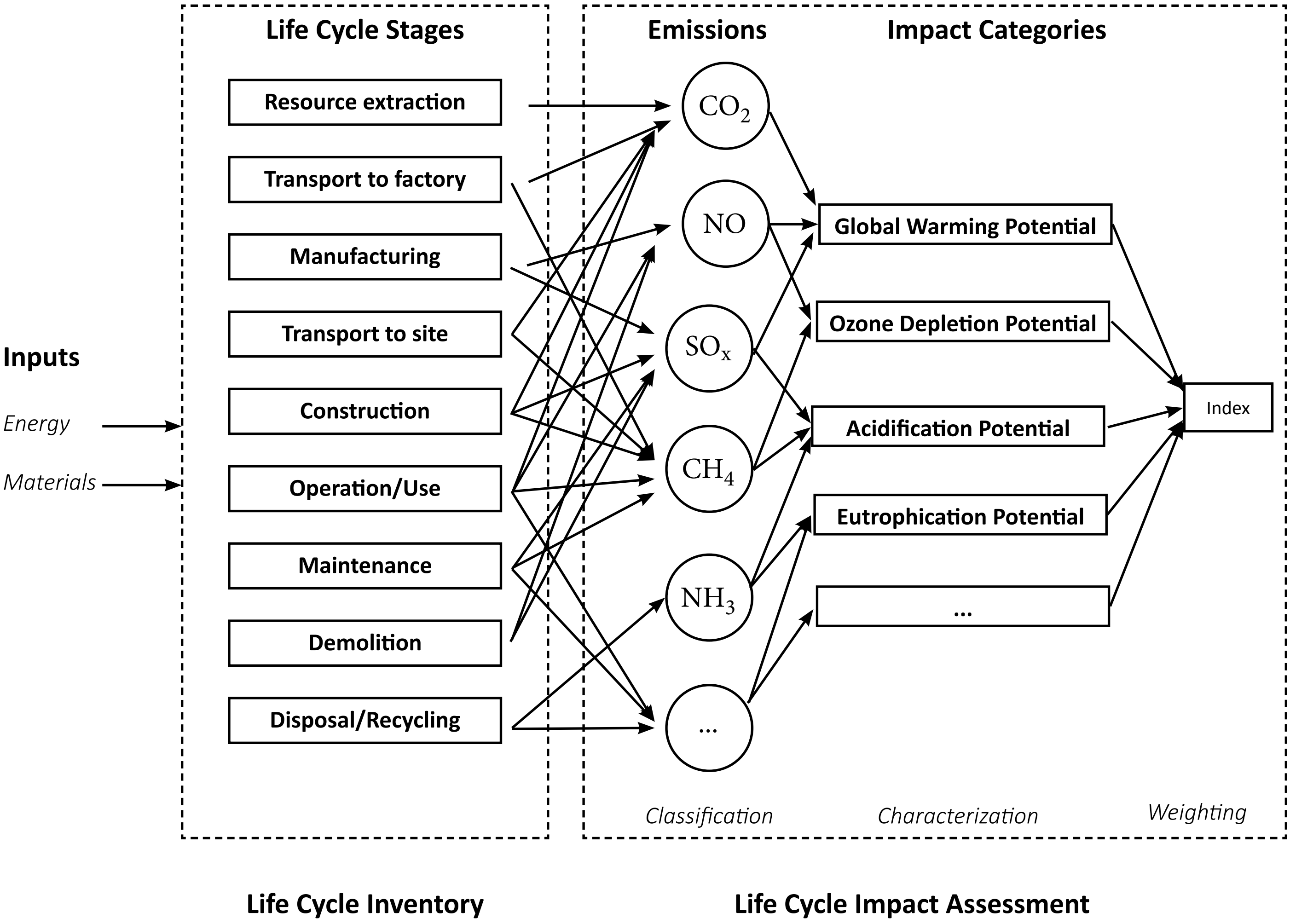


FIGURE 2.5 - Generic LCA model

2.3 Impact Categories

As described in the previous paragraph, the LCIA phase evaluates the significance of environmental impacts based on the LCI results.

The main environmental impacts most commonly cconsidered in a Life Cycle Assessment of a construction product, or a building stage, are:

- Climate Change
- Acidification
- Eutrophication
- Stratospheric Ozone Depletion
- Photochemical Ozone Creation

Other indicators commonly provided in a LCA include:

- Renewable and Non-renewable Primary Energy
- Water Consumption
- Waste for Disposal
- Toxicity to ecosistams and Humans
- Resource Depletion
- Radioactivity

The following Impact Categories have been considered to develop the LCA: Global Warming Potential (GWP), Ozone Depletion Potential (ODP), Acidification Potential (AP) and Eutrophication Potential (EP).
The reason for choosing these impact categories is that in literature they are considered especially important. They have been chosen also for their availability in selected databases.

A detailed description of the impact indicators considered follows.

GLOBAL WARMING POTENTIAL
- GWP -

Also known as Embodied Carbon, Carbon Footprint, Climate Change, Green House Effect, ECO2.
The impact represents an average increase in earth's temperature due to the concentration in the atmosphere of gases (called Green House Gases - GHGs) such as Carbon Dioxide (CO_2), Methane (CH_4), Nitrous Oxide (N_2O),Hydrofluorocarbons (HFC), and others. Short-wave radiation from the sun comes into contact with earth's surface and is partially reflected back. GHGs absorb this reflected radiation in the troposphere and emit back in all directions, including backwards to the earth's surface. Thus the amount of radiation our planet is able to give away to the outer space is reduced, and the mean temperature of the atmospheric envelop's layers tends to increase.

For other gases than CO_2, the impact category of Global Waring Potential (GWP) is calculated in carbon dioxides equivalents (kg CO_2-eq). This means that the GWP of every emission is expressed in relation to CO_2 . A period of 100 years is typical for GWP databases and is consistent with the building's LCA.
Energy production is the main contributor of CO_2 emissions. Therefore, based on *figure 2.2* the building sector is the most significant contributor to total GHGs emissions with estimates between 38% and 60%. Government targets througout the world are to reduce GHG emissions by 34% in 2020 and 80% in 2050 *[Climate Change Act]*. These goals are unachivable without a significant reduction in the carbon performance of new and existing buildings.

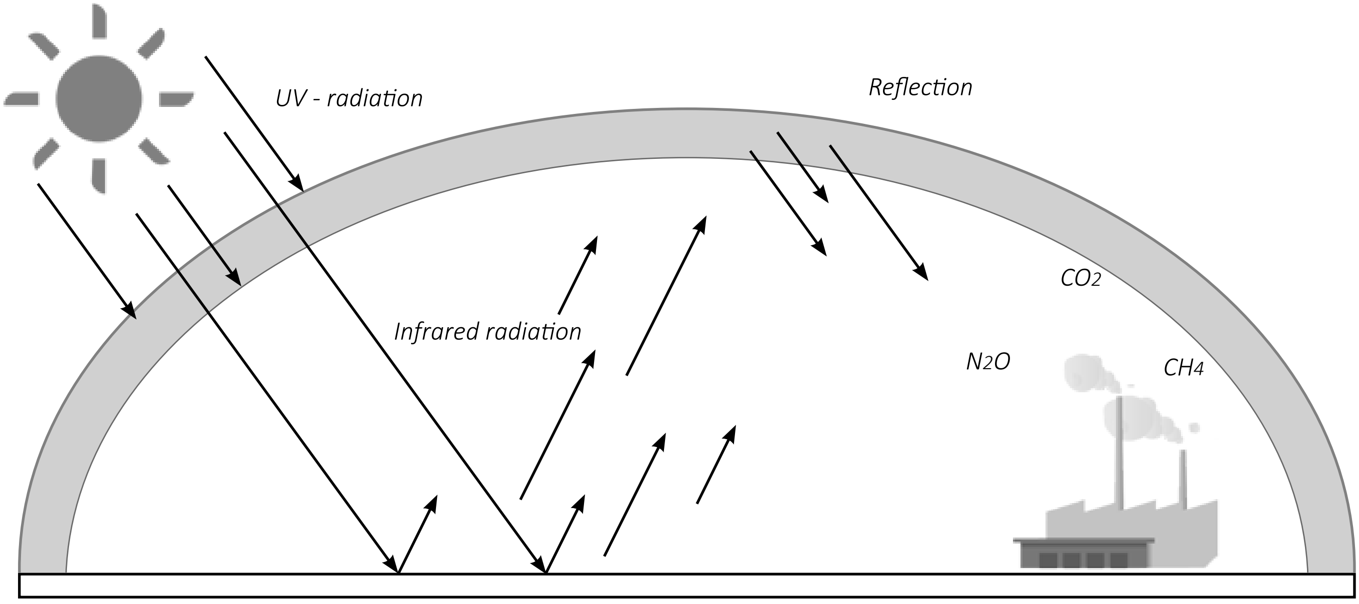


FIGURE 2.6 - Main process of the Green House Gas effect

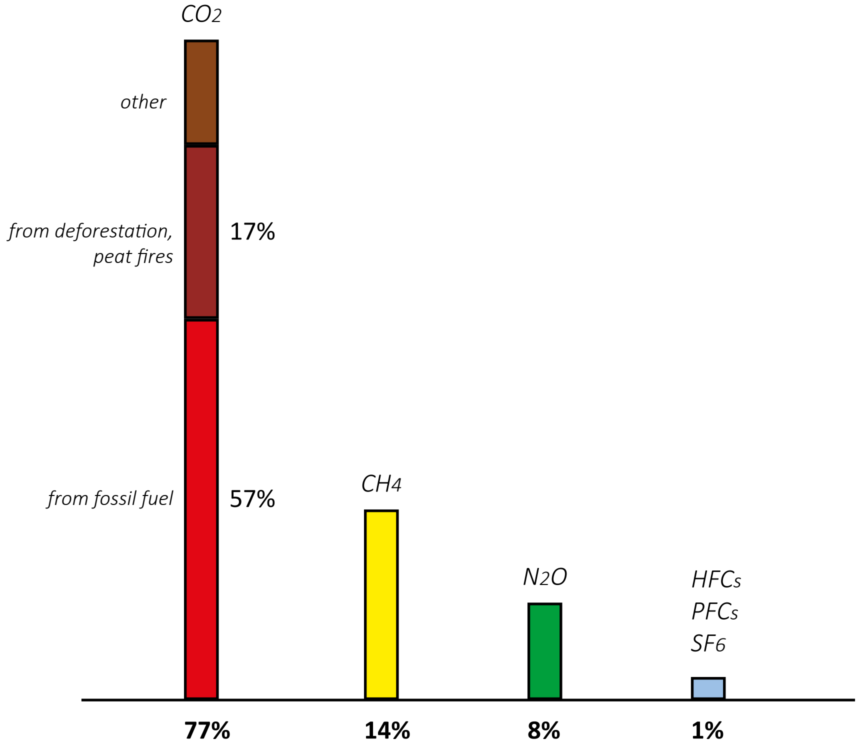


FIGURE 2.7 - GHGs distribution

OZONE DEPLETION POTENTIAL
- ODP -

Also known as Stratospheric Ozone Depltion Potential, Ozone Degradation Potential, Depletion of the Ozone Layer, Ozone Hole Effect.
The athmospherical ozone (O_3) absorbs a large portion of the UV sun rays, preventing the ultraviolet light to pierce the earth's atmosphere, therefore protecting from carcinogenic UVB rays. Depending on climatic conditions, the action of Chloroflurocarbons compounds (CFC) and other gases breakdown the ozone layer, thus reducing the protective effect on the earth's surface.
The ODP is expressed in therms of equivalent mass of Trichlorofluoromethane (kg CFC_{11}-eq).
Common sources of ozone depleting gases are refrigerants and blowing agents. In the building material's manufacturing industry, steps have been taken to replace ozone depletin gases with non-depleting ones such as Hydroflurocarbons (HFCs). These, however, have quite often an high impact on GWP, showing the importance of considering multiple impacts to address the sustainability of a system, product or process.

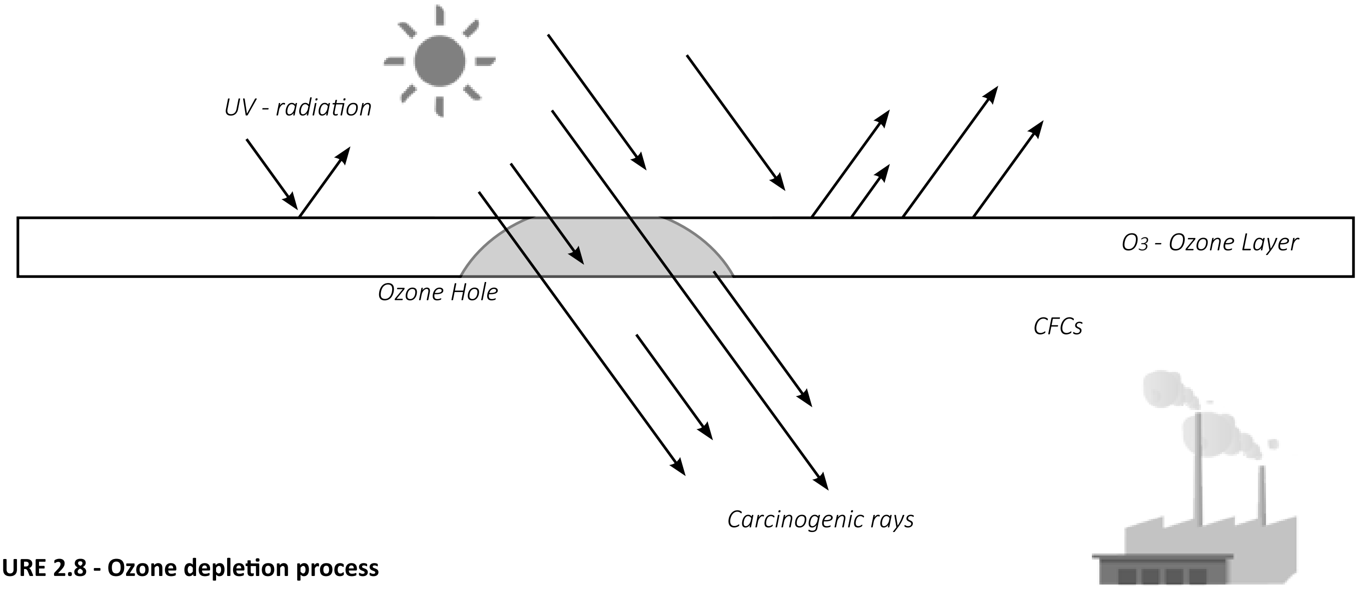


FIGURE 2.8 - Ozone depletion process

ACIDIFICATION POTENTIAL - AP

Also known as Acidification of Soil and Water, Acidifying Pollution, Acid Rain.
It comprises processes that increase the acidity, hydrogen ion concentration (H^+), of water, air and soil systems. The acidification of soils occurs through the transformation of air pollutants into acids. This leads to a decrease in the pH value of rainwater and fog, producing and effect called "acid rain", that causes damage to ecosystems even at considerable distances from the original source of the emission.
The main gases that cause AP are Nitrogen Oxides (NO_x) and Sulphur Oxides (SO_x). Ammonia and Hydrogen Fluoride are also contributors of acid rains although to a lesser extent.
NO_x and SO_x are commonly emitted as result of combustion of fossil fuels, which have a great relevance in the building sector.

The resulting AP factors are expressed in Hydrogen mole or Sulphur Dioxide equivalent deposition per kg of emission (kg SO_2-eq).

EUTROPHICATION POTENTIAL - EP

Also known as Over Fertilization, Nutrification Potential.
Eutrophic means well-nourishes, thus referring to natural or artificial addition of nutrients to the environment, especially bodies of water. Nitrates and Phosphates are essential for life, but increased concentrations in water bodies can promote an excessive growth of algae. As algae die and decompose, high levels of organic matter deplete the available oxigen, causing death of other organisms. This leads to an overall reduction in biodiversity of these environments and, as a secondary effect, on harm of non-aquatic animals and humans which rely on these ecosystems.

Eutrophication is measured using the reference unit of kg Nitrogen or Phospate equivalents (kg $[PO_4]_3$ -eq).

2.4 LCA and ISO containers: literature review

Before considering which conclusions have been drawn from the state of the art of current literature, it is worthwhile considering the diversity of approaches available. Almost all LCA's are done in accordance with ISO14040 standards, in which are stated the key elements to be addresses in the study, even though they do not prescribe how comparisons should be undertaken.

A fundamental requirement of the LCA standard is the definition of a functional unit which serves as a base of comparison. As described in previously, the functional unit defines how results will be reported and " is intended to allow comparisons to be drawn between products that provide similar functions yet exist in different forms" *[Andrew Carre, 2011]* .
In literature this unit of comparison is defined as either "*per square meter*" or "*per house*". Most of researches assume that a "*per house*" functional unit allows only to compare houses of similar floor space, while "*per square meter*" units open up to a wider range of comparisons. Issues associated with nonlinearities when scaling are usually espected to be minimal.

As stated previously within this chapter, LCA follows a relative and predictive approach since it does not provide absolute values but references to which inputs and outputs are related *[ISO 14040]*. Normalizing results per square meters, or mass, could be appropriate when comparing simple systems. When conclusions need to be drawn from products composed by multiple sub-systems, such as buildings, comparability becomes particularly critical. To ensure that such comparisons are made on a common basis it is necessary to define a much more complex and detailed functional unit *[31]*.
Building's outputs are produced by systems and mechanisms that depend on multiple factors: geometry, location, performance, use and materials.
When the Goal and Scope of an LCA is defined we need to compare buildings which differ mainly on the object of the analysis, keeping all other indipendent variables equal. It is important to keep in mind that to ensure an equal comparison is necessary to consider buildings that are functionally equivalent. For this very reason, the present thesis argues that the use of a simple spatial function of buldings, as "*per square meter*" or "*per house*", is sufficient to ensure compatibility of buildings to be compared.

For instance we can consider a study which scope is to evaluate the environmental impact of different insulation materials.
A Life Cycle Analysis has to be conducted within buildings that present differences solely on insulation, keeping every other aspect equivalent. If a variation is to be applied to any other building feature, for instance wall finishes, the results of the entire analysis will be affected also by this other system's change. Hence the outcomes of the study will depend on the combined environmental impact of insulation and finishes, therefore results will be diffucult to read and interpret correctly.

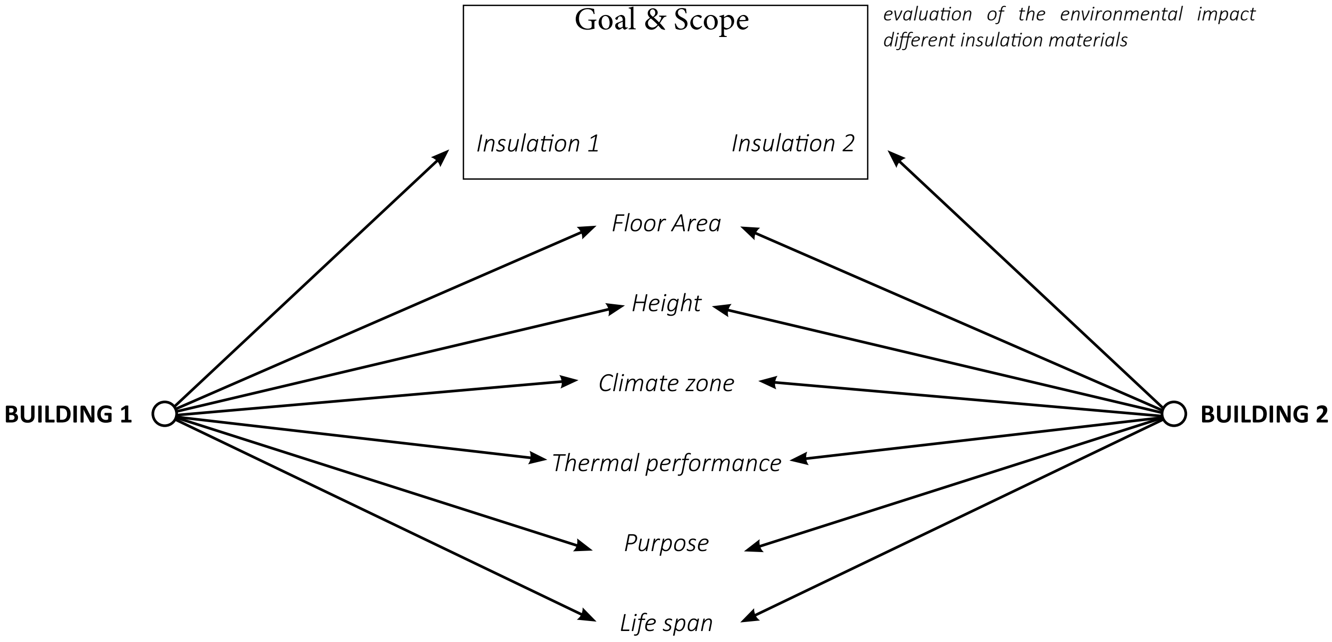


FIGURE 2.9 - Comparability of buildings

The scope of this research is to understand how the use of shipping containers affects the sustainability of the building sector. In the available literature the same scope is addressed by a comparison of traditional structures to shipping container dwellings. Freight container buildings are usually compared per square meter, without considering differences on thermal properties of the envelopes, nor carefully developing construction and demolition stages. The use of intermodal containers affects every stage of a building's life cycle and can't be limited to Embodied Energies or addressed using results from steel construction's performances.

It is difficult to summarize the wide range of outcomes derived from literature as there is a great difference between system boundaries, climate zones, materials, and funcctional units among them. Similar differences on a methodological level were found even within some comparative researches.

In order to address correctly the topic, for this research a Life Cycle Analysis has been conducted by clearly defining a functional unit which consists in a "whole house" unit with additional specific requirements of geometry - volumes and areas - and thermal performances. Then three buildings have been designed with different structural technologies that comply to the reference unit. Details and procedures of this workflow are described in the following chapter.

FIGURE 2.10 - Life cycle of a building

CHAPTER

III

Life Cycle Analysis

3.1 Research structure

The primary objective of this thesis, as it will be addressed in detail in the Goal and Scope definition, is to understand and compare the environmental impact caused by the use of shipping containers as building components.
Moreover the study will address the main differences and impacts of the application of these upcycled structures to three benchmark climate zones, which are representative of: yearly cold, hot and variable temperatures.

The study also aims to define a workflow to address the limitations of actual comparability methods of most diffused functional units.
Multiple secondary scopes will be inferred from the overall conclusions. The study also determines which products, processes or systems are the most incisive for each stage of building's lifecycle.

A fundamental hypothesis to be considered is that shipping containers used as building components are used, upcycled, available and intact. It is not possibile to draw the same conclusions on newly manufactured containers, in consequence of the need of considering emissions of the manufacturing stage. Moreover containers are considered intact, with any evident sign of corrosion or parts to be substituted. Emissions related to the processes of repair of the container are not taken into account. Finally containers have to be available. The meaning of "availability" by means of a distance from an accumulation depot will be addressed.

A brief summary of contents for each chapter follows. Each one consists on the description and evaluation of each stage of the life cycle of a building.

The current Chapter, is directly related to Step 1 of the LCA framework. It establishes goal and scope of the LCA study, system boundaries and assumptions. Then the process of definition for the functional unit is clearly described, as well as the three scenarios considered. Finally are introduced the three technologies to be compared and reasons for the choice.

Chapter 4 considers the whole Embodied Energy stage and transportation to site, modules A1-2-3-4. It is provided all necessary information about databases and resources for the Life cycle Inventory and bills of quantities for each case study and scenario. Within the evaluation of gate to site stage, module A4, are provided directions about the concept of environmental advantage and material availability.

Chapter 5 is focused on the construction stage, providing construction schedules and databases for equipment's emissions.
It also provides a brief analysis of the operational stage, which, for the conditions created by the functional unit, does not add any indication on the different environmental impacts between case studies.

Chapter 6 describes the end of life stage, module C, from demolition through waste processing. Then attention is then focused on recycling potential of construction materials, module D, and the difference between recycling and downlcycling.

Chapter 7 performs an analysis of whole life cycle results, drawing conclusions of the impact of each stage.

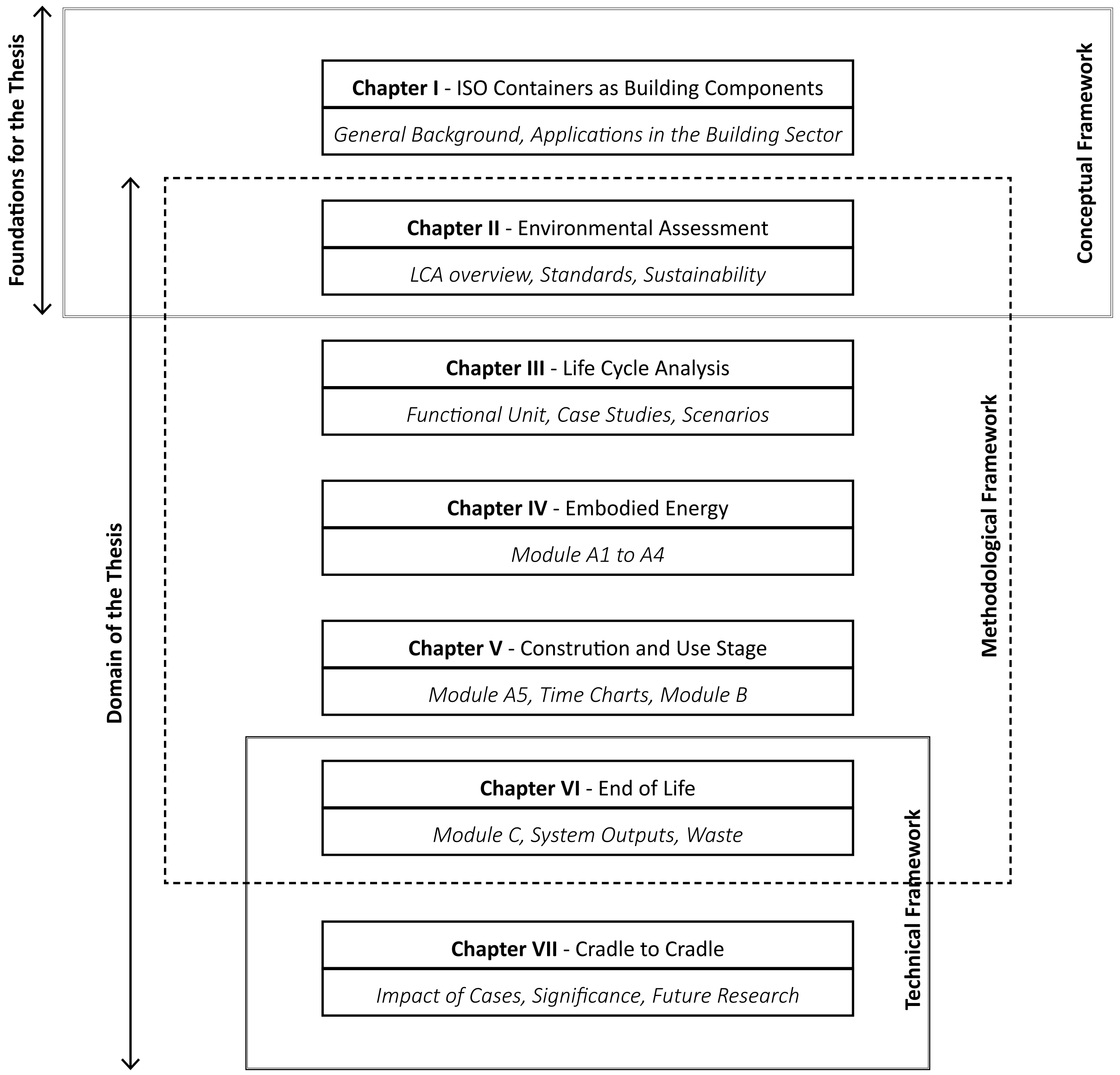


FIGURE 3.1 - Research design and organization

3.2 Goal and Scope definition

The primary goal of the study is to evaluate the environmental impact of a shipping container bulding compared to typical construction methods. The problem is addressed as the impact of the variation solely in the main struture of a single family house. The reference house is designed to include all typical modifications of a shipping container that occur during the construction process.
The scope of the research is to respond to the following questions:

How is it quantified the sustainability of an upcycled object?

What is the relationship between freight containers and the building sector?

What is the main feature of a container building? In what does it diverge from traditional technologies?

What is the impact of refittings necessary to make containers inhabitable?

How does the selection of a material affect the environmental impact through the lifespan of a building?

How much does the location's climate affect the environmental impact of a container building?

What is the maximum distance we can transport an empty container to keep the environmental advantage of upcycling?

What is the effect of reduced time in the construction schedule?

Fundamental assumption of this research is the existence of a shipping container accumulation issue. Similar studies and further research can be conducted only considering this assumption: availability of empty container in the study location.
Regarding the concept of availability, different assumptions can be made on the distance from site within we can consider an empty container to be available. Newly manufactured containers are never taken into account in this study since there is no point to choose them as building materials.
As described in the intruductive chapter, the interest of architecture in freight containers is mainly caused by the awareness of the availability of plenty of material in depots around the world. Shipping containers are outputs, waste of a linear system, such as the trading economy, and intended to be used as input of a different economy, the building sector, which aims to be circular.
The production on newly manufactured containers as raw materials for the construction sector has many drawbacks.
On one hand it does not save embodied energies in the product stage since emissions from the manufacturing process have to be considered.
On the other hand the use of newly manufactured containers actually increases overall emissions since containers have to be manufactured as per ISO standards and then refitted to be habitable, thus producing unreasonable emissions.
Finally it can be proposed to manufacture containers designed to directly fit inhabitability requirements, therefore not complying with ISO standards, in order to avoid the refitting stage. The result of this kind of process can't be named shipping container, and the overall process has to be addresses as a strictly defined Prefabricated Architecture.

The study has been conceived to be a desktop study, and is therefore intended to use only published data to undertake the assessment. Thus the research does not specifically address an actual buiding. This results in assumptions regarding bills of material quantities and overall operational requirements which are based on theoretical estimates rather than actual measurements. Data sources are indicated in References and come from pubblications, Environmental Product Declarations (EPDs) and the BSRIA guide from Bath University.
While these stimates are believed to be sufficient to compare alternative construction types, they could be further enhanced by a study that involves a Data Quality Assessment or actual measurements, especially when it comes to construction and demolition waste and processes or reuse-recycling-downcycling considerations.

The only allocation procedure used within the study is related to the apportion of recycling credits to the steel structure. In order to avoid double counting of credits, steel is considered virgin as input of the system (product stage) then all credits are given after the End of Life stage, in module D related to recycling. This procedure, called 0-100, has been chosen in order to have an equal comparison of module D. Therefore is necessary to consider this allocation procedure when addressing the product stage, module A1-2-3. Anyhow, results from a whole life cycle assessment comparison will represent emissions of recycle steel rather than virgin since redits are negative (subtractive).

3.3 System Boundaries

The main scope of the study is to compare three different building technologies related to the main structure of a single family house. Excluded from the study is every element that is not affected by the change of structural material.
It is assumed that emissions related to foundations, stairs, doors, windows, fixtures, interior decoration, furnishing cabinetry, skirting and trim, electrical and plumbing fit -out, garden and mechanical systems are constant for every different case study and not dependent on the selection of a certain structural typology. Therefore the above mentioned items are excluded from the system boundary.
The same way are not considered earthworks, civil works, plumbing and final fit-out construction processes.
Finally, stages such as maintenance, repair, replacement and refurbishment are excluded from the boundary due to the uncertainity of their emissions.
Therefore are excluded from the boundary all products that does not provide a significant variation of emissions between case studies.

Overall results have to be interpreted carefully since they provide a relative impact of each structural technolgy, rather than an absolute evaluation of the environmental performance .

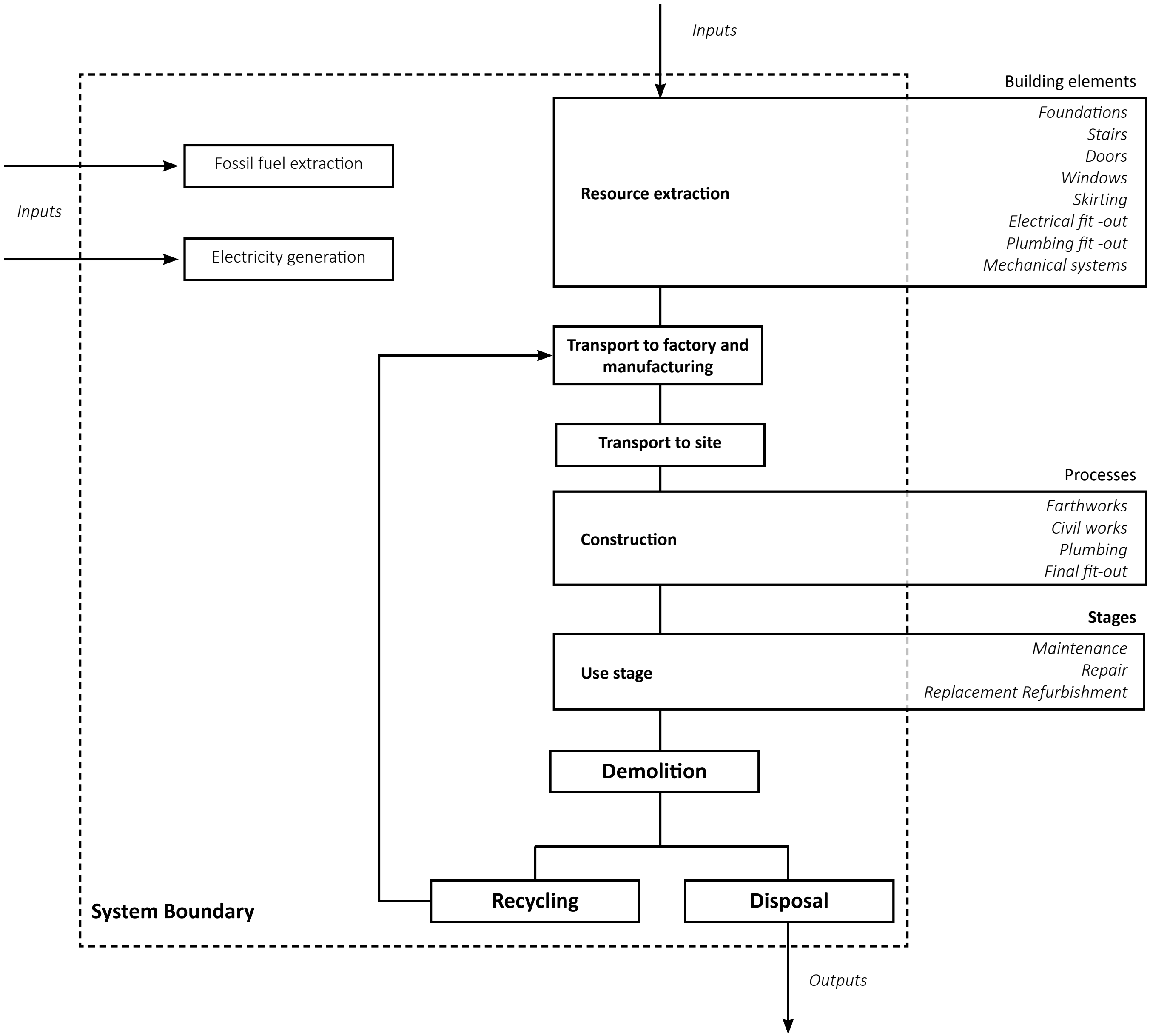


FIGURE 3.2 - System boundary diagram

3.4 Functional unit: comparability and requirements

The purpose of the functional unit is to provide an equitable measure to compare buildings, or structures, considered that is exclusively based on the service provided by the house. Due to the complexity and variety of purposes provided by a house, defining the core function of a house is not straightforward. Shelter, comfort, storage, protection, entertainment, visual amenity are only few of the possibile detectable functions. Among these, human shelter and comfort are arguably priorities, thus are used as core functions to define the functional unit of the study.

The outcome determined by considering the comfort of interior spaces, especially expressed as thermal comfort, along with spatial requirements strikes the conservative definition of functional unit "*per square meter*" and "*per total house*", which consist only in geometrical requirements.

The study is moved by the aim of evaluating the impact of shipping containers in the buuilding sector. Thus spatial requirements will be related to "geometrical limitations" imposed by the standardization of intermodal containers. Benchmark technologies compared represent alternative structural frames fitting with the geometry of freight containers.
The functional unit could be defined as a "*per house with defined thermal requirements*" unit.

The spatial organization of the reference unit is based on possibilities given by containers' dimensions and operations: siding, stacking, shifting and overhanging. These are assumed to be the fundamental operations. This allows to keep in consideration even operations as overhanging and shifting which can cause higher refitting work and thus the addition of supplementary structural material.

Further research could aim to understand the relative impact of each possibile operation, which has not been addressed in the present study.
The three structural system analized have been designed to fit with the spatial requirement presented above.

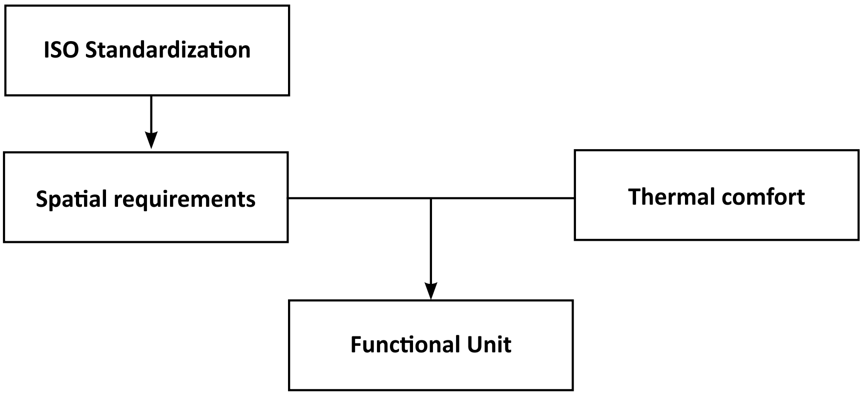


FIGURE 3.3 - Combined requirements for LCA functional unit

Thermal requirements have been combined to spatial dimensions in accordance with the “International Energy Conservation Code” (IECC) and “American Society of Heating, Refrigeration and Air conditioning Engineers” (ASHRAE) requirements.
In particular, the 2015 IECC defines in its chapter 4 criteria and requirements for Residential Energy Efficiency.

It is important to underline that climate zones are defined on the basis of yearly Heating Degree Days (HDD) and Cooling Degree Days (CDD) of a location.
Follows a recapitulary table showing maximum transmittance value (U-factors expressed in W/m^2-K) for each assembly type in each different climate zone.

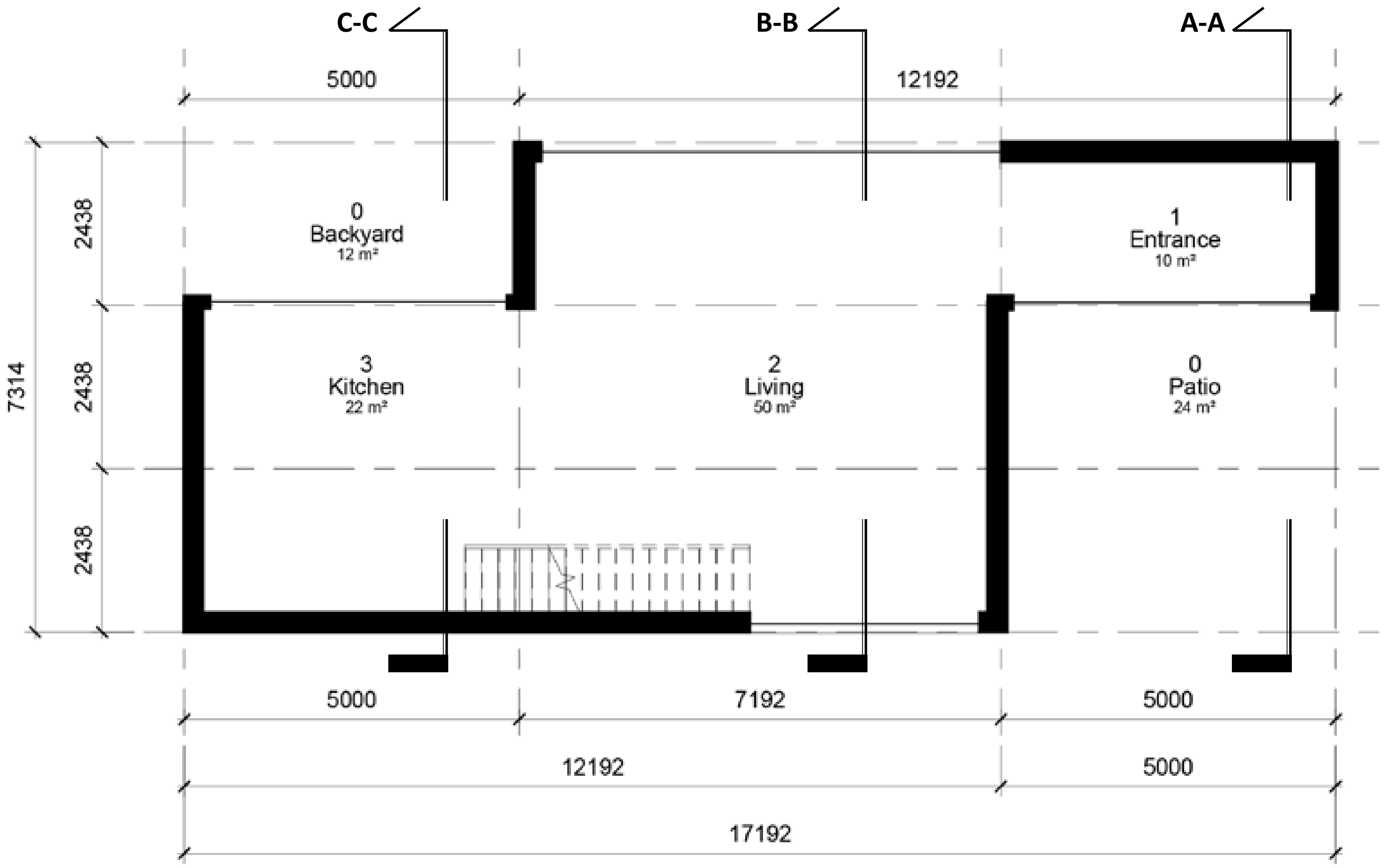
In addition to transmittance requirements, for hot climates, an additional dynamic requirement has been imposed.
In order to ensure an interior comfort for passive cooling necessities, hass been imposed a maximum Periodic Thermal Transmittance (Yie) of 0,18 W/m^2-K for every orizontal or inclined assembly and 0.10 W/m^2-K for vertical assemblies, as stated on the italian regulation *[Dlgs n.162, 26/06/2015]*, along with a time shift of 10 hours *[Dm n.158 16/06/2009]*.
These additional requirements allow for a good performance of the envelope, enabling the assemblies to store heat coming from high exterior temperature, and slowly release heat with a time shift of 10 hours, during the night.
In order to achieve these results, it is necessary to add mass to the assemblies and this can lead to additiovnal embodied energies as it will be addresses in the following chapters.

Functional Unit Thermal Requirements

Italian Climate Zone	***ASHRAE Climate zone***	*Description*	*Heating Degree Days* ***HDD*** *(18°)*	*Cooling Degree Days* ***CDD*** *(25°)*	Ceilng U	Frame Wall U	Mass wall U	Floor U
/	Zone 0 (A,B)	Extremely hot	/	6000 - over	/	/	/	/
/	Zone 1 (A,B)	Very Hot	/	5000 - 6000	0,198	0,476	1,116	0,363
/	Zone 2 (A,B)	Hot	/	3500 - 5000	0,17	0,476	1,116	0,363
/	Zone 3 (A,B,C)	Warm	/	2500 - 3500	0,17	0,34	0,555	0,266
A		Warm	0 - 600		0,17	0,34	0,555	0,266
B		Warm	600 -900		0,17	0,34	0,555	0,266
C		Warm	900-1400		0,17	0,34	0,555	0,266
D		Warm	1400-2100		0,17	0,34	0,555	0,266
E	Zone 4 (A,B,C)	Mixed	2100-3000	0 - 2500	0,147	0,34	0,555	0,266
F	Zone 5 (A,B,C)	Cool	3000 - 4000	/	0,147	0,34	0,555	0,187
/	Zone 6 (A,B)	Cold	4000-5000	/	0,147	0,255	0,34	0,187
/	Zone 7	Very Cold	5000-7000	/	0,147	0,255	0,323	0,159
/	Zone 8	Sub-Artic	7000 - over	/	0,147	0,255	0,323	0,159

A: humid - B: Dry - C: marine

FIGURE 3.4 - IECC transmittance factors for assembly and climate zone

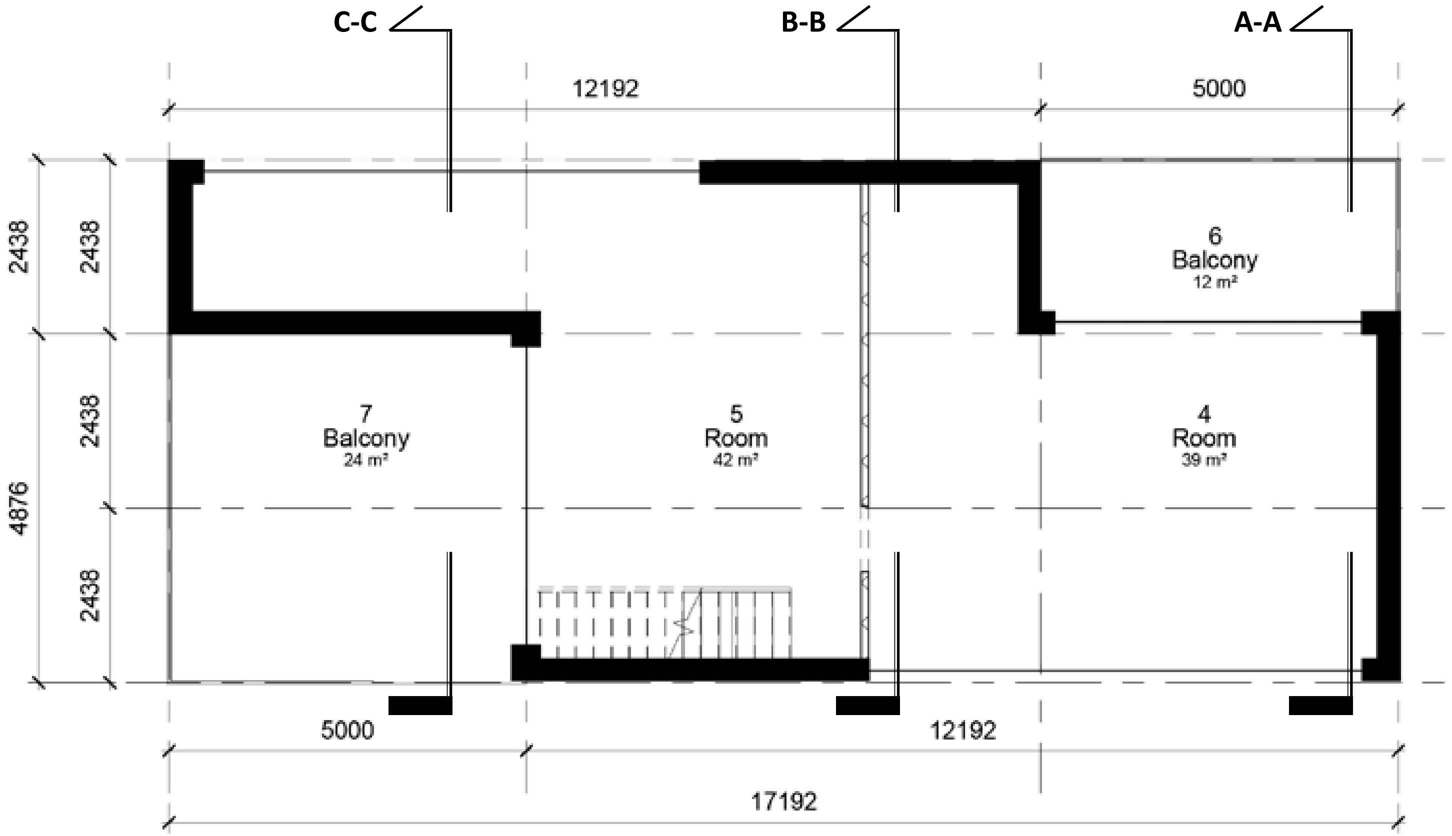


Ground floor gross surface:	84,31 m^2
Interior height:	2,64 *m*
Ground floor interior volume:	223,90 m^3
Ground floor vertical surfaces:	132,50 m^2
First floor surface:	121,81 m^2
Roof surface:	89,31 m^2
Total walls surface:	265,00 m^2
Total floor surface:	206,12 m^2

Interior floor area is intended from the exterior side of perimetral walls, whaterever their thickness.

Ground Floor Plan

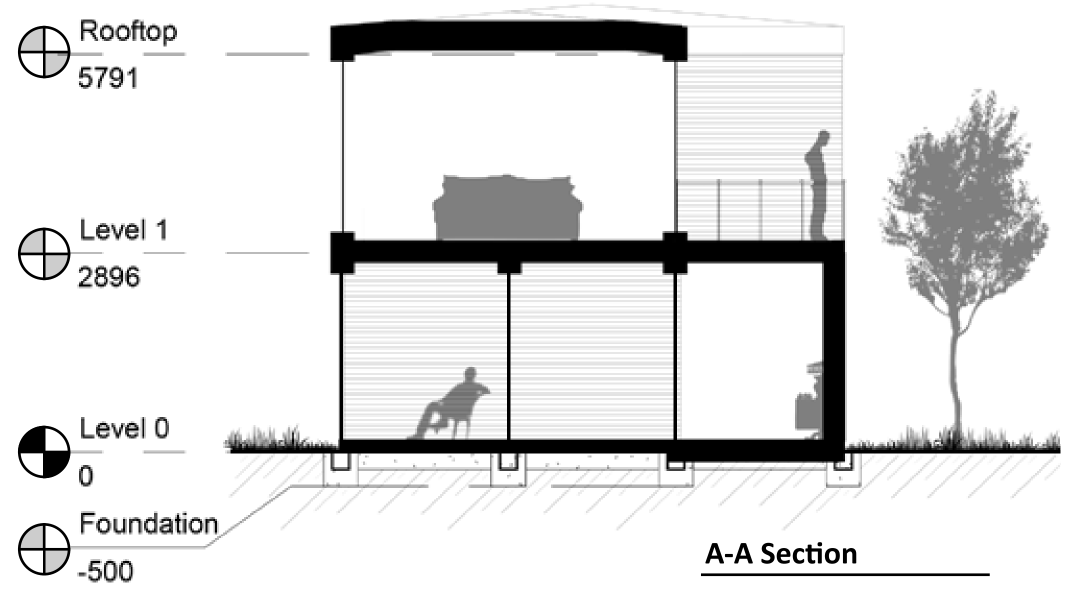
Scale 1:100



First Floor Plan

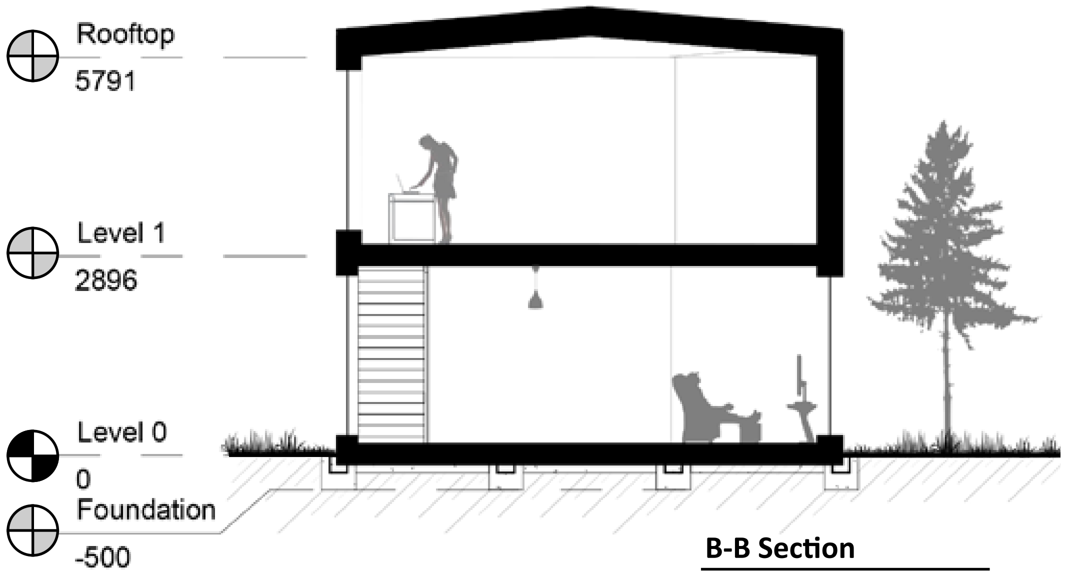
Scale 1:100

Dimensions are external, units in mm.



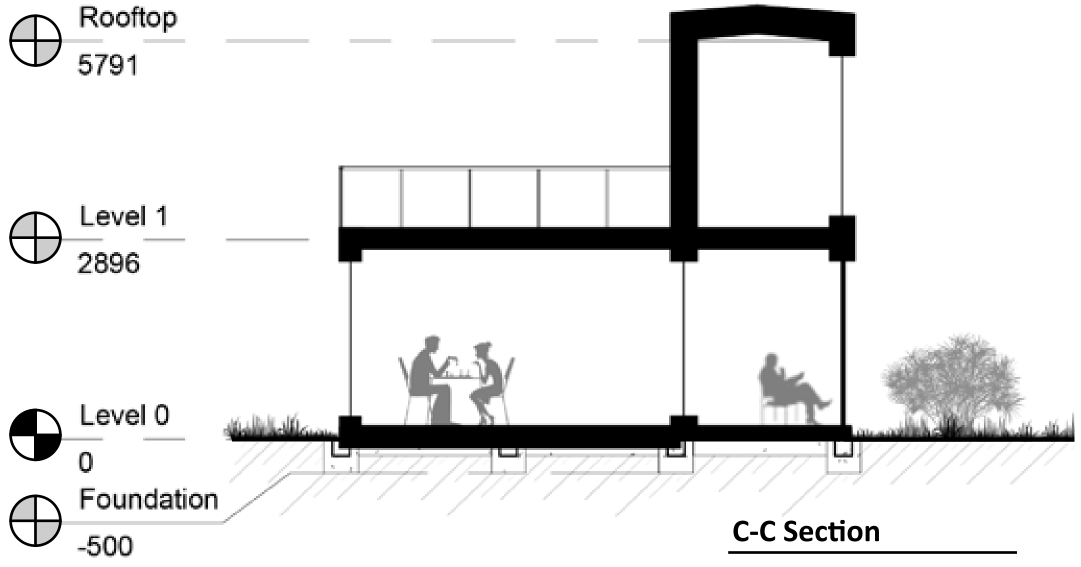
A-A Section

Scale 1:100



B-B Section

Scale 1:100



C-C Section

Scale 1:100

3.5 Scenarios

In order to correctly address the impact of technologies, it is necessary to state where the study is located. Envelopes and materials behave distinctly depending on the location and specifically the thermal comfort of a house is strictly related to the climate zone. The study has been carried out for three different scenarios representing contrasting thermal requirements. Since the fundamental assumption of the research is the availability of shipping containers, locations have been defined combining information about containers' availability and climate zones.

The whole "container matter" begins with the accumulation of freight containers in intermodal depots where they are unloaded and then left empty. Each year about 2 milion TEU - Twenty-foot Equivalent Unit, that represents the cargo capacity of a 20 foot container - of containers are manufactured. The production is mainly located in China, taking advantage of its export-oriented economy. A dramatically small portion of those newly manufactured containers will be used for more than one trip. Therefore, generally, the container life cycle within the trading industry can be considered linear, with its End of Life corresponding to the accumulation of empty containers in intermodal depots.
Emissions from this first life cycle of each container are not accounted to the building sector.

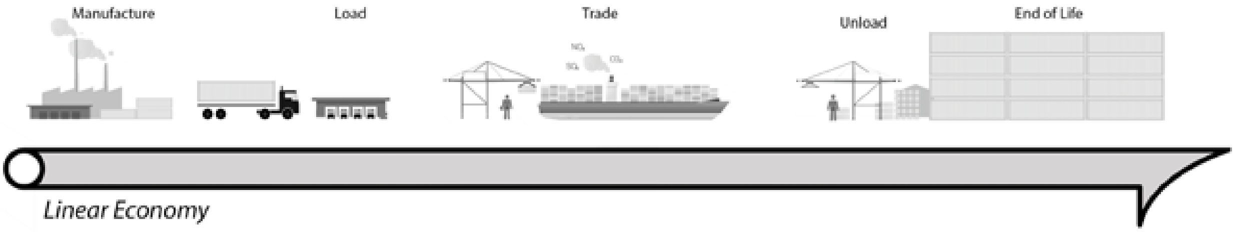


FIGURE 3.5 - Life cycle of shipping containers

Therefore it is possibile to determine the availability of containers by understanding the balance of worldwide economies.

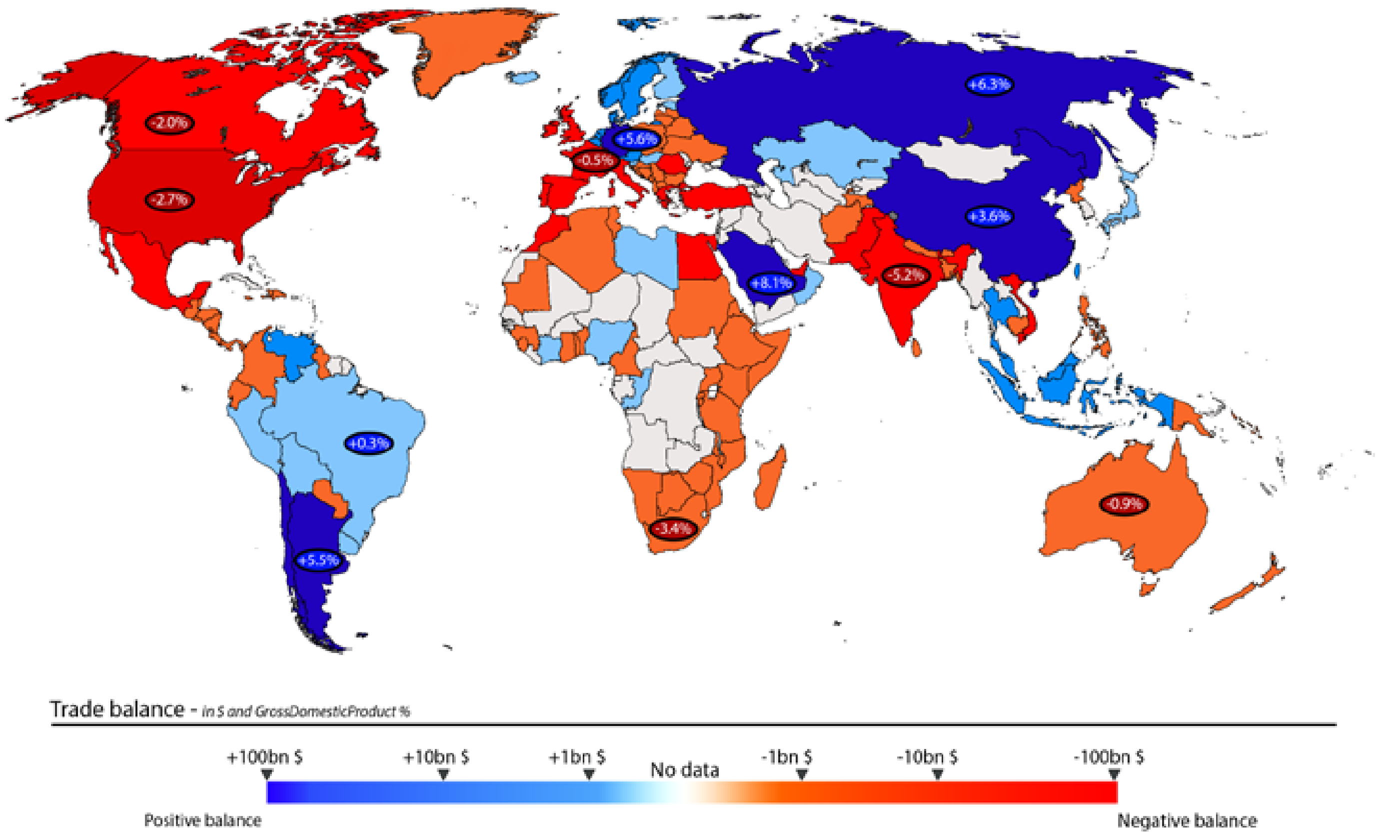


FIGURE 3.6 - Worldwide trade balance

Based on "*Sustainbaility Report*" and "*Group Annual Magazine*" from *Maersk Group*, the world leading company of shipping containers, it is possibile to define worldwide seaports, focusing only on those belonging to import-oriented countries. Resulting seaports are depots of accumulation of intermodal containers.
It is evident how these considerations can be extended to continental depots to which containers are moved by rail or truck and accumulate.
Maersk line has been chosen also for the availability of data and reports online.

Rank	Company	TEU Capacity	Market Share
1	Maersk Line	2'921'125	15.50%
2	MSC	2'550'147	13.60%
3	CMA CGM Group	1'628'269	8.70%
4	Hapag / Lloyd	965'168	5.10%
5	Evergreen	948'220	5.00%
6	COSC	819'429	4.40%
7	China Shipping Container	656'050	3.50%
8	Hanjin Shipping Company	608'459	3.20%
9	OSK	604'720	3.20%
10	America President Lines	562'346	3.00%

FIGURE 3.7 - Ranking of shipping lines by *alphaliner*

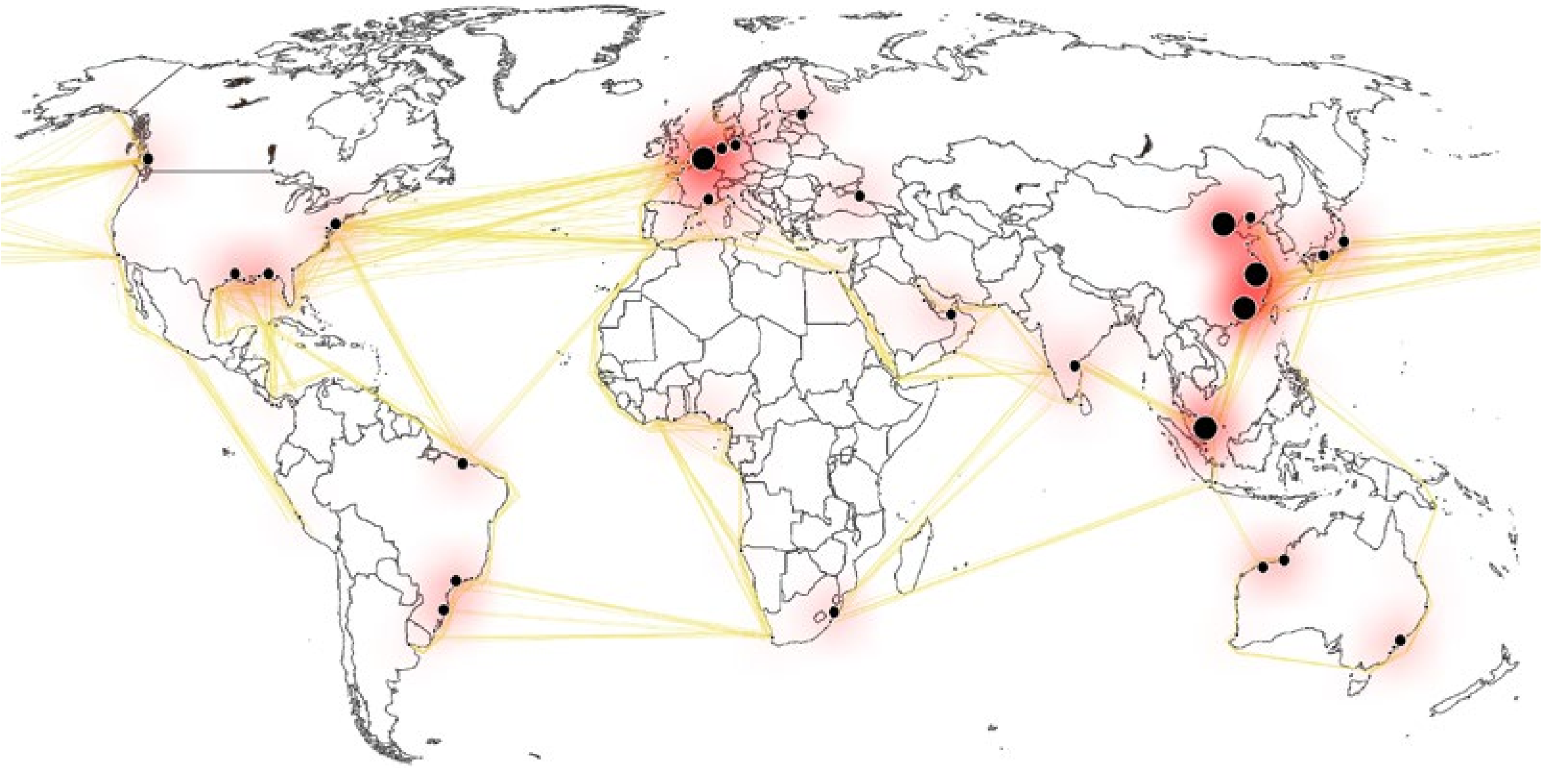


FIGURE 3.8 - Trade flows of shipping containers

Among the import-oriented seaport have been chosen three located in the most representative climate areas: Tropical Humid, Col Dry and Temperate. Therefore the different scenarios in which the thesis has been developed are Vancouver (zone 5), Durban (zone 3), Chennai (zone 1).

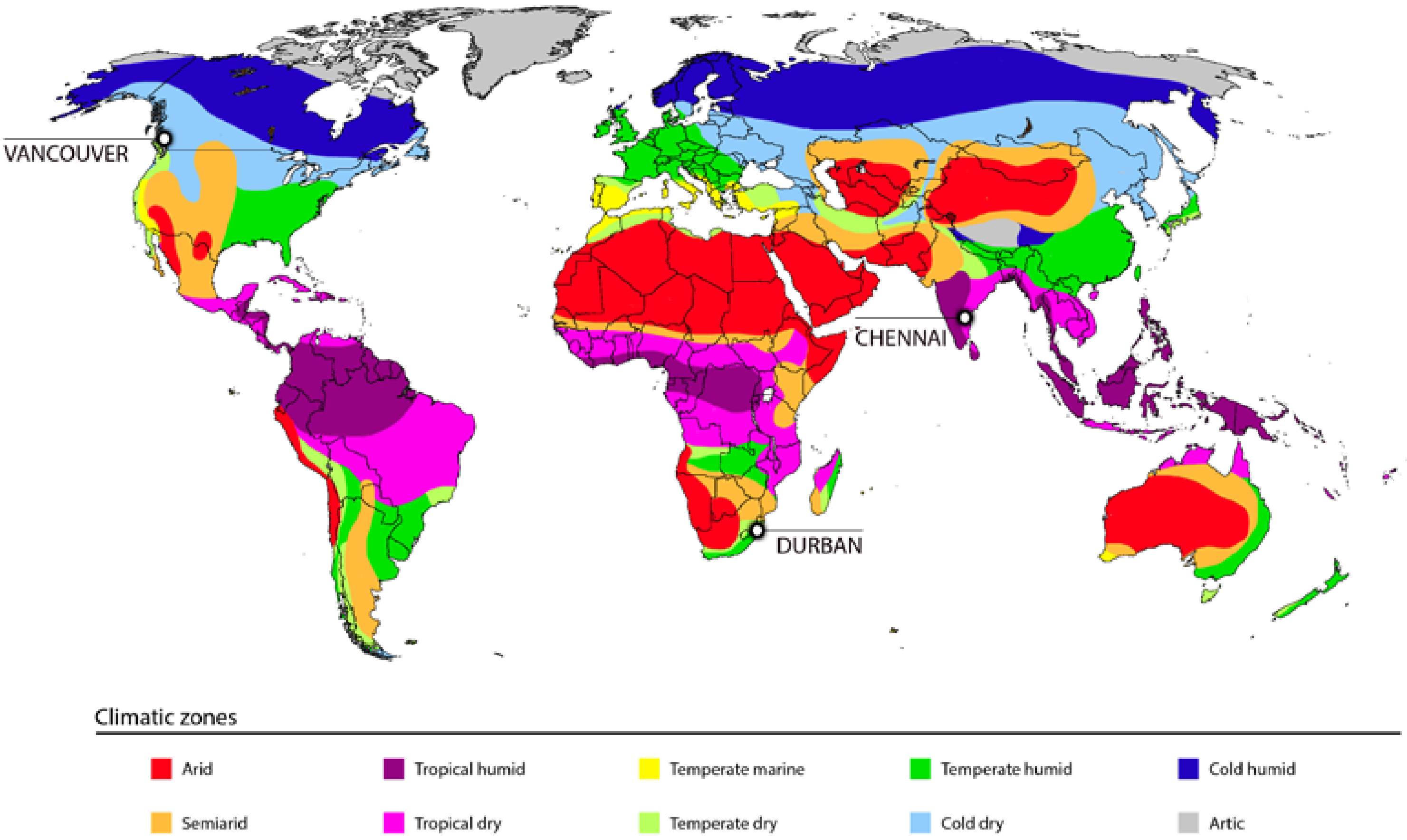


FIGURE 3.9 - Koppen climate zones and reaserch scearios

Follows a brief sumamry of climatic data used for each scenario.

City	**VANCOUVER**										
Latitude	49°16'57.82" **N**										
Longitude	123°07'14.66" **W**										
ASHRAE Zone	Zone 6										
Desctiption	COLD										
Heating D.D.	4251										
Cooling D.D.	/										
	Temperature (°C)			Humidity (%)		Day lenght (hrs)	Daily Solar Radiation [MJ/m2*day]				Monthly Solar Radiation [W/m2]
	Max	Min	Avg	Morning	Evening		Global	Diffuse	Reflected	Direct	
JAN	9	-2	6	90	65	9,4	4,1	2,5	7	6,2	71,7588
FEB	11	2	8	83	18	10,8	7,3	4	11,2	10	115,74
MAR	12	1	9	84	52	12,5	11,3	5,9	14	12,2	141,2028
APR	12	1	9	79	45	14,4	16,3	7,6	17,1	16,2	187,4988
MAY	14	3	10	78	44	16	19,3	9	17,8	17,6	203,7024
JUN	19	6	15	74	42	16,9	20,4	9,7	17,6	17,9	207,1746
JUL	23	11	19	69	33	16,4	21,5	9,3	19,1	20,6	238,4244
AUG	25	13	20	75	40	14,9	18,6	8,1	18,6	18,9	218,7486
SEP	23	12	19	78	35	131	14,4	6,5	16,9	16,3	188,6562
OCT	18	8	14	85	43	11,3	7,9	4,2	10,9	10	115,74
NOV	15	6	12	83	37	9,7	4,6	2,8	7,6	6,6	76,3884
DEC	9	-1	6	91	47	8,9	3,3	2,1	6,1	5,4	62,4996

City	DURBAN										
Latitude	-29°51'28.44" **S**										
Longitude	31°01'45.12" **E**										
ASHRAE Zone	Zone 3										
Desctiption	TEMPERATE										
Heating D.D.	184										
Cooling D.D.	1924										
	Temperature (°C)			Humidity (%)		Day lenght (hrs)	Daily Solar Radiation [MJ/m2*day]				Monthly Solar Radiation [W/m2]
	Max	Min	Avg	Morning	Evening		Global	Diffuse	Reflected	Direct	
JAN	27	22	24	86	76	14,2	19,9	9,4	18,1	15,4	178,2396
FEB	27	22	25	87	75	13,5	18,8	8,4	18,2	15,8	182,8692
MAR	27	21	24	86	75	12,6	17,3	6,8	18	16,7	193,2858
APR	25	19	22	85	74	11,7	14,6	5	17,4	17,4	201,3876
MAY	23	16	20	83	70	11	12,2	3,7	16,2	17,9	207,1746
JUN	22	12	17	78	67	10,7	10,7	3,2	15,2	17,2	199,0728
JUL	22	12	17	78	66	10,9	11,4	3,4	15,8	17,8	206,0172
AUG	22	14	18	82	70	11,5	13,6	4,4	17,2	17,7	204,8598
SEP	22	16	20	83	74	12,3	15,7	6,1	17,1	16	185,184
OCT	23	17	20	84	75	13,2	16,4	7,9	15,9	13	150,462
NOV	24	19	22	85	76	14,1	17,5	9	16,2	12,5	144,675
DEC	26	21	23	86	76	14,5	19,6	9,6	17,6	14,5	167,823

City	CHENNAI										
Latitude	13°04'57.65" **N**										
Longitude	80°16'14.59" **E**										
ASHRAE Zone	Zone 1										
Desctiption	HOT - HUMID										
Heating D.D.	/										
Cooling D.D.	6779										
	Temperature (°C)			Humidity (%)		Day lenght (hrs)	Daily Solar Radiation [MJ/m2*day]				Monthly Solar Radiation [W/m2]
	Max	Min	Avg	Morning	Evening		Global	Diffuse	Reflected	Direct	
JAN	28,8	20,4	24,6	90	64	11,8	17,8	5,4	19,6	20,9	241,8966
FEB	30,5	21,1	25,8	90	64	12,1	21,2	5,5	22,6	24,6	284,7204
MAR	32,6	23	27,8	90	63	12,4	23,9	6	24,3	26,3	304,3962
APR	34,7	25,8	30,3	88	67	12,8	24,2	6,9	23,4	24,6	284,7204
MAY	37,4	27,6	32,5	77	61	13,1	22	7,6	21,8	20,6	238,4244
JUN	37,3	27,4	32,4	68	55	13,3	18,9	8,1	18,8	15,6	180,5544
JUL	35,3	26,1	30,7	77	61	13,2	17	8,3	16,8	12,6	145,8324
AUG	34,5	25,5	30	79	63	12,9	17,3	8,4	16,9	12,6	145,8324
SEP	33,9	25,2	29,6	86	69	12,5	18	7,8	17,9	14,7	170,1378
OCT	31,8	24,2	28	90	72	12,2	15,9	7,1	16,4	13,4	155,0916
NOV	29,4	22,6	26	91	73	11,9	14,6	6,3	15,7	13,8	159,7212
DEC	28,4	21,2	24,8	90	70	11,8	15,3	5,6	16,9	16,7	193,2858

FIGURE 3.10 - Climatic data for Vancouver, Durban, Chennai.

3.6 Benchmark technologies: Steel and X-Lam

In order to evaluate the impact of the use of freight containers as building components it is necessary to have references from which draw conclusions.
Structural steel is the most straightfoward technology to compare with container components from the point of view of materials. A wide range of pubblished researches and data are available and makes it an easy technology to address.
However structural steel buildings are completely divergent technologies from the point of view of construction operations and assemblies design: they are typically structural frames, with different needs of assembly enclosures and construction practices.
The steel frame design for this study is composed by HEA 120 vertical columns, IPE 100 beams, C-channel C76x38mm joists and T-tees 152x76x12 mm bracings.

The methodological approach to freight containers is much closer to prefabricated building. Its box-like behaviour is addressed in comparison to Cross Laminated Timber structures. X-Lam structures have similar on-site methodologies. Moreover, from the point of view of materials and ebodied energies, timber is the commonly seen as the ultimate “eco-friendly” building material.
The third structure is designed with X-Lam panels 150mm thick with 5 cross laminated layers C24 timber, calculated to guaranteee a fire resistance R60 with the carbonating profundity.

Due to the high impact of manufacturing and glues needed for the production of Cross Laminated Timber panels, it can be argued that the comparison should be made even using typical hardwood frames as a reference.
Further reasearch should draw conclusions from the comparison of a wider range of technologies including hardwood timber frames, concrete, bricks, prefabricated assemblies.

Shipping container structural materials - Schedule

Element Type	***Dimensions*** [mm]	***Lenght*** [m]	***Count***	***Volume*** [m^3]	***Density*** [Kg/m^3]	***Weight*** [Kg]
Square Hollow Section	50x50x3	192.49	/	0.074	7850	580.25
Columns	HEA 120	13.83	5	0.035	7850	273.97

Steel frame structural materials - Schedule

Element Type	***Dimensions*** [mm]	***Lenght*** [m]	***Count***	***Volume*** [m^3]	***Density*** [Kg/m^3]	***Weight*** [Kg]
Beams	IPE 100	266.62	31	0.275	7850	2155.64
Columns	HEA 120	74.24	14	0.188	7850	1474.48
C-channel joists	C-76x38	635.41	110	0.642	7850	5037.35
T-tees bracings	T-152x76	122.90	24	0.175	7850	1373.75

X-Lam structure materials - Schedule

Element Type	***Dimensions*** [mm]	***Unit***	***Count***	***Volume*** [m^3]	***Density*** [Kg/m^3]	***Weight*** [Kg]
X-Lam	150	569.93 m^2	/	0.074	7850	580.25
Hardwood Columns	150x150	8.70 m	3	0..196	491.65	47.78

FIGURE 3.11 - Structural quantities

3.7 Building assemblies

Follows the description of the assemblies for each structural technology and scenario considered.

SHIPPING CONTAINER STRUCTURE

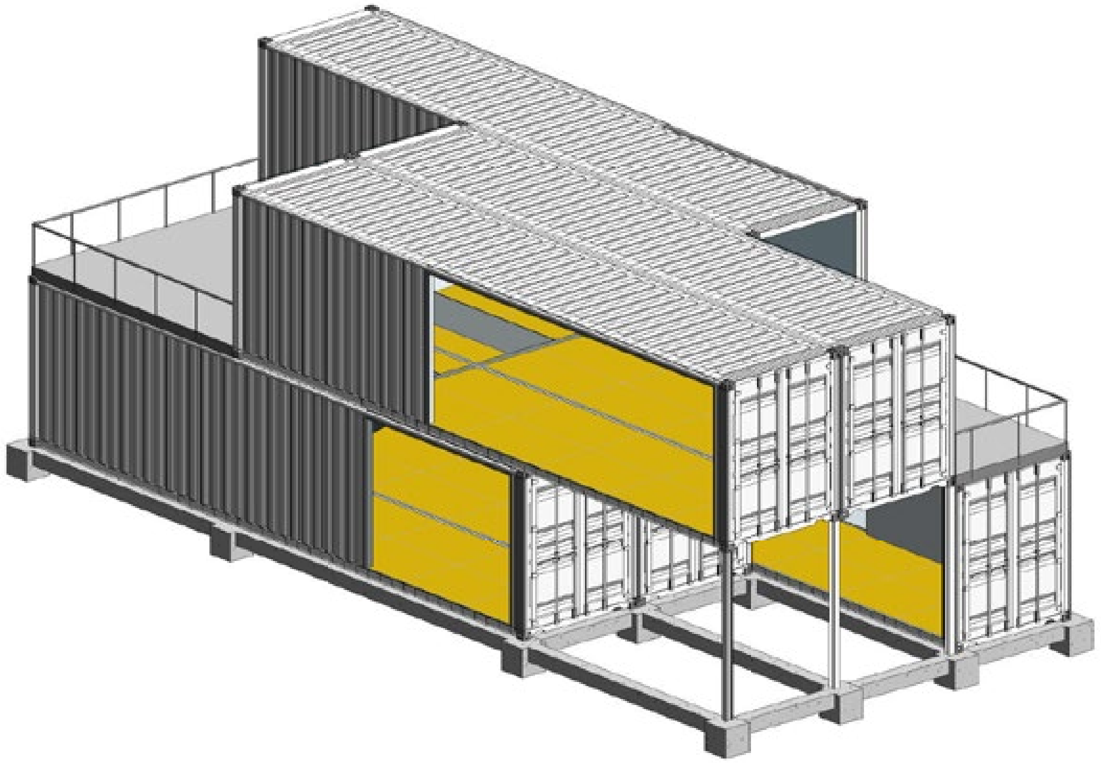


FIGURE 3.12 - Container structure. Front perspective

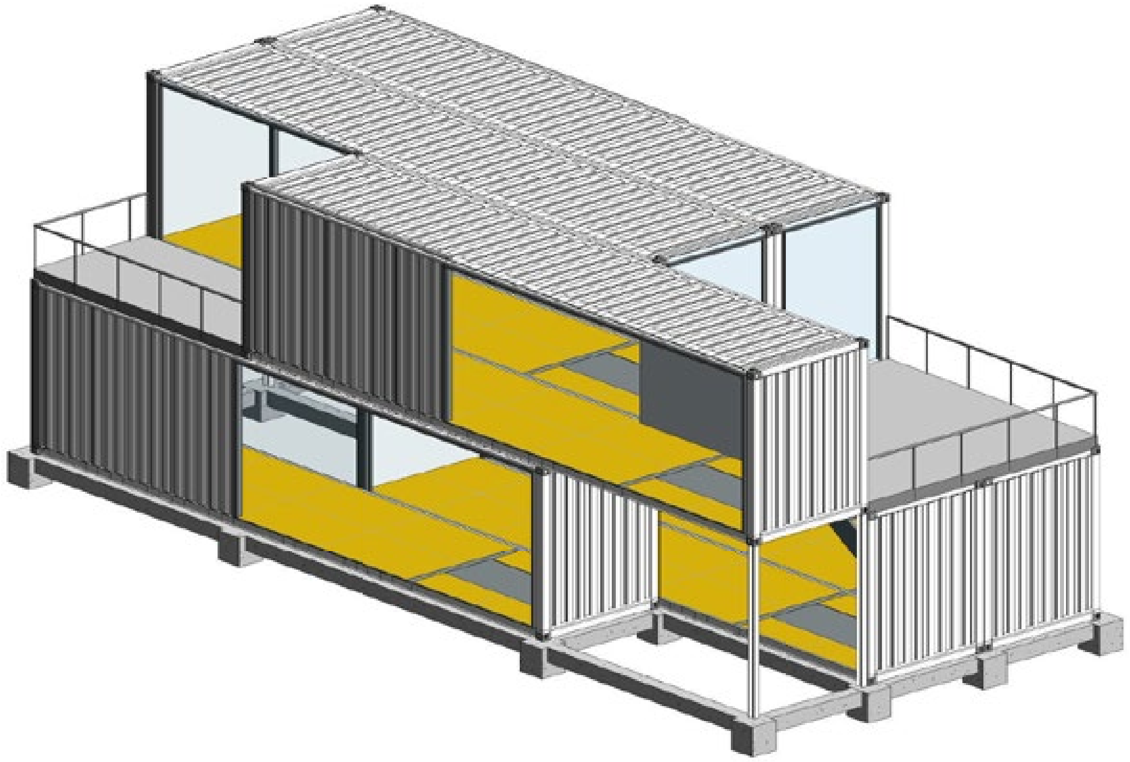


FIGURE 3.13 - Container structure. Rear perspecive

Wall frames - *U-factor = 0,255*			
Uassembly	0,247	*1 / R*	[W / m2*K]
Mass	**28,461**		[kg/m2]
Yie	**0,243**		[W / m2*K]
Time shift	**1,153**		[h]
Floor - *U-factor = 0,187*			
Uassembly	0,186	*1 / R*	[W / m2*K]
Mass	**28,461**		[kg/m2]
Yie	**0,169**		[W / m2*K]
Time shift	**1,153**		[h]
Ceiling - *U-factor = 0,147*			
Uassembly	0,144	*1 / R*	[W / m2*K]
Mass	**29,650**		[kg/m2]
Yie	**0,129**		[W / m2*K]
Time shift	**3,453**		[h]

Scenario 1 -Vancouver

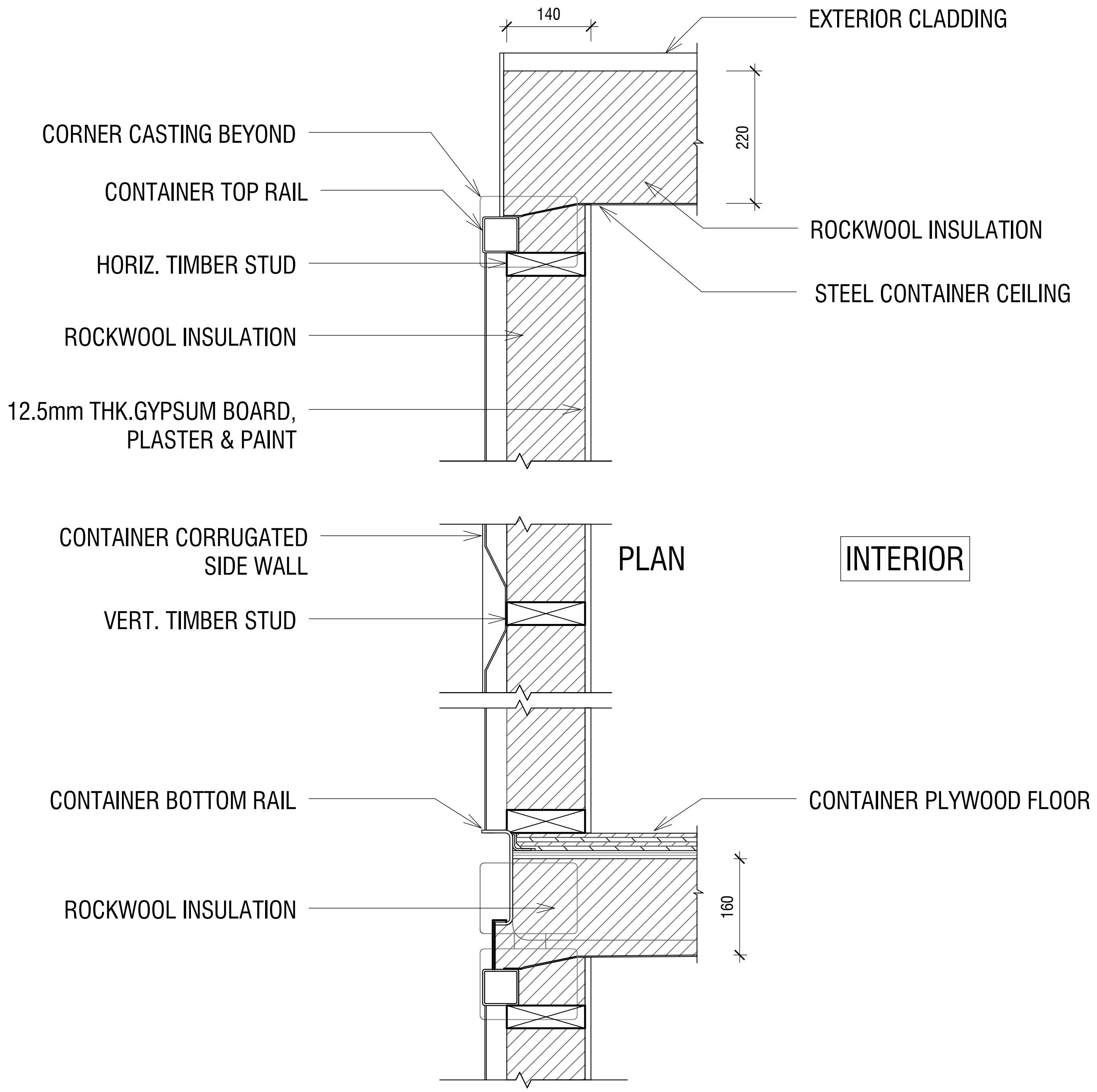


FIGURE 3.14 - Container structure assemblies. Vancouver 1:10

Scenario 2 -Durban

***Wall frames -** U-factor = 0,34*			
$U_{assembly}$	0,241	*1 / R*	[W / m2*K]
Mass	**123,386**		[kg/m2]
Yie	**0,067**		[W / m2*K]
Time shift	**10,060**		[h]
***Floor -** U-factor = 0,266*			
$U_{assembly}$	0,255	*1 / R*	[W / m2*K]
Mass	**123,386**		[kg/m2]
Yie	**0,237**		[W / m2*K]
Time shift	**10,060**		[h]
***Ceiling -** U-factor = 0,17*			
$U_{assembly}$	0,141	*1 / R*	[W / m2*K]
Mass	**115,650**		[kg/m2]
Yie	**0,028**		[W / m2*K]
Time shift	**11,964**		[h]

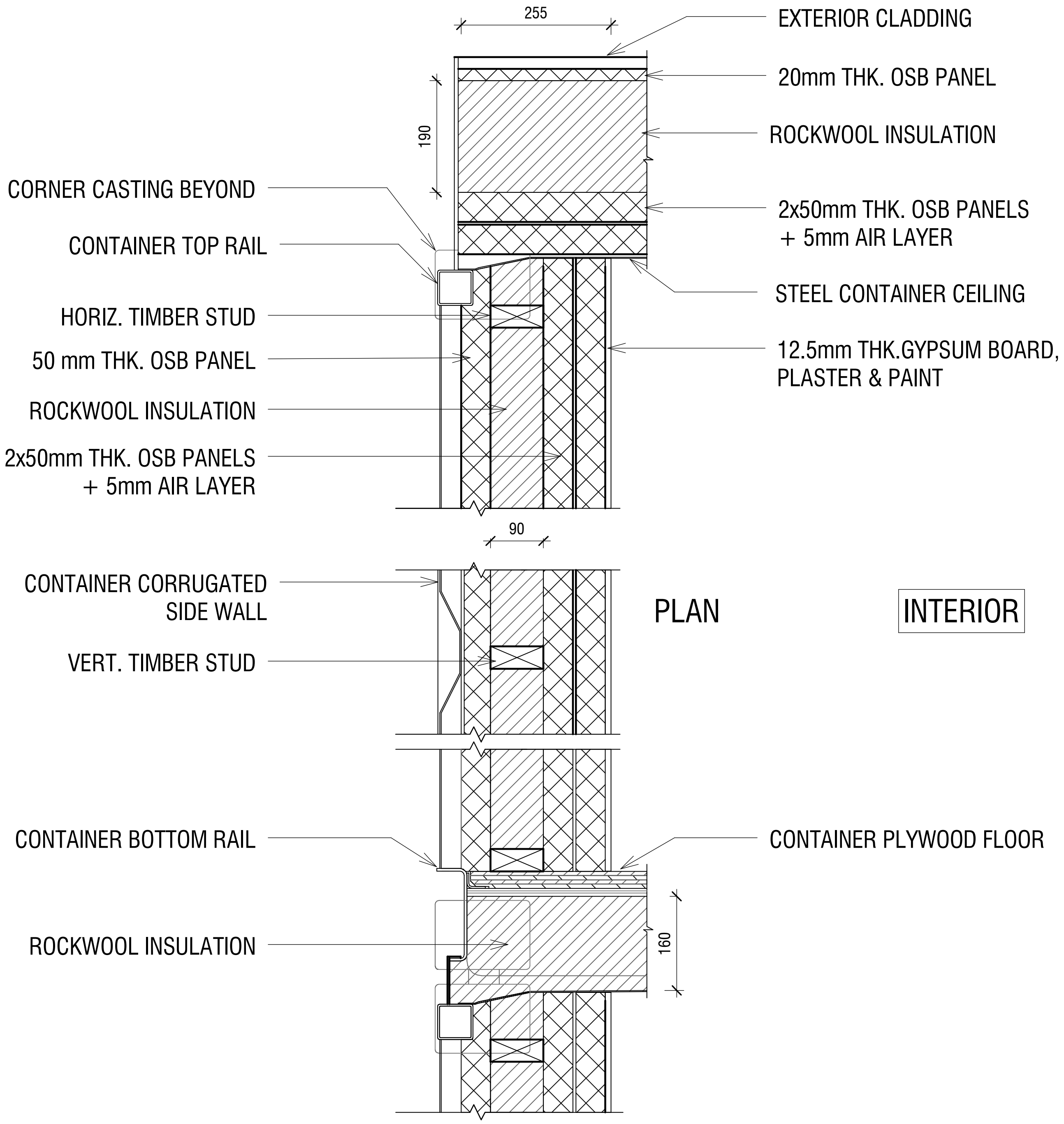


FIGURE 3.15 - Container structure assemblies. Durban 1:10

Scenario 3 -Chennai

***Wall frames -** U-factor = 0,476*			
$U_{assembly}$	0,532	*1 / R*	[W / m2*K]
Mass	**348,786**		[kg/m2]
Yie	**0,116**		[W / m2*K]
Time shift	**10,062**		[h]
***Floor -** U-factor = 0,363*			
$U_{assembly}$	0,330	*1 / R*	[W / m2*K]
Mass	**348,786**		[kg/m2]
Yie	**0,309**		[W / m2*K]
Time shift	**10,062**		[h]
***Ceiling -** U-factor = 0,198*			
$U_{assembly}$	0,189	*1 / R*	[W / m2*K]
Mass	**96,890**		[kg/m2]
Yie	**0,056**		[W / m2*K]
Time shift	**9,997**		[h]

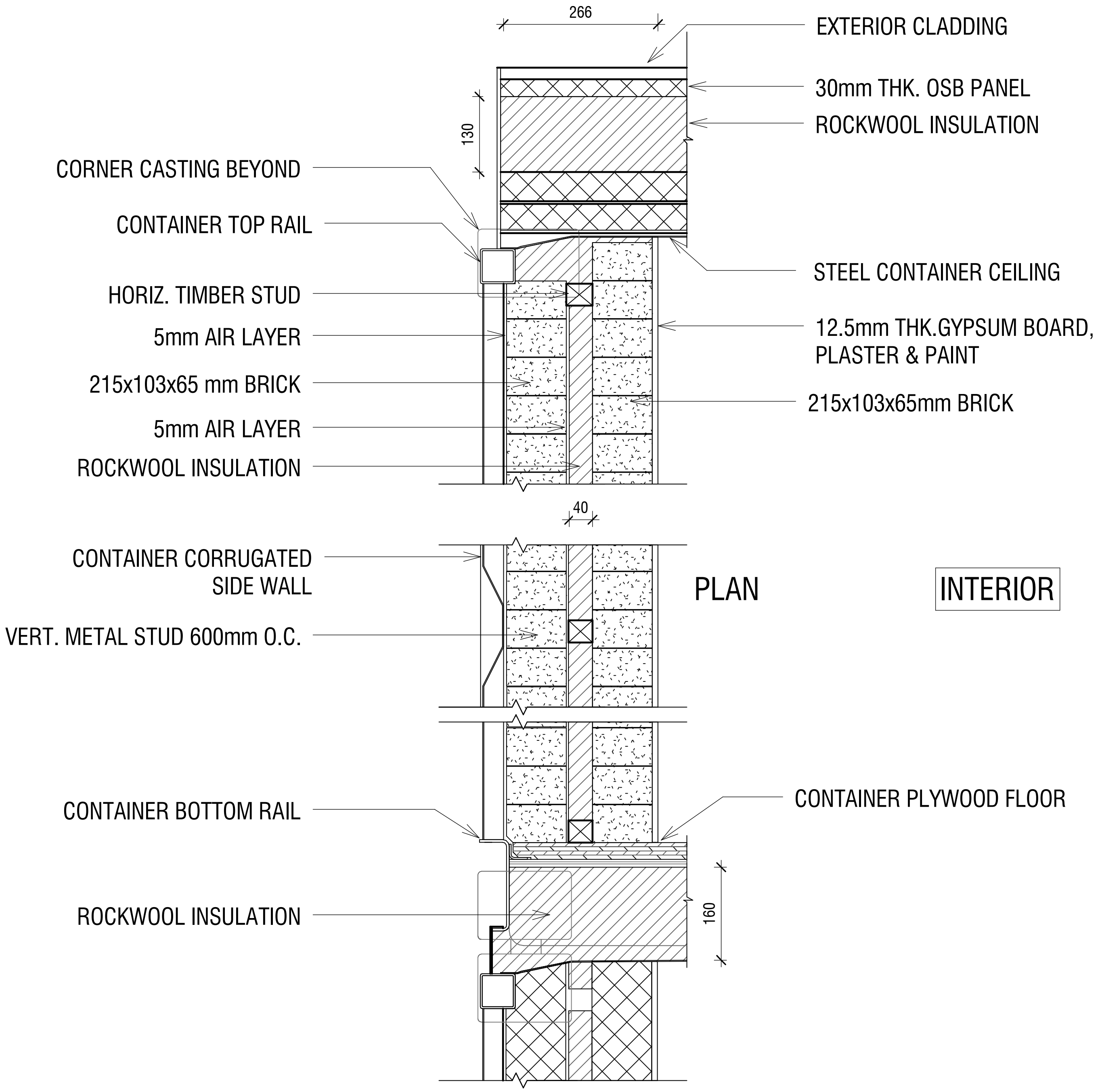


FIGURE 3.16 - Container structure assemblies. Chennai 1:10

STEEL FRAME STRUCTURE

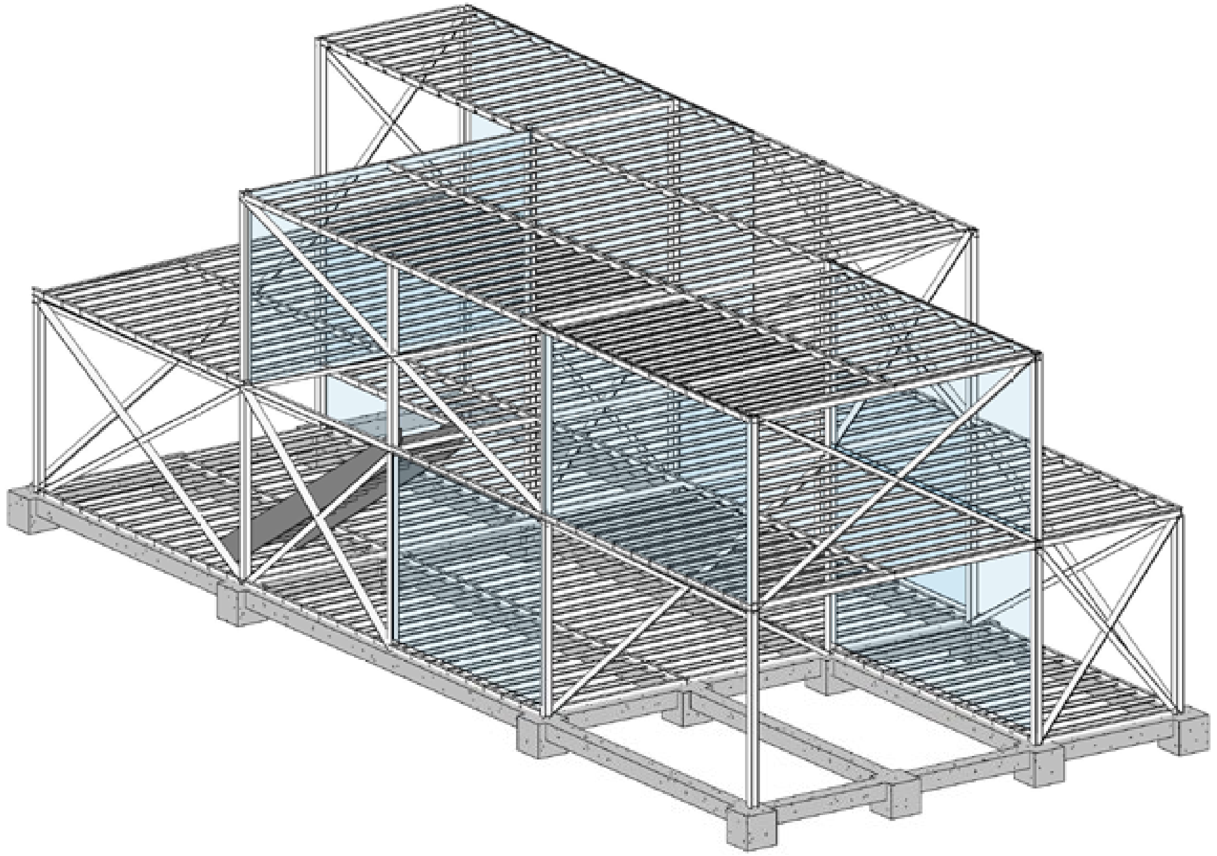


FIGURE 3.17 - Steel structure. Front perspective

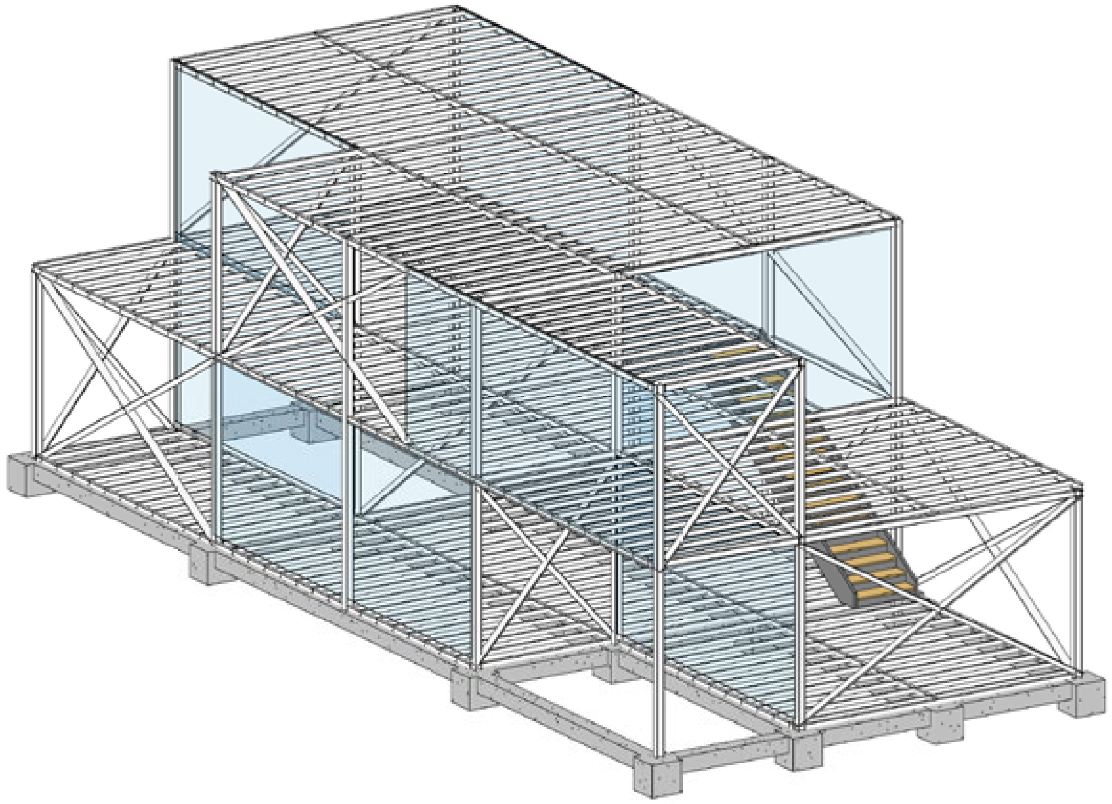


FIGURE 3.18 - Steel structure. Rear perspective

Scenario 1 -Vancouver

Wall frames - *U-factor = 0,255*			
$U_{assembly}$	0,241	*1 / R*	[W / m2*K]
Mass	**17,942**		[kg/m2]
Yie	**0,238**		[W / m2*K]
Time shift	**1,256**		[h]
Floor - *U-factor = 0,187*			
$U_{assembly}$	0,185	*1 / R*	[W / m2*K]
Mass	**17,942**		[kg/m2]
Yie	**0,017**		[W / m2*K]
Time shift	**1,256**		[h]
Ceiling - *U-factor = 0,147*			
$U_{assembly}$	0,142	*1 / R*	[W / m2*K]
Mass	**34,861**		[kg/m2]
Yie	**0,123**		[W / m2*K]
Time shift	**4,084**		[h]

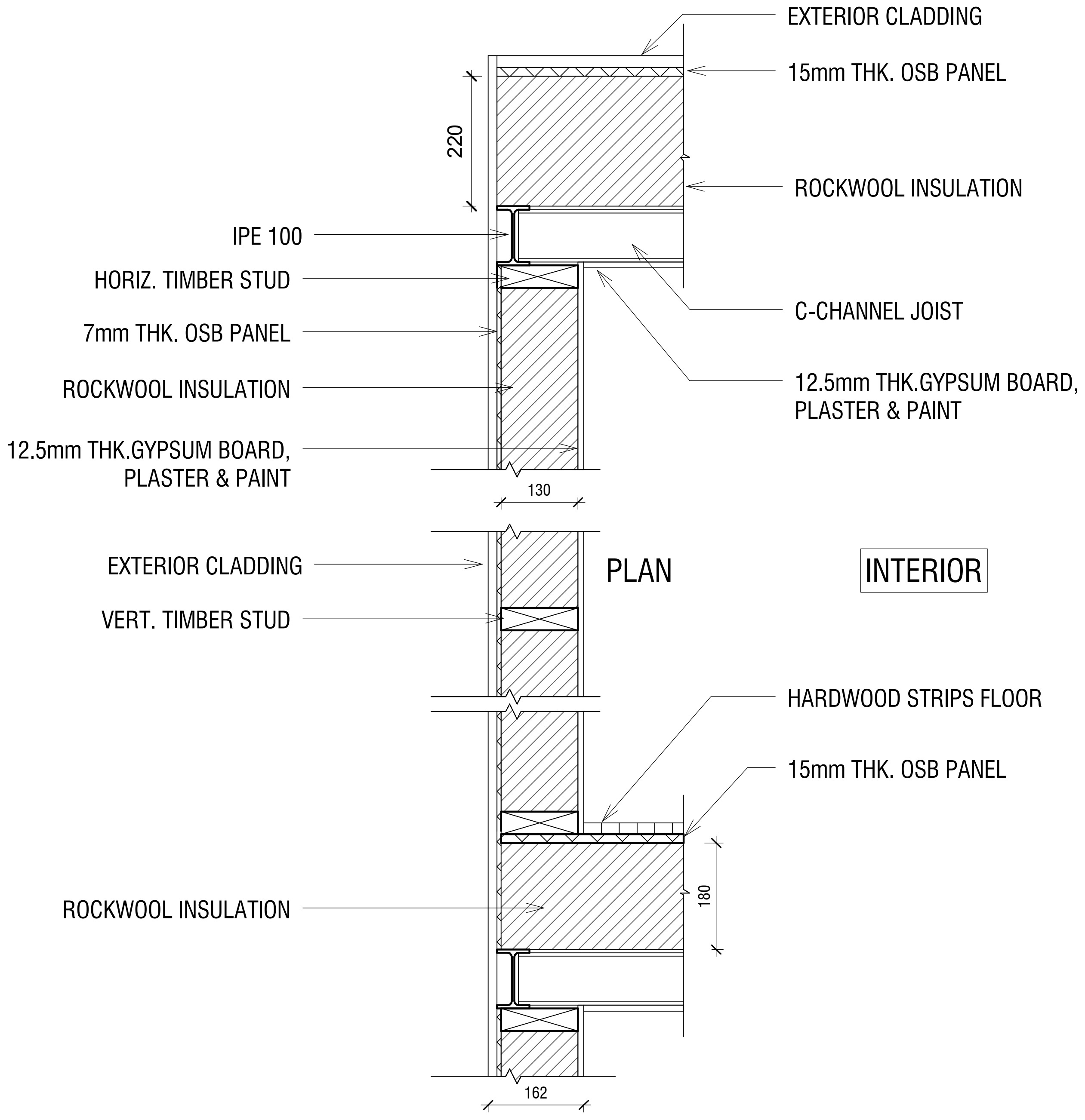


FIGURE 3.19 - Steel structure assemblies. Vancouver 1:10

Scenario 2 -Durban

Wall frames - *U-factor = 0,34*			
$U_{assembly}$	0,179	*1 / R*	[W / m2*K]
Mass	**101,586**		[kg/m2]
Yie	**0,048**		[W / m2*K]
Time shift	**10,135**		[h]
Floor - *U-factor = 0,266*			
$U_{assembly}$	0,255	*1 / R*	[W / m2*K]
Mass	**101,586**		[kg/m2]
Yie	**0,028**		[W / m2*K]
Time shift	**10,135**		[h]
Ceiling - *U-factor = 0,17*			
$U_{assembly}$	0,142	*1 / R*	[W / m2*K]
Mass	**107,886**		[kg/m2]
Yie	**0,058**		[W / m2*K]
Time shift	**10,862**		[h]

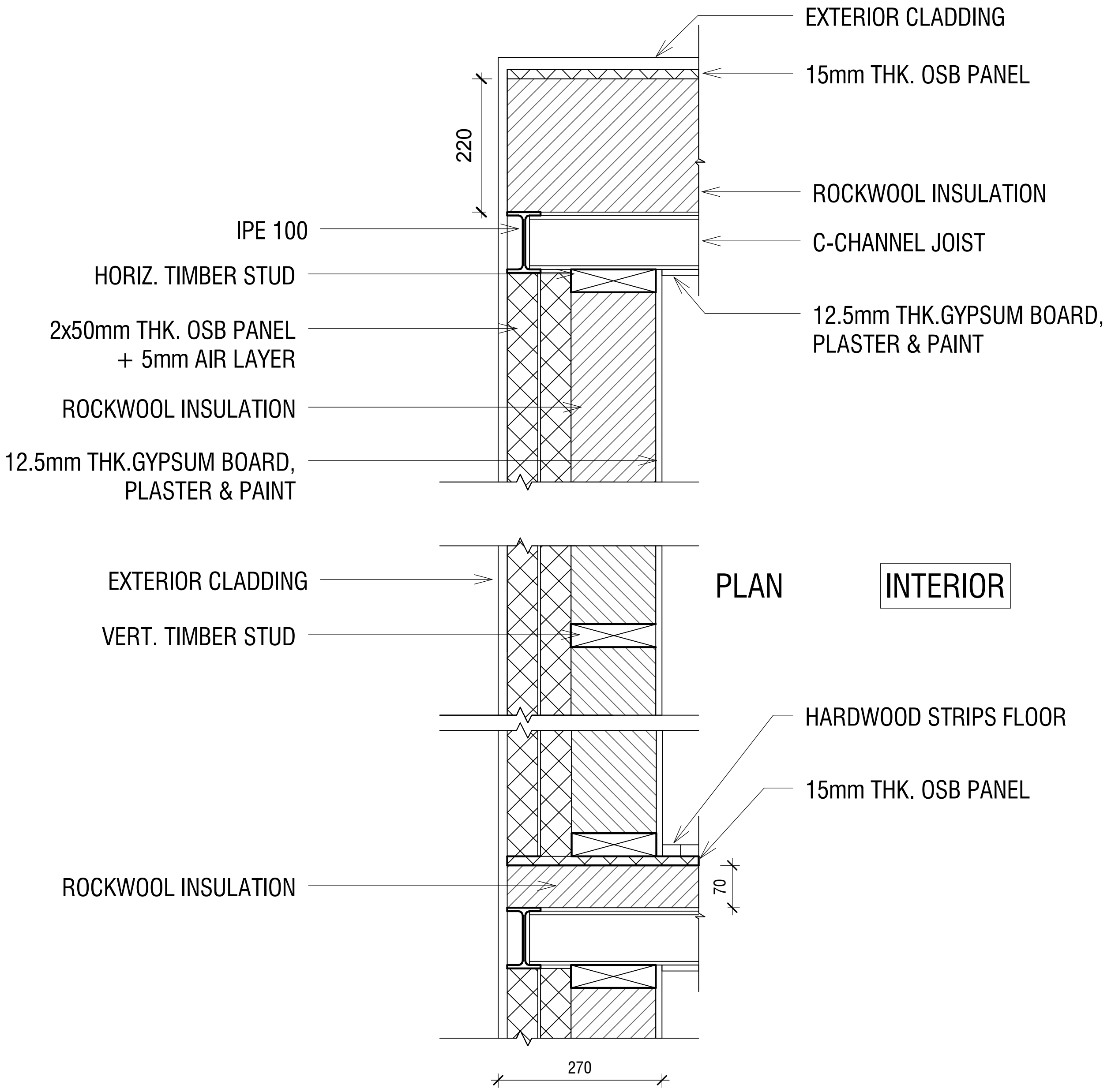


FIGURE 3.20 - Steel structure assemblies. Durban 1:10

Scenario 3 -Chennai

Wall frames - *U-factor = 0,476*			
$U_{assembly}$	0,442	*1 / R*	[W / m2*K]
Mass	**371,811**		[kg/m2]
Yie	**0,056**		[W / m2*K]
Time shift	**11,811**		[h]
Floor - *U-factor = 0,363*			
$U_{assembly}$	0,363	*1 / R*	[W / m2*K]
Mass	**371,811**		[kg/m2]
Yie	**0,056**		[W / m2*K]
Time shift	**11,811**		[h]
Ceiling - *U-factor = 0,198*			
$U_{assembly}$	0,192	*1 / R*	[W / m2*K]
Mass	**95,286**		[kg/m2]
Yie	**0,053**		[W / m2*K]
Time shift	**10,275**		[h]

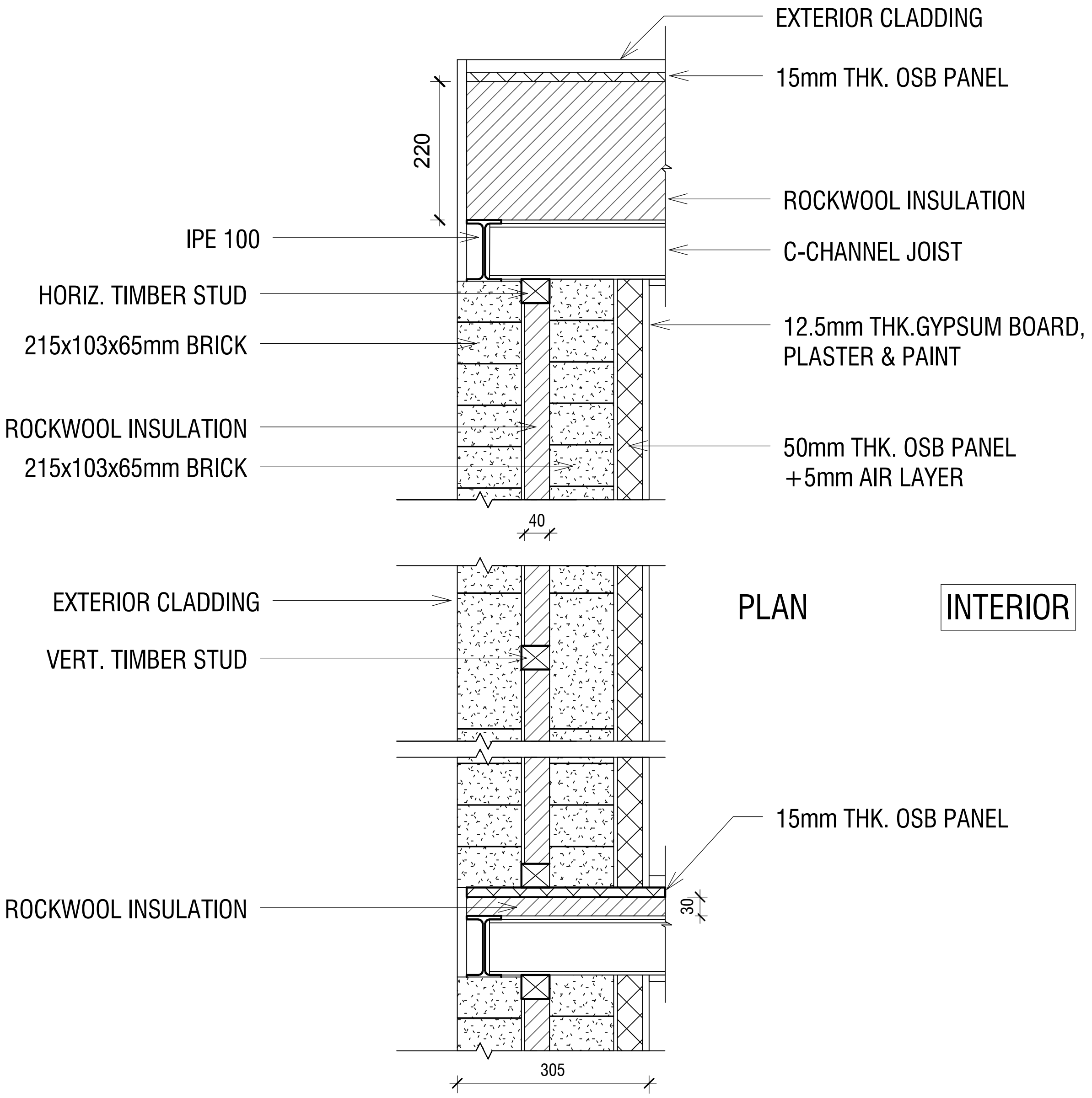


FIGURE 3.21 - Steel structure assemblies. Chennai 1:10

X-LAM STRUCTURE

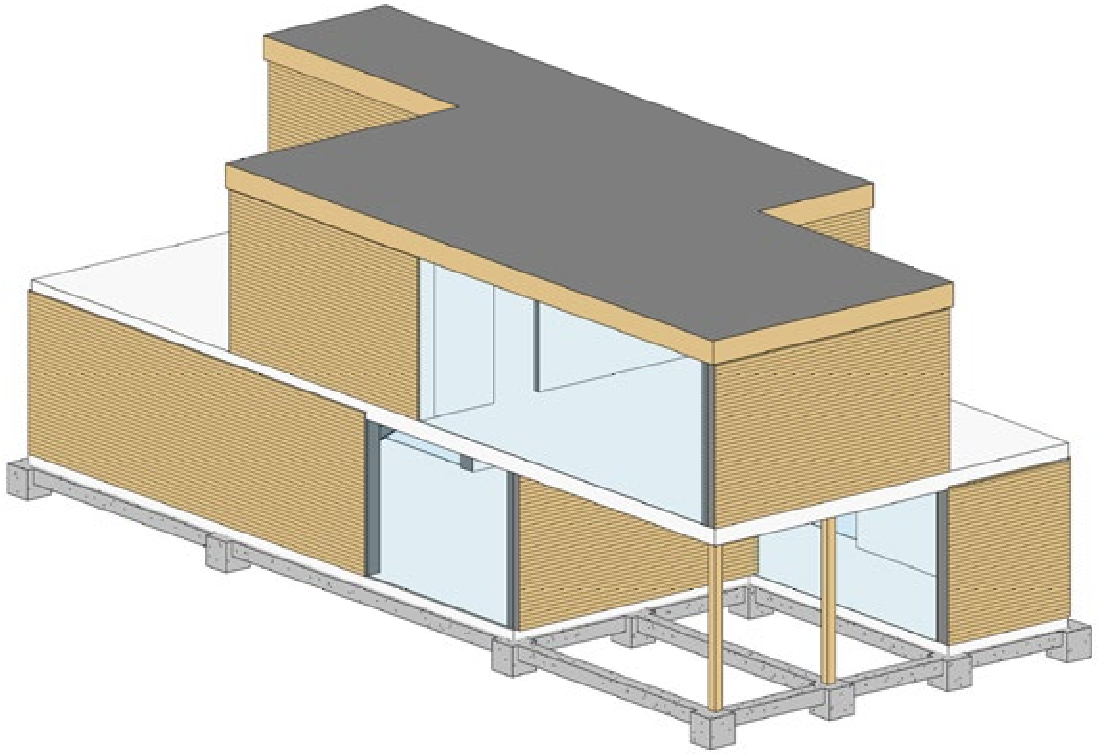


FIGURE 3.22 - X-Lam structure. Front perspective

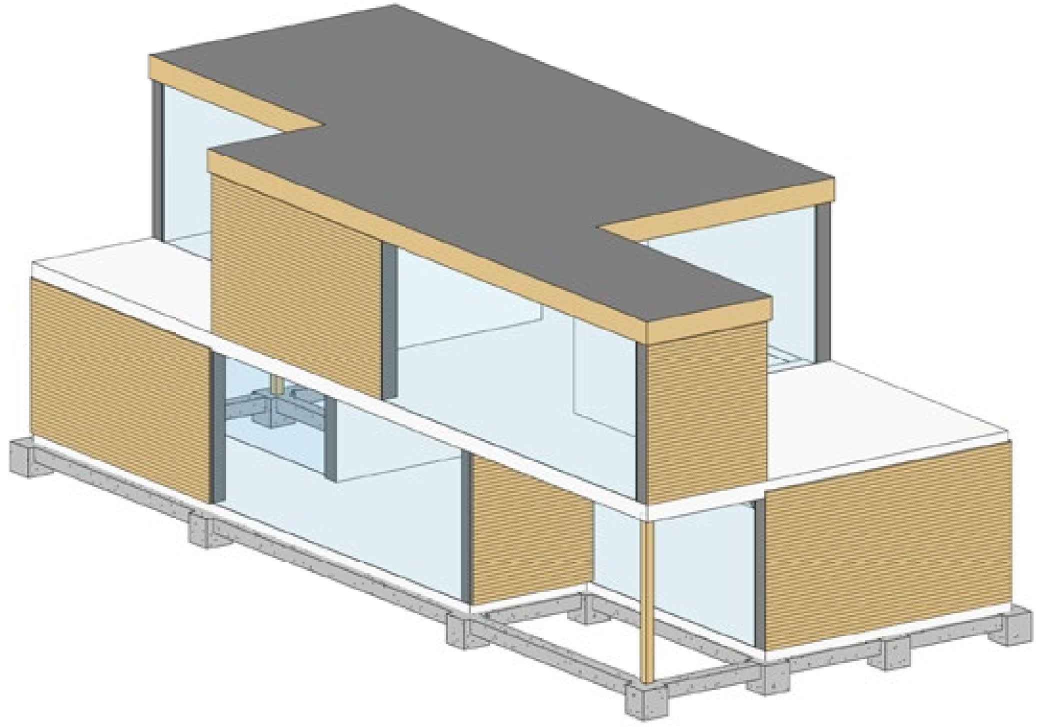


FIGURE 3.23 - X-Lam structure. Rear perspective

Scenario 1 -Vancouver

Wall frames - *U-factor = 0,255*			
$U_{assembly}$	0,245	*1 / R*	[W / m2*K]
Mass	**99,721**		[kg/m2]
Yie	**0,015**		[W / m2*K]
Time shift	**16,614**		[h]
Floor - *U-factor = 0,187*			
$U_{assembly}$	0,179	*1 / R*	[W / m2*K]
Mass	**99,721**		[kg/m2]
Yie	**0,003**		[W / m2*K]
Time shift	**16,614**		[h]
Ceiling - *U-factor = 0,147*			
$U_{assembly}$	0,142	*1 / R*	[W / m2*K]
Mass	**102,721**		[kg/m2]
Yie	**0,018**		[W / m2*K]
Time shift	**12,616**		[h]

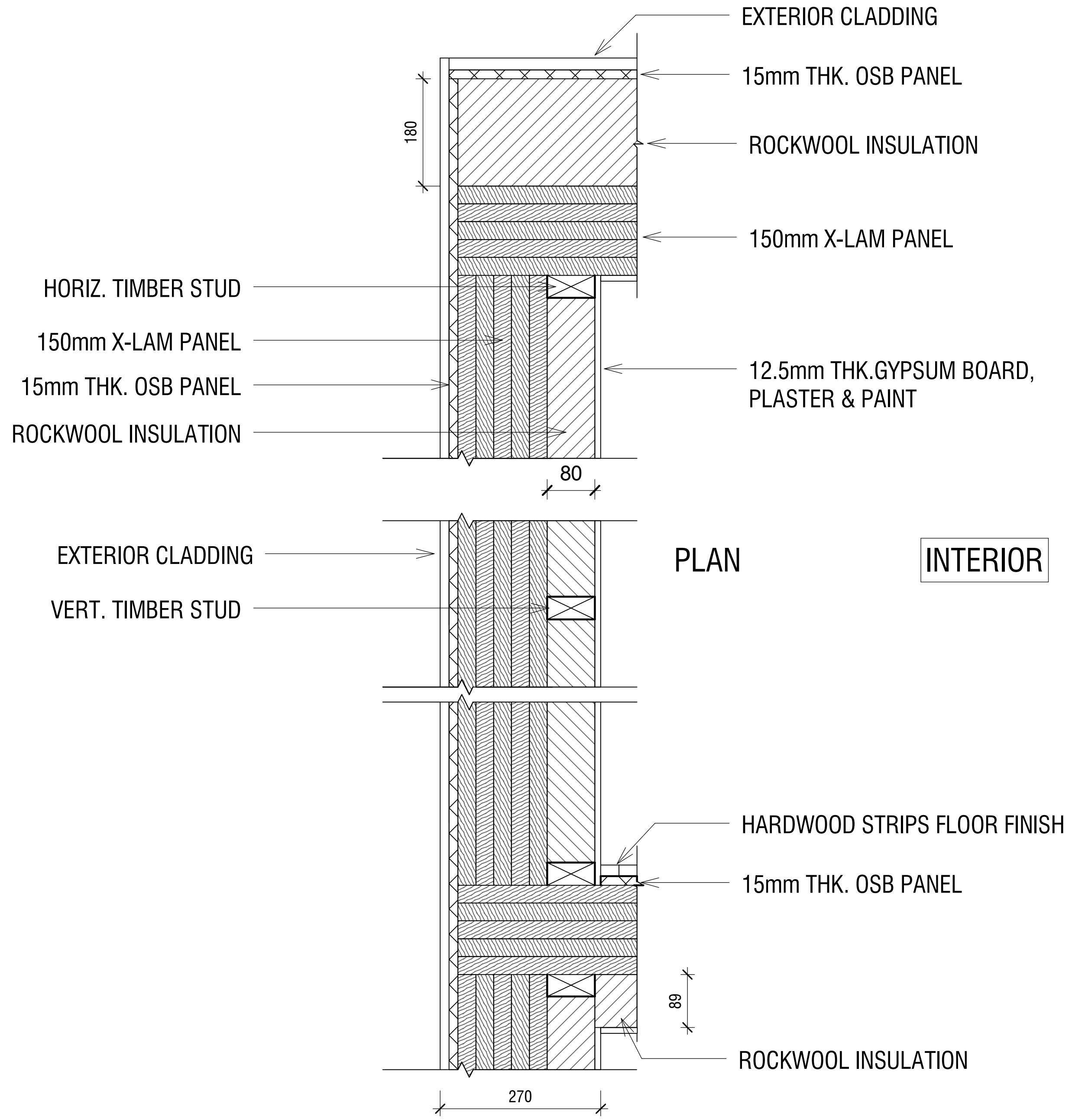


FIGURE 3.24 - Steel structure assemblies. Vancouver 1:10

Scenario 2 -Durban

Wall frames - *U-factor = 0,34*			
$U_{assembly}$	0,236	*1 / R*	[W / m2*K]
Mass	**170,371**		[kg/m2]
Yie	**0,007**		[W / m2*K]
Time shift	**19,488**		[h]
Floor - *U-factor = 0,266*			
$U_{assembly}$	0,261	*1 / R*	[W / m2*K]
Mass	**170,371**		[kg/m2]
Yie	**0,007**		[W / m2*K]
Time shift	**19,488**		[h]
Ceiling - *U-factor = 0,17*			
$U_{assembly}$	0,165	*1 / R*	[W / m2*K]
Mass	**96,721**		[kg/m2]
Yie	**0,027**		[W / m2*K]
Time shift	**11,495**		[h]

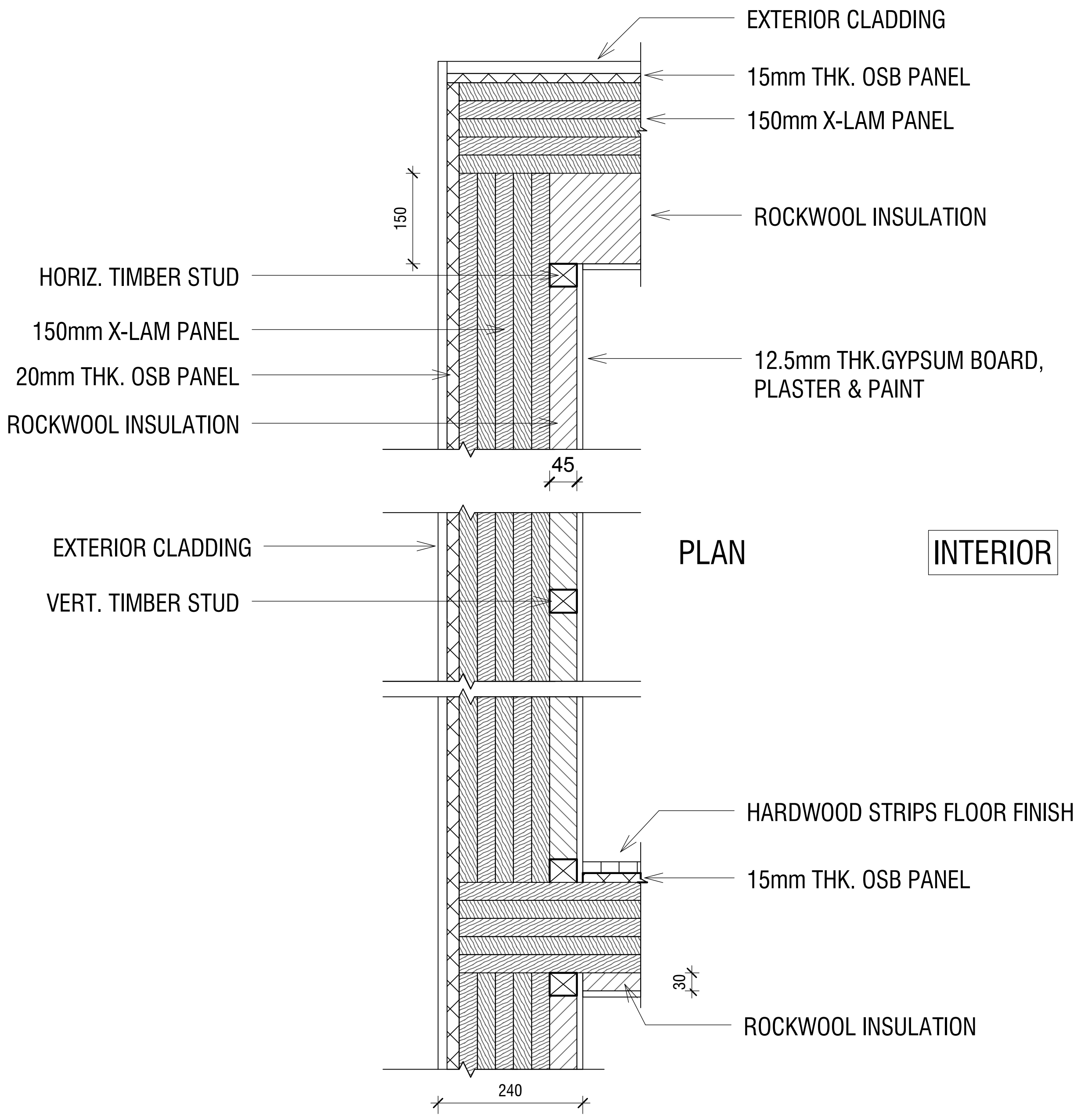


FIGURE 3.25 - X-Lam structure assemblies. Durban 1:10

Scenario 3 -Chennai

Wall frames - *U-factor = 0,476*			
$U_{assembly}$	0,467	*1 / R*	[W / m2*K]
Mass	**239,396**		[kg/m2]
Yie	**0,122**		[W / m2*K]
Time shift	**11,399**		[h]
Floor - *U-factor = 0,363*			
$U_{assembly}$	0,323	*1 / R*	[W / m2*K]
Mass	**239,396**		[kg/m2]
Yie	**0,017**		[W / m2*K]
Time shift	**11,399**		[h]
Ceiling - *U-factor = 0,198*			
$U_{assembly}$	0,188	*1 / R*	[W / m2*K]
Mass	**128,646**		[kg/m2]
Yie	**0,018**		[W / m2*K]
Time shift	**14,586**		[h]

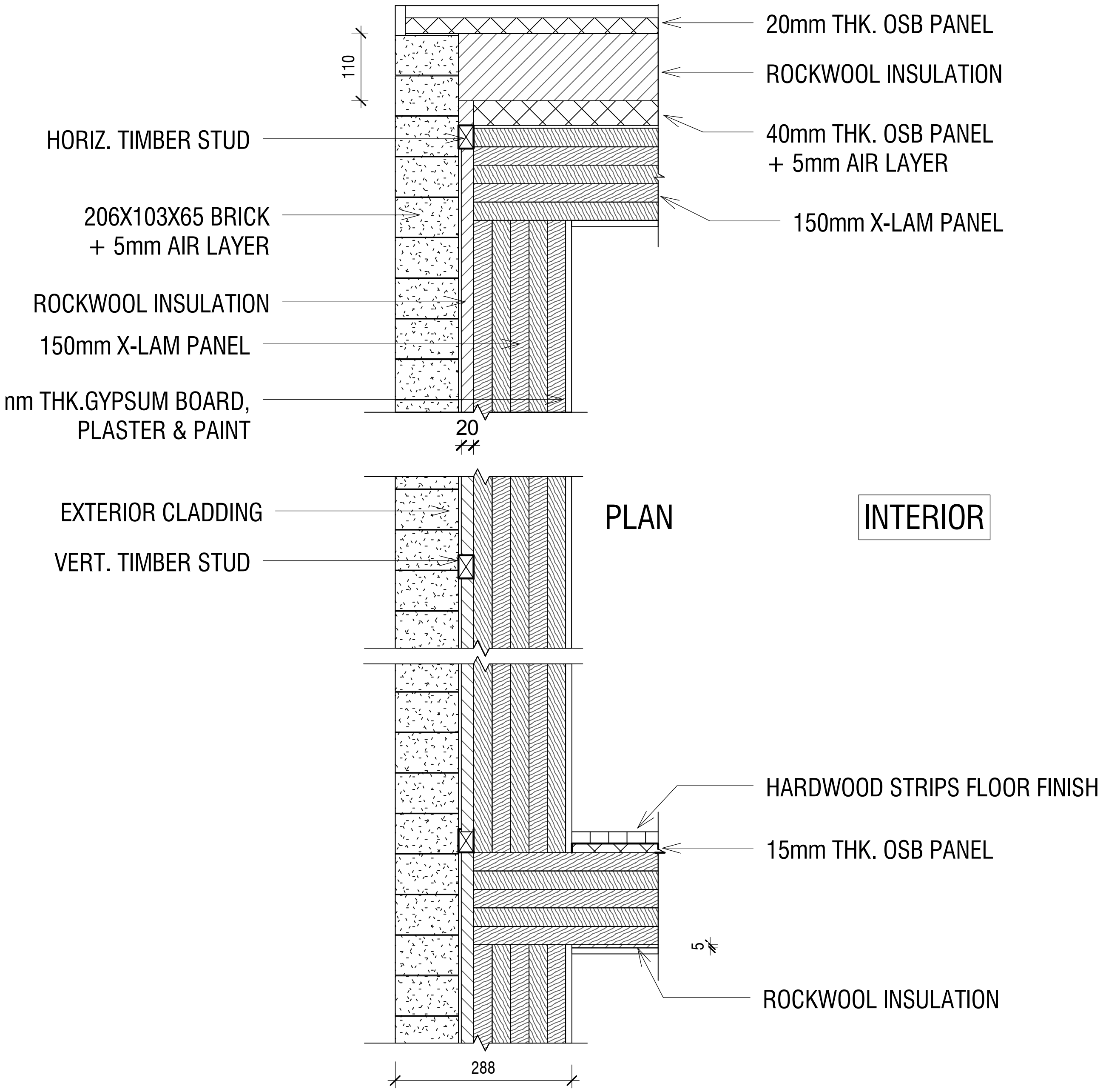


FIGURE 3.26 - X-Lam structure assemblies. Chennai 1:10

CHAPTER

IV

Embodied Energy

.1 Cradle to Gate

.2 Bills of quantities

.3 Module A1-2-3: results

.4 Gate to site

.5 Module A4 : results

.6 Environmental advantage

.7 Summary and observations

4.1 Cradle to Gate

The life cycle of most building products begins with the extraction of raw resources. In addition to the actual harvesting, mining or quarrying of resources. Data from the extraction phase includes transportation of raw materials to the plant, which defines the boundary between extraction and manufacturing. Then during the manufacturing stage, raw materials are converted into building materials and ready for the delivery to site. This phase typically accounts for the largest proportion of embodied energy and emissions associated with the life cycle of building products.
Embodied Energy is defined by the BSRIA guide as “the total primary energy consumed from direct and indirect processes associated with a product or service and within the boundary of cradle-to-gate. This includes every stage and emission produced until the product is ready to leave the factory gate”.
Therefore the cradle-to-gate stage includes modules A1-2-3 and is defined the Product Stage within the life cycle of a building.

As mentioned earlier, LCI inventory analysis involves mainly data collection and calculations to quantfy material and energy inputs-outputs of the building assemblies.

One of the major barriers in a lifecycle assessment is the availability of data. Several pubblications have used the concept of pedigree matrix for data quality assessment. The goal of this matrix is to give an indication of the reliability of data and to analyze its coherence with goal and boundaries. Further research development should aim at the inclusion of a quality data assessment within the study.

Data used for LCI is generally based on the ICE - *Inventory of Carbon and Energy* - guide from BSRIA and pubblished Environmental Product Declarations -*EPDs*.

Emissions related to each building material are expressed in mass of impact category equivalent per kg of material.
To define the total ammount of emissions for the Product Stage it is necessary to define a Bill of Quantities for each building.

	Thermal Properties				Emissions- Stage **A1/A3**			
	λ [W/mK]	**ρ** [Kg/m3]	**cp** [kJ/Kg*K]	**δ** [m]	**GWP** [KgCO2e/kg]	**ODP** [KgCFC11e/kg]	**AP** [KgSO2e/kg]	**EP** [Kg(PO4)3e/kg]
INSULATION								
Mineral wool	0,035	19,5	0,85	0,13	1,28	1,164E-09	9,800E-03	2,036E-03
Rockwool	0,034	30	0,84	0,1	1,12	4,414E-08	7,928E-03	3,780E-04
EPS - Expanded Polystyrene	0,034	25	1,5	0,16	3,29	5,200E-08	5,600E-03	6,400E-04
XPS - Extruded Polystyrene	0,035	33,7	1,5	0,16	2,8	3,710E-09	7,896E-03	6,136E-04
PU - Polyurethane Rigid foam	0,026	31	1,47	0,16	3,85	5,100E-06	9,288E-03	1,196E-03
INTERIOR FINISH								
Gypsum board -13mm	0,21	697	1,1	0,018	0,276	1,030E-08	7,277E-04	1,433E-04
Plywood flooring - 15mm	0,12	493	1,215	0,06	-0,737	2,351E-12	3,960E-03	1,030E-03
Hardwood strips finish -19mm	0,12	629,43	1,215	0,06	-0,093	1,890E-09	3,240E-03	2,130E-04
STRUCTURE								
Container corrugation - SPA-H corten steel	42,7	7750	0,477	0,7	/	/	/	/
Structural Steel - S235 to S960	48	7850	0,48	0,7	2,61	2,720E-11	8,320E-03	7,290E-04
Avg Recycled Structural Steel - S235 to S960	48	7850	0,48	0,7	0,72	3,900E-11	1,970E-03	1,930E-04
Hardwood structural timber	0,15	735	1,7	0,06	-1,21	1,010E-11	2,435E-03	5,700E-04
X-Lam (51mm to 500mm)	0,12	491,65	1,61	0,06	0,167	8,726E-09	4,902E-04	1,186E-04
Concrete	1,8	2400	1000	0,14	0,72	2,338E-09	9,540E-04	2,830E-05
SUB-STRUCTURE								
Hot-dip galvanized Steel Stud Frame	83	7870	0,481	0,7	2,9	1,100E-02	7,000E-03	6,100E-04
Timber frame - min 12mm	0,13	507	1,6	0,06	0,09827	1,260E-07	2,218E-03	2,160E-04
Brick all purpose - 215 x 102,5 x 65mm	0,82	1550	0,84	0,12	0,158	5,370E-10	1,350E-03	5,000E-05
EXTERIOR FINISH								
OSB panel (6 to 40mm)	0,13	600	1,55	0,06	0,4138	4,217E-08	2,174E-01	1,702E-04
Plywood panel - 7mm	0,12	493	1,215	0,06	-1,467	9,970E-12	1,270E-02	3,710E-03
Radiata pine weatherboard cladding (12% moisture)	0,1	510	1,95	0,06	0,465725	1,540E-07	6,772E-03	5,990E-04

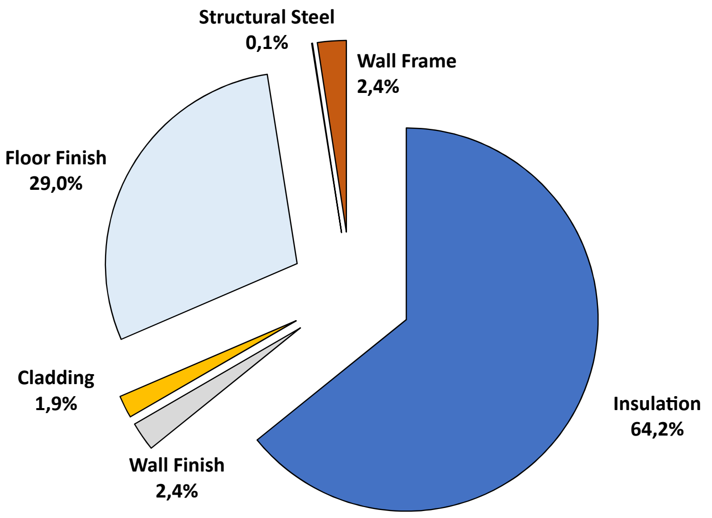
FIGURE 4.1 - Matierials inventory database used

4.2 Bills of Quantities

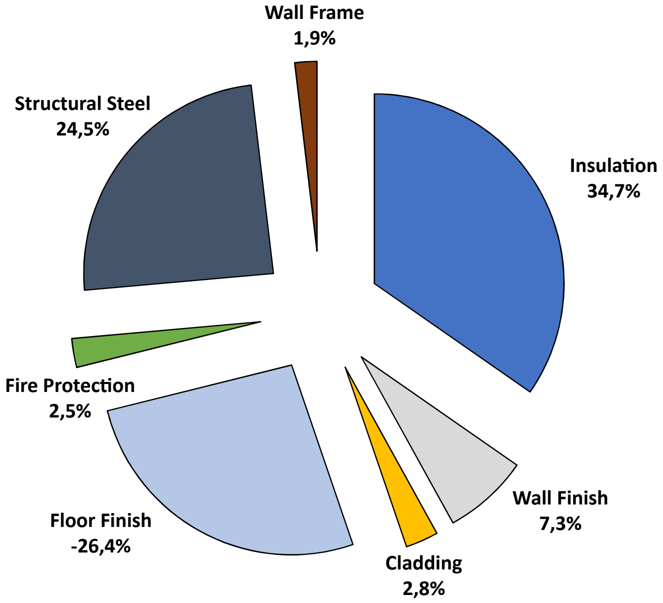
CONTAINER STRUCTURE - *Vancouver*

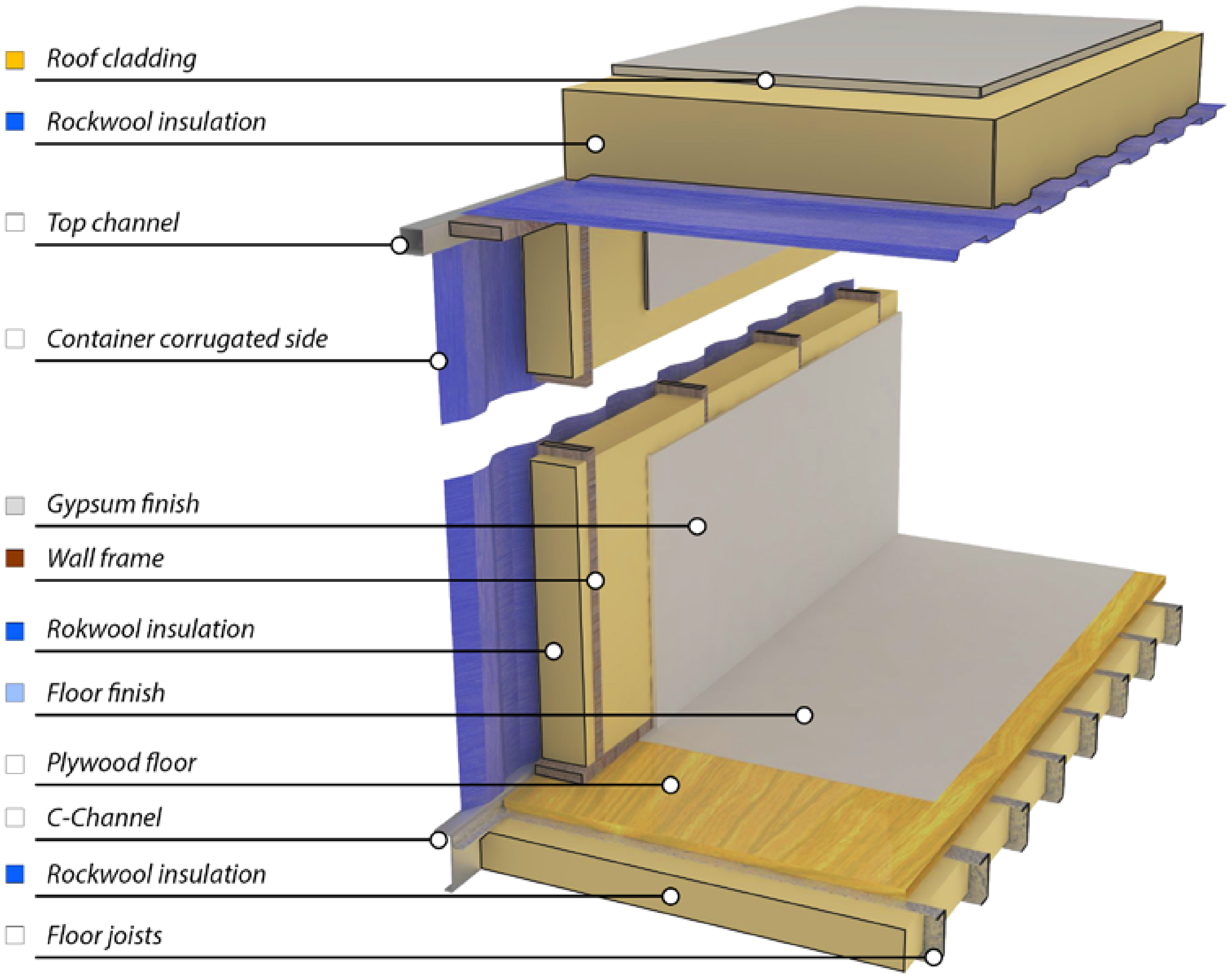
		Ptot [kg]	Embodied Energies - Stage A1/A3			
			GWP [KgCO2e/kg]	**ODP** [KgCFC11e/kg]	**AP** [KgSO2e/kg]	**EP** [Kg(PO4)3e/kg]
🟦	*Insulation - Rockwool*	2813,374	3150,979436	0,000124182	22,304433	1,063455559
⬜	*Wall finish - Gypsum board*	2401,194	662,7295427	2,47323E-05	1,74734887	0,3440911
🟨	*Cladding - Radiata pine*	83,058	12,49146997	3,66287E-06	0,162545093	0,013953794
🟩	*Fire protection - R120*	25768,746	-2396,493397	4,87029E-05	83,49073769	5,488742941
🟦	*Structure - Steel*	89,310	224,1681	1,42896E-05	1,143168	0,455481
🟦	*Floor Finish - Hardwood strips*	854,210	2229,487762	2,32345E-08	7,107026122	0,622718996
🟫	*Wall Frame - Hardwood Timber*	1732,793	170,2815964	0,000218332	3,843335512	0,37428335
	TOTALs	**33742,686**	**4053,64451**	**0,000433925**	**119,7985943**	**8,36272674**

Volume of materials [m^3]

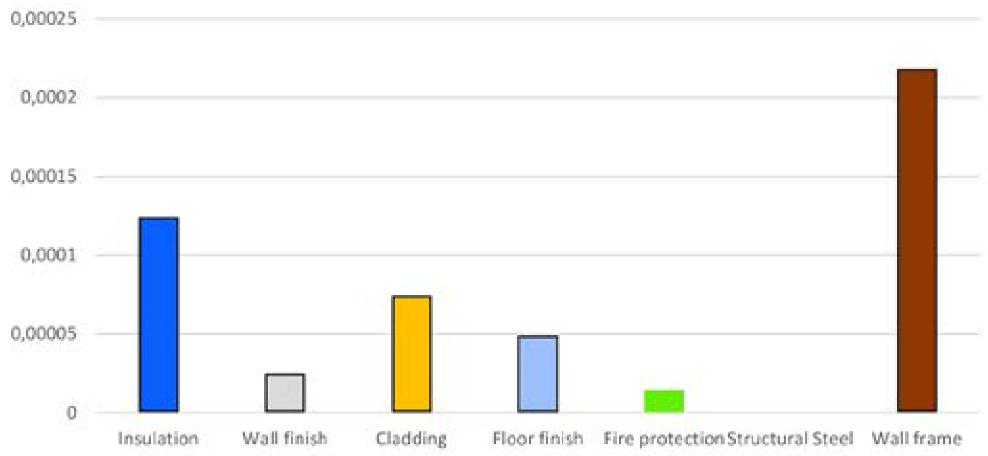


Global Warming Potential [kg CO_2e]

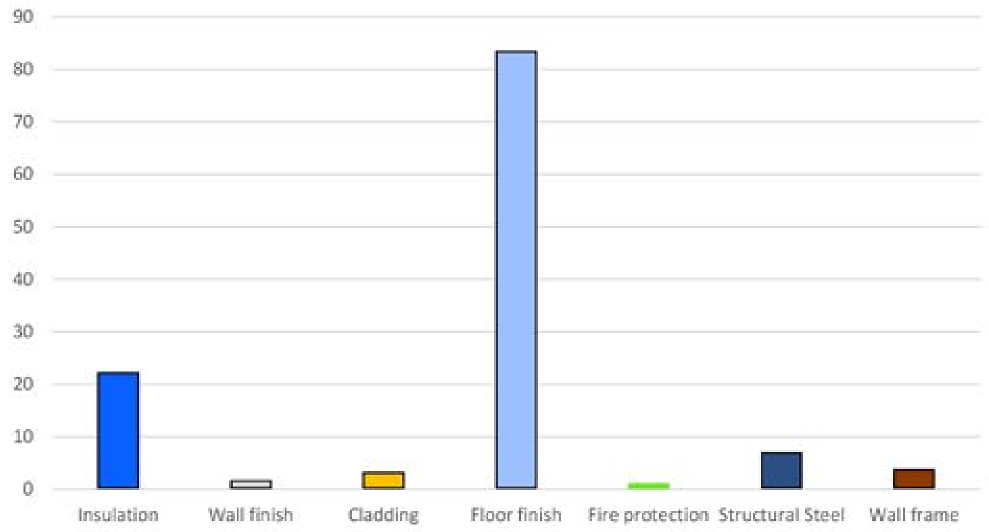




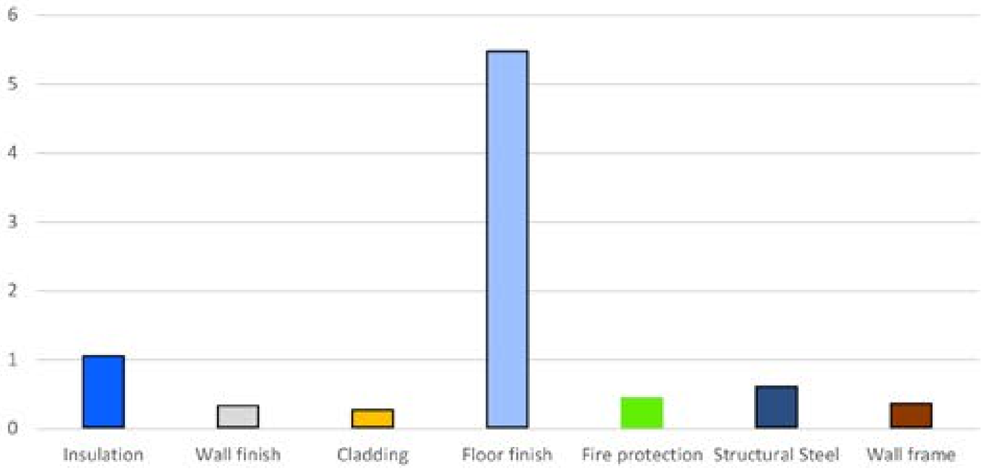
Ozone Depletion Potential [kg $CFC_{11}e$]



Acidification Potential [kg SO_2e]

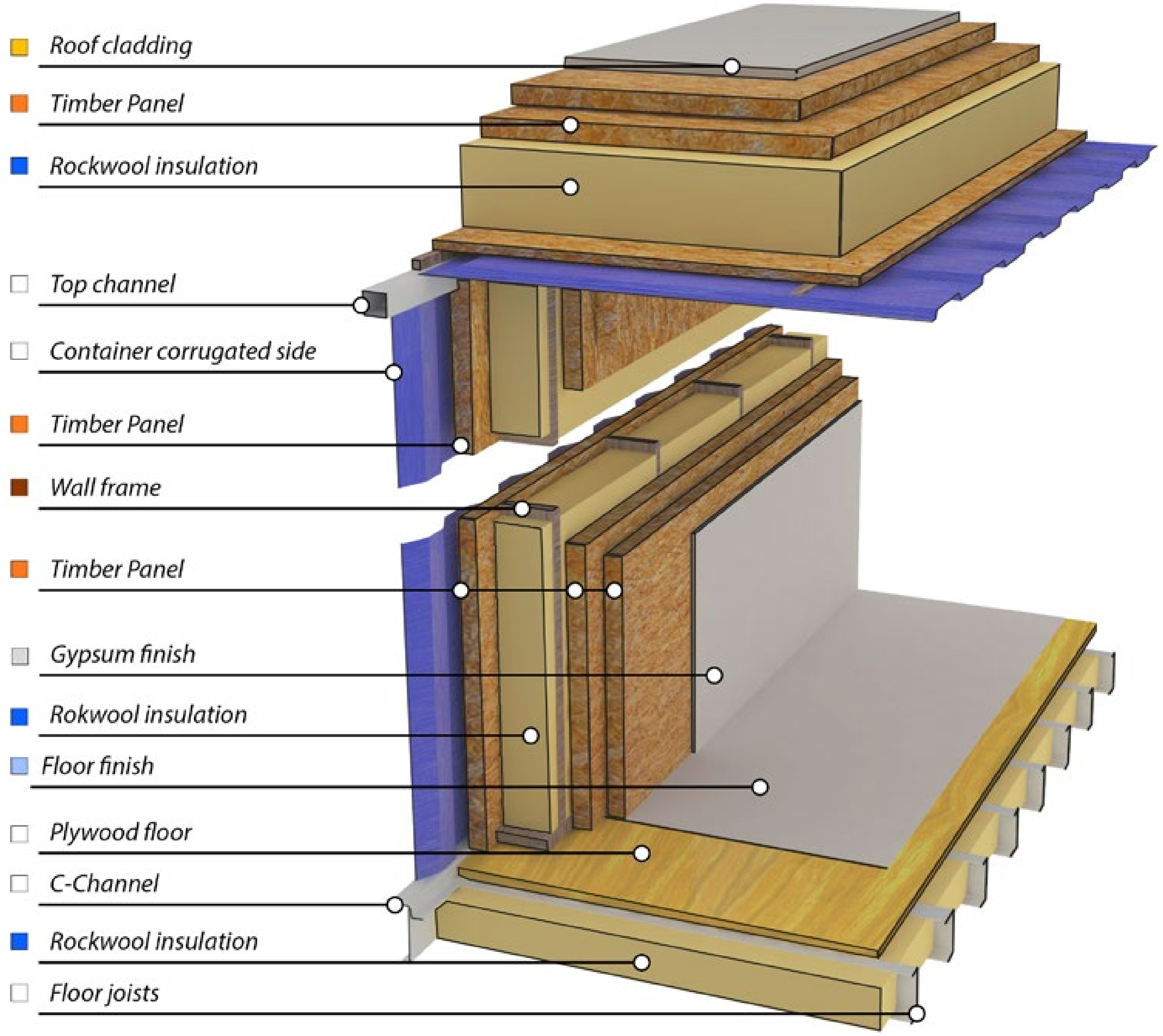


Eutrophication Potential [kg $(PO_4)3e$]

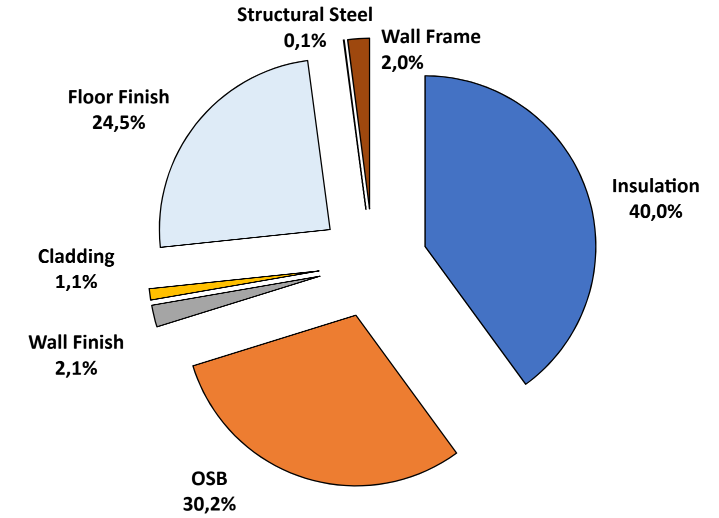


CONTAINER STRUCTURE - *Durban*

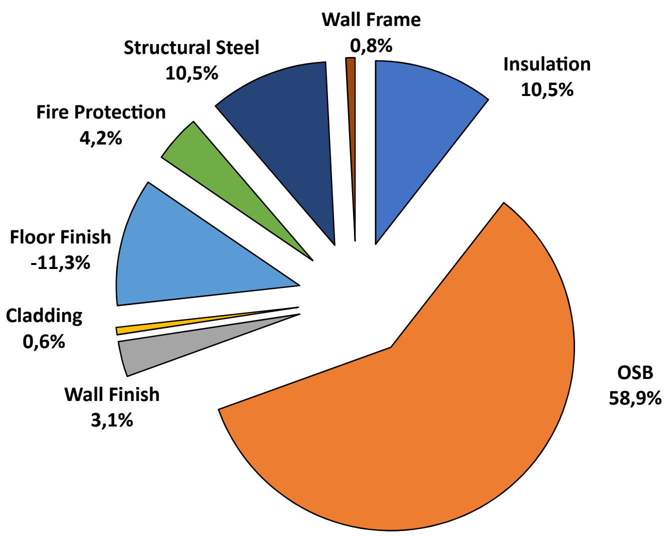
	Ptot [kg]	**Embodied Energies** - Stage A1/A3			
		GWP [KgCO2e/kg]	**ODP** [KgCFC11e/kg]	**AP** [KgSO2e/kg]	**EP** [Kg(PO4)3e/kg]
🟦 *Insulation - Rockwool*	2000,808	2,241E+03	8,832E-05	1,586E+01	7,563E-01
🟧 *OSB - Timber panel*	30280,608	1,253E+04	1,277E-03	6,583E+03	5,153E+00
⬜ *Wall finish - Gypsum board*	2401,194	6,627E+02	2,473E-05	1,747E+00	3,441E-01
🟨 *Cladding - Radiata pine*	910,962	1,370E+02	4,017E-05	1,783E+00	1,530E-01
🟦 *Floor Finish - Hardwood strips*	25768,746	-2,396E+03	4,870E-05	8,349E+01	5,489E+00
🟩 *Fire protection - R120*	354,313	8,893E+02	5,669E-05	4,535E+00	1,807E+00
🟦 *Structure - Steel*	854,210	2,229E+03	2,323E-08	7,107E+00	6,227E-01
🟫 *Wall Frame - Hardwood Timber*	1732,793	1,703E+02	2,183E-04	3,843E+00	3,743E-01
TOTALs	64303,634	**1,646E+04**	**1,754E-03**	**6,701E+03**	**1,470E+01**

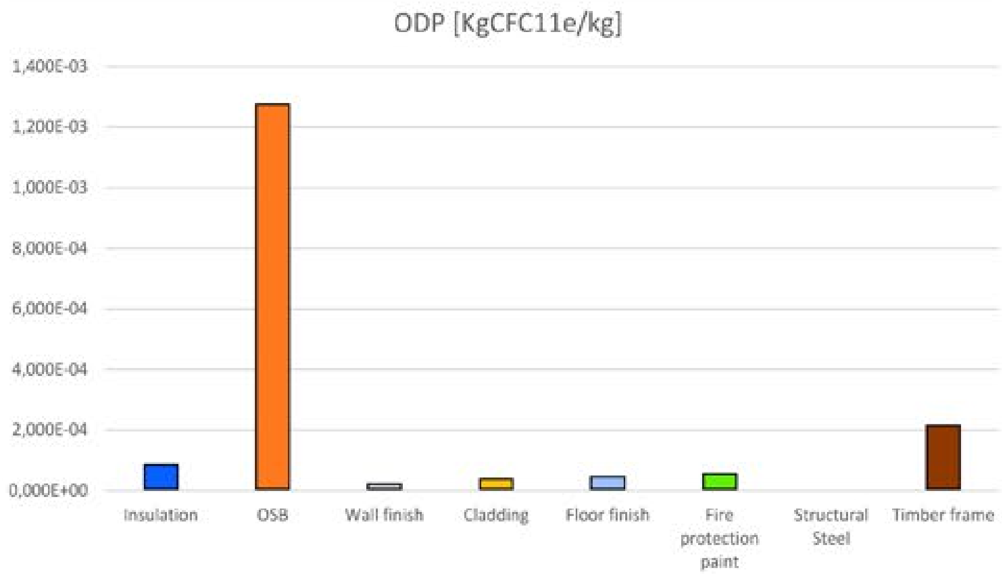


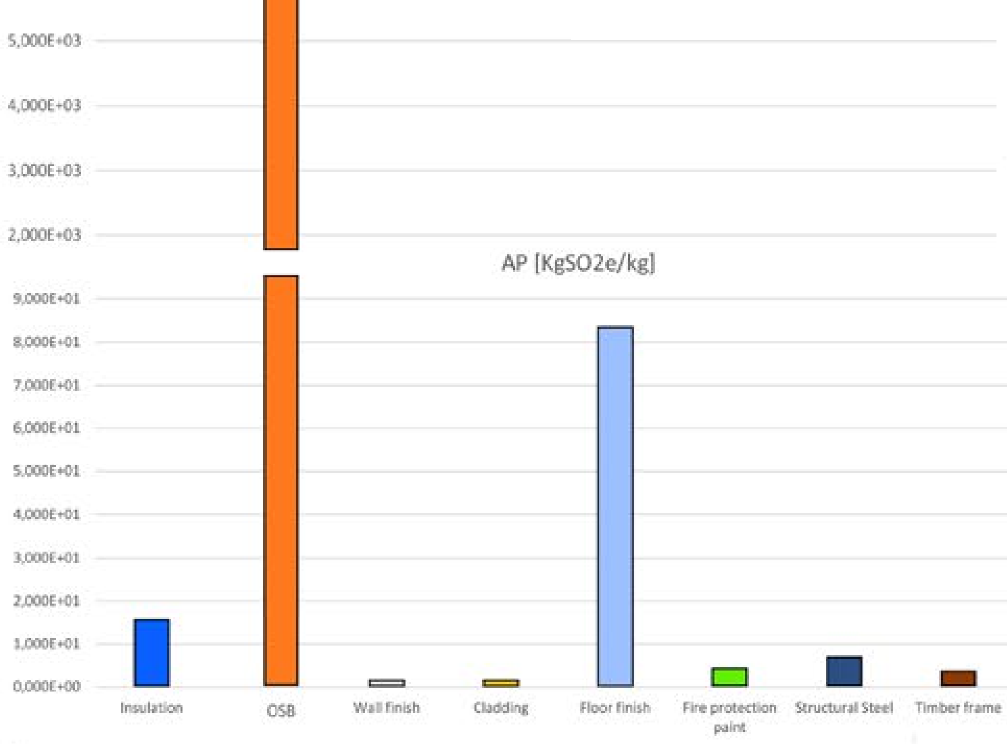
Volume of materials [m^3]

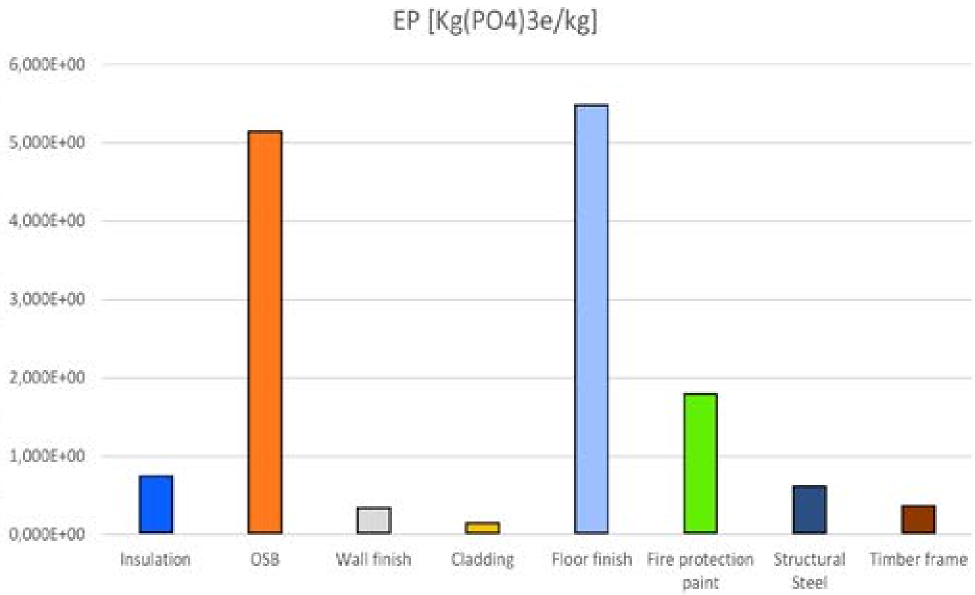


Global Warming Potential [kg CO_2e]





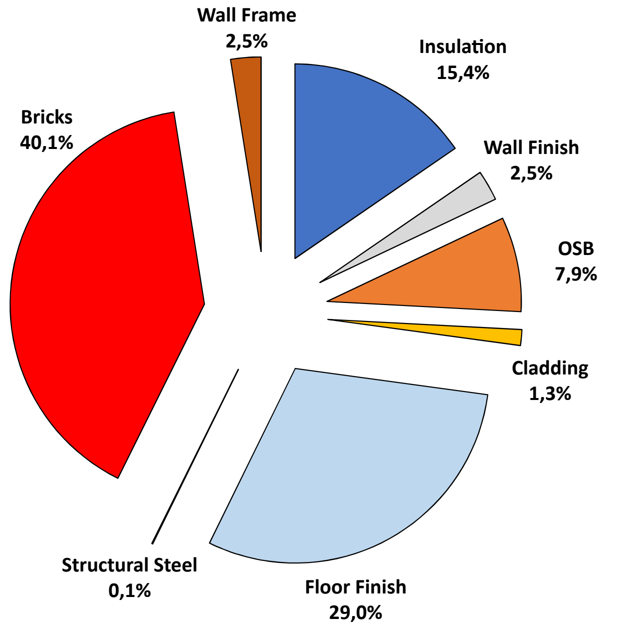




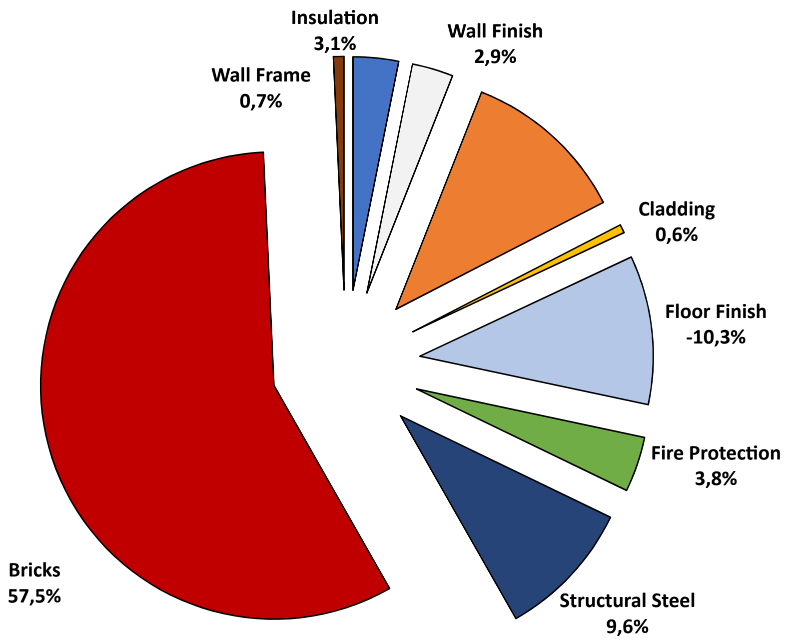
CONTAINER STRUCTURE - *Chennai*

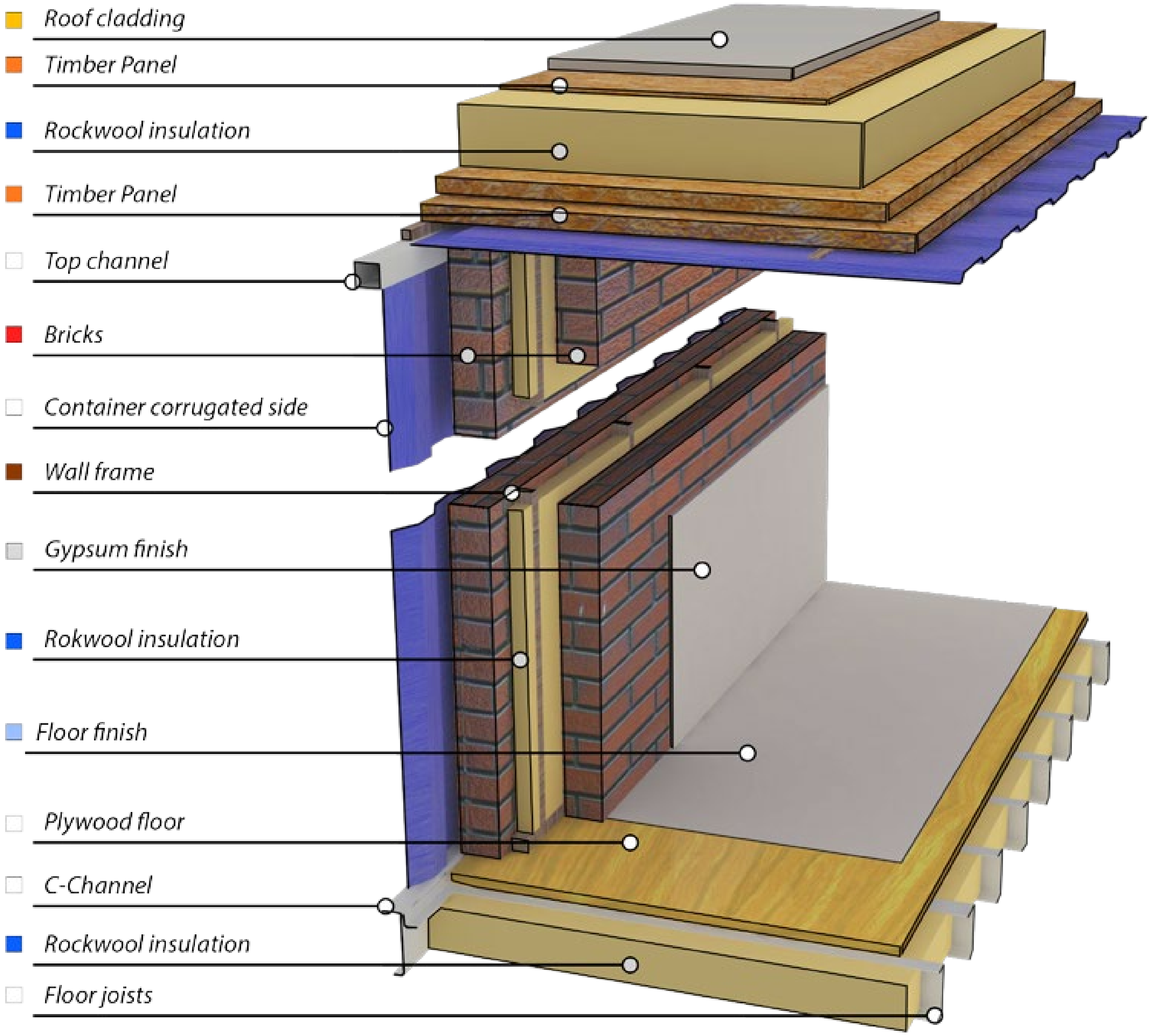
		Ptot [kg]	Embodied Energies - Stage A1/A3			
			GWP [KgCO2e/kg]	**ODP** [KgCFC11e/kg]	**AP** [KgSO2e/kg]	**EP** [Kg(PO4)3e/kg]
🟦	*Insulation - Rockwool*	650,356	728,3987962	2,87067E-05	5,156022907	0,245834594
⬜	*Wall finish - Gypsum board*	2401,194	662,7295427	2,47323E-05	1,74734887	0,3440911
🟧	*OSB - Timber panel*	6430,320	2660,866416	0,000271167	1397,951568	1,094247554
🟨	*Cladding - Radiata pine*	910,962	137,003219	4,01734E-05	1,782752634	0,153041616
🟦	*Floor Finish - Hardwood strips*	25768,746	-2396,493397	4,87029E-05	83,49073769	5,488742941
🟩	*Fire protection - R120*	354,313	889,326132	5,66901E-05	4,53520896	1,80699732
🟦	*Structure - Steel*	854,210	2229,487762	2,32345E-08	7,107026122	0,622718996
🟥	*Brick - Mass*	84615,522	13369,25244	4,54385E-05	114,2309544	4,230776088
🟫	*Wall Frame - Hardwood Timber*	1732,793	170,2815964	0,000218332	3,843335512	0,37428335
	TOTALs	**123718,416**	**18450,85251**	**0,000733966**	**1619,844955**	**14,36073356**

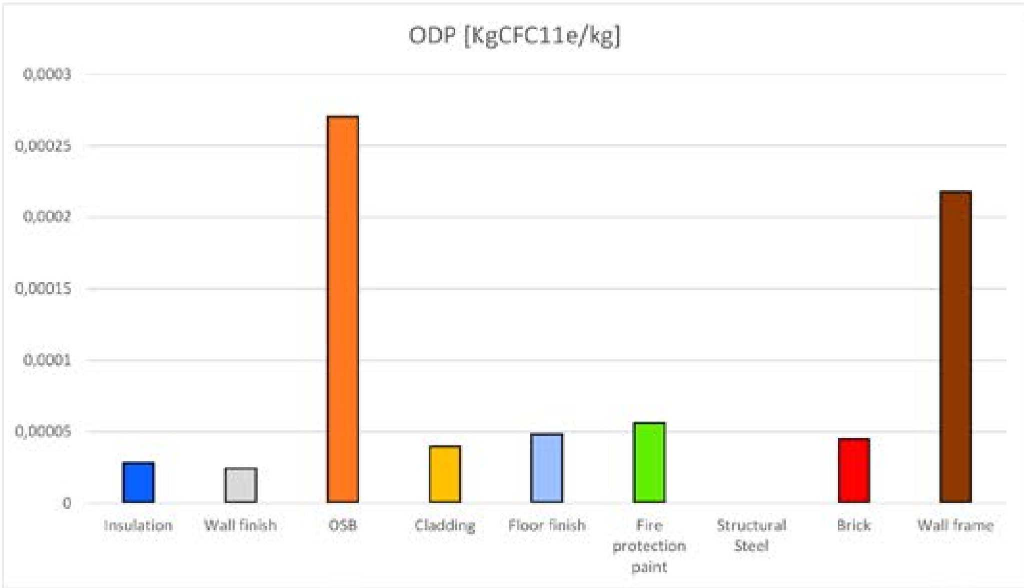
Volume of materials [m^3]

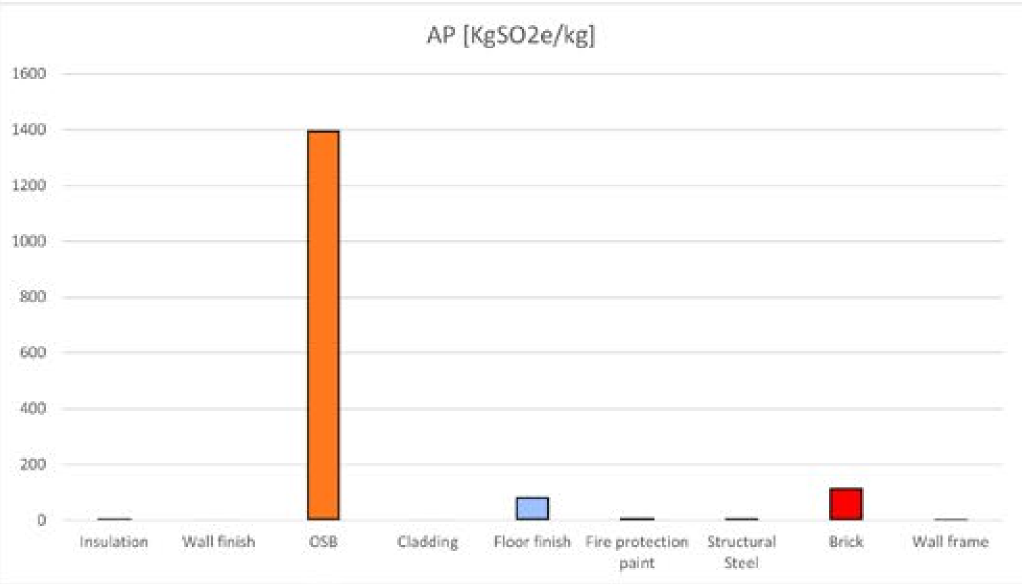


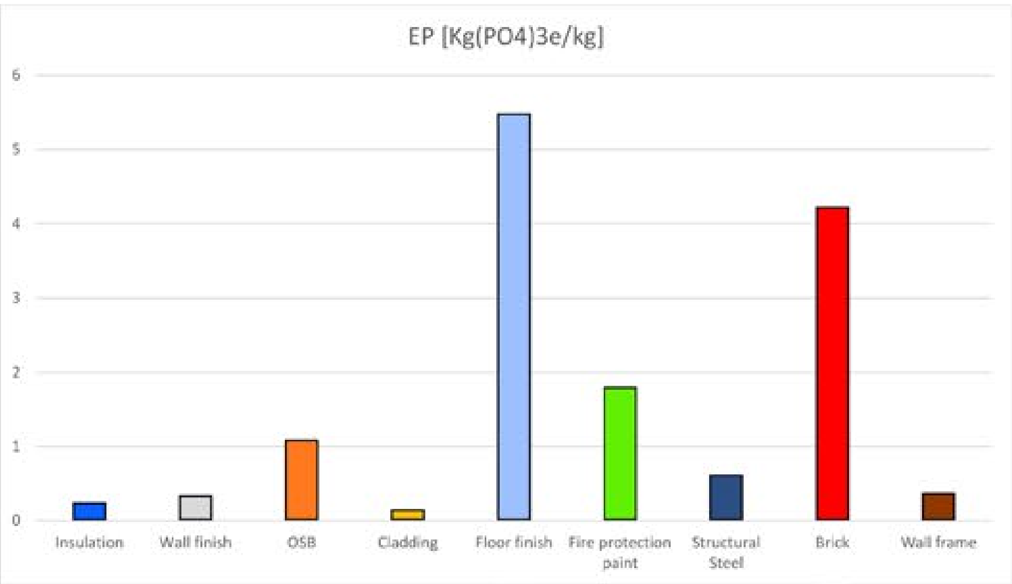
Global Warming Potential [kg CO_2e]





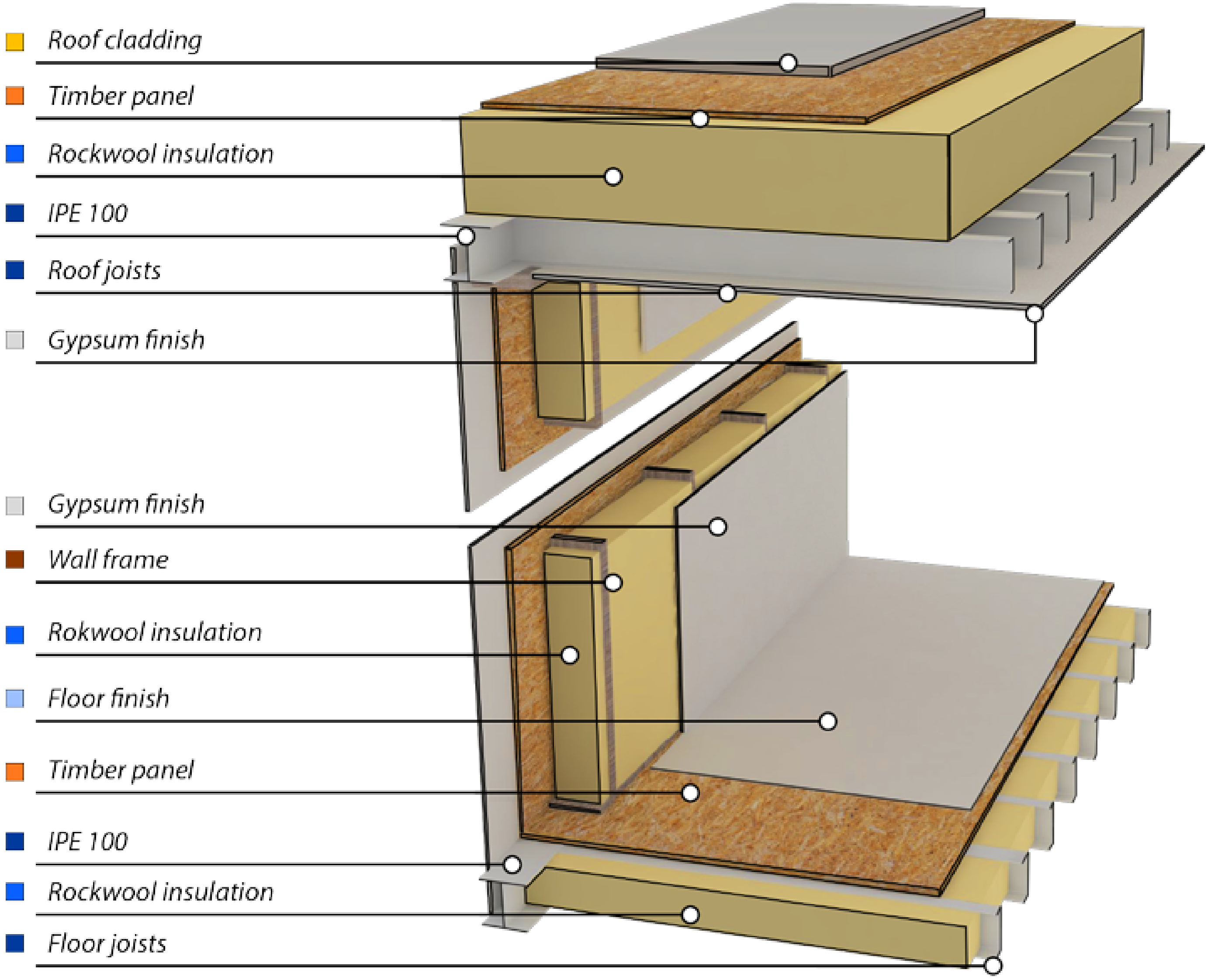




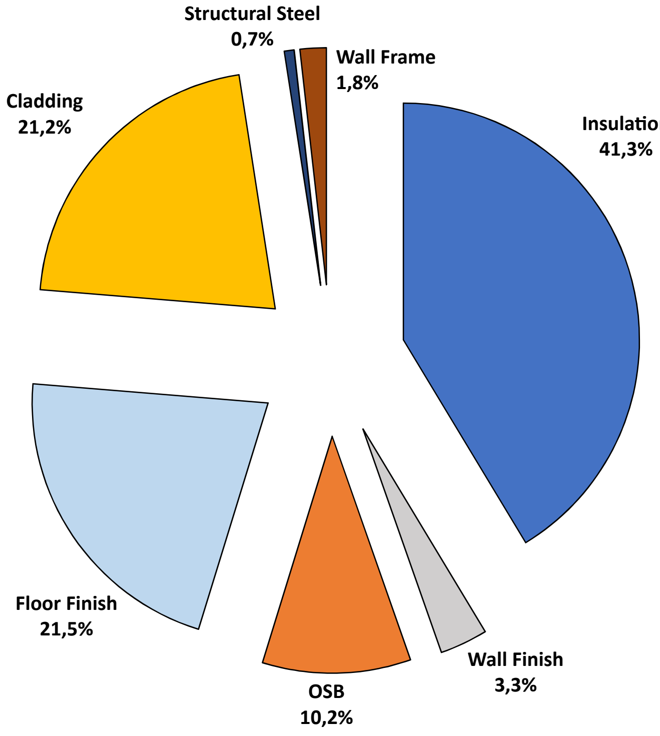


STEEL STRUCTURE - *Vancouver*

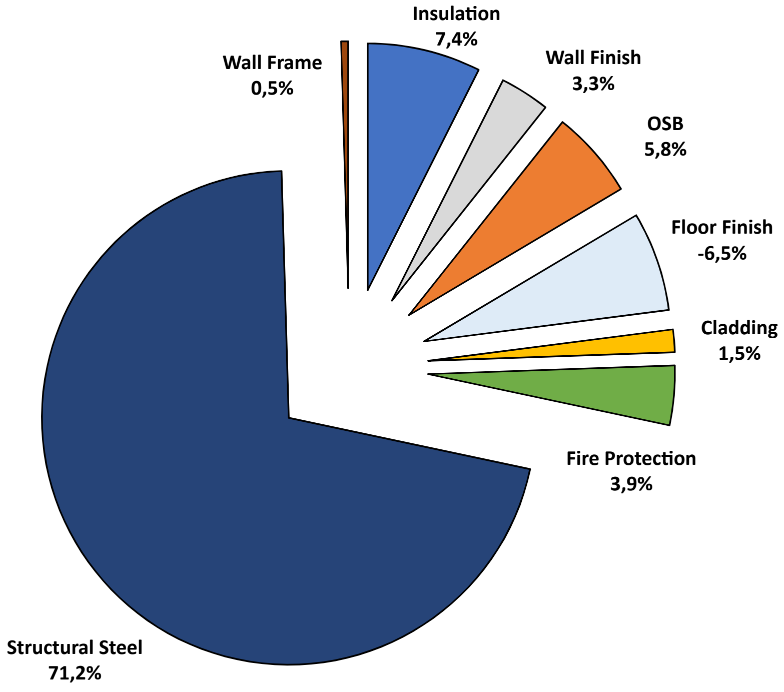
		Ptot [kg]	Embodied Energies - Stage A1/A3			
			GWP [KgCO2e/kg]	**ODP** [KgCFC11e/kg]	**AP** [KgSO2e/kg]	**EP** [Kg(PO4)3e/kg]
■	*Insulation - Rockwool*	2440,007	2732,808284	0,000107702	19,34437864	0,922322796
■	*Wall finish - Gypsum board*	4354,927	1201,959801	4,48557E-05	3,169080243	0,624061013
■	*OSB - Timber panel*	5129,399	2122,545223	0,000216307	1115,131299	0,872869794
■	*Floor Finish - Hardwood strips*	25768,746	-2396,493397	4,87029E-05	83,49073769	5,488742941
■	*Cladding - Radiata pine*	3613,995	543,5231099	0,000159377	7,07258751	0,6071511
■	*Fire protection - R120*	569,933	1430,532332	9,11893E-05	7,29514496	2,90665932
■	*Structure - Steel*	10041,221	26207,58695	2,73121E-07	83,54295917	7,320050148
■	*Wall Frame - Hardwood Timber*	1732,793	170,2815964	0,000218332	3,843335512	0,37428335
	TOTALs	53651,021	32012,7439	0,000886739	1322,889523	19,11614046

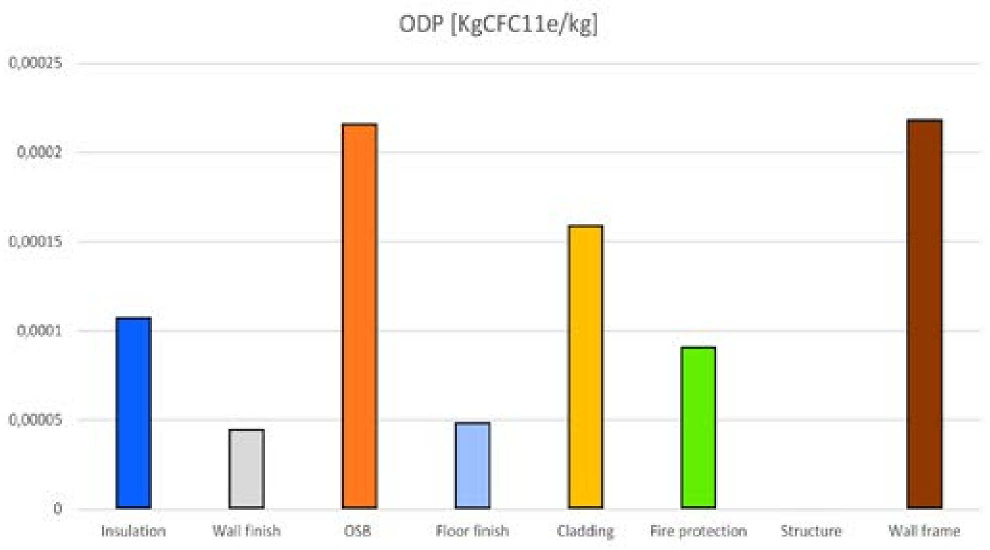


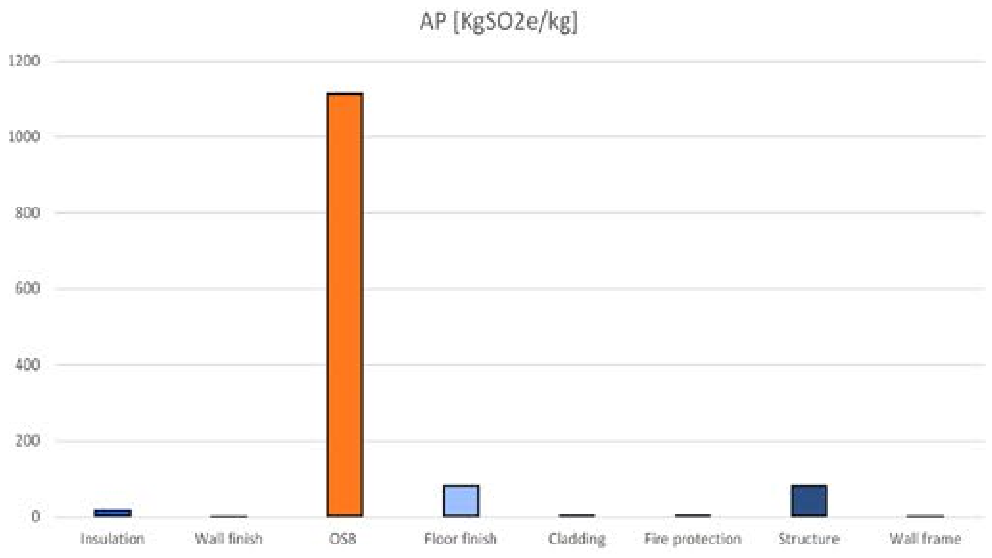
Volume of materials [m^3]

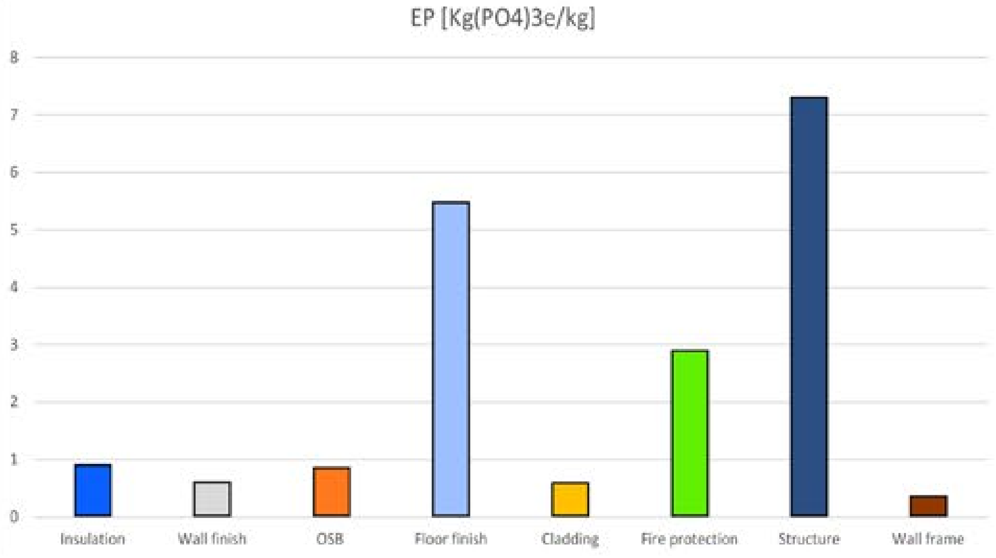


Global Warming Potential [kg CO$_2$e]



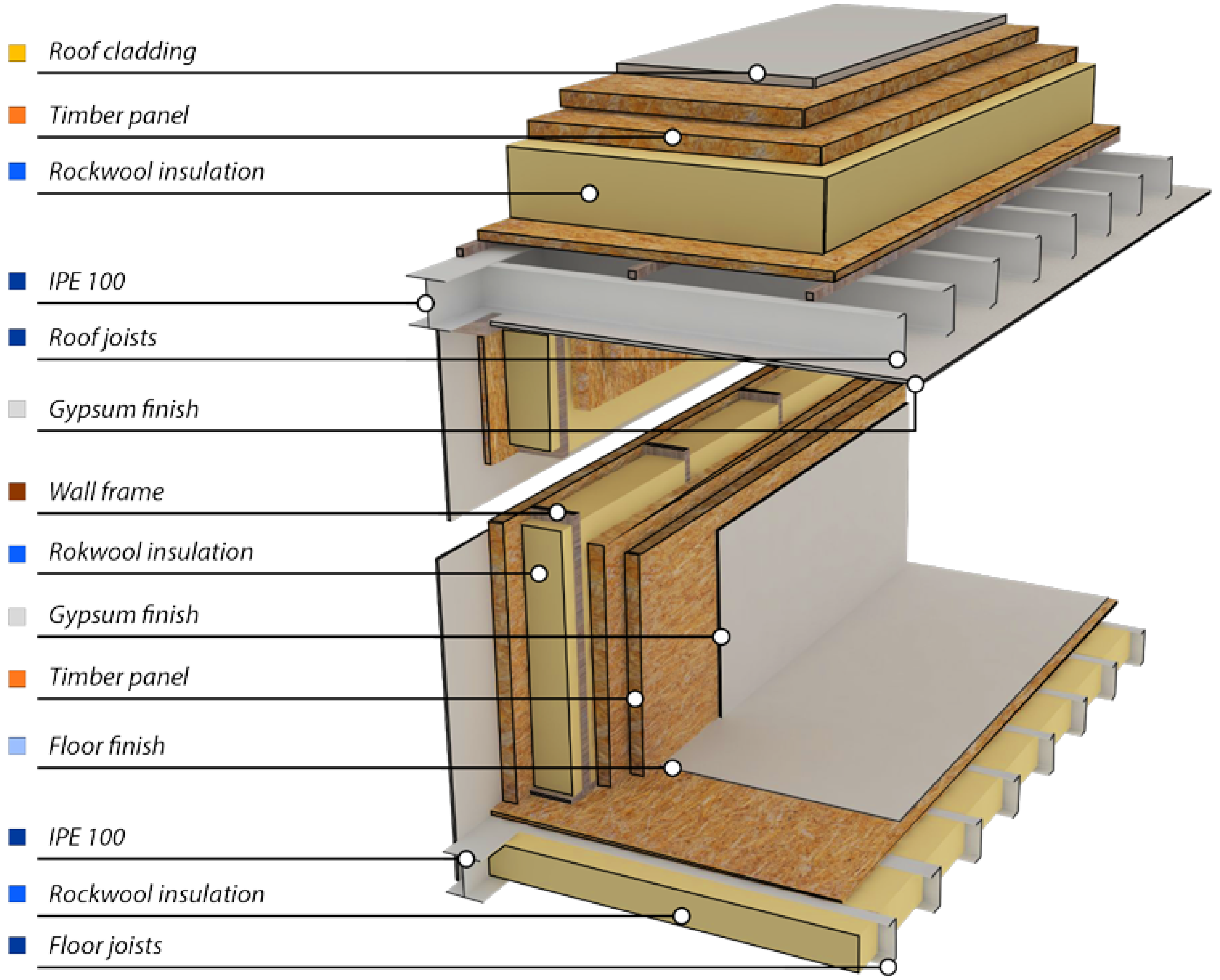




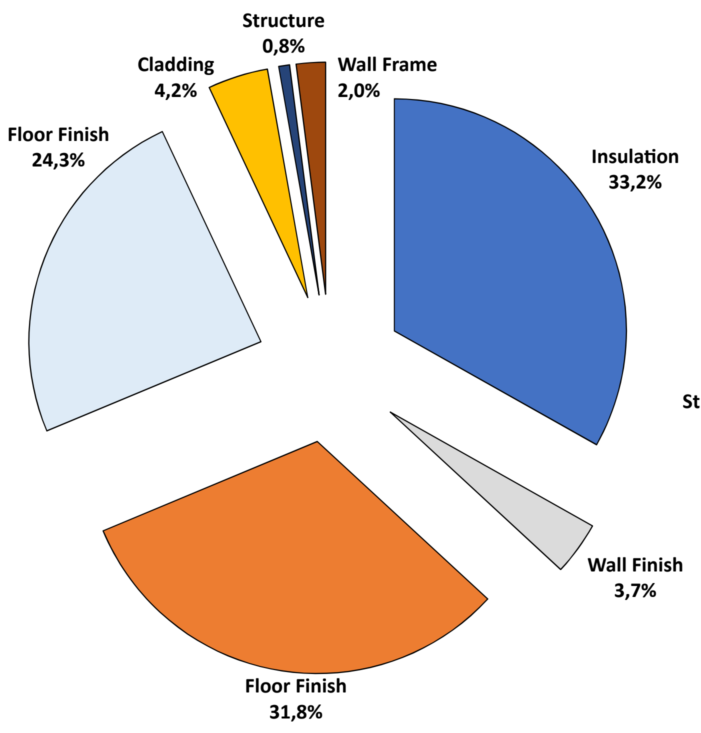


STEEL STRUCTURE - *Durban*

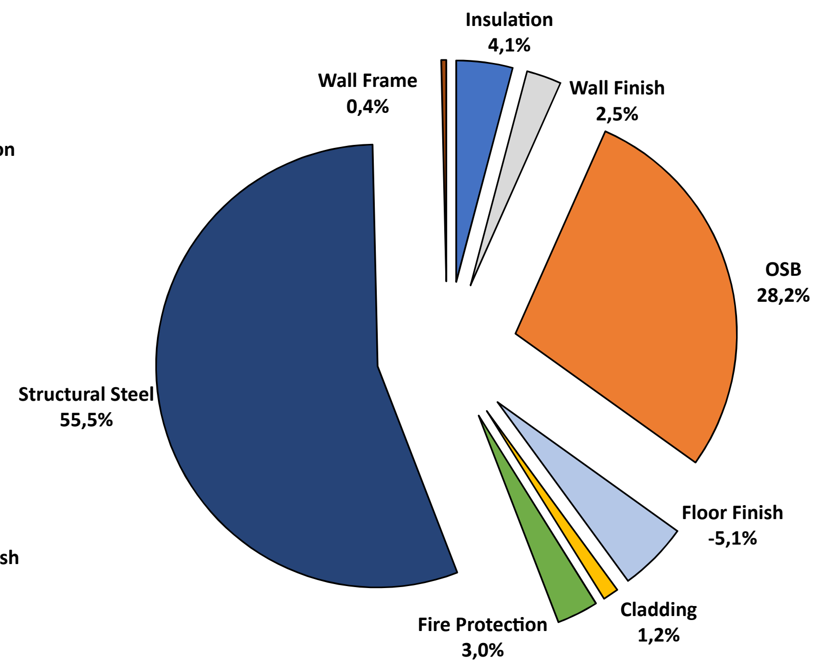
		Ptot [kg]	Embodied Energies - Stage A1/A3			
			GWP [KgCO2e/kg]	**ODP** [KgCFC11e/kg]	**AP** [KgSO2e/kg]	**EP** [Kg(PO4)3e/kg]
🟦	*Insulation - Rockwool*	1733,290	1,941E+03	7,651E-05	1,374E+01	6,552E-01
⬜	*Wall finish - Gypsum board*	4354,927	1,202E+03	4,486E-05	3,169E+00	6,241E-01
🟧	*OSB - Timber panel*	32221,188	1,333E+04	1,359E-03	7,005E+03	5,483E+00
🟦	*Floor Finish - Hardwood strips*	25768,746	-2,396E+03	4,870E-05	8,349E+01	5,489E+00
🟨	*Cladding - Radiata pine*	3613,995	5,435E+02	1,594E-04	7,073E+00	6,072E-01
🟩	*Fire protection - R120*	569,933	1,431E+03	9,119E-05	7,295E+00	2,907E+00
🟦	*Structure - Steel*	10041,221	2,621E+04	2,731E-07	8,354E+01	7,320E+00
🟫	*Wall Frame - Hardwood Timber*	1732,793	1,703E+02	2,183E-04	3,843E+00	3,743E-01
	TOTALs	80036,093	**4,243E+04**	**1,998E-03**	**7,207E+03**	**2,346E+01**

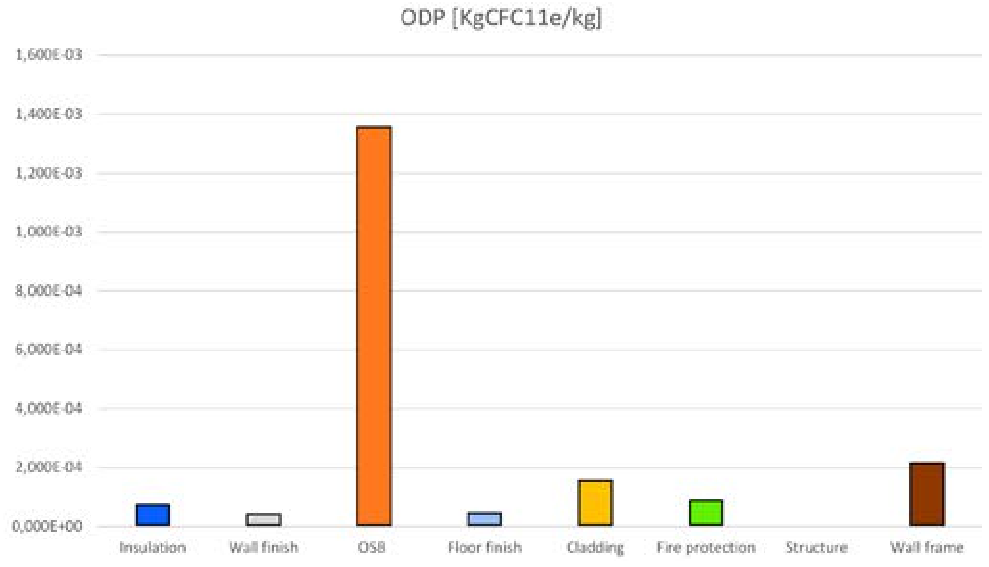


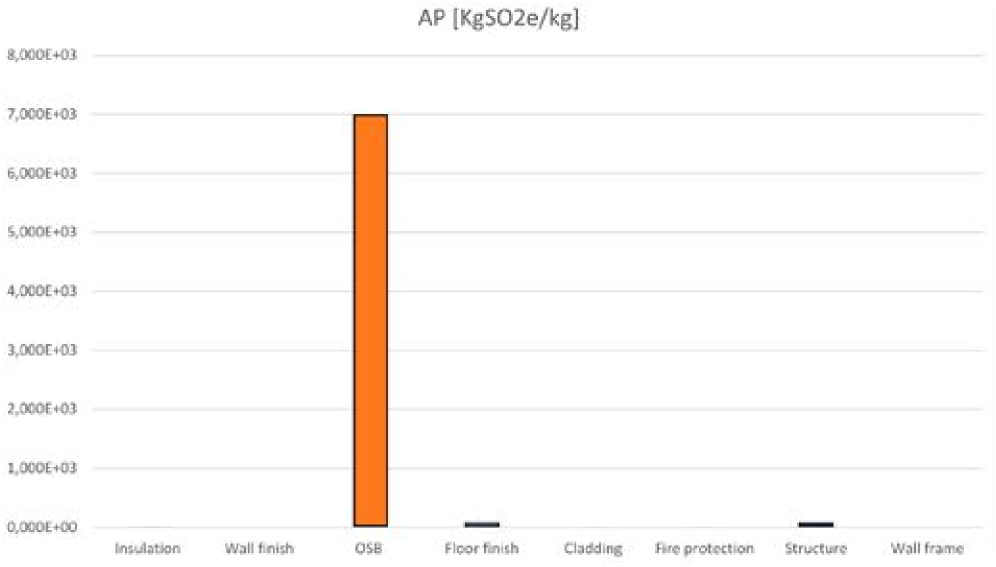
Volume of materials [m^3]

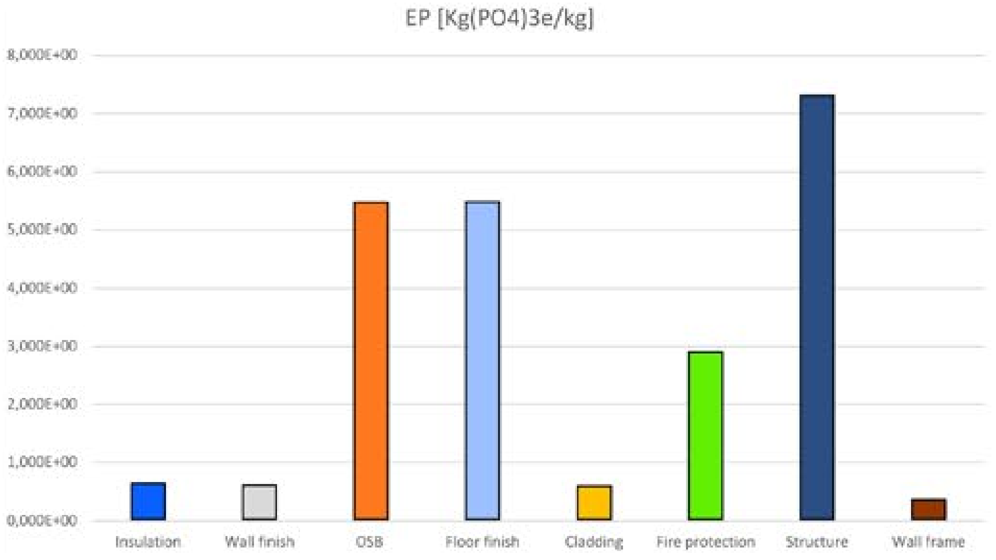


Global Warming Potential [kg CO_2e]



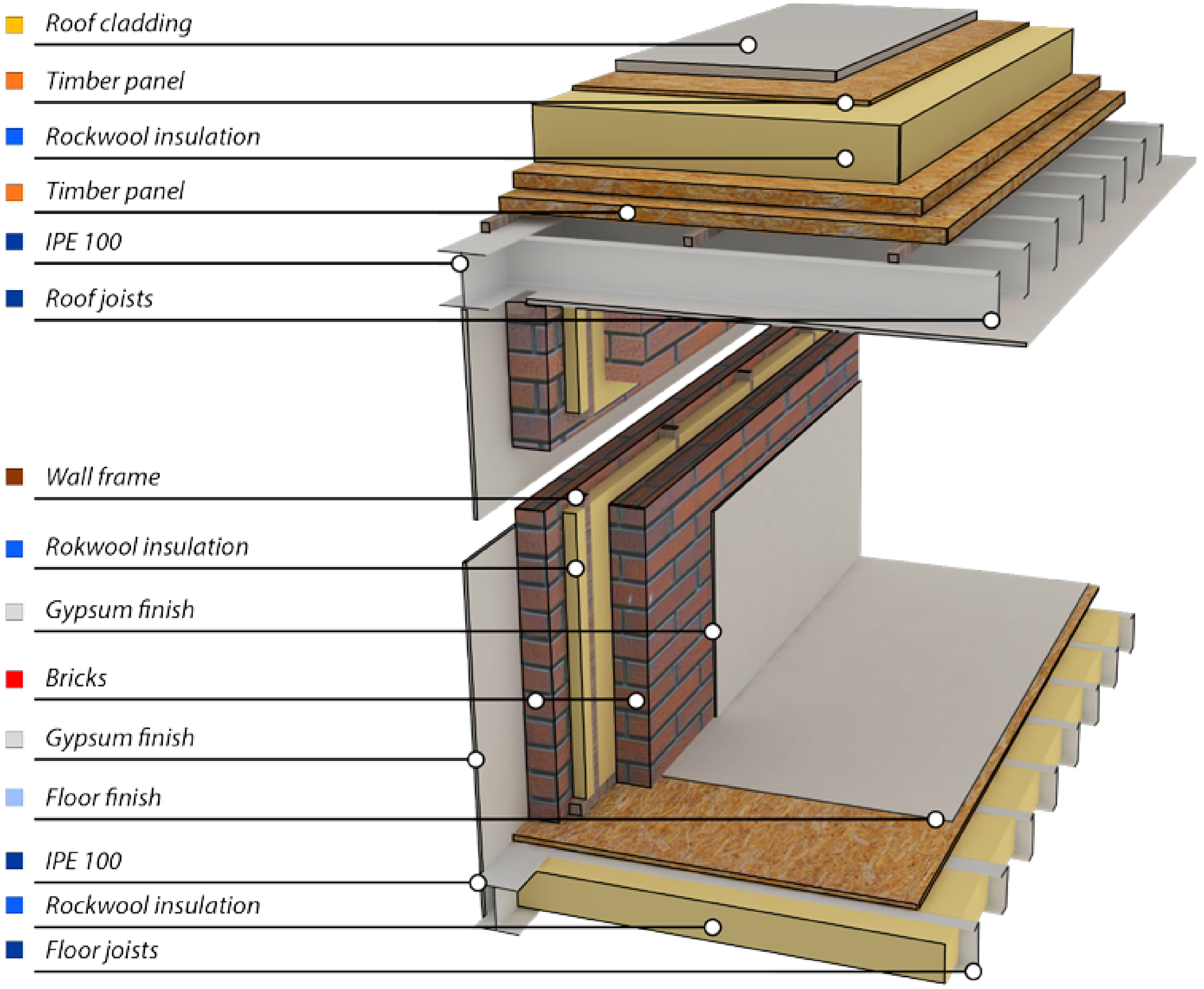




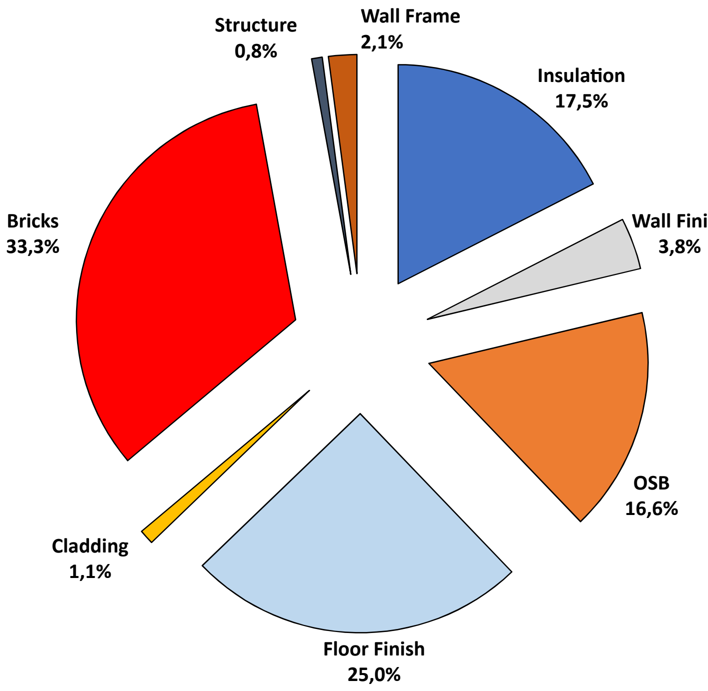


STEEL STRUCTURE - *Chennai*

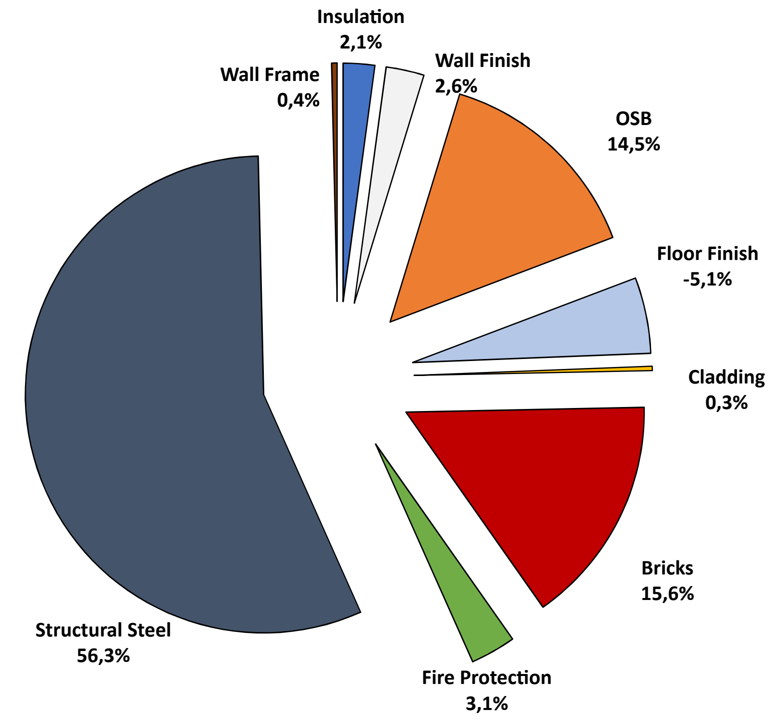
		Ptot [kg]	Embodied Energies - Stage A1/A3			
			GWP [KgCO2e/kg]	**ODP** [KgCFC11e/kg]	**AP** [KgSO2e/kg]	**EP** [Kg(PO4)3e/kg]
🟦	*Insulation - Rockwool*	889,050	995,7358522	3,92427E-05	7,048387354	0,33606085
◼	*Wall finish - Gypsum board*	4354,927	1201,959801	4,48557E-05	3,169080243	0,624061013
🟧	*OSB - Timber panel*	16320,996	6753,628145	0,000688256	3548,18453	2,777343889
🟦	*Floor Finish - Hardwood strips*	25768,746	-2396,493397	4,87029E-05	83,49073769	5,488742941
🟨	*Cladding - Radiata pine*	910,962	137,003219	4,01734E-05	1,782752634	0,153041616
🟥	*Brick - Mass*	45856,154	7245,272289	2,46248E-05	61,90580753	2,292807686
🟩	*Fire protection - R120*	569,933	1430,532332	9,11893E-05	7,29514496	2,90665932
🟦	*Structure - Steel*	8667,471	22622,09945	2,35755E-07	72,11335917	6,318586398
🟫	*Wall Frame - Hardwood Timber*	1732,793	170,2815964	0,000218332	3,843335512	0,37428335
	TOTALs	105071,032	**38160,01929**	**0,001195613**	**3788,833135**	**21,27158706**

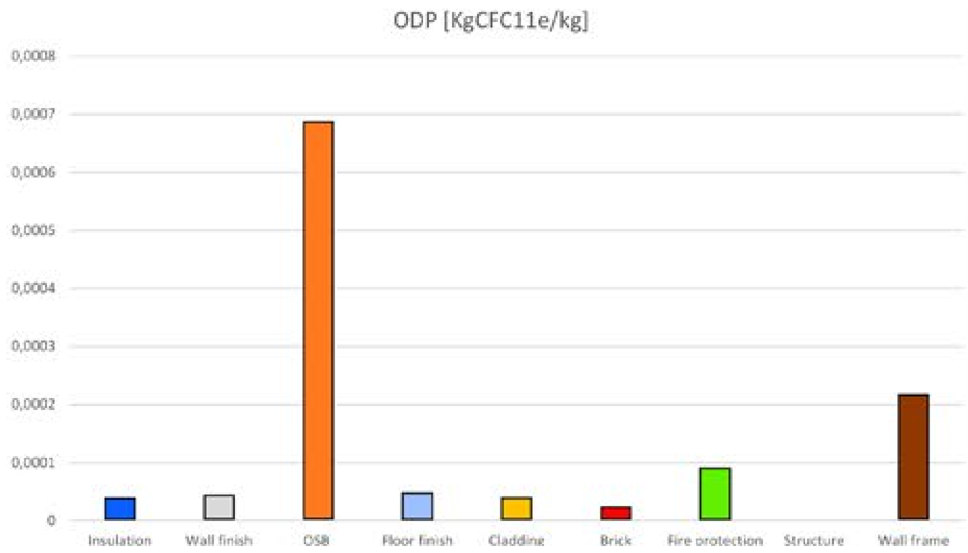


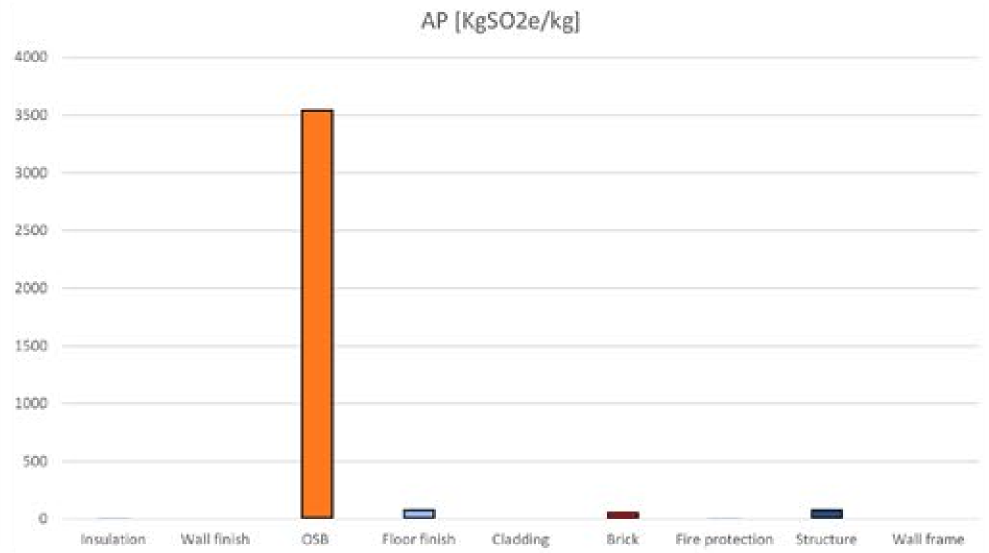
Volume of materials [m^3]

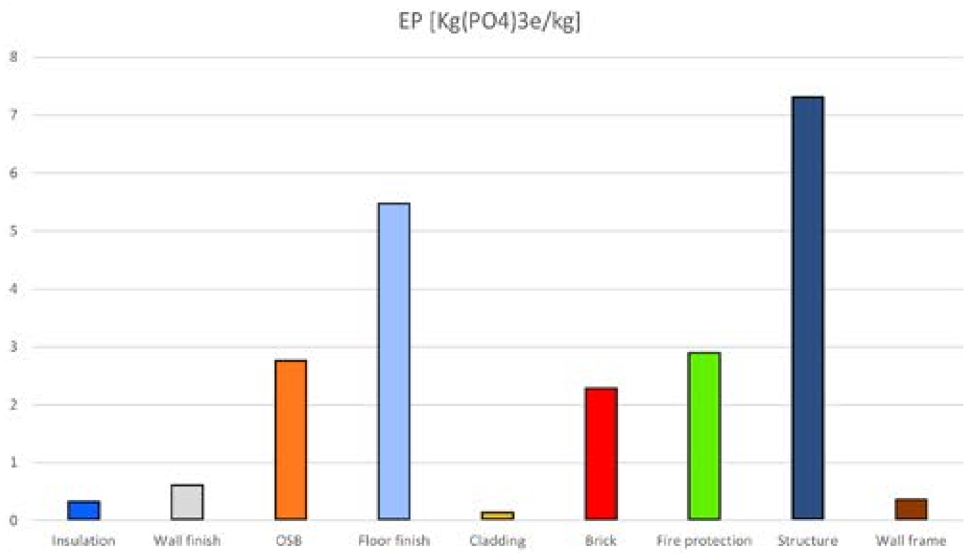


Global Warming Potential [kg CO$_2$e]



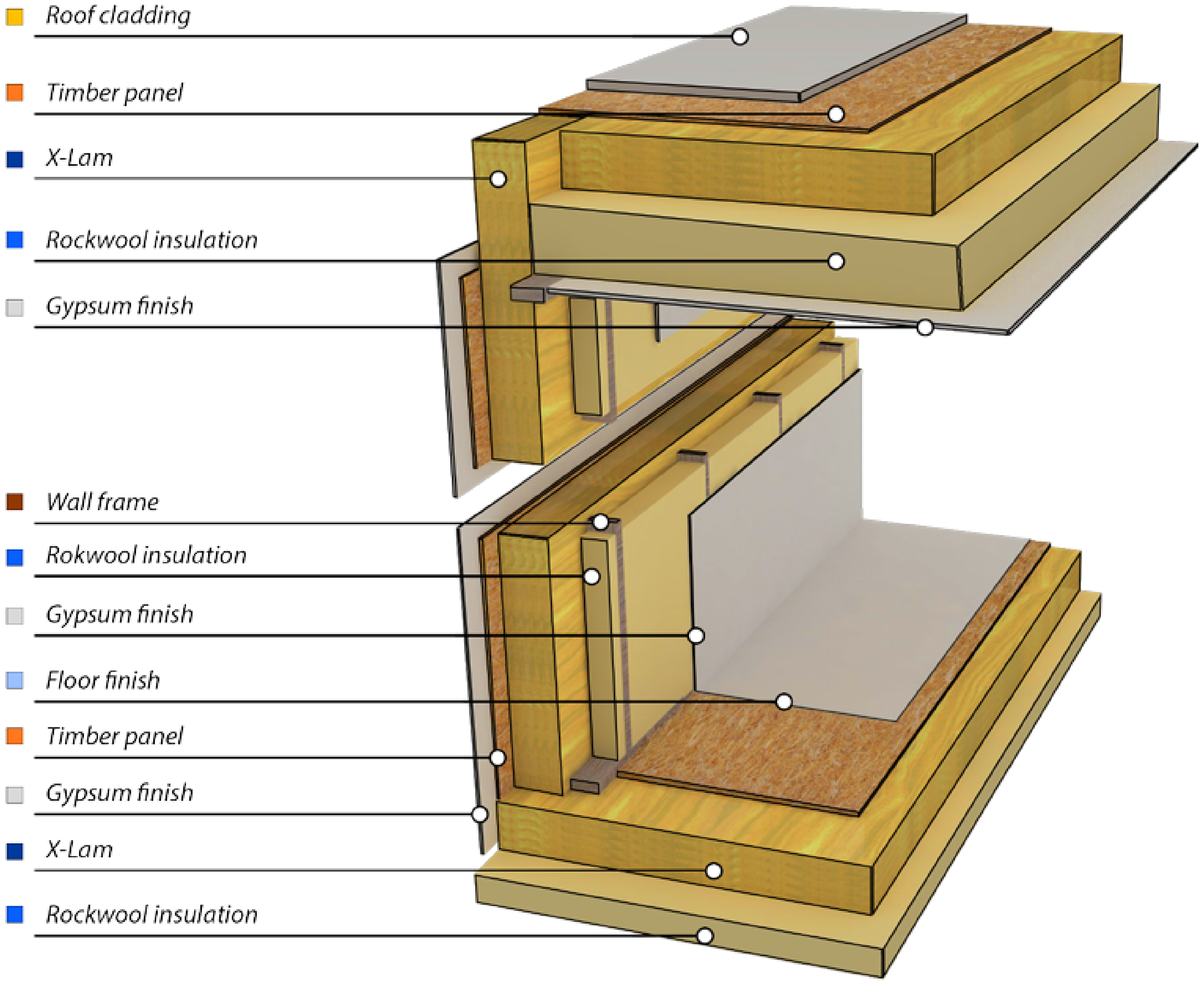




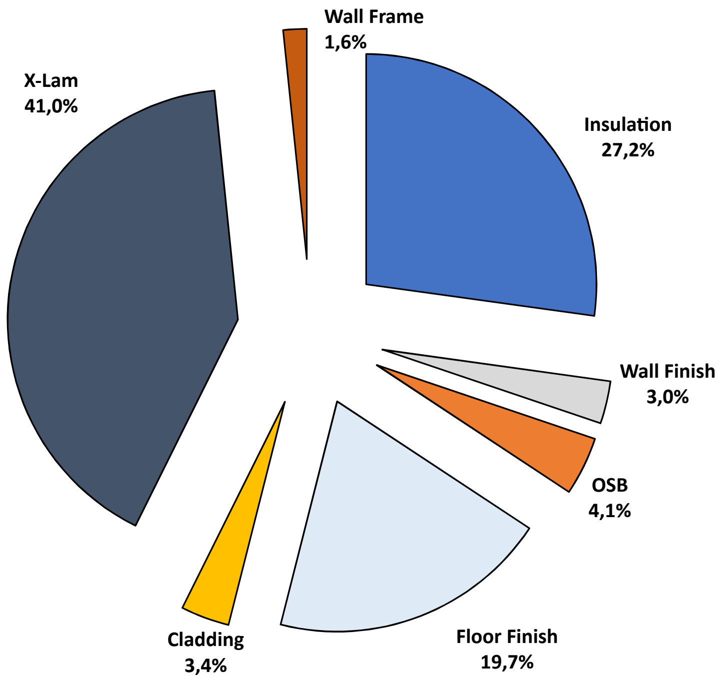


X-LAM STRUCTURE - *Vancouver*

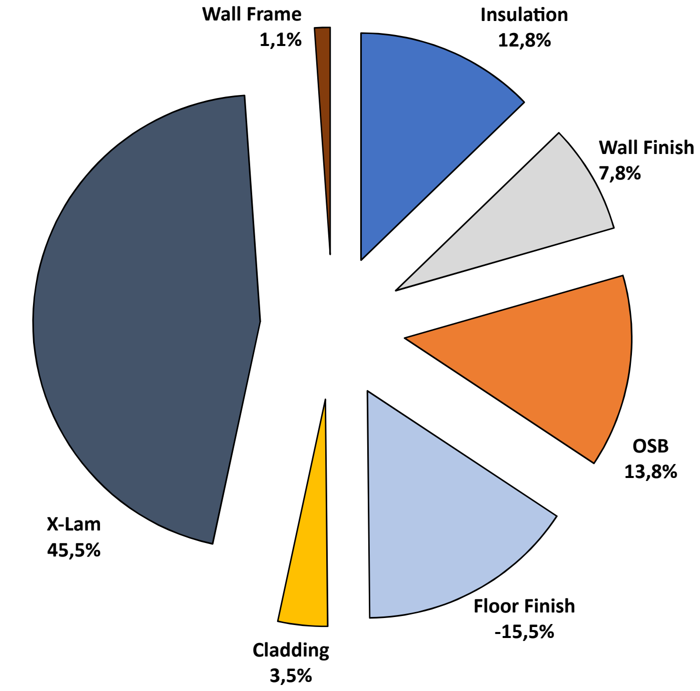
	Ptot [kg]	Embodied Energies - Stage A1/A3			
		GWP [KgCO2e/kg]	**ODP** [KgCFC11e/kg]	**AP** [KgSO2e/kg]	**EP** [Kg(PO4)3e/kg]
🟦 *Insulation - Rockwool*	1757,138	1967,99404	7,75601E-05	13,93058639	0,664197989
⬜ *Wall finish - Gypsum board*	4354,927	1201,959801	4,48557E-05	3,169080243	0,624061013
🟧 *OSB - Timber panel*	5129,399	2122,545223	0,000216307	1115,131299	0,872869794
🟦 *Floor Finish - Hardwood strips*	25768,746	-2396,493397	4,87029E-05	83,49073769	5,488742941
🟨 *Cladding - Radiata pine*	3613,995	543,5231099	0,000159377	7,07258751	0,6071511
🟦 *Structure - X-Lam*	42061,070	7024,198717	0,000367025	20,61833659	4,988442921
🟫 *Wall Frame - Hardwood Timber*	1732,793	170,2815964	0,000218332	3,843335512	0,37428335
TOTALs	84418,067	10634,00909	0,001132159	1247,255963	13,61974911

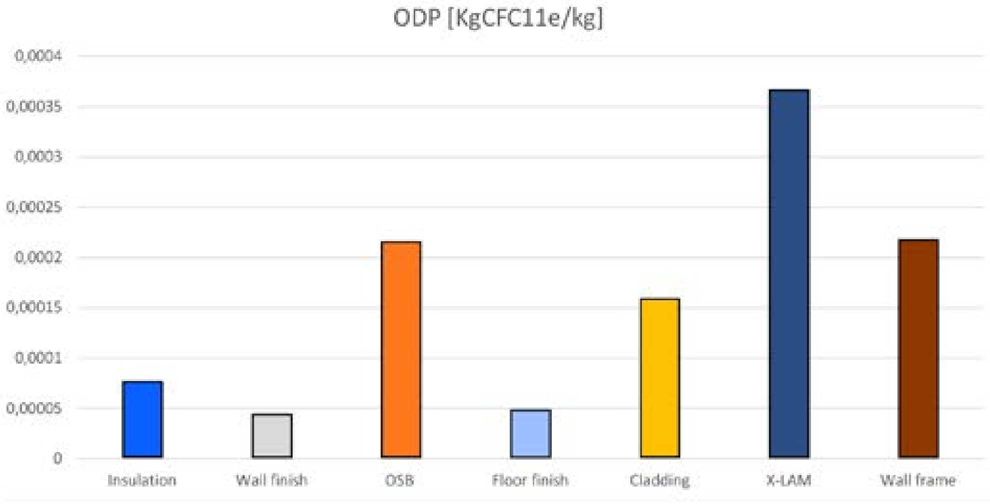


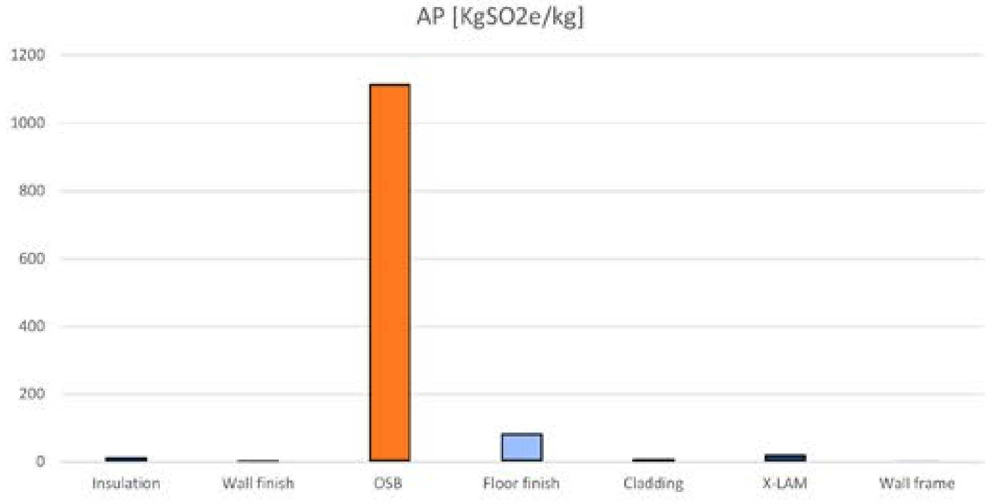
Volume of materials [m^3]

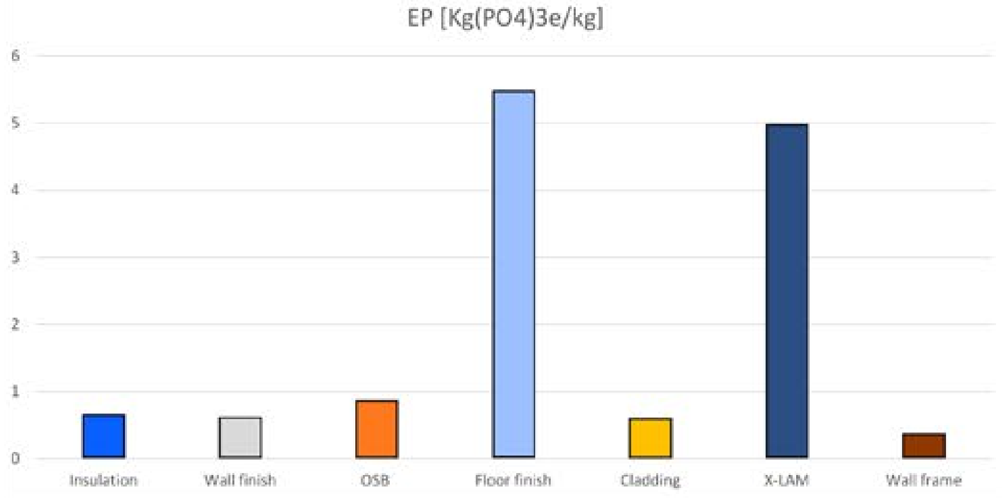


Global Warming Potential [kg CO$_2$e]



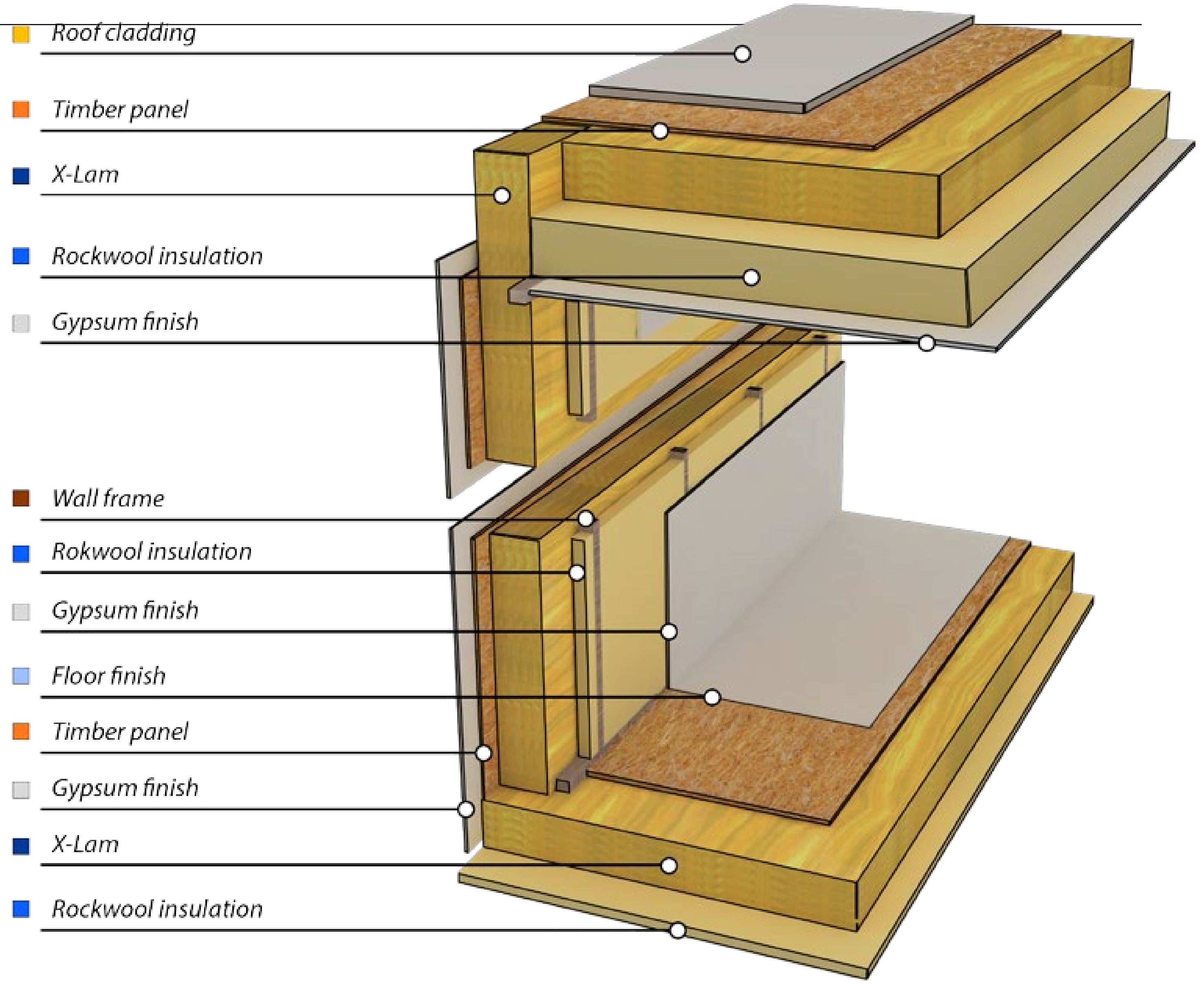




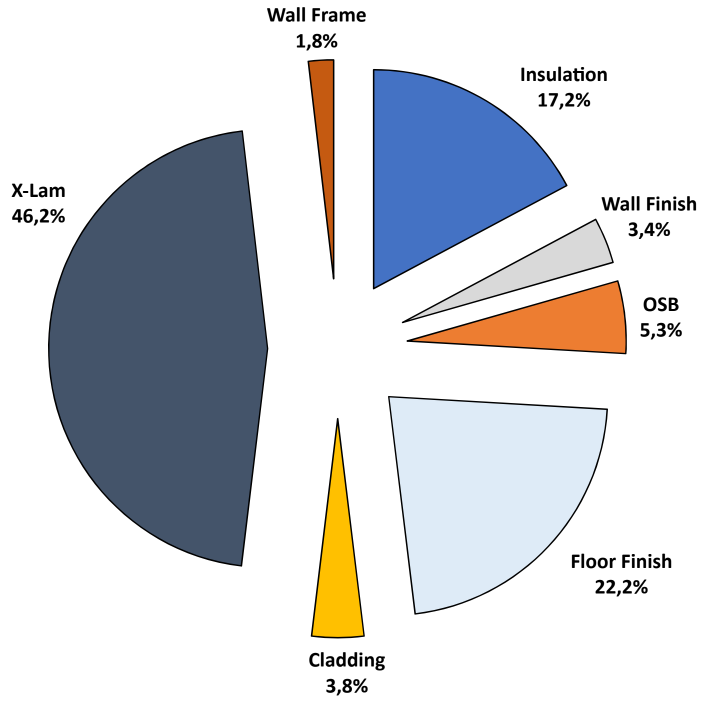


X-LAM STRUCTURE - *Durban*

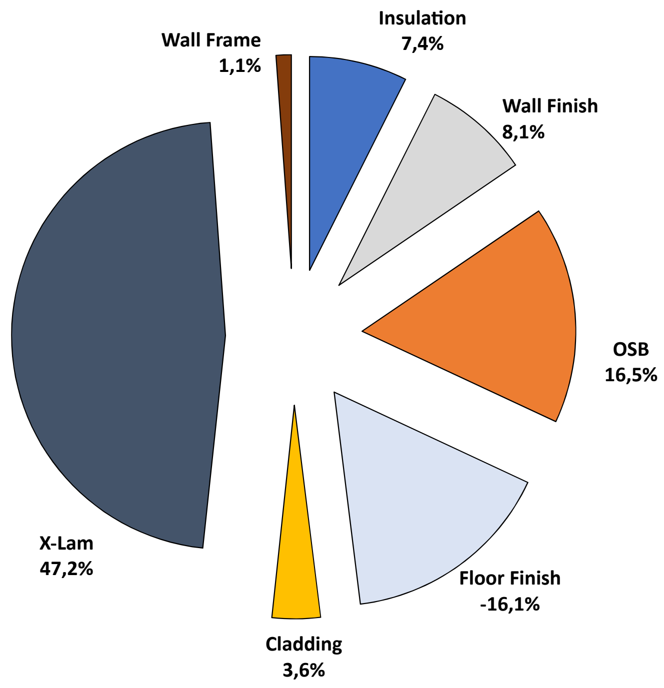
	Ptot [kg]	Embodied Energies - Stage A1/A3			
		GWP [KgCO2e/kg]	**ODP** [KgCFC11e/kg]	**AP** [KgSO2e/kg]	**EP** [Kg(PO4)3e/kg]
🟦 *Insulation - Rockwool*	985,498	1103,757272	4,34999E-05	7,813024687	0,372518079
⬜ *Wall finish - Gypsum board*	4354,927	1201,959801	4,48557E-05	3,169080243	0,624061013
🟧 *OSB - Timber panel*	5924,408	2451,520196	0,000249832	1287,966386	1,008156577
🟦 *Floor Finish - Hardwood strips*	25768,746	-2396,493397	4,87029E-05	83,49073769	5,488742941
🟨 *Cladding - Radiata pine*	3613,995	543,5231099	0,000159377	7,07258751	0,6071511
🟦 *Structure - X-Lam*	42061,070	7024,198717	0,000367025	20,61833659	4,988442921
🟫 *Wall Frame - Hardwood Timber*	1732,793	170,2815964	0,000218332	3,843335512	0,37428335
TOTALs	84441,437	**1,010E+04**	**1,132E-03**	**1,414E+03**	**1,346E+01**

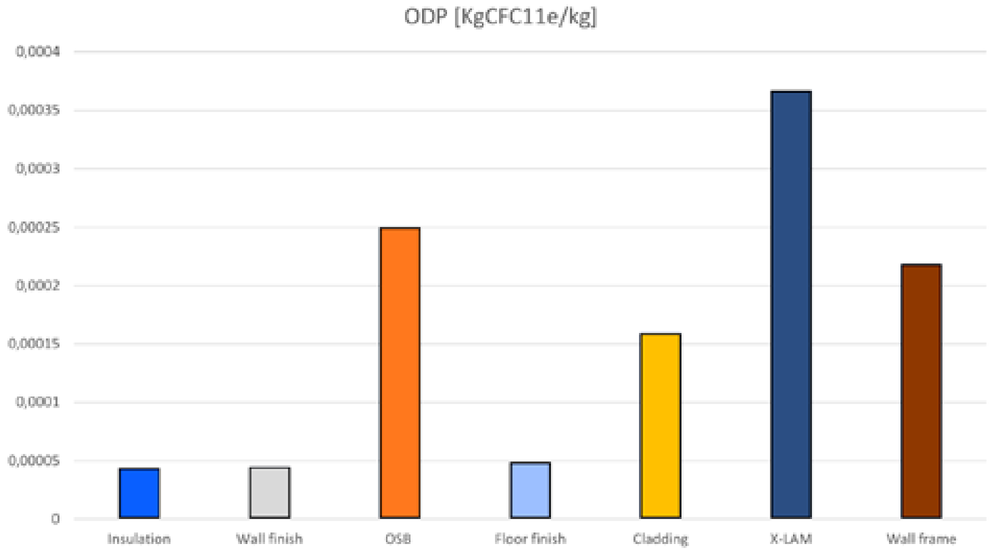


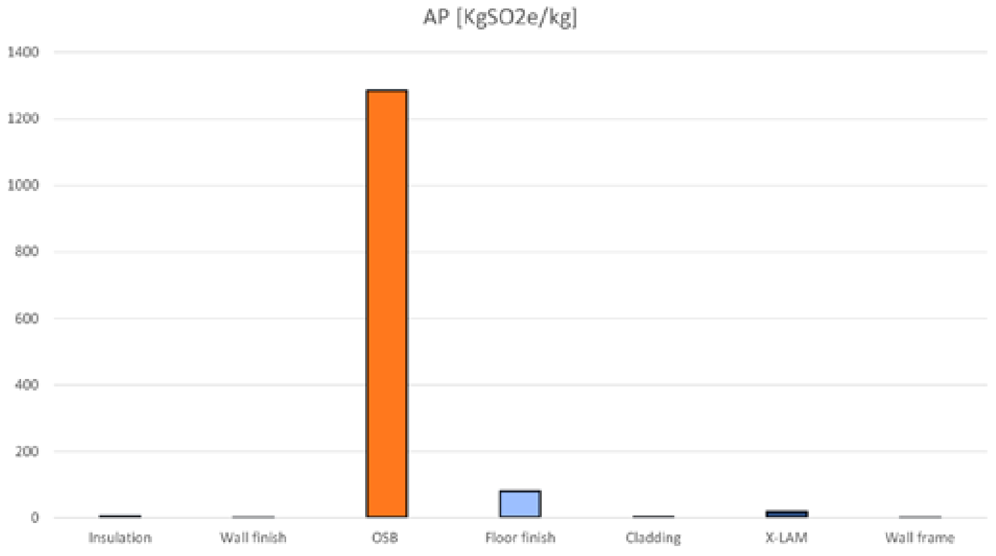
Volume of materials [m^3]

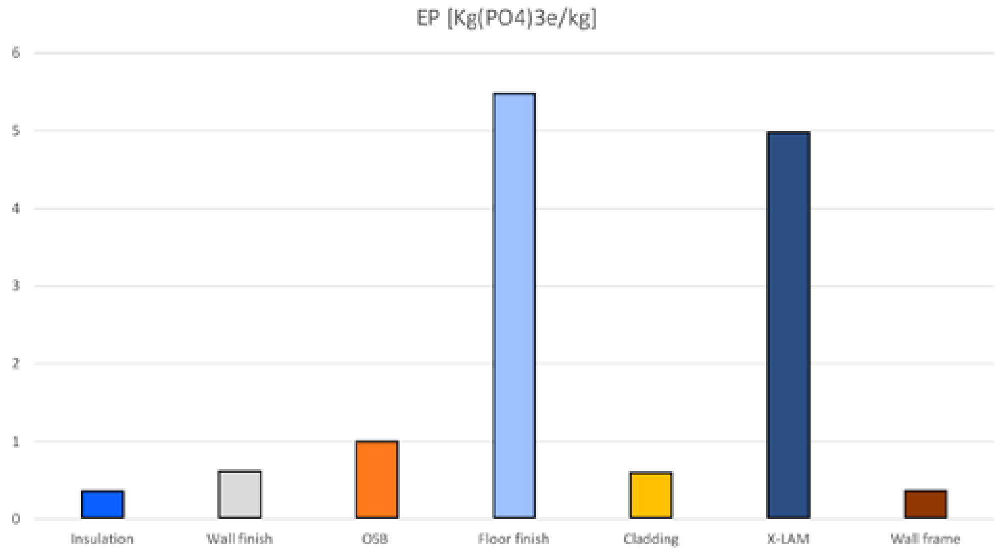


Global Warming Potential [kg CO$_2$e]



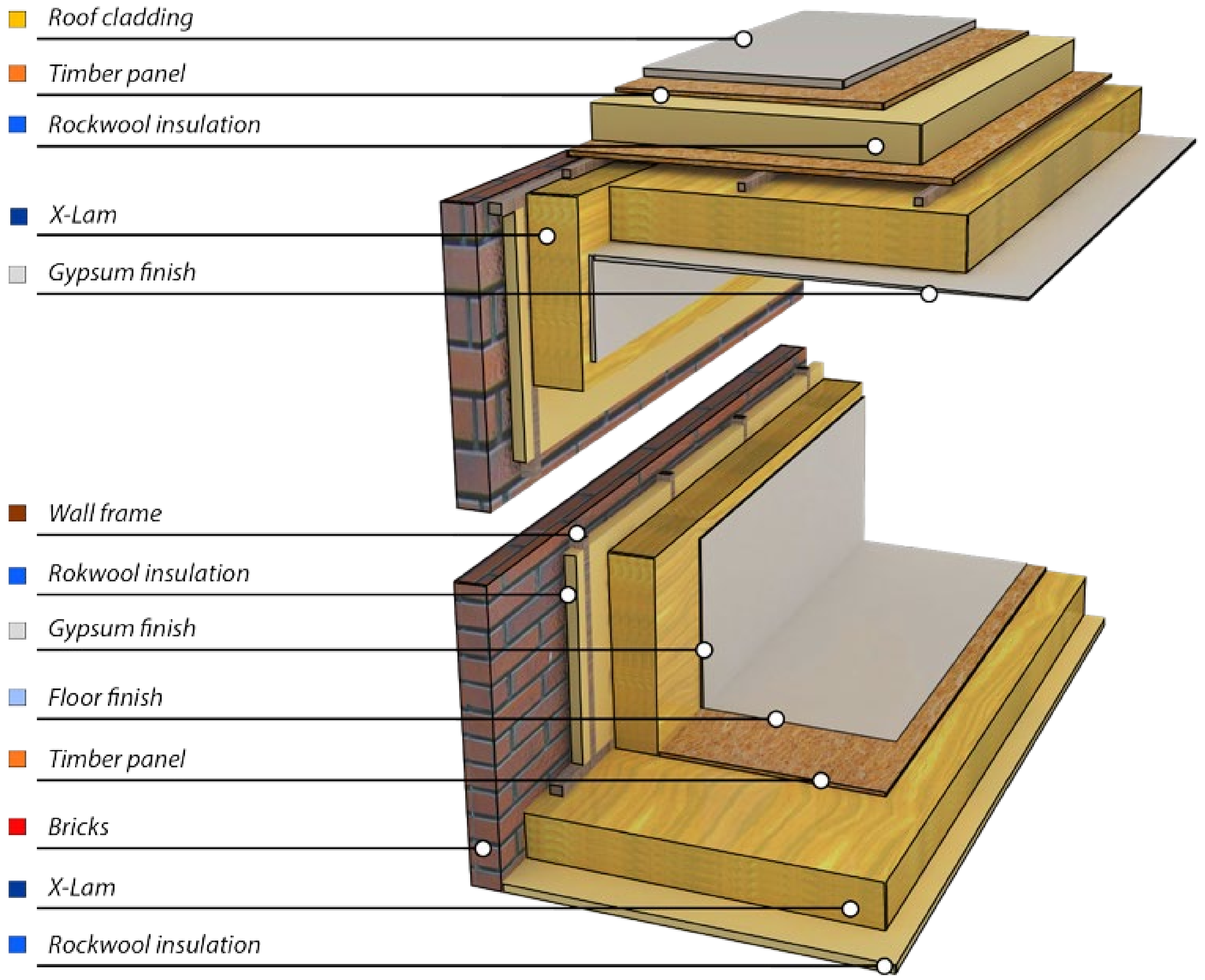




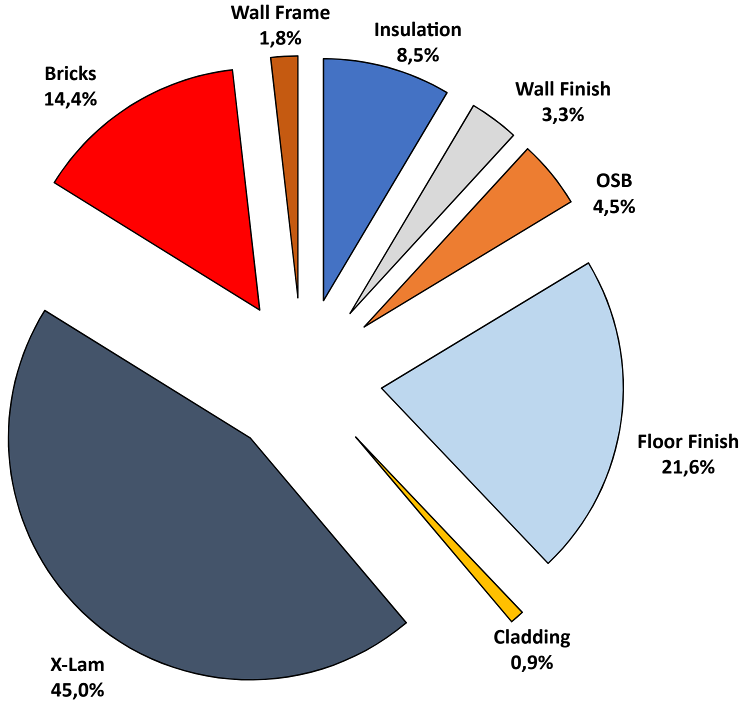


X-LAM STRUCTURE - *Chennai*

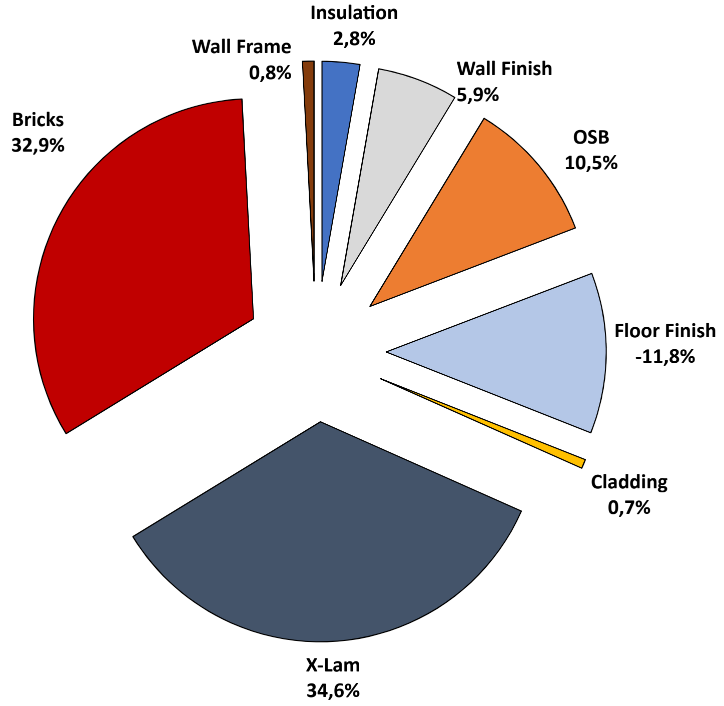
		Ptot [kg]	Embodied Energies - Stage A1/A3			
			GWP [KgCO2e/kg]	**ODP** [KgCFC11e/kg]	**AP** [KgSO2e/kg]	**EP** [Kg(PO4)3e/kg]
🟦	*Insulation - Rockwool*	502,270	562,5426061	2,21702E-05	3,981998019	0,18985813
⬜	*Wall finish - Gypsum board*	4354,927	1201,959801	4,48557E-05	3,169080243	0,624061013
🟧	*OSB - Timber panel*	5155,740	2133,445212	0,000217418	1120,857876	0,877352276
🟦	*Floor Finish - Hardwood strips*	25768,746	-2396,493397	4,87029E-05	83,49073769	5,488742941
🟨	*Cladding - Radiata pine*	910,962	137,003219	4,01734E-05	1,782752634	0,153041616
🟦	*Structure - Steel*	42061,070	7024,198717	0,000367025	20,61833659	4,988442921
🟥	*Brick - Mass*	42307,761	6684,626219	2,27193E-05	57,11547719	2,115388044
🟫	*Wall Frame - Hardwood Timber*	1732,793	170,2815964	0,000218332	3,843335512	0,37428335
	TOTALs	122794,270	**15517,56397**	**0,000981396**	**1294,859594**	**14,81117029**

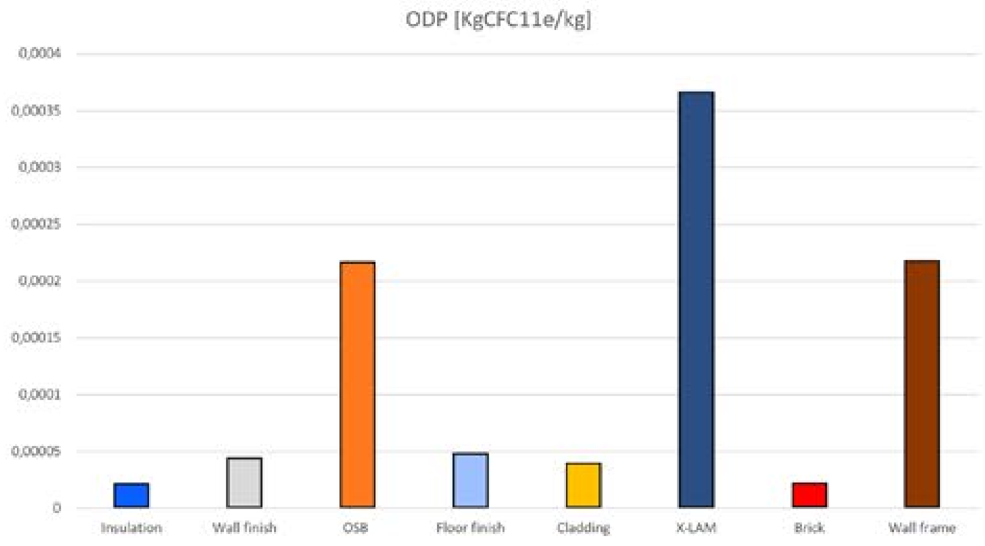


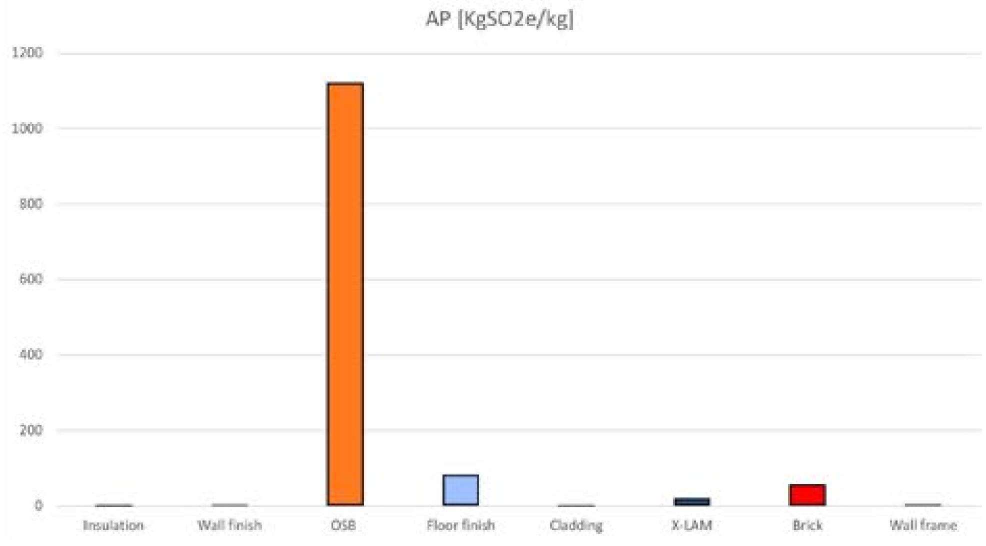
Volume of materials [m^3]

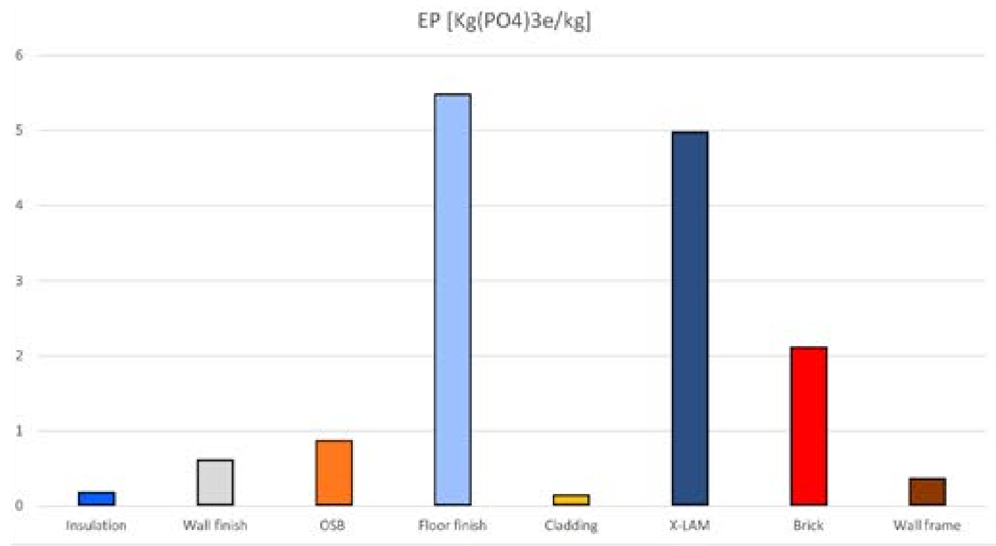


Global Warming Potential [kg CO_2e]









4.3 Module A 1-2-3 : Resulsts

Results of the total Embodied Energy for each scenario are compared below.

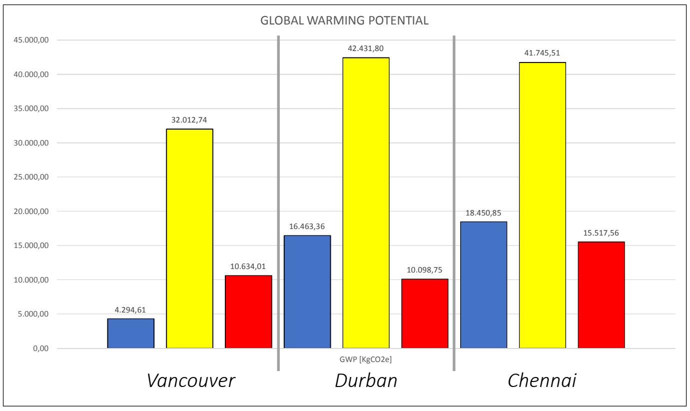
PRODUCT STAGE

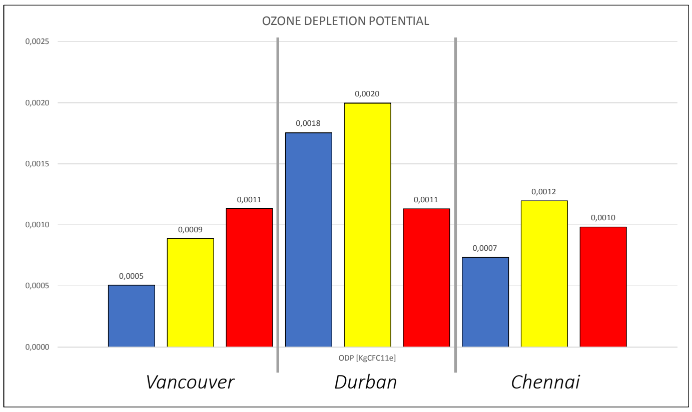
Scenario	VANCOUVER		
Technology	**CONTAINER**	**STEEL**	**XLAM**
GWP [KgCO2e]	4,295E+03	3,201E+04	1,063E+04
ODP [KgCFC11e]	5,046E-04	8,867E-04	1,132E-03
AP [KgSO2e]	1,229E+02	1,323E+03	1,247E+03
EP [Kg(PO4)3e]	8,632E+00	1,912E+01	1,362E+01

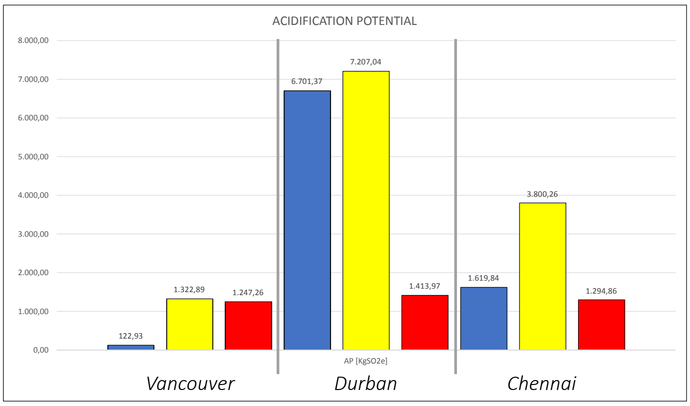
Scenario	DURBAN		
Technology	**CONTAINER**	**STEEL**	**XLAM**
GWP [KgCO2e]	1,646E+04	4,243E+04	1,010E+04
ODP [KgCFC11e]	1,754E-03	1,998E-03	1,132E-03
AP [KgSO2e]	6,701E+03	7,207E+03	1,414E+03
EP [Kg(PO4)3e]	1,470E+01	2,346E+01	1,346E+01

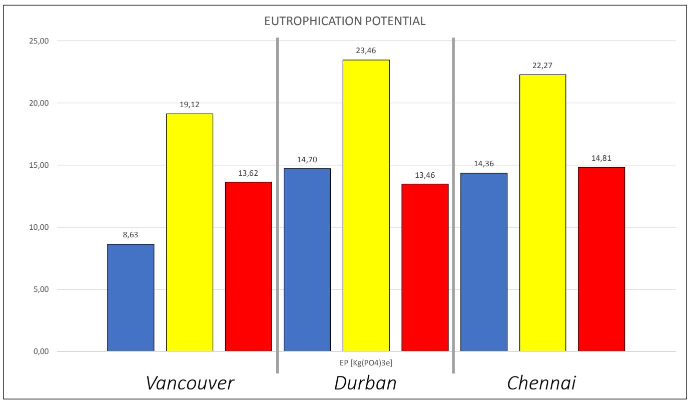
Scenario	CHENNAI		
Technology	**CONTAINER**	**STEEL**	**XLAM**
GWP [KgCO2e]	1,845E+04	4,175E+04	1,552E+04
ODP [KgCFC11e]	7,340E-04	1,196E-03	9,814E-04
AP [KgSO2e]	1,620E+03	3,800E+03	1,295E+03
EP [Kg(PO4)3e]	1,436E+01	2,227E+01	1,481E+01

🟦 *Shipping Container* 🟨 *Steel Frame* 🟥 *X-Lam*









4.4 Gate to Site

Commonly there are three main transportation phases within the life cycle of a building. The first coincides with the transportation of raw resources to the manufacturing facility, which belongs to module A2, included in the Embodied Energy stage. The second is from Gate to Site, module A5. The last transportation stage is included in the demolition stage, from site to landfill.

It is necessary to underline the main limitation of the study which is t focused on abstract scenarios, rather than real ones. Therefore data regarding distances from gate to site are not available, and each transportation stage has been expressed in a "*per km*" basis.

Fuel type	**GWP** [KgCO2e / kW-h]	**ODP** [KgCFC11e/ kW-h]	**AP** [KgSO2e/ kW-h]	**EP** [Kg(PO4)3e/ kW-h]
Diesel	0,26	0,0000092	0,0008	0,0001
Gasoline	0,3	0,0000092	0,0008	0,0001
Electricity- Canada	0,6585	0,00000000089	0,000795	0,000681
Electricity- South Africa	1,1002	0,0000000015	0,00133	0,0011
Electricity- India	0,782	0,0000000011	0,000944	0,000809

FIGURE 4.2 - Power emissions

Average construction truck specifications for the calculation

Engine Power: 380 *kW*
Maximum Load: 36 500 *kg*
Full Load Speed: 60 *km/h*
Fuel Tank: 184 *L*

In order to express the total emissions results in mass of impact equilavant per km, has been used a conversion factor to transform kW-h power-emissions from *figure 4.2* to km distance-emissions as follows:

Conversion factor = *[**Engine power**]* / *[**Full load speed**]* = 380 / 60 = 6,43 *[kW-h / km]*

To calculate normalized emissions for the transportation of building materials, unit emissions from *figure 4.2* have been multiplied for the conversion factor and Load factor which represents the percentage of the whole building material weight based on the maximum truck load:

Emission *[kg impact-equivalent / km]* = *[**Impact category emission**]* X *[**Conversion factor**]* X *[**kg of Building material**]* / *[**Max load**]*

The use of a load fator comes from the assumption that empty vehicles produce lower emissions than fully loaded trucks.

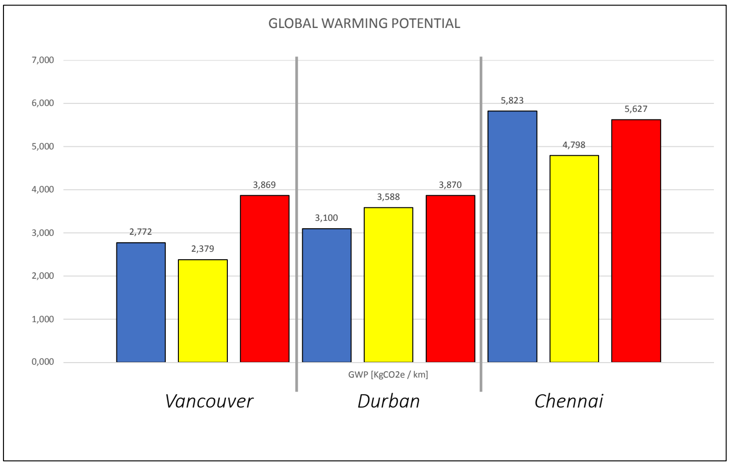
4.5 Module A4: results

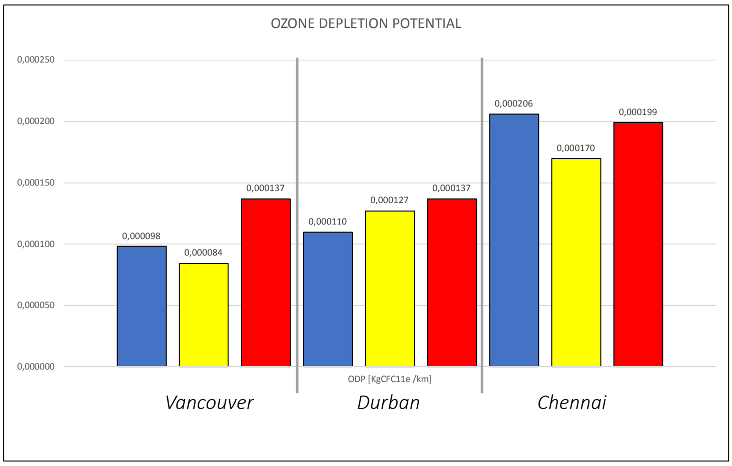
	VANCOUVER		
	CONTAINER	**STEEL**	**XLAM**
GWP [KgCO2e / km]	2,772	2,379	3,869
ODP [KgCFC11e /km]	0,000098	0,000084	0,000137
AP [KgSO2e /km]	0,0085	0,0073	0,0119
EP [Kg(PO4)3e /km]	0,00107	0,00107	0,00149

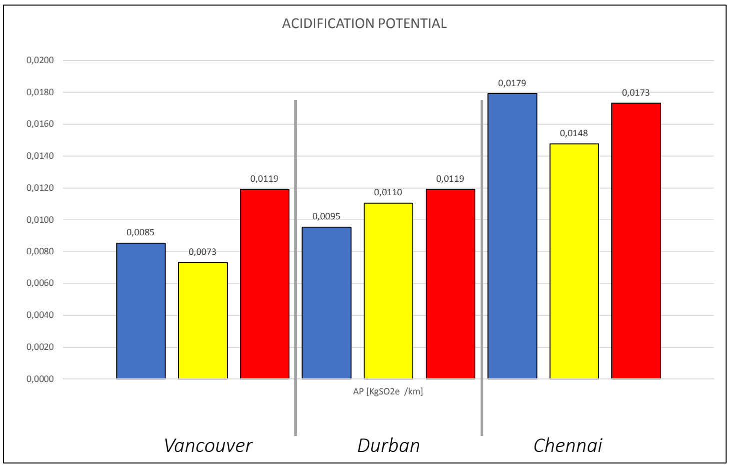
	DURBAN		
	CONTAINER	**STEEL**	**XLAM**
GWP [KgCO2e / km]	3,100	3,588	3,870
ODP [KgCFC11e /km]	0,000110	0,000127	0,000137
AP [KgSO2e /km]	0,0095	0,0110	0,0119
EP [Kg(PO4)3e /km]	0,00119	0,00138	0,00149

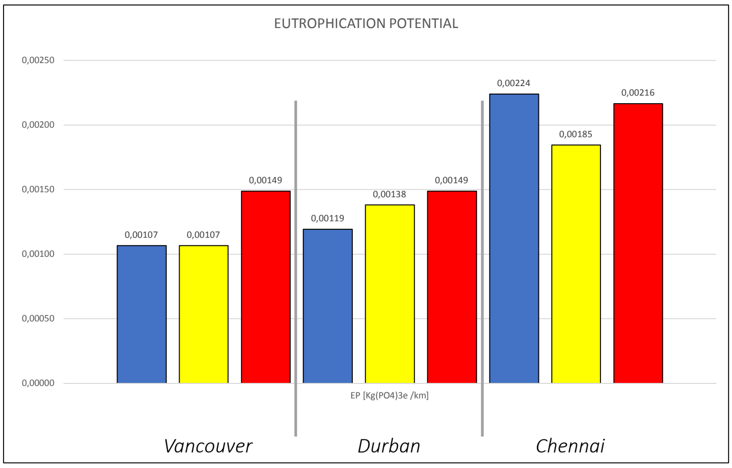
	CHENNAI		
	CONTAINER	**STEEL**	**XLAM**
GWP [KgCO2e / km]	5,823	4,798	5,627
ODP [KgCFC11e /km]	0,000206	0,000170	0,000199
AP [KgSO2e /km]	0,0179	0,0148	0,0173
EP [Kg(PO4)3e /km]	0,00224	0,00185	0,00216

🟦 *Shipping Container* 🟨 *Steel Frame* 🟥 *X-Lam*









4.6 Environmental Advantage

Results of embodied energies show the environmental advantage of the shipping container structure compared to the steel frame. Therefore, moving from "per km" results of the gate to site stage, it is possibile to define a maximum distance "before environmental advantage is lost".

This distance is defined by dividing embodied energy for the production of steel with emissions for transportation of freight containers, excluding other building materials.

Maximum transport distance *[km]* = ***Embodied Energy [**Steel**]*** / ***Transport Emissions [**Containers**] =*** **1 700** *km*

The result is consistent with data pubblicated by the BRE Group in the "*Green Guide to Specification*".
The study shows the environmental distance for the benefit of reusing structural steel profiles compared to the production of new material, which is methodologically identical to the aim of this paragraph. It results in a maximum distance of 4000 km.

Comparing the weight of materials involved in the two case studies,

Shipping Container load (6 units):	23 400 *kg*
Structural Steel:	10 041,22 *kg*

Is possible to define a "conversion factor" of 0,43 which indicates the proportion of structural steel compared to the weight of a comparable container structure.
The conversion factor mulltiplied by BRE's maximum distance (4 000 km) leads to

1 716,45 *km distance before environmental advantage is lost*

As it is specifically addressed in the chapter regarding allocation procedures for the calculation of recycling credits, in this study steel is considered virgin as input of the system and the environmental benefits for recycling are computed directly at the End of Life stage.
As widely described in literature, considering emissions for recycled steel in the production stage and also credits for recycling after demolition will result in a double counting of reclying benefits. Comparing emissions with recycled steel will obviously lead to a reduction of the maximum distance. Neverheless using that calculation method imposes to exclude recycling credits of steel from module D, to avoid double counting. To ensure comparability of each stage, benefits have been included completely after demolition. Therefore the the calculation of the maximum distance for environmental advantage of containers is calculated using emissions for the production of virgin steel rather than recyced material.

Map in *figure 4.3* highlights the impact of a 1700km distance from shipping containers' accumulation seaports.
The map can be extended by including in the study also continental accumulation depot, which are actually excluded from the boundary of the study.

Further research should define de environmental advantage of upcycling containers compared to each different traditional construction material.

4.7 Summary and observations

From the point of view of Embodied Energy, generally shipping containers show a lower environmental impact.
Colder climates enhance the environmental advantage of shipping containers, while tropical zones are much more favorable to X-Lam technologies due to the need of additional mass in the envelope.

It is evident a peak in Ozone depletion Potential and Acidification Potential within the container structure caused by the amount of OSB used to provide superficial mass for passive cooling. Bricks used for the tropical climate (Chennai) lower emissions while providing a great time shift for thermal comfort.
Therefore it is evident how mass materials are the main contributors of emissions for a container structure.

Embodied energies for structural steel are not comaprable to the other technologies due to the allocation criteria of the study which considers virgin steel and gives credits for recycling in the module D.
Performing the study with an allocation procedure 100-0, including credits from steel recycling at the beginning, will lead a lower impact of the steel structure. Even considering such scenario, the container structure still shows lower emissions.

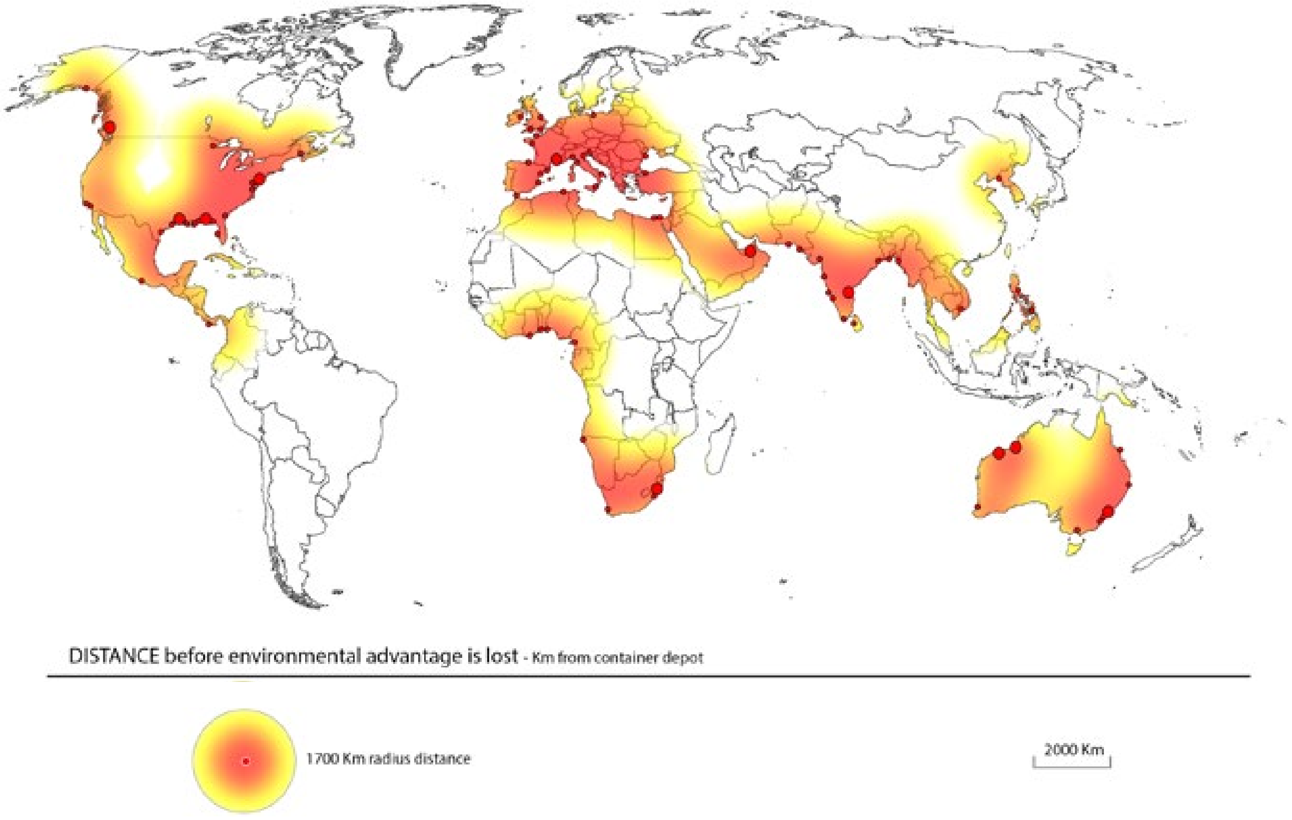


FIGURE 4.3 - Distance for environmental advantage from seaports

CHAPTER

V

Construction and Use Stage

.1 Building construction phase

.2 Construction schedules

.3 Module A5 : results

.4 Operational energy

5. Summary and observations

.5 Module B : results

5.1 Building construction phase

This stage can be considered as an additional manufacturing phase in which building materials, considered as individual products, come together in the manufacturing of the entire building.
This stage can be important in terms of energy used for the major machinery involved in construction operations. Generally speaking, emissions during the construction phase are related to the result of the only equipment operation, which usually consumes electricity and fuels.

Little detailed information exists regarding impacts from the constrction stage in the building sector, even less for residential buildings. Moreover the current literature usually does not consider onsite fabrication impacts, assuming them to be minimal on the whole life cycle of a building.
Nevertheless experience shows that shipping container structures, as well as prefabricated or X-Lam, are much faster than traditional technologies. Therefore it is essential to include even the construction stage to ensure a fair comparison including all benefits and disadvantages from each technology.

To develop the calculation of emissions from this stage it has been used a time chart of building operations. For each operation needed was then defined the duration of the construction process and emission of major equipment used.
Operations are not considered to overlap due to the lack of data regarding this topic.
Time schedules for the container structure were defined from the experience gained during the construction of Drivelines Studios and verified with the methodology developed in the study to ensure they were consistent.
In each construction site was assumed the presence of 5 workers (2 basic, 1 qualified and 1 specialized) with 8 labour hours per day.

Power emissions for electricity or fuel are indicated in *figure 5.2 .*
Specifications for the considered equipment are sumarized in the following table.

Machinery involved	**Engine Power** *[Hp]*	**Engine Power** ***[kW]***	**Engine type**
Cement mixer	11	8,203	*diesel*
Excavator	180	134,226	*diesel*
End Cutter	34	25,354	*electric*
Welder	35	26,100	*electric*
Forklift	83	61,893	*diesel*
Crane	175	130,498	*diesel*
Saw blade		1,800	*electric*
Generic light sets	110	82,027	*electric*
Generator/Compressor	37	27,591	*diesel*
Sander		0,800	*electric*
Dump truck		386,000	*diesel*

FIGURE 5.1 - Machinery specifications

Operations for the arrangement of the construction site such as demolitions, earthworks, fundations and crane positioning were excluded from the study considering the correspondence throughout each structural technology. The same way were excluded operations for mechanical systems, stairs and finishes.

5.2 Construction schedules

CONSTRUCTION PHASE	WORK	Code	Unit	Quantity [unit]	[hours /unit]	Total hours [h]	Days (8h working day)	Machinery involved	%	Engine Power [kW]	Total [kW-h] - DIESEL	Total [kW-h] - ELECTRICITY
STRUCTURAL	*Cut out for openings*	TOC.30,340	m2	**322,550**	0,270	**87,089**	**2,177**	*End Cutter*	*1*	25,354		**2208,024**
	Reinforce openings	TOC.160.110	kg	**580,245**	0,025	**14,506**	**0,363**	Welder	1	26,100		**378,603**
	Place containers - Gfloor					**4,000**	**0,500**	Forklift	1	61,893	**247,572**	
	HEA columns	TOC.110,30	kg	**273,965**	0,060	**16,438**	**0,411**	Welder	0,75	26,100		**321,766**
								Crane	0,25	130,498	**536,276**	
	Cut out stair opening + reinforce	TOC.30,340	m2	**6,460**	0,270	**1,744**	**0,044**	End cutter	1	25,354		**44,222**
	Place containers - 1st Floor					**4,000**	**0,500**	Crane	0,7	130,498	**365,393**	
								Forklift	0,3	61,893	**74,272**	
	Fire protection	TOC,180,920	m2	**68,763**	0,240	**16,503**	**0,413**					
	Roof Sloped structure	TOC,110,30	kg	2397,663	0,060	**143,860**	**3,596**	Welder	0,75	26,100		**2816,001**
								Crane	0,25	130,498	**4693,335**	
	TOTALS					**288,140**	**8,003**				**5916,848**	**5768,616**
FIT OUT	*Wall frame*	TOC.150.510,a	m2	**265,003**	0,360	**95,401**	**2,385**	Saw blade	0,3	1,800		**51,517**
	Insulation	TOC.150.460.b	m2	**569,933**	0,160	**91,189**	**2,280**					
	Floor Sanding		m2	**172,160**	0,138	**23,758**	**0,594**	Sander	1	0,800		**19,006**
	Floor finishes	TOC.190.210	m2	**215,620**	0,420	**90,560**	**2,264**					
	TOTALS					**300,909**	**7,523**				**0,000**	**70,523**
								Generator	0,3	27,591	**4875,714**	
								Light Sets	0,3	82,027		**14495,367**
TOTAL						**589,049**	**15,526**				**10792,562**	**20334,505**

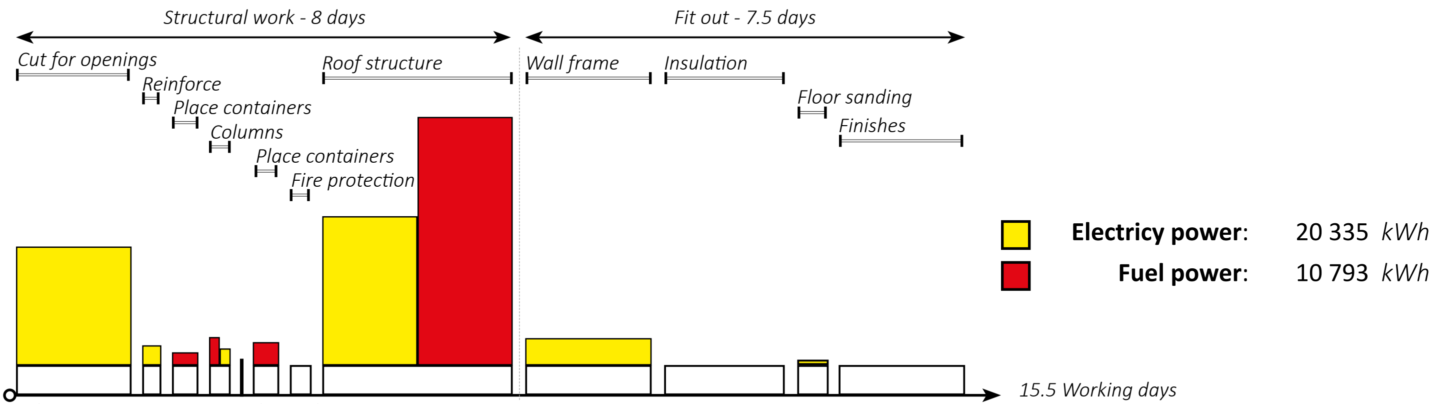
FIGURE 5.2 - Construction schedule Container structure - Vancouver

CONSTRUCTION PHASE	WORK	Code	Unit	Quantity [unit]	[hours /unit]	Total hours [h]	Days (8h working day)	Machinery involved	%	Engine Power [kW]	Total [kW-h] - DIESEL	Total [kW-h] - ELECTRICITY
STRUCTURAL	*Structural frame*	TOC.110,30	kg	**10041,221**	0,060	**602,473**	**15,062**	Welder	0,75	26,100		**11793,188**
								Crane	0,25	130,498	**19655,314**	
	Floor base	TOC.110.360	m3	**3,234**	0,500	**1,617**	**0,040**	Crane	0,2	130,498	**42,207**	
	Fire protection	TOC,180,920	m2	**569,933**	0,240	**136,784**	**3,420**					
	TOTALS					**740,874**	**18,522**				**19697,520**	**11793,188**
FIT OUT	*Wall frame*	TOC.150.510,a	m2	**265,003**	0,360	**95,401**	**2,385**	Saw blade	0,3	1,800		**51,517**
	Insulation	TOC.150.460.b	m2	**569,933**	0,160	**91,189**	**2,280**					
	Floor finishes	TOC.190.210	m2	**215,620**	0,420	**90,560**	**2,264**					
	Exterior Cladding	TOC.200	m2	**265,003**	0,400	**106,001**	**2,650**					
	TOTALS					**383,152**	**9,579**				**0,000**	**51,517**
								Generator	0,3	27,591	**9303,871**	
								Light Sets	0,3	82,027		**27660,157**
TOTAL						**1124,027**	**28,101**				**29001,392**	**39504,862**

FIGURE 5.3 - Construction schedule Steel structure - Vancouver

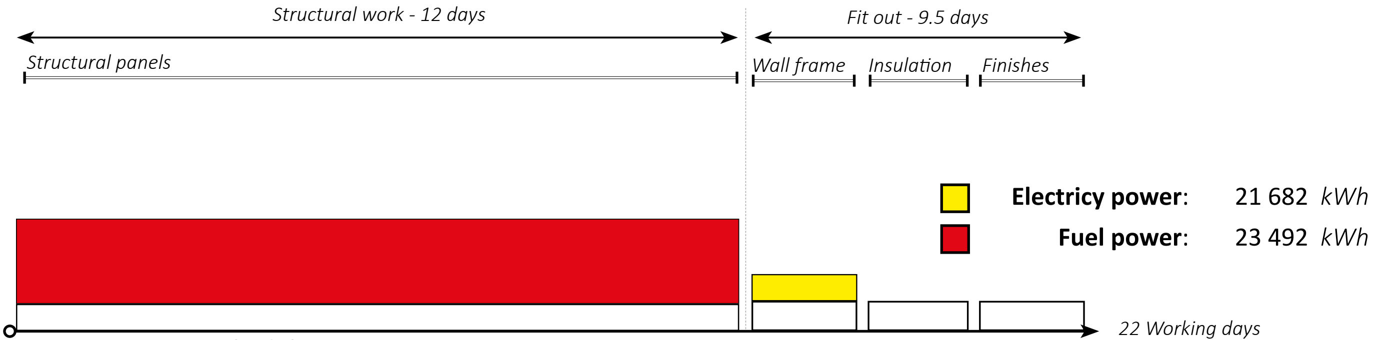
CONSTRUCTION PHASE	WORK	Code	Unit	Quantity [unit]	[hours /unit]	Total hours [h]	Days (8h working day)	Machinery involved	%	Engine Power [kW]	Total [kW-h] - DIESEL	Total [kW-h] - ELECTRICITY
STRUCTURAL	*Structural panels*		m2	**569,933**	0,870	**495,842**	**12,396**	Crane	0,25	130,498	**16176,532**	
	TOTALS					**495,842**	**12,396**				**16176,532**	**0,000**
FIT OUT	*Wall frame*	TOC.150.510,a	m2	**265,003**	0,360	**95,401**	**2,385**	Saw blade	0,3	1,800		**51,517**
	Insulation	TOC.150.460.b	m2	**569,933**	0,160	**91,189**	**2,280**					
	Floor finishes	TOC.190.210	m2	**215,620**	0,420	**90,560**	**2,264**					
	Exterior Cladding	TOC.200	m2	**265,003**	0,400	**106,001**	**2,650**					
	TOTALS					**383,152**	**9,579**				**0,000**	**51,517**
								Generator	0,3	27,591	**7275,671**	
								Light Sets	0,3	82,027		**21630,373**
TOTAL						**878,994**	**21,975**				**23452,202**	**21681,890**

FIGURE 5.4 - Construction schedule X-Lam structure - Vancouver



Shipping container schedule - Vancouver

Steel frame schedule - Vancouver



X-Lam structure schedule - Vancouver

FIGURE 5.5 - Construction schedules compared - Vancouver

CONSTRUCTION PHASE	WORK	Code	Unit	Quantity [unit]	[hours /unit]	Total hours [h]	Days (8h working day)	Machinery involved	%	Engine Power [kW]	Total [kW-h] - DIESEL	Total [kW-h] - ELECTRICITY
STRUCTURAL	*Cut out for openings*	TOC.30,340	m2	322,550	0,270	87,089	2,177	*End Cutter*	*1*	25,354		2208,024
	Reinforce openings	TOC.160.110	kg	580,245	0,025	14,506	0,363	Welder	1	26,100		378,603
	Place containers - Gfloor					4,000	0,500	Forklift	1	61,893	247,572	
	HEA columns	TOC.110,30	kg	273,965	0,060	16,438	0,411	Welder	0,75	26,100		321,766
								Crane	0,25	130,498	536,276	
	Cut out stair opening + reinforce	TOC.30,340	m2	6,460	0,270	1,744	0,044	End cutter	1	25,354		44,222
	Place containers - 1st Floor					4,000	0,500	Crane	0,7	130,498	365,393	
								Forklift	0,3	61,893	74,272	
	Fire protection	TOC,180,920	m2	68,763	0,240	16,503	0,413					
	TOTALS					144,280	4,407				1223,513	2952,615
FIT OUT	*Wall frame*	TOC.150.510,a	m2	265,003	0,360	95,401	2,385	Saw blade	0,3	1,800		51,517
	Insulation	TOC.150.460.b	m2	569,933	0,160	91,189	2,280					
	Floor Sanding		m2	172,160	0,138	23,758	0,594	Sander	1	0,800		19,006
	Floor finishes	TOC.190.210	m2	215,620	0,420	90,560	2,264					
	TOTALS					300,909	7,523				0,000	70,523
								Generator	0,3	27,591	3684,948	
								Light Sets	0,3	82,027		10955,251
TOTAL						445,189	11,930				4908,462	13978,389

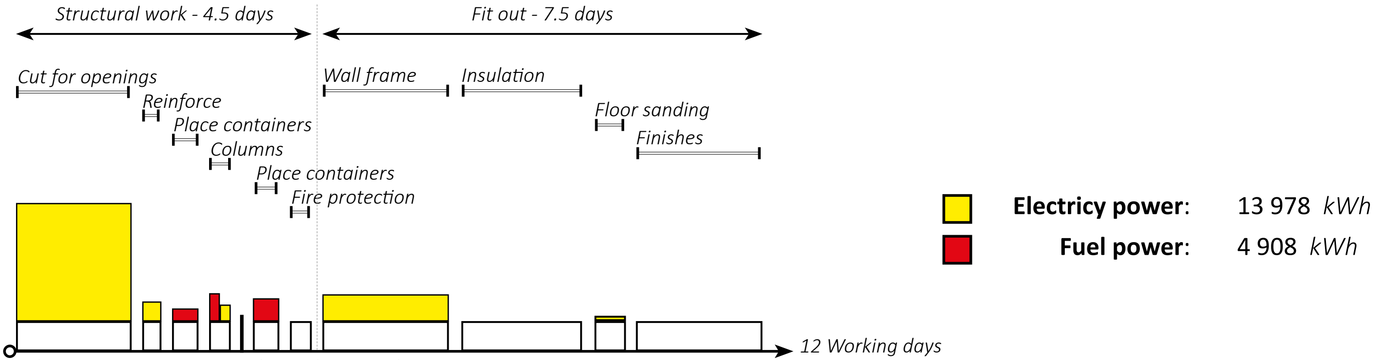
FIGURE 5.6 - Construction schedule Container structure - Durban

CONSTRUCTION PHASE	WORK	Code	Unit	Quantity [unit]	[hours /unit]	Total hours [h]	Days (8h working day)	Machinery involved	%	Engine Power [kW]	Total [kW-h] - DIESEL	Total [kW-h] - ELECTRICITY
STRUCTURAL	*Structural frame*	TOC.110,30	kg	10041,221	0,060	602,473	15,062	Welder	0,75	26,100		11793,188
								Crane	0,25	130,498	19655,314	
	Floor base	TOC.110.360	m3	3,234	0,500	1,617	0,040	Crane	0,2	130,498	42,207	
	Fire protection	TOC,180,920	m2	569,933	0,240	136,784	3,420					
	TOTALS					740,874	18,522				19697,520	11793,188
FIT OUT	*Wall frame*	TOC.150.510,a	m2	265,003	0,360	95,401	2,385	Saw blade	0,3	1,800		51,517
	Insulation	TOC.150.460.b	m2	569,933	0,160	91,189	2,280					
	Floor finishes	TOC.190.210	m2	215,620	0,420	90,560	2,264					
	Exterior Cladding	TOC.200	m2	265,003	0,400	106,001	2,650					
	TOTALS					383,152	9,579				0,000	51,517
								Generator	0,3	27,591	9303,871	
								Light Sets	0,3	82,027		27660,157
TOTAL						1124,027	28,101				29001,392	39504,862

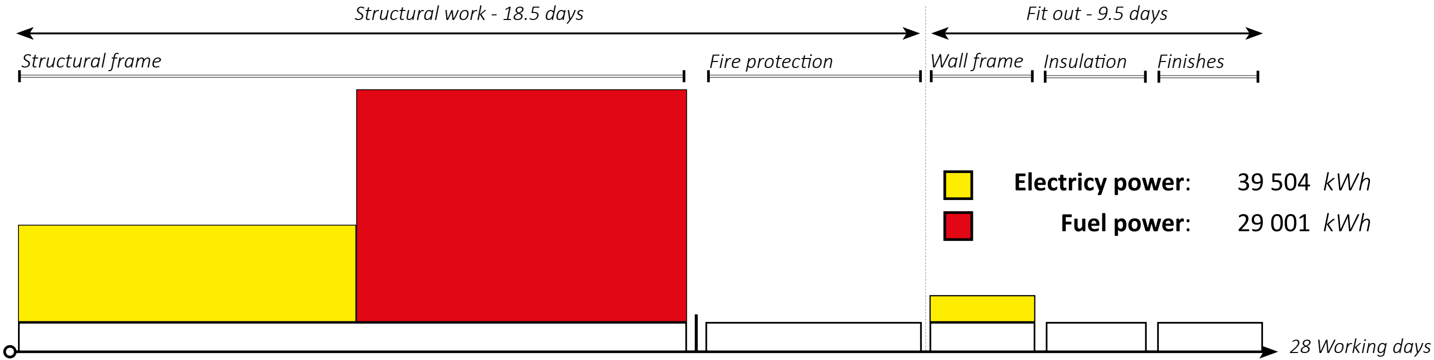
FIGURE 5.7 - Construction schedule Steel structure - Durban

CONSTRUCTION PHASE	WORK	Code	Unit	Quantity [unit]	[hours /unit]	Total hours [h]	Days (8h working day)	Machinery involved	%	Engine Power [kW]	Total [kW-h] - DIESEL	Total [kW-h] - ELECTRICITY
STRUCTURAL	*Structural panels*		m2	**569,933**	0,870	**495,842**	**12,396**	Crane	0,25	130,498	**16176,532**	
	TOTALS					**495,842**	**12,396**				**16176,532**	**0,000**
FIT OUT	*Wall frame*	TOC.150.510,a	m2	**265,003**	0,360	**95,401**	**2,385**	Saw blade	0,3	1,800		**51,517**
	Insulation	TOC.150.460.b	m2	**569,933**	0,160	**91,189**	**2,280**					
	Floor finishes	TOC.190.210	m2	**215,620**	0,420	**90,560**	**2,264**					
	Exterior Cladding	TOC.200	m2	**265,003**	0,400	**106,001**	**2,650**					
	TOTALS					**383,152**	**9,579**				**0,000**	**51,517**
								Generator	0,3	27,591	**7275,671**	
								Light Sets	0,3	82,027		**21630,373**
TOTAL						**878,994**	**21,975**				**23452,202**	**21681,890**

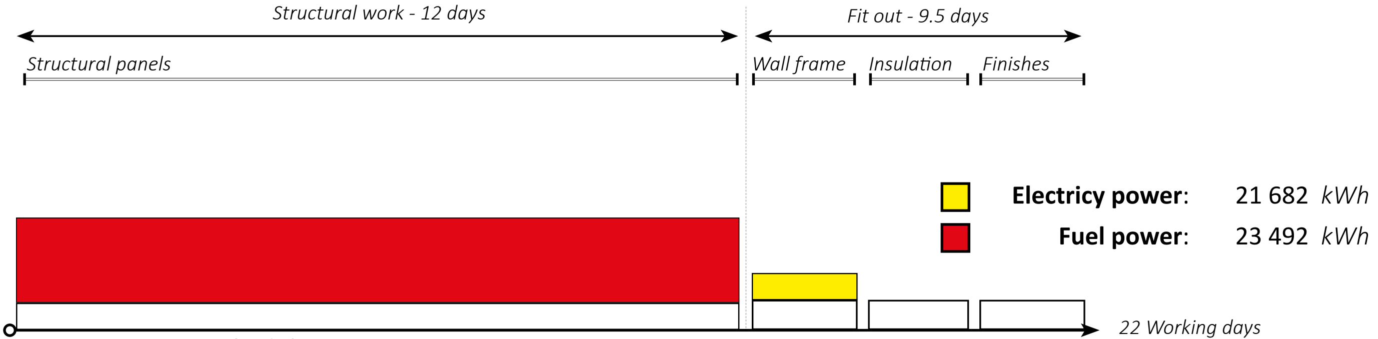
FIGURE 5.8 - Construction schedule X-Lam structure - Durban



Shipping container schedule - Durban



Steel frame schedule - Vancouver



X-Lam structure schedule - Vancouver

FIGURE 5.9 - Construction schedules compared - Durban

CONSTRUCTION PHASE	WORK	Code	Unit	Quantity [unit]	[hours /unit]	Total hours [h]	Days (8h working day)	Machinery involved	%	Engine Power [kW]	Total [kW-h] - DIESEL	Total [kW-h] - ELECTRICITY
STRUCTURAL	*Cut out for openings*	TOC.30,340	m2	**322,550**	0,270	**87,089**	**2,177**	*End Cutter*	*1*	25,354		**2208,024**
	Reinforce openings	TOC.160.110	kg	**580,245**	0,025	**14,506**	**0,363**	Welder	1	26,100		**378,603**
	Place containers - Gfloor					**4,000**	**0,500**	Forklift	1	61,893	**247,572**	
	HEA columns	TOC.110,30	kg	**273,965**	0,060	**16,438**	**0,411**	Welder	0,75	26,100		**321,766**
								Crane	0,25	130,498	**536,276**	
	Cut out stair opening + reinforce	TOC.30,340	m2	**6,460**	0,270	**1,744**	**0,044**	End cutter	1	25,354		**44,222**
	Place containers - 1st Floor					**4,000**	**0,500**	Crane	0,7	130,498	**365,393**	
								Forklift	0,3	61,893	**74,272**	
	Fire protection	TOC,180,920	m2	**68,763**	0,240	**16,503**	**0,413**					
	TOTALS					**144,280**	**4,407**				**1223,513**	**2952,615**
FIT OUT	*Wall frame*	TOC.150.510,a	m2	**265,003**	0,360	**95,401**	**2,385**	Saw blade	0,3	1,800		**51,517**
	Insulation	TOC.150.460.b	m2	**569,933**	0,160	**91,189**	**2,280**					
	Floor Sanding		m2	**172,160**	0,138	**23,758**	**0,594**	Sander	1	0,800		**19,006**
	Floor finishes	TOC.190.210	m2	**215,620**	0,420	**90,560**	**2,264**					
	TOTALS					**300,909**	**7,523**				**0,000**	**70,523**
								Generator	0,3	27,591	**3684,948**	
								Light Sets	0,3	82,027		**10955,251**
TOTAL						**445,189**	**11,930**				**4908,462**	**13978,389**

FIGURE 5.10 - Construction schedule Container structure - Chennai

CONSTRUCTION PHASE	WORK	Code	Unit	Quantity [unit]	[hours /unit]	Total hours [h]	Days (8h working day)	Machinery involved	%	Engine Power [kW]	Total [kW-h] - DIESEL	Total [kW-h] - ELECTRICITY
STRUCTURAL	*Structural frame*	TOC.110,30	kg	**10041,221**	0,060	**602,473**	**15,062**	Welder	0,75	26,100		**11793,188**
								Crane	0,25	130,498	**19655,314**	
	Floor base	TOC.110.360	m3	**3,234**	0,500	**1,617**	**0,040**	Crane	0,2	130,498	**42,207**	
	Fire protection	TOC,180,920	m2	**569,933**	0,240	**136,784**	**3,420**					
	TOTALS					**740,874**	**18,522**				**19697,520**	**11793,188**
FIT OUT	*Wall frame*	TOC.150.510,a	m2	**265,003**	0,360	**95,401**	**2,385**	Saw blade	0,3	1,800		**51,517**
	Insulation	TOC.150.460.b	m2	**569,933**	0,160	**91,189**	**2,280**					
	Floor finishes	TOC.190.210	m2	**215,620**	0,420	**90,560**	**2,264**					
	Exterior Cladding	TOC.200	m2	**265,003**	0,400	**106,001**	**2,650**					
	TOTALS					**383,152**	**9,579**				**0,000**	**51,517**
								Generator	0,3	27,591	**9303,871**	
								Light Sets	0,3	82,027		**27660,157**
TOTAL						**1124,027**	**28,101**				**29001,392**	**39504,862**

FIGURE 5.11 - Construction schedule Steel structure - Chennai

CONSTRUCTION PHASE	**WORK**	**Code**	Unit	**Quantity** [unit]	[hours /unit]	**Total hours** [h]	**Days** (8h working day)	**Machinery involved**	**%**	**Engine Power** [kW]	**Total** [kW-h] - DIESEL	**Total** [kW-h] - ELECTRICITY
STRUCTURAL	*Structural panels*		m2	**569,933**	0,870	**495,842**	**12,396**	Crane	0,25	130,498	**16176,532**	
	TOTALS					**495,842**	**12,396**				**16176,532**	**0,000**
FIT OUT	*Wall frame*	TOC.150.510,a	m2	**265,003**	0,360	**95,401**	**2,385**	Saw blade	0,3	1,800		**51,517**
	Insulation	TOC.150.460.b	m2	**569,933**	0,160	**91,189**	**2,280**					
	Floor finishes	TOC.190.210	m2	**215,620**	0,420	**90,560**	**2,264**					
	Exterior Cladding	TOC.200	m2	**265,003**	0,400	**106,001**	**2,650**					
	TOTALS					**383,152**	**9,579**				**0,000**	**51,517**
								Generator	0,3	27,591	**7275,671**	
								Light Sets	0,3	82,027		**21630,373**
TOTAL						**878,994**	**21,975**				**23452,202**	**21681,890**

FIGURE 5.12 - Construction schedule X-Lam structure - Chennai

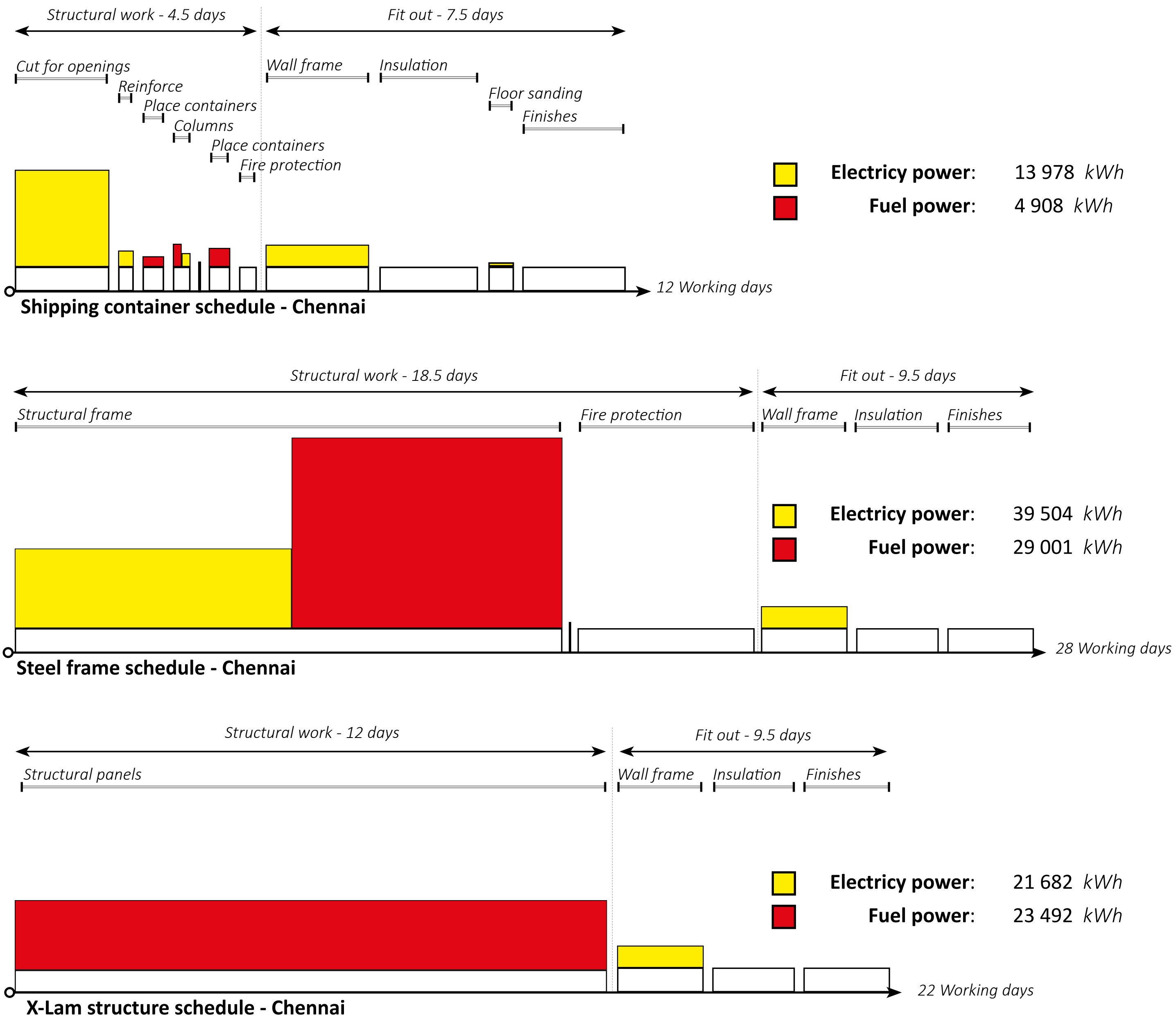


FIGURE 5.13 - Construction schedules compared - Chennai

5.3 Module A5 : results

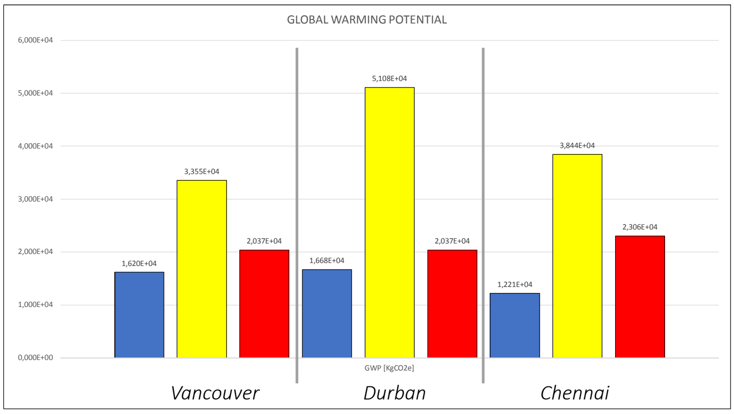
CONSTRUCTION STAGE

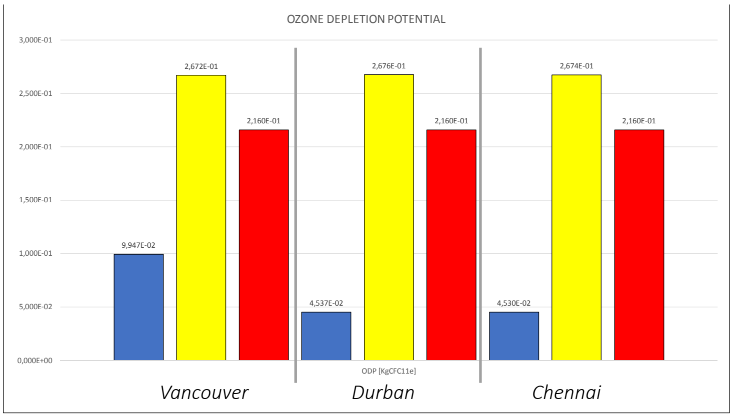
Scenario	VANCOUVER		
	CONTAINER	**STEEL**	**XLAM**
GWP [KgCO2e]	1,620E+04	3,355E+04	2,037E+04
ODP [KgCFC11e]	9,947E-02	2,672E-01	2,160E-01
AP [KgSO2e]	2,479E+01	5,460E+01	3,599E+01
EP [Kg(PO4)3e]	1,493E+01	2,981E+01	1,711E+01

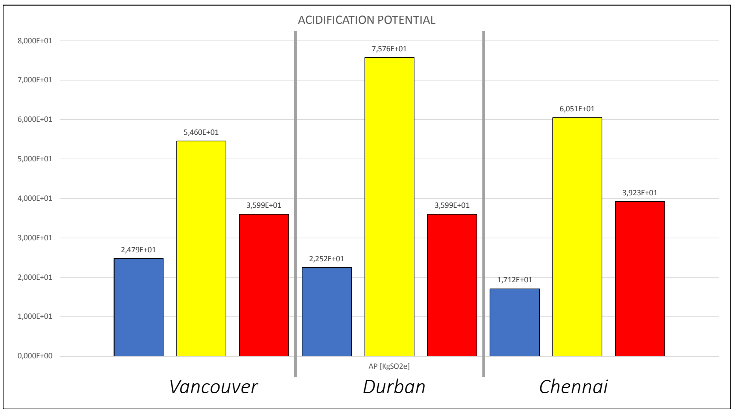
Scenario	DURBAN		
	CONTAINER	**STEEL**	**XLAM**
GWP [KgCO2e]	1,668E+04	5,108E+04	2,037E+04
ODP [KgCFC11e]	4,537E-02	2,676E-01	2,160E-01
AP [KgSO2e]	2,252E+01	7,576E+01	3,599E+01
EP [Kg(PO4)3e]	1,643E+01	4,794E+01	1,711E+01

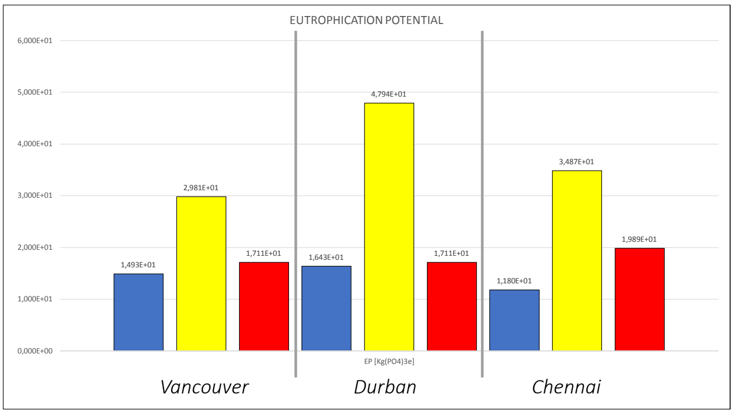
Scenario	CHENNAI		
	CONTAINER	**STEEL**	**XLAM**
GWP [KgCO2e]	1,221E+04	3,844E+04	2,306E+04
ODP [KgCFC11e]	4,530E-02	2,674E-01	2,160E-01
AP [KgSO2e]	1,712E+01	6,051E+01	3,923E+01
EP [Kg(PO4)3e]	1,180E+01	3,487E+01	1,989E+01

🟦 *Shipping Container* 🟨 *Steel Frame* 🟥 *X-Lam*









5.4 Summary and observations

Construction Stage's results show that the theorical rapidity of shipping container structures lead to lower emissions compared to traditional structures.
It is necessary to highlight that on a practical point of view, container buildings are non-standard structures. This means that the construction could run into delays due to permissions. It has been assumed that breaks on the construction schedule won't increase emissions. If the study will be extended including economical aspects, delays in the constrution schedule have to be considered and modelled within the system.
Moreover these non-standards structures may need operations in which contractors are unfamiliar within the residential sector, therefore limitating the availability of labour force in some locations. This aspect might affect social aspects of container sustainability
Nevertheless these issues are limitations only from the pont of view of labour force availability and do not affect the environmental impact of a constainer structure, which is the parameter of sustainability addressed in this thesis.

Finally it is important to underlinde that a cold climate scenario leads to lower differences between emissions due to the presence of a sloped roof structure in the container building. Compared to the overall rapidity of construction of shipping containers, assembling a sloped roof structure highly increases the construction time. Further attention should be put into the analysis of the impact of different light roof structures in order to contain emissions of this stage and enhancing the environmental benefits of the use of shipping containers as bulding components.

5.5 Operational energy

During the occupancy stage it is necessary to take into account functions as heating, cooling, lighting, water use, refurbishment and maintenance. During this phase the building may be remodeled partially and internally reconfigured number of times. Commonly the stage is evaluated by means of its energy use. Annual energy is calculated taking into account the use and occupancy patterns of each space, the mechanical features of the building and local climate.
Moving from these considerations becomes evident that the operational stage is highly related to design and technical decisions, which are completely indipendent from the structural material selected. Therefore the whole Use Stage does not affect the scope of this study.

Literature regarding life cycle assessment of buildings focuses its attention on the operational phase, mainly because it accounts for a large portion of the environmental impacts over the whole life cycle. Reducing the operational impact of a building has thus been by far the main target of researches, and as a result the methodology to correctly address and reduce impacts from this stage is widely available. With the mitigation of impacts related to the operational stage the relative importance of other life cycle stages has increased.
The present study is a comparative analysis and results are intended to be relative to each case study compared, rather than absolute. Since the functional unit includes requirements of thermal performance, the amount of energy produced during the use stage is exactly the same for each technology.
Furthermore literature clearly shows that operational energy is mainly affected by the thermal performance of the envelope, properties of glazing elements and efficiency of mechanical systems rather than the choice of structural materials.
Variations in emissions can be found in different scenarios due to obvious changes in exterior temperature.

The present paragraph shows how the inclusion of operational energy is not essential for the comparison of technologies, increasing the overall emissions of the whole life cycle proportionally.
Moreover the inclusion of operational stage leads to a difficult comparison of global emissions in different scenarios due to the need of larger amount of energy to heat colder climates.

The Maintenance Stage has been completely excluded from the study due to the lack of detailed data.

The calculation has been made, considering a lifetime of 50 years, as follows,

$$Q\,[kWh] = 0.024 * HDD * (H_{tr} + H_{v}) * 50\text{years}$$

where,

Q : global heating power required;
HDD : yearly heating degree days;
$H_{tr} = \Sigma\, U * S$: heat transfer of each assembly;
U : assembly's trasmittance;
S : assembly's surface;
$H_{v} = 0.34 * 0.3 * V$: Heat transfer for ventilation;
V : internal volume.

5.5 Module B : results

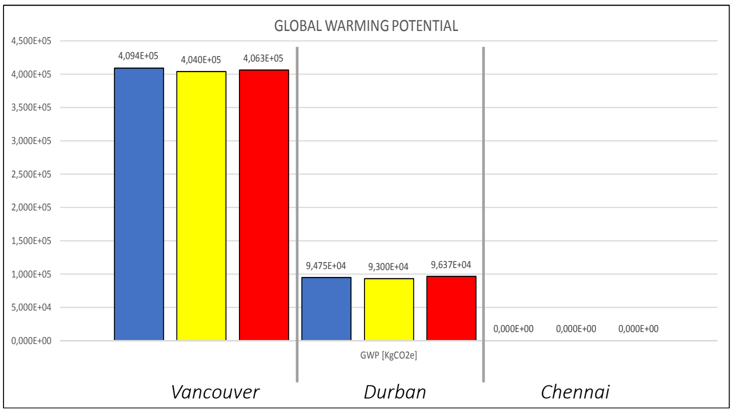
OPERATIONAL ENERGY

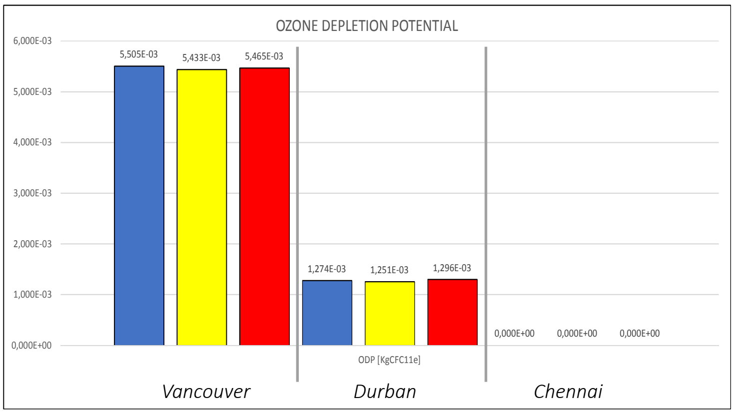
	VANCOUVER		
	CONTAINER	**STEEL**	**XLAM**
GWP [KgCO2e]	4,094E+05	4,040E+05	4,063E+05
ODP [KgCFC11e]	5,505E-03	5,433E-03	5,465E-03
AP [KgSO2e]	4,941E+02	4,876E+02	4,904E+02
EP [Kg(PO4)3e]	4,235E+02	4,179E+02	4,204E+02

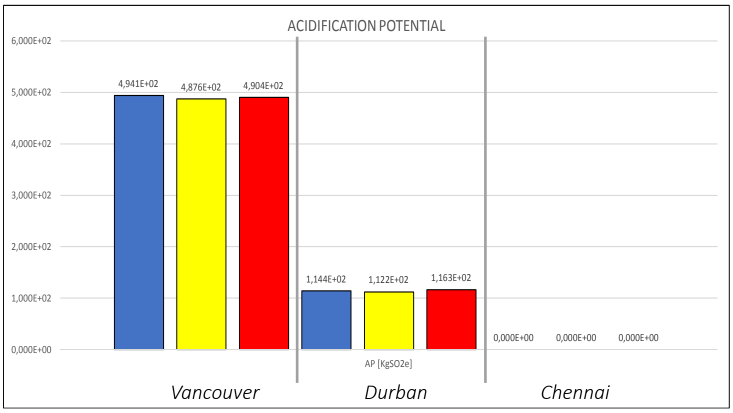
	DURBAN		
	CONTAINER	**STEEL**	**XLAM**
GWP [KgCO2e]	9,475E+04	9,300E+04	9,637E+04
ODP [KgCFC11e]	1,274E-03	1,251E-03	1,296E-03
AP [KgSO2e]	1,144E+02	1,122E+02	1,163E+02
EP [Kg(PO4)3e]	9,802E+01	9,621E+01	9,970E+01

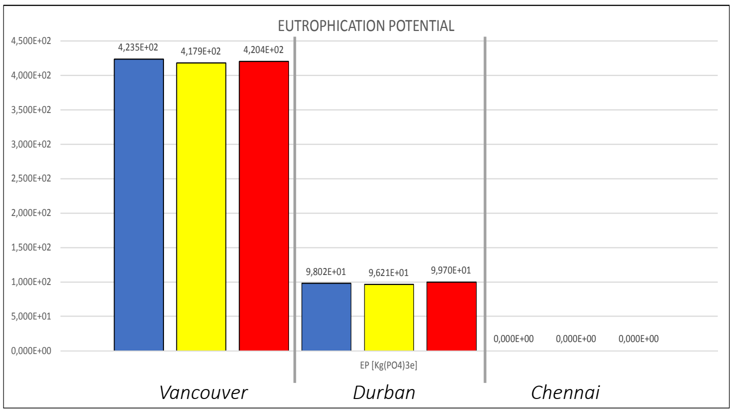
	CHENNAI		
	CONTAINER	**STEEL**	**XLAM**
GWP [KgCO2e]	0,000E+00	0,000E+00	0,000E+00
ODP [KgCFC11e]	0,000E+00	0,000E+00	0,000E+00
AP [KgSO2e]	0,000E+00	0,000E+00	0,000E+00
EP [Kg(PO4)3e]	0,000E+00	0,000E+00	0,000E+00

🟦 *Shipping Container* 🟨 *Steel Frame* 🟥 *X-Lam*









CHAPTER

VI

End of Life

6.1 End of Life stages

The End of Life of a building is marked by the demolition phase athough it is not the end for each individual material which faces a subsequent phase of Reuse-Recovery-Recycling or final disposal.
It is a particularly difficult stage for a Life Cycle Assessment because, for a building being assessed and designed now, it deals with practices far away in the future and is therefore subject to high uncertainities.

Several sub-stages compose the entire End of Life of a Building, including Demolition, Waste Processing, Waste Transport and Landfilling for Module C with the additional attribution of recycling credits for Module D, which is considered out of system boundary.
The focus of this stage is primarly with the implications of the environmental burdens associated to waste processing and landfilling or recycling, which are the most relevant ones.

Current demolition practices depend on highly variable factors such as contractor's practice, market prices and demand which are quite unpredictable.
The demolition stage has been assessed with the same method of the construction stage: defining operations needed, using time charts and computing the hourly usage of each equipment resulting in fuel and electricity power consumed, then converted in their relative impacts.

After the demolition phase, it has been computed the whole amount of materials resulted from the process. Then building materials have been divided into different flows with the support of EPDs and Recycling-Reuse rates.
Environmental Product Declarations usually provide information for the next step, which consists on waste processing.
System boundaries have been expanded until landfilling therefore waste transport and landfill emissions have been calculated for the correspondent material flows.
Life Cycle Assessment's literature agrees with the assumption that flows of materials for Reuse and Recycling fall outside of the building's system boundaries. Therefore emissions for the transport of these material flows has not been computed to the building system, they pertain to the module A2 - transport's product stage - of the next life cycle.

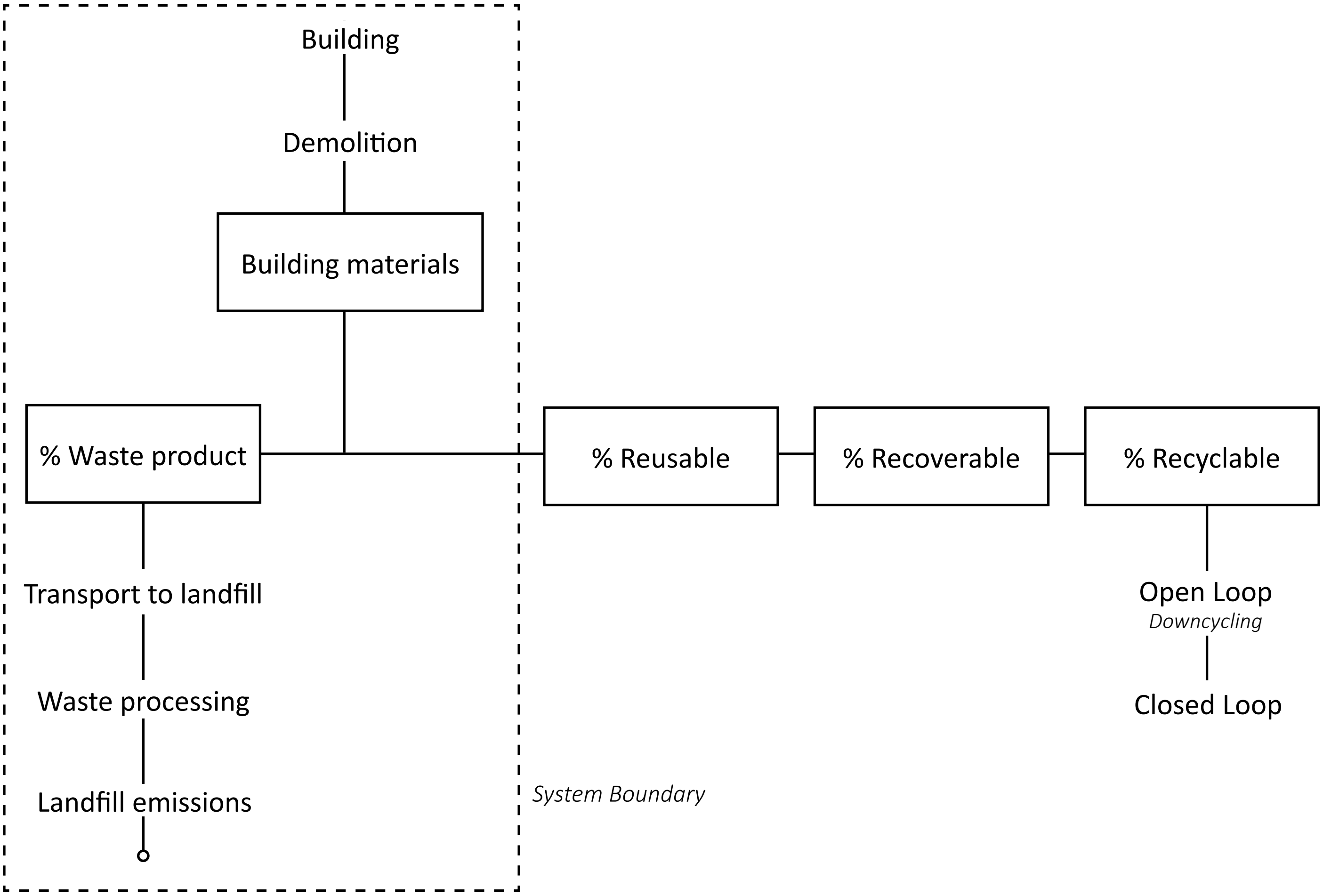


FIGURE 6.1 - Material flows at the End of Life

For what concerns Waste Processing, it has been assessed in the same way of Embodied Energies: EPDs provided emissions for mass of waste product to be landfilled. Then the total amount of building material to be landfilled, which can be just a part of the material available from the demolition process, is multiplied by unit emissions to get the overall waste processing’s category impacts. Recycling and Reuse rates are summarized in the following table. Waste material for landfill consists on the amount of material not included in Reuse and Recycling rates.

Material	Recycling rate	Reuse rate	Disposal rate
Structural steel	80%	10%	10%
X-Lam panels	50%	40%	10%
Hardwood timber	50%	40%	10%
OSB	100%	0%	0%
Gypsum	0%	0%	100%
Timber finishes	40%	50%	10%
Rockwool insulation	90%	0%	10%
Bricks	50%	40%	10%

FIGURE 6.2 - Reuse-Recycling-Disposal rates

Follows a brief desription of possible scenarios and common practices for the managment of the End of Life of building materials considered within this study.

STRUCTURAL STEEL

Iron and Steel account for around 90% of the mass of metals consumed worldwide. Iron is used as raw material for the production of steel, which requires an intermediate step material called Pig Iron, produced by combining iron and carbon. Pig Iron is then used for the final production of steel in a smelting process involving use of high temperatures and therefore high consumption of energy.
Metals are considered infinitely recyclable in principle, but “in practice recycling is often inefficient because of limits imposed by social behaviour, product design, recycling technologies and the thermodynamics of separation”, as stated by an *OECD report (2010)*.
The main issue consists in the separation and contamination of various metals used to produce steel alloys and coatings in order to properly control the quality of the product for the next life cycle.
Moreover it has been estimated that a portion of steel will never become available for recycling, in part due to ongoing corrosion losses, estimated at 0,5% rate per year, along with retrieval cost issues.

Recycling rates highly depend upon who is doing surveys and calculations, they can range from 97% to 60%, based on researches from *Steel Recycling Institute (SRI), US Geological Survey (USGS*) or the *Canadian Steel Producers Association (CSPA)*.
Great differences in recycling rates are also to be attributed to the definition of scarp, which is steel potentially available for recycling.

The majority of metal scarp is processed using one of two technologies: Basic Oxygen Furnace (BOF) or Electric Arc Furnace (EAF).
EAF is limited to the production of large structural shapes due to the inhability to totally remove contaminats from the scarp steel processed. Contaminations are the main cause of preformance issues only for thin and light producccts. Up to 100% of scarp steel can be used as input for an EAF mill. When steel is used to make large structural shapes, the contamination problem is buried within a large mass of material so that they have minimal impact on the resulting product. About 8% of the material entering the furnace is lost during the re-melting and recycling process. The inclusion of re-melting losses is one of the major causes of discrepancies in recycling rates.

For all the above reasons, rates for steel are assumed to be 80% for recycling, 10% for direct reuse, considering 10% of material to be lost or disposed to landfill due to imprecisions in material sorting an retrieval.
Due to the lack of avilable data from recycling of shipping containers, it has been assumed for the End of Life that, after shattering the container structure into pieces, scrap material is considered as scrap metal, with the same rates of steel.

TIMBER PRODUCTS

Timber products can be dived into different categories, depending on the properties and utilization of the matierial. In this study timber products are used for structural, partitioning and finishing purposes. Timber products have a common input material which is wood, therefore they all share Carbon Sequestration properties during their Embodied Energy stage. Variations of emissions throughout different products are related mainly to the manufacturing process and the use of additional products such as glues or resines.

Structural products considered in the study are X-Lam and Hardwood timber.
X-Lam is used in buildings for load-bearing structures such as walls, roofs and ceilings. It consists on layers of wood, which are arranged crosswise and glued together under high pressure, using diffent kinds of glue. X-Lam panels are large, solid wood elements, which are cut to size.
Hardwood timber is usually produced without additional products such as glues, hence leading to negative carbon footprint. Logs are seasoned and cut to size.

Finishes are made with Laminate flooring, which is used as decorative hard surface floor elements. The floor is installed as floating floor without any adhesives, using click connections. The laminate flooring combines a coreboard with a decorative paper, which are pressed together in a hot press. The pressed product forms a single element, called master board. After the master board is cooled, it is cut to size, and click profile is added to its edges. The product is packed in ready packets with a protective film. All material wastage is fed back to process for heat production.

For partitioning and superficial mass have been used OSB panels. Oriented Strand Boards are produced with cross-oriented layers of thin, rectangular wooden strips compressed and bonded together with wax and resin adhesives. The board production starts by reducing different assortments of wood into rectangular chips. The chips are then dried to the wanted moisture level, after which they are glued together. All material wastage is used as input for another production stage. Wood used as input material is usually scrap material from other lifecycles.

Whatever the use of each product, at the end of life the managment of timber is quite the same. Due to the inherent renewable and living nature of input material, the production of high quality timber can’t be made in close loop recycling.
Waste timber products can be reused, reduced to chips to be used for downcycled products or used for the production of energy. It is evident that is not possible to remanufacture structural boards into wood logs therefore the the lifecycle loop has to be opened to other products such as Chipboard or OSB. Oriented Strand Board is the only timber product that due to its production process can be modelled in close loop recycling.
Moving from these considerations, it is important to highlight that even with the impossibility of recycling timber products, they cannot be considered a linear economy due to the overall renewable nature of wood resources.

It has been considered that 40% of timber products can be reused and 50% recycled. Closed or Open Loop recycling concepts will be addressed in module D.

ROCKWOOL INSULATION

Rockwool insulation is based on natural stone and recycled post-production of waste materials. Binder and impregnation oil are added to achieve the technical properties requested. Materials are bond together into briquettes from a variety of stones along with pre-and-post-consumer rockwool products. Input materials are melt in a blast furnace oven and the influence of a powerful air flow creates fibers.
It is evident the close-recycling-loop nature of rockwool insulations, therefore a rate of 90% recycling has been used in order to consider material losses during all lifecycles of the building.

GYPSUM BOARD

Gypsum plasterboard is a standard mineral product used as dry mortarless building material indoors. It consists of two sheets of cardboard and a gypsum layer in between them. Raw materials for gypsum plasterboards are calcinated gypsum, cardboard and additives. Gypsum is either coming from mined gypsum, gypsum from flue-gas desulphurization in coal plants (FSG) or other synthetic gypsums.
Gypsum is considered to be completelly landfilled at the End of Life.

6.2 Demolition schedules

DEMOLITION PHASE	WORK	Code	Unit	Quantity [unit]	[hours /unit]	Total hours [h]	Days (8h working day)	Machinery involved	%	Engine Power [kW]	Total [kW-h] - DIESEL	Total [kW-h] - ELECTRICITY
FINISHES												
	Wall system removal	TOC.30.260.c	m2	**480,623**	0,180	**86,512**	**2,163**					
	Floor removal	TOC.30.230.j	m2	**215,620**	0,220	**47,436**	**1,186**					
								Forklift (similar)	1	61,893	**2935,986**	
	Roofing system removal	TOC.30.220.b	m2	**89,310**	0,180	**16,076**	**0,402**					
								Forklift (similar)	1	61,893	**994,981**	
	TOTALS					**150,024**	**3,751**				**3930,967**	**0,000**
STRUCTURE												
	Sloped roof removal	TOC.30.180	m2	**89,310**	0,100	**8,931**	**0,223**					
								Forklift (similar)	1	61,893	**552,767**	
	Floor structure	TOC.30.130	m2	**215,620**	0,510	**109,966**	**2,749**					
								Saw blade	0,5	1,800		**98,970**
								Forklift (similar)	0,5	61,893	**3403,075**	
	Container structure demolition	TOC.30.340.b	kg	**16957,810**	0,024	**406,987**	**10,175**					
								Saw blade	0,5	1,800		**366,289**
								Forklift (similar)	0,5	61,893	**12594,857**	
	TOTALS					**525,885**	**13,147**				**16550,699**	**465,258**
								Generator	0,3	27,591	**5594,681**	
								Light Sets	0,3	82,027		**16632,836**
TOTAL						**675,909**	**16,898**				**26076,347**	**17098,095**

FIGURE 6.3 - Demolition stage - Container structure - Vancouver/Durban/Chennai

DEMOLITION PHASE	**WORK**	**Code**	Unit	**Quantity** [unit]	[hours /unit]	**Total hours** [h]	**Days** (8h working day)	**Machinery involved**	**%**	**Engine Power** [kW]	**Total** [kW-h] - DIESEL	**Total** [kW-h] - ELECTRICITY
						*E*F*	*G / (8h * workers)*				*k*G*J*	*k*G*J*
FINISHES	*Wall system removal*	TOC.30.260.c	m2	**480,623**	0,180	**86,512**	**2,163**					
	Floor removal	TOC.30.230.j	m2	**215,620**	0,220	**47,436**	**1,186**	Forklift (similar)	1	61,893	**2935,986**	
	Roofing system removal	TOC.30.220.b	m2	**89,310**	0,180	**16,076**	**0,402**	Forklift (similar)	1	61,893	**994,981**	
	TOTALS					**150,024**	**3,751**				**3930,967**	**0,000**
STRUCTURE	*Floor structure*	TOC.30.130	m2	**215,620**	0,510	**109,966**	**2,749**	Saw blade	0,5	1,800		**98,970**
								Forklift (similar)	0,5	61,893	**3403,075**	
	Steel structure	TOC.30.340.b	kg	**10041,221**	0,024	**240,989**	**6,025**	Saw blade	0,5	1,800		**216,890**
								Forklift (similar)	0,5	61,893	**7457,788**	
	TOTALS					**350,956**	**8,774**				**10860,862**	**315,860**
								Generator	0,3	27,591	**4146,746**	
								Light Sets	0,3	82,027		**12328,163**
TOTAL						**500,980**	**12,524**				**18938,575**	**12644,023**

FIGURE 6.4 - Demolition stage - Steel frame - Vancouver/Durban/Chennai

WASTE	**P** [Kg]	**Recycling rate**	$P_{recycle}$ [Kg]	**Reuse rate**	$P_{recovery}$ [Kg]	P_{waste} [Kg]
OSB	5129,399	1,000	**5129,399**	0,000	**0,000**	**0,000**
Steel	10041,221	0,900	**9037,099**	0,000	**0,000**	**1004,122**
Wall frame	1732,793	0,500	**866,397**	0,500	**866,397**	**0,000**
Insulation	2440,007	0,900	**2196,007**	0,000	**0,000**	**244,001**
Gypsum board	4354,927	0,000	**0,000**	0,000	**0,000**	**4354,927**
Cladding	3613,995	0,400	**1445,598**	0,500	**1806,997**	**361,399**
Floor finish	25768,746	0,400	**10307,498**	0,500	**12884,373**	**2576,875**
TOTAL	**5,308E+04**		**2,898E+04**		**1,556E+04**	**8,541E+03**

FIGURE 6.5 - Materials flows - Steel frame - Vancouver/Durban/Chennai

DEMOLITION PHASE	**WORK**	**Code**	Unit	**Quantity** [unit]	[hours /unit]	**Total hours** [h]	**Days** (8h working day)	**Machinery involved**	**%**	**Engine Power** [kW]	**Total** [kW-h] - DIESEL	**Total** [kW-h] - ELECTRICITY
						*E*F*	*G / (8h * workers)*				*k*G*J*	*k*G*J*
FINISHES	*Wall system removal*	TOC.30.260.c	m2	**480,623**	0,180	**86,512**	**2,163**					
	Floor removal	TOC.30.230.j	m2	**215,620**	0,220	**47,436**	**1,186**	Forklift (similar)	1	61,893	**2935,986**	
	Roofing system removal	TOC.30.220.b	m2	**89,310**	0,180	**16,076**	**0,402**	Forklift (similar)	1	61,893	**994,981**	
	TOTALS					**150,024**	**3,751**				**3930,967**	**0,000**
STRUCTURE	*Floor structure*	TOC.30.130	m2	**215,620**	0,510	**109,966**	**2,749**	Saw blade	0,5	1,800		**98,970**
								Forklift (similar)	0,5	61,893	**3403,075**	
	XLAM	TOC.30.130	m2	**569,933**	0,390	**222,274**	**5,557**	Saw blade	0,5	1,800		**200,047**
								Forklift (similar)	0,5	61,893	**6878,612**	
	TOTALS					**332,240**	**8,306**				**10281,686**	**299,016**
								Generator	0,3	27,591	**3991,834**	
								Light Sets	0,3	82,027		**11867,614**
TOTAL						**482,265**	**12,057**				**18204,487**	**12166,630**

FIGURE 6.6 - Demolition stage - Xlam - Vancouver/Durban/Chennai

WASTE	**P** [Kg]	**Recycling rate**	$P_{recycle}$ [Kg]	**Reuse rate**	$P_{recovery}$ [Kg]	P_{waste} [Kg]
OSB	5129,399	1,000	**5129,399**	0,000	**0,000**	**0,000**
XLAM	42061,070	0,500	**21030,535**	0,400	**16824,428**	**4206,107**
Wall frame	1732,793	0,500	**866,397**	0,400	**693,117**	**173,279**
Insulation	1757,138	0,900	**1581,424**	0,000	**0,000**	**175,714**
Gypsum board	4354,927	0,000	**0,000**	0,000	**0,000**	**4354,927**
Cladding	3613,995	0,400	**1445,598**	0,500	**1806,997**	**361,399**
Floor finish	25768,746	0,400	**10307,498**	0,500	**12884,373**	**2576,875**
TOTAL	**8,442E+04**		**4,036E+04**		**3,221E+04**	**1,185E+04**

FIGURE 6.7 - Materials flows - Xlam - Vancouver/Durban/Chennai

Very little variation has been found withind results for the different scenarios, therefore emissions are not subdivided into different climate zones.

Follows a comparison of emissions in each case study for the Module C1 - demolition - and Module C2 -transport to landfill..

DEMOLITION STAGE - C1			
	CONTAINER	**STEEL**	**XLAM**
GWP [KgCO2e]	1,804E+04	1,325E+04	1,274E+04
ODP [KgCFC11e]	2,401E-01	1,743E-01	1,676E-01
AP [KgSO2e]	3,445E+01	2,520E+01	2,423E+01
EP [Kg(PO4)3e]	1,425E+01	1,051E+01	1,011E+01

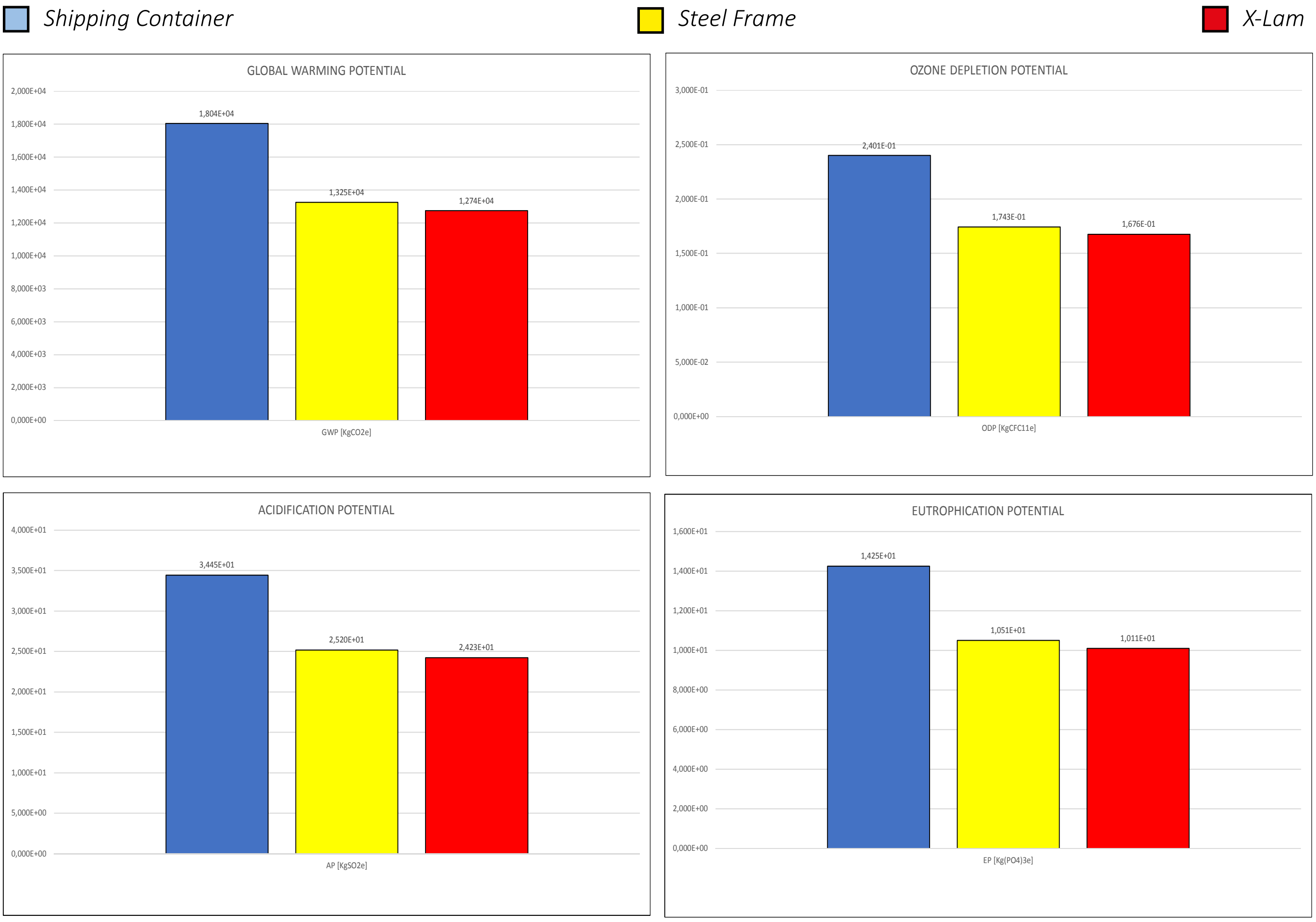


FIGURE 6.8 - Demolition stage - Module C1 emissions

LANDFILL WASTE TRANSPORT / km

	VANCOUVER		
	CONTAINER	**STEEL**	**XLAM**
GWP [KgCO2e]	3,480E-01	4,229E-01	5,665E-01
ODP [KgCFC11e]	1,232E-05	1,496E-05	2,004E-05
AP [KgSO2e]	1,071E-03	1,301E-03	1,743E-03
EP [Kg(PO4)3e]	1,339E-04	1,626E-04	2,179E-04

	DURBAN		
	CONTAINER	**STEEL**	**XLAM**
GWP [KgCO2e]	4,795E-01	5,438E-01	5,666E-01
ODP [KgCFC11e]	1,697E-05	1,924E-05	2,005E-05
AP [KgSO2e]	1,475E-03	1,673E-03	1,743E-03
EP [Kg(PO4)3e]	1,844E-04	2,091E-04	2,179E-04

	CHENNAI		
	CONTAINER	**STEEL**	**XLAM**
GWP [KgCO2e]	7,518E-01	7,377E-01	7,423E-01
ODP [KgCFC11e]	2,660E-05	2,610E-05	2,627E-05
AP [KgSO2e]	2,313E-03	2,270E-03	2,284E-03
EP [Kg(PO4)3e]	2,892E-04	2,837E-04	2,855E-04

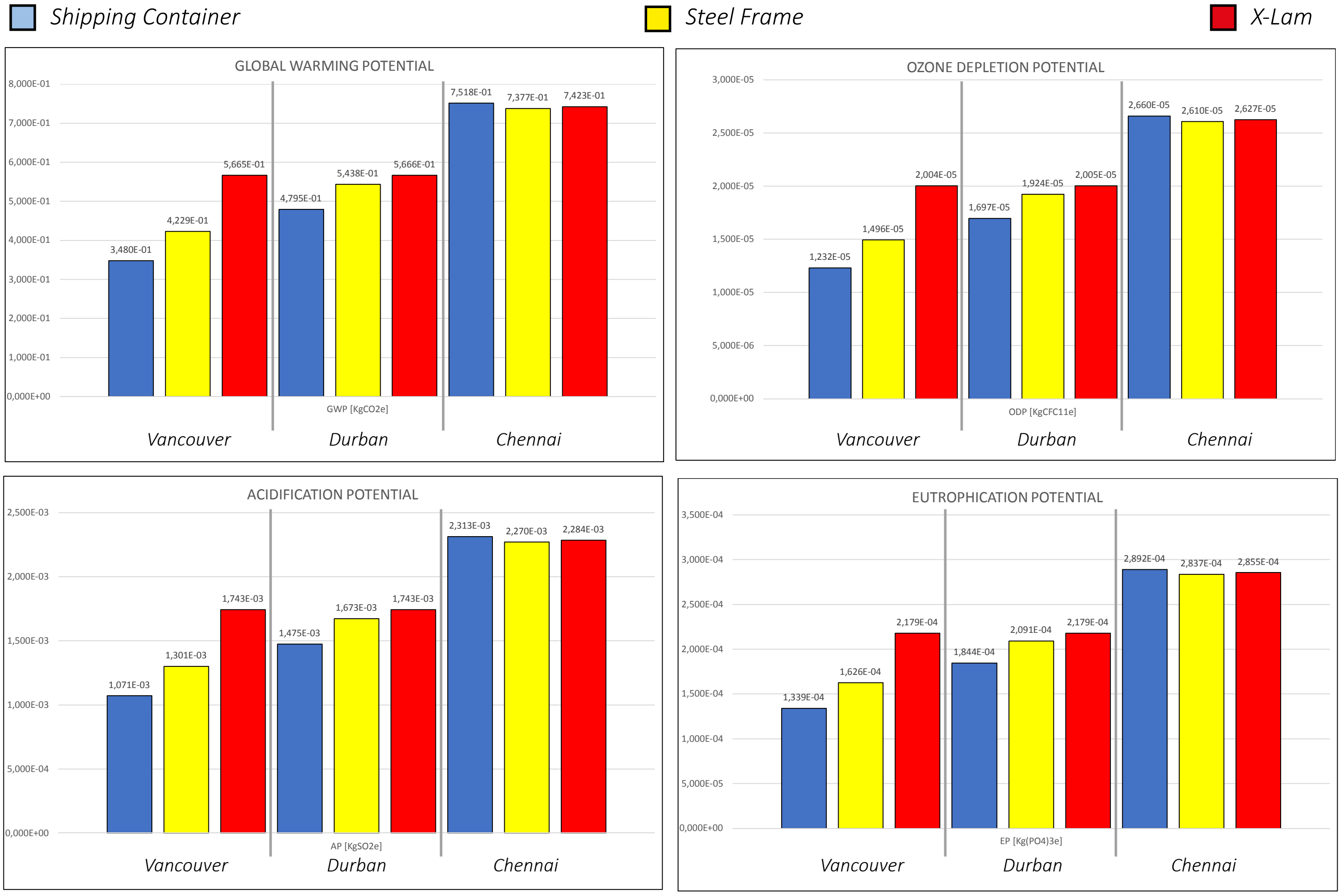


FIGURE 6.9 - Waste Transport Stage - Module C2 emissions

6.3 Landfill emissions

Although demolition waste is a problem of increasing relevance, there is little reliable statistic and literature that allows to address its magnitude in detail.

When organic materials are landfilled, anaerobic bacteria degrade them, producing both Carbon Dioxide (CO2) and Methane (CH4), along with other gases. Among them Methane is the most impactant from a Global Warming perspective due to its high potential, considered around 21-25 times CO2-equivalents.
Carbon entering the landfill can have several outputs: exit as CH4, as CO2, as volatile organic compounds (VOCs), dissolved in leachate, or remain stored in the landfill.

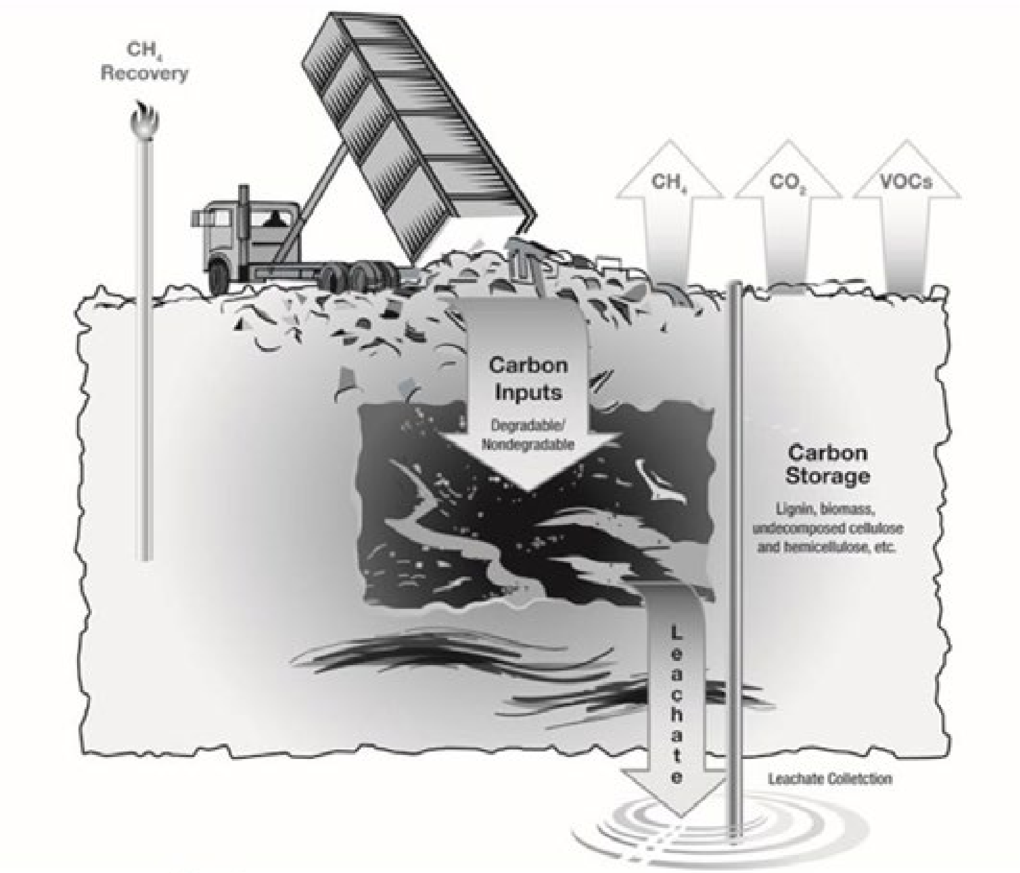


FIGURE 6.10 - Landfill carbon mass balance
- source US EPA archive/Freed et al.(2004)

Literature agrees with the assumption that CO_2 emitted in the process of degradation is not cause of environmental harm, because is considered part of the natural carbon cycle process of growth and decomposition. On the other hand CH_4 is accounted as an anthropogenic emission. In fact degradation would not naturally result in methane production if materials were not landfilled. Moreover when materials are landfilled a portion of carbon does not decompose, being subtracted from the natural carbon cycle completing the photosynthesis-respiration dualism. Carbon removed from the global carbon cycle is defined as “stored” in landfill and is accounted as anthropogenic environmental harm.

The US Environmental Protection Agency developed separate estimates from different kinds of landfill: without gas recovery systems, with flare CH_4, with combustion of CH_4 for energy recovery and average mixes.
It can be assumed that building demolition waste landfills do not manage CH_4 emissions.
Follows a description of the method.

The main stocks and flows in the landfill carbon balance are:
- Initial carbon content - Initial C;
- Carbon output as CH_4;
- Carbon output as CO_2;
- Residual carbon - landfill carbon storage.

WASTE	P [Kg]	Recycling rate	$P_{recycle}$ [Kg]	Reuse rate	$P_{recovery}$ [Kg]	P_{waste} [Kg]
Plywood (floor)	2976,418	0,500	**1488,209**	**0,400**	**1190,567**	**297,642**
Steel	16957,810	0,800	**13566,248**	**0,100**	**1695,781**	**1695,781**
Wall frame	1732,793	0,500	**866,397**	**0,500**	**866,397**	**0,000**
Insulation	2813,374	0,900	**2532,037**	**0,000**	**0,000**	**281,337**
Gypsum board	2401,194	0,000	**0,000**	**0,000**	**0,000**	**2401,194**
Cladding	1685,280	0,400	**674,112**	**0,500**	**842,640**	**168,528**
Floor finish	25768,746	0,400	**10307,498**	**0,500**	**12884,373**	**2576,875**
TOTAL			2,943E+04		1,748E+04	7,421E+03

FIGURE 6.11 - Materials flows - Container structure - Vancouver/Durban/Chennai

The following table resumes the environmental impacts related to waste processing and landfill disposal for each building material. For all the above mentioned reasons, the main impact categories affected by landfill emissions are the Global Warming Potential indicator, related to methane emissions, and the Eutrophication Potential indicator, related to lechate and solid breaking of materials.
Further reasearch should be made in order to analyze the quality of data collected.

Material	**GWP** *[kg CO2-eq/kg]*	**ODP** *[kg CFC11-eq/kg]*	**AP** *[kg SO2-eq]*	**EP** *[kg* $(PO_4)_3$*-eq]*
Structural steel	0	0	0	0
X-Lam panels	1.613	2.42x10^$^{-9}$	1.42x10^$^{-8}$	1.198x10^$^{-6}$
Hardwood timber	1.838	4.56x10^$^{-16}$	6.66x10^$^{-5}$	1.56x10^$^{-5}$
OSB	1.838	4.56x10^$^{-16}$	6.66x10^$^{-5}$	1.56x10^$^{-5}$
Gypsum	2.65x10^$^{-3}$	3.42x10^$^{-10}$	2.00x10^$^{-5}$	4.54x10^$^{-6}$
Timber finishes	1.838	4.56x10^$^{-16}$	6.66x10^$^{-5}$	1.56x10^$^{-5}$
Rockwool insulation	1.6x10^$^{-3}$	3.42x10^$^{-10}$	1.00x10^$^{-6}$	2.7x10^$^{-7}$
Bricks	2.45x10^$^{-4}$	0	1.0x10^$^{-6}$	0

FIGURE 6.12 - Waste Processing emissions -Module C3

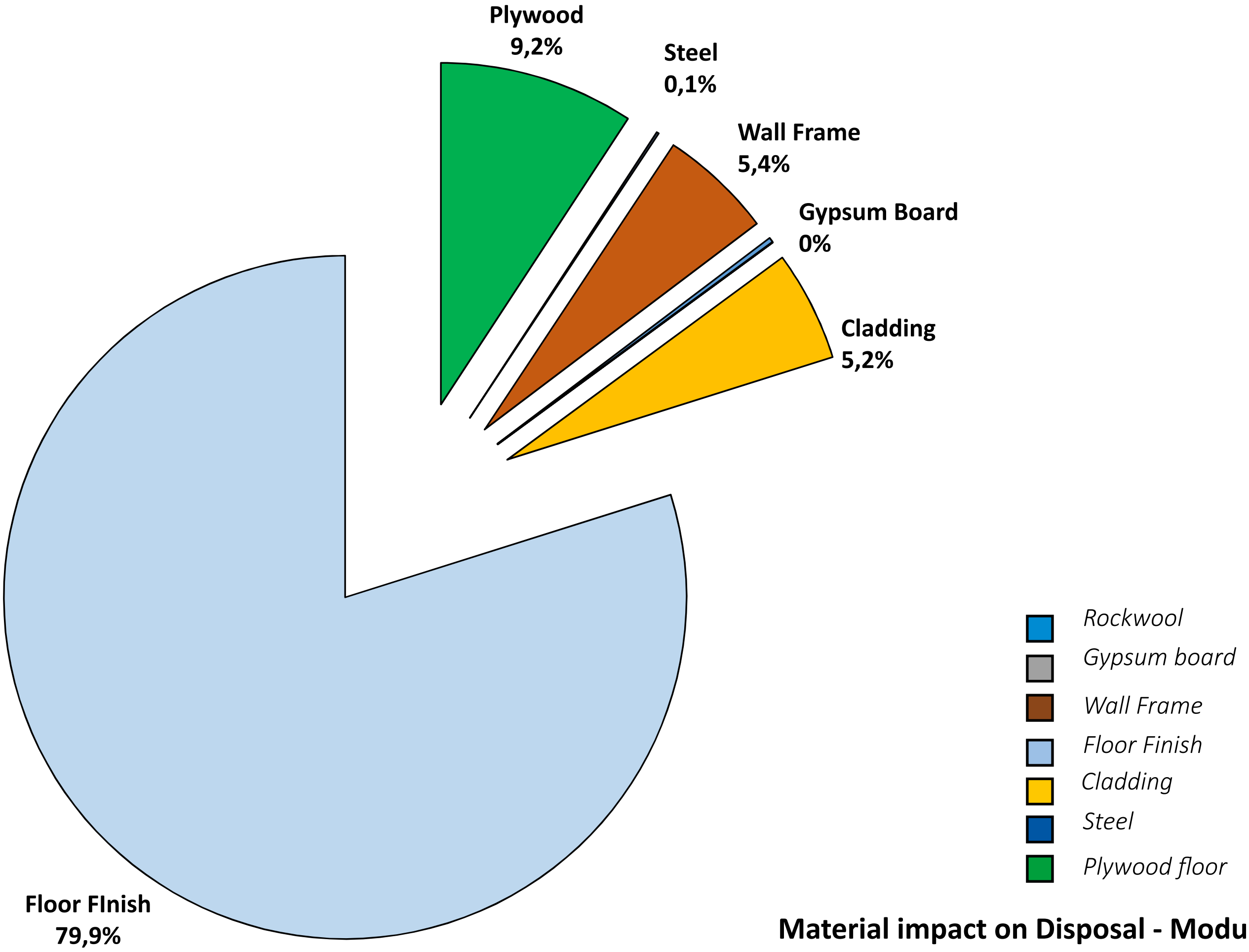
Material	**GWP** *[kg CO2-eq/kg]*	**ODP** *[kg CFC11-eq/kg]*	**AP** *[kg SO2-eq]*	**EP** *[kg* $(PO_4)_3$*-eq]*
Structural steel	1.28x10^$^{-4}$	1.41x10^$^{-14}$	7.0x10^$^{-6}$	1.05x10^$^{-6}$
X-Lam panels	0.626	3.823x10^$^{-14}$	2.53x10^$^{-4}$	3.32x10^$^{-5}$
Hardwood timber	0.626	3.823x10^$^{-14}$	2.53x10^$^{-4}$	3.32x10^$^{-5}$
OSB	0.626	3.823x10^$^{-14}$	2.53x10^$^{-4}$	3.32x10^$^{-5}$
Gypsum	0	0	0	1.6x10^$^{-5}$
Timber finishes	0.626	3.823x10^$^{-14}$	2.53x10^$^{-4}$	3.32x10^$^{-5}$
Rockwool insulation	0.0155	3.5x10^$^{-9}$	1.3x10^$^{-5}$	3.6x10^$^{-6}$
Bricks	2.4x10^-4	0	-3.2x10^$^{-5}$	-7.0x10^$^{-6}$

FIGURE 6.13 - Landfill emissions -Module C4

CONTAINER STRUCTURE - *Vancouver*

WASTE	Waste processing - Stage C3			
	GWP [KgCO2e]	**ODP** [KgCFC11e]	**AP** [KgSO2e]	**EP** [Kg(PO4)3e]
Plywood (floor)	5,471E+02	1,357E-13	1,982E-02	4,643E-03
Steel	0,000E+00	0,000E+00	0,000E+00	0,000E+00
Wall frame	3,185E+02	7,902E-14	1,154E-02	2,703E-03
Insulation	4,501E-01	7,877E-08	2,813E-04	7,596E-05
Gypsum board	6,354E+00	8,209E-07	4,812E-02	1,089E-02
Cladding	3,098E+02	7,685E-14	1,122E-02	2,629E-03
Floor finish	4,736E+03	1,175E-12	1,716E-01	4,020E-02
TOTAL	5,918E+03	8,997E-07	2,626E-01	6,114E-02

WASTE	Disposal - Stage C4			
	GWP [KgCO2e]	**ODP** [KgCFC11e]	**AP** [KgSO2e]	**EP** [Kg(PO4)3e]
Plywood (floor)	1,863E+02	1,138E-11	7,532E-02	9,881E-03
Steel	2,171E+00	2,391E-11	1,187E-02	1,781E-03
Wall frame	1,084E+02	6,625E-12	4,385E-02	5,752E-03
Insulation	4,361E+00	9,847E-07	3,657E-03	1,013E-03
Gypsum board	0,000E+00	0,000E+00	0,000E+00	3,832E-02
Cladding	1,055E+02	6,443E-12	4,265E-02	5,595E-03
Floor finish	1,613E+03	9,852E-11	6,521E-01	8,555E-02
TOTAL	2,019E+03	9,848E-07	8,295E-01	1,479E-01

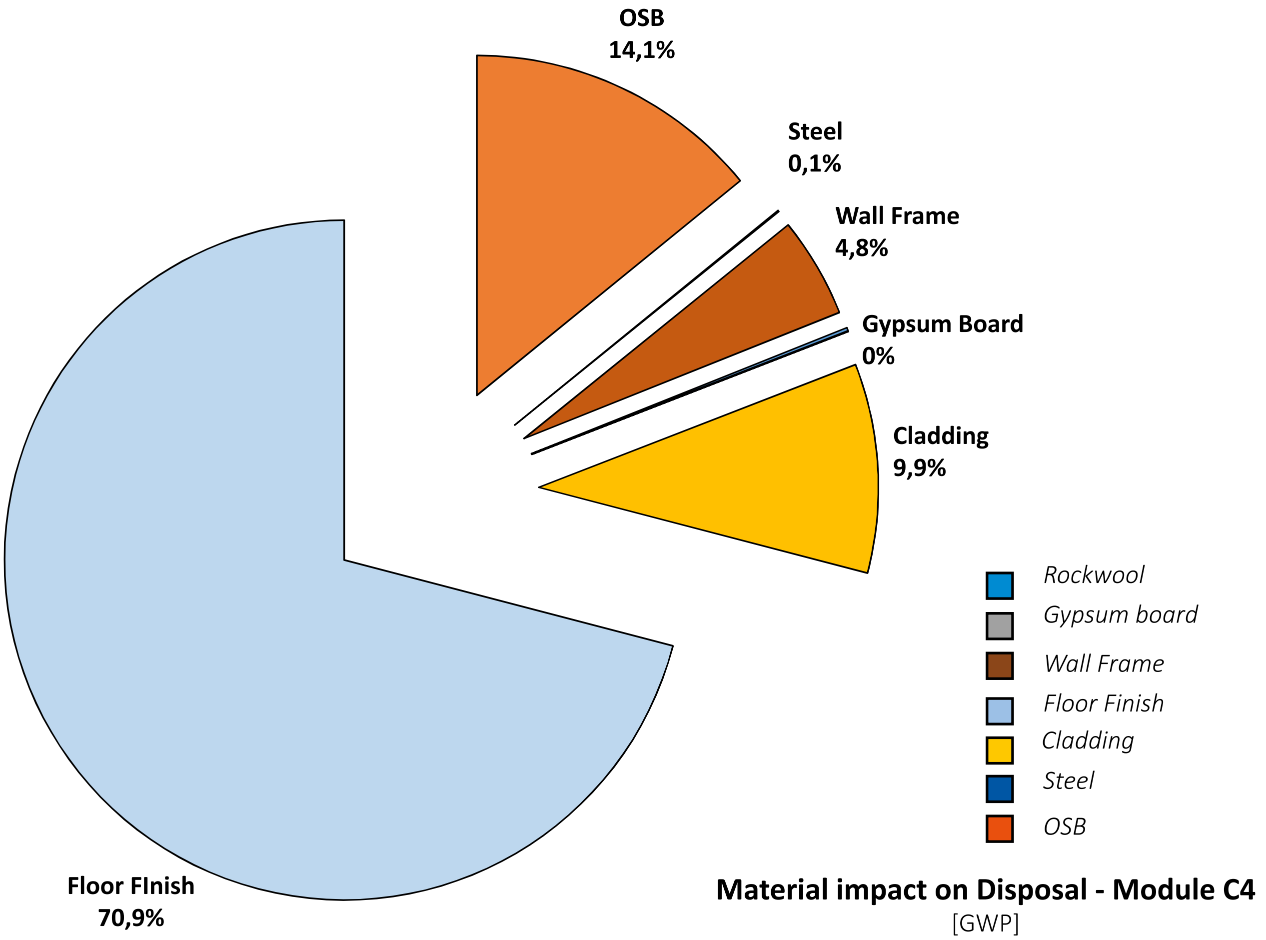


Material impact on Disposal - Module C4
[GWP]

STEEL FRAME - *Vancouver*

WASTE	Waste processing - Stage C3			
	GWP [KgCO2e]	**ODP** [KgCFC11e]	**AP** [KgSO2e]	**EP** [Kg(PO4)3e]
OSB	9,428E+02	2,339E-13	3,416E-02	8,002E-03
Steel	0,000E+00	0,000E+00	0,000E+00	0,000E+00
Wall frame	3,185E+02	7,902E-14	1,154E-02	2,703E-03
Insulation	3,904E-01	6,832E-08	2,440E-04	6,588E-05
Gypsum board	1,152E+01	1,489E-06	8,727E-02	1,975E-02
Cladding	6,643E+02	1,648E-13	2,407E-02	5,638E-03
Floor finish	4,736E+03	1,175E-12	1,716E-01	4,020E-02
TOTAL	6,674E+03	1,557E-06	3,289E-01	7,636E-02

WASTE	Disposal - Stage C4			
	GWP [KgCO2e]	**ODP** [KgCFC11e]	**AP** [KgSO2e]	**EP** [Kg(PO4)3e]
OSB	3,210E+02	1,961E-11	1,298E-01	1,703E-02
Steel	1,285E+00	1,416E-11	7,029E-03	1,054E-03
Wall frame	1,084E+02	6,625E-12	4,385E-02	5,752E-03
Insulation	3,782E+00	8,540E-07	3,172E-03	8,784E-04
Gypsum board	0,000E+00	0,000E+00	0,000E+00	6,950E-02
Cladding	2,262E+02	1,382E-11	9,146E-02	1,200E-02
Floor finish	1,613E+03	9,852E-11	6,521E-01	8,555E-02
TOTAL	2,273E+03	8,542E-07	9,274E-01	1,918E-01

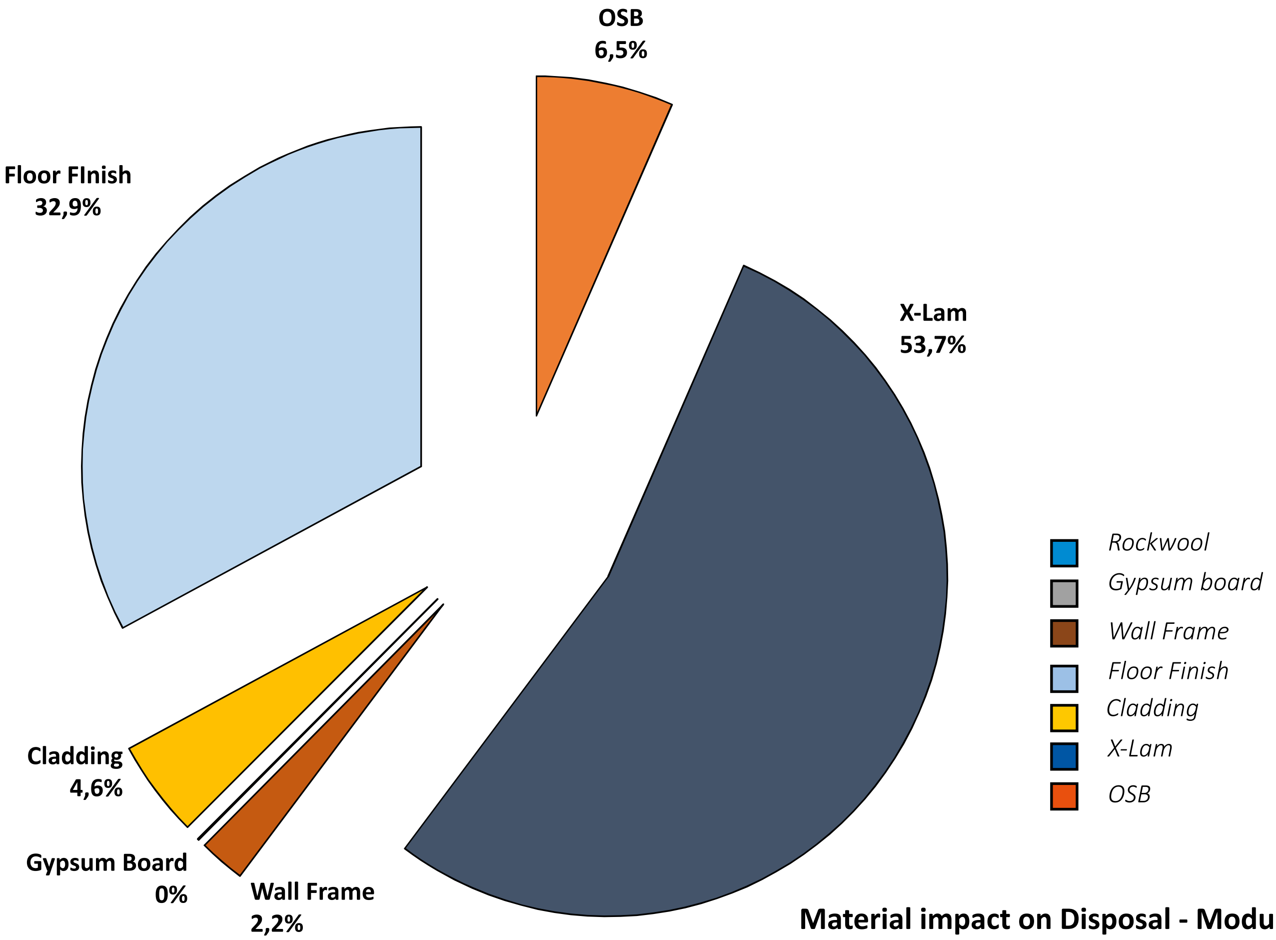


Material impact on Disposal - Module C4
[GWP]

X-LAM STRUCTURE - *Vancouver*

WASTE	Waste processing - Stage C3			
	GWP [KgCO2e]	**ODP** [KgCFC11e]	**AP** [KgSO2e]	**EP** [Kg(PO4)3e]
OSB	9,428E+02	2,339E-13	3,416E-02	8,002E-03
XLAM	6,784E+03	1,018E-05	5,972E-05	5,039E-03
Wall frame	3,185E+02	7,902E-14	1,154E-02	2,703E-03
Insulation	2,811E-01	4,920E-08	1,757E-04	4,744E-05
Gypsum board	1,152E+01	1,489E-06	8,727E-02	1,975E-02
Cladding	6,643E+02	1,648E-13	2,407E-02	5,638E-03
Floor finish	4,736E+03	1,175E-12	1,716E-01	4,020E-02
TOTAL	1,346E+04	1,172E-05	3,289E-01	8,138E-02

WASTE	Disposal - Stage C4			
	GWP [KgCO2e]	**ODP** [KgCFC11e]	**AP** [KgSO2e]	**EP** [Kg(PO4)3e]
OSB	3,210E+02	1,961E-11	1,298E-01	1,703E-02
XLAM	2,632E+03	1,608E-10	1,064E+00	1,396E-01
Wall frame	1,084E+02	6,625E-12	4,385E-02	5,752E-03
Insulation	2,724E+00	6,150E-07	2,284E-03	6,326E-04
Gypsum board	0,000E+00	0,000E+00	0,000E+00	6,950E-02
Cladding	2,262E+02	1,382E-11	9,146E-02	1,200E-02
Floor finish	1,613E+03	9,852E-11	6,521E-01	8,555E-02
TOTAL	4,904E+03	6,153E-07	1,984E+00	3,301E-01

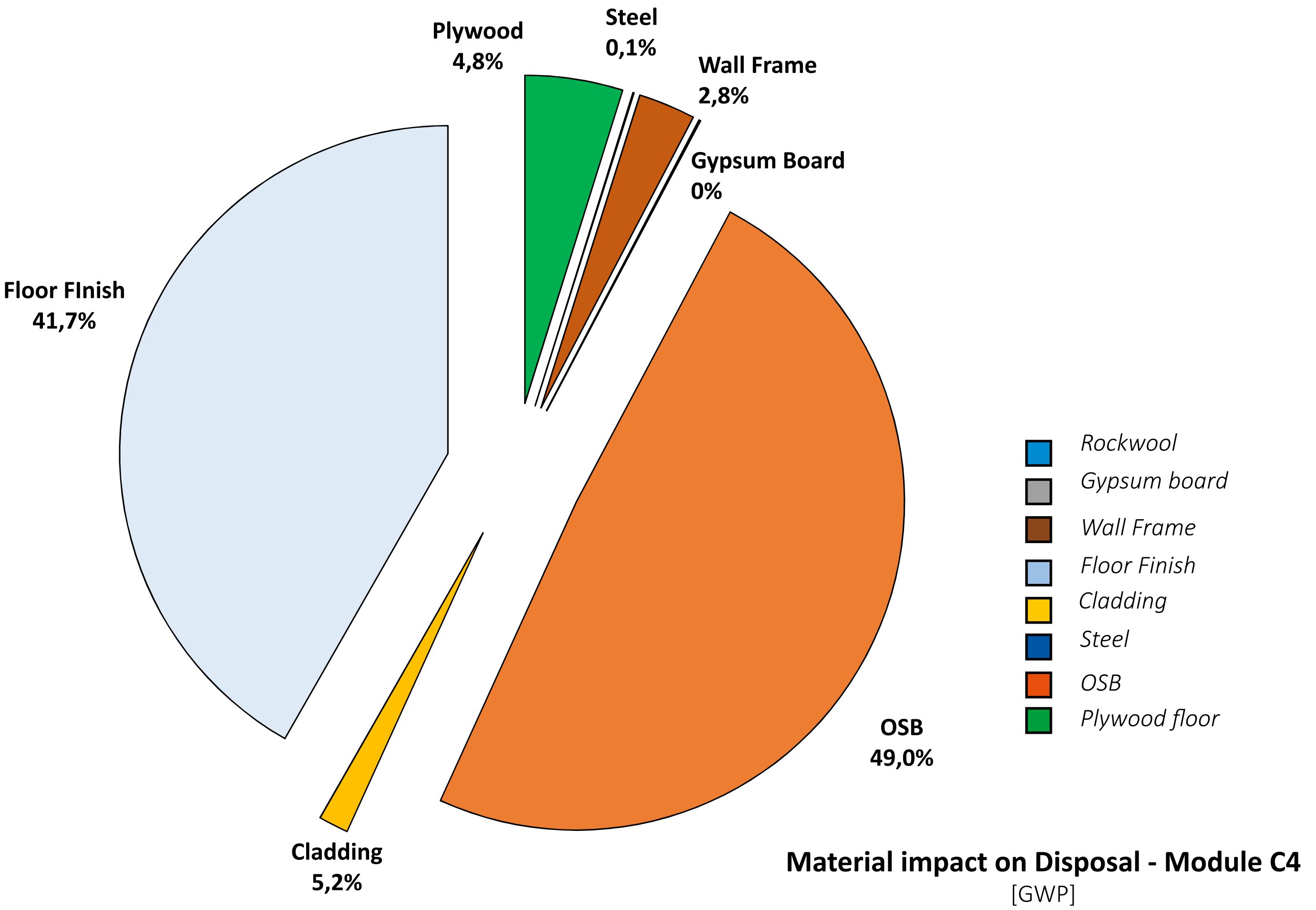


Material impact on Disposal - Module C4
[GWP]

CONTAINER STRUCTURE - *Durban*

WASTE	Waste processing - Stage C3			
	GWP [KgCO2e]	**ODP** [KgCFC11e]	**AP** [KgSO2e]	**EP** [Kg(PO4)3e]
Plywood (floor)	5,471E+02	1,357E-13	1,982E-02	4,643E-03
Steel	0,000E+00	0,000E+00	0,000E+00	0,000E+00
Wall frame	3,185E+02	7,902E-14	1,154E-02	2,703E-03
Insulation	3,201E-01	5,602E-08	2,001E-04	5,402E-05
Gypsum board	6,354E+00	8,209E-07	4,812E-02	1,089E-02
OSB	5,566E+03	1,381E-12	2,017E-01	4,724E-02
Cladding	1,674E+02	4,154E-14	6,067E-03	1,421E-03
Floor finish	4,736E+03	1,175E-12	1,716E-01	4,020E-02
TOTAL	1,134E+04	8,769E-07	4,590E-01	1,072E-01

WASTE	Disposal - Stage C4			
	GWP [KgCO2e]	**ODP** [KgCFC11e]	**AP** [KgSO2e]	**EP** [Kg(PO4)3e]
Plywood (floor)	1,863E+02	1,138E-11	7,532E-02	9,881E-03
Steel	2,171E+00	2,391E-11	1,187E-02	1,781E-03
Wall frame	1,084E+02	6,625E-12	4,385E-02	5,752E-03
Insulation	3,101E+00	7,003E-07	2,601E-03	7,203E-04
Gypsum board	0,000E+00	0,000E+00	0,000E+00	3,832E-02
OSB	1,895E+03	1,158E-10	7,663E-01	1,005E-01
Cladding	5,701E+01	3,483E-12	2,305E-02	3,024E-03
Floor finish	1,613E+03	9,852E-11	6,521E-01	8,555E-02
TOTAL	3,865E+03	7,005E-07	1,575E+00	2,455E-01

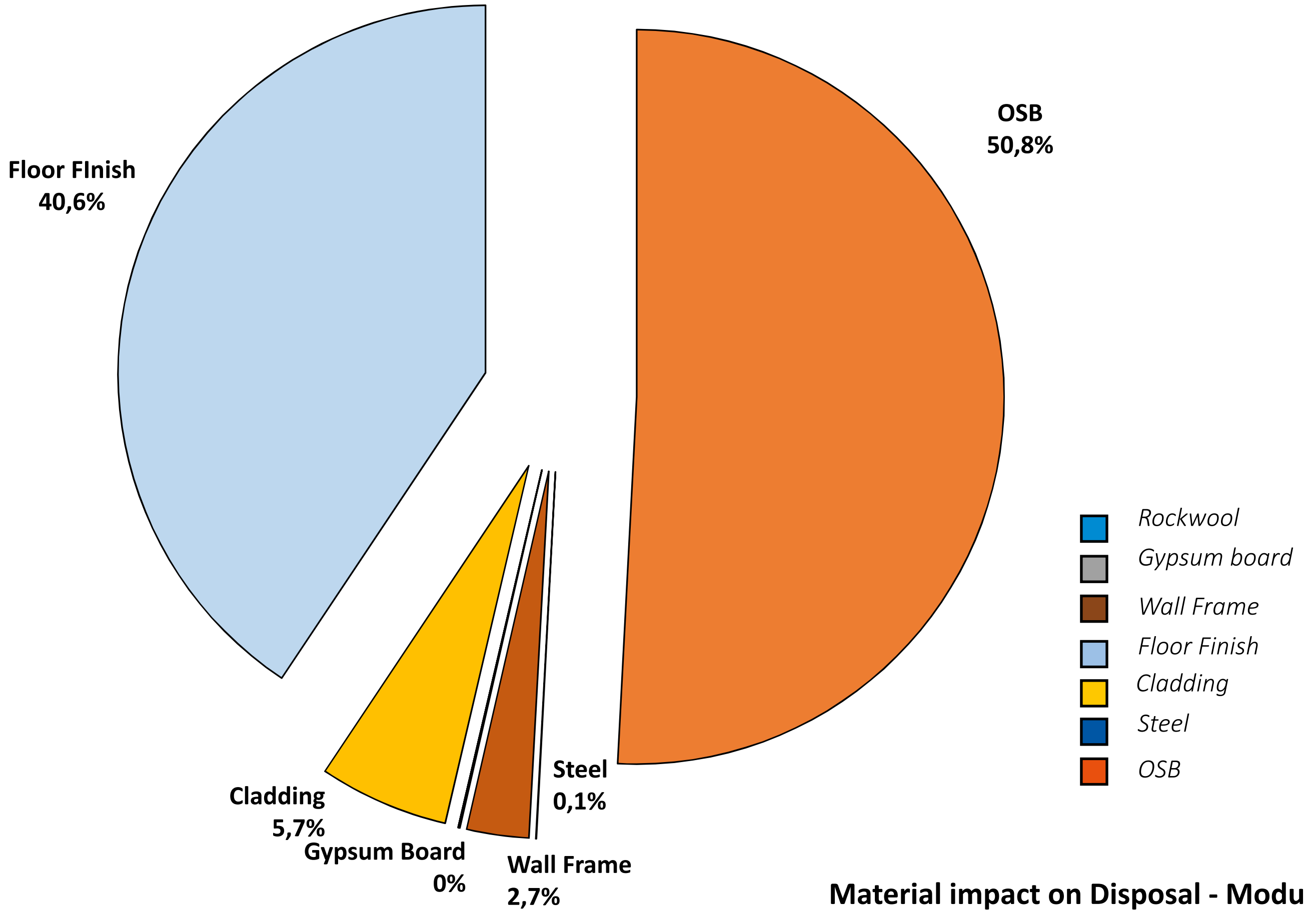


Material impact on Disposal - Module C4
[GWP]

STEEL FRAME - *Durban*

WASTE	Waste processing - Stage C3			
	GWP [KgCO2e]	**ODP** [KgCFC11e]	**AP** [KgSO2e]	**EP** [Kg(PO4)3e]
OSB	5,922E+03	1,469E-12	2,146E-01	5,027E-02
Steel	0,000E+00	0,000E+00	0,000E+00	0,000E+00
Wall frame	3,185E+02	7,902E-14	1,154E-02	2,703E-03
Insulation	2,773E-01	4,853E-08	1,733E-04	4,680E-05
Gypsum board	1,152E+01	1,489E-06	8,727E-02	1,975E-02
Cladding	6,643E+02	1,648E-13	2,407E-02	5,638E-03
Floor finish	4,736E+03	1,175E-12	1,716E-01	4,020E-02
TOTAL	1,165E+04	1,537E-06	5,093E-01	1,186E-01

WASTE	Disposal - Stage C4			
	GWP [KgCO2e]	**ODP** [KgCFC11e]	**AP** [KgSO2e]	**EP** [Kg(PO4)3e]
OSB	2,017E+03	1,232E-10	8,154E-01	1,070E-01
Steel	1,285E+00	1,416E-11	7,029E-03	1,054E-03
Wall frame	1,084E+02	6,625E-12	4,385E-02	5,752E-03
Insulation	2,687E+00	6,067E-07	2,253E-03	6,240E-04
Gypsum board	0,000E+00	0,000E+00	0,000E+00	6,950E-02
Cladding	2,262E+02	1,382E-11	9,146E-02	1,200E-02
Floor finish	1,613E+03	9,852E-11	6,521E-01	8,555E-02
TOTAL	3,968E+03	6,069E-07	1,612E+00	2,814E-01

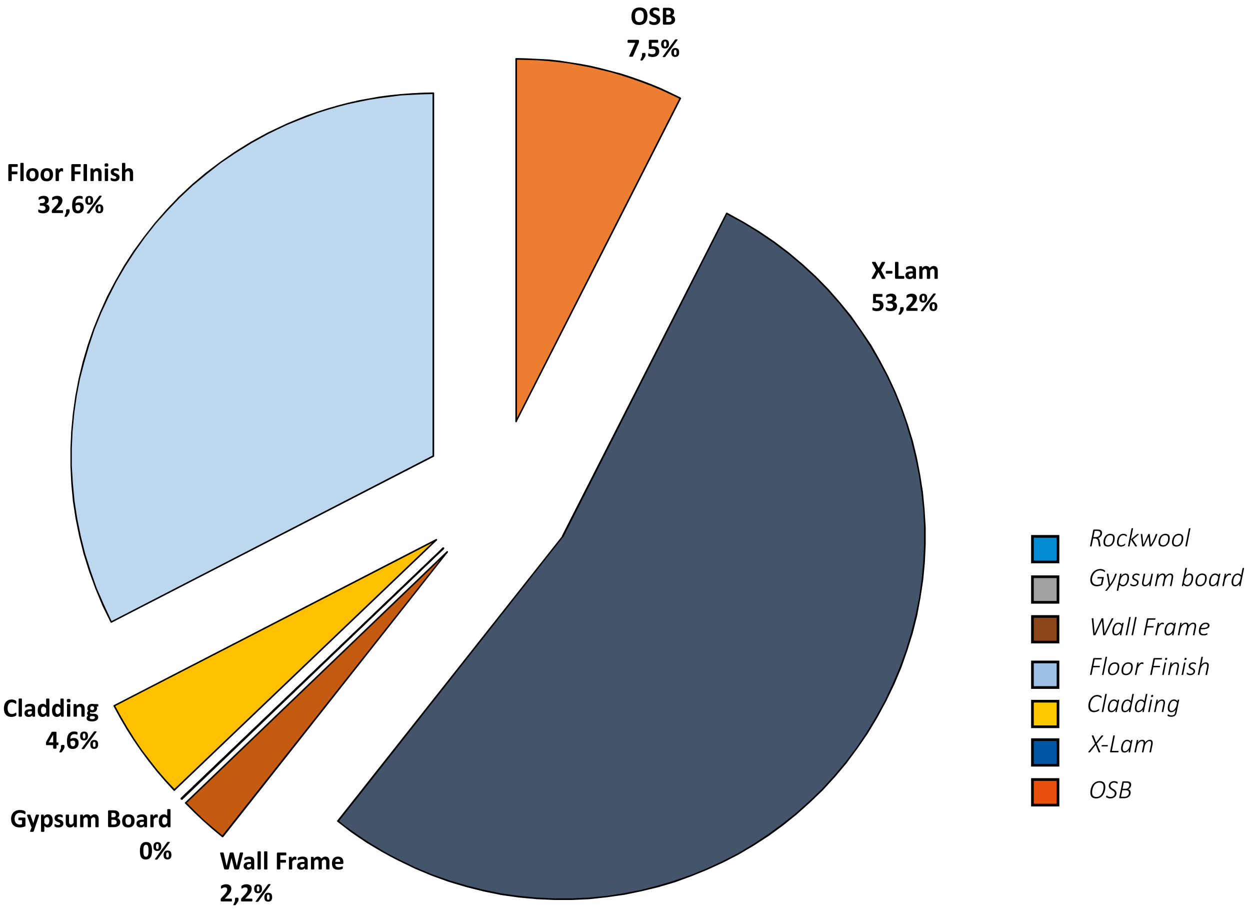


Material impact on Disposal - Module C4
[GWP]

X-LAM STRUCTURE - *Durban*

WASTE	Waste processing - Stage C3			
	GWP [KgCO2e]	**ODP** [KgCFC11e]	**AP** [KgSO2e]	**EP** [Kg(PO4)3e]
OSB	1,089E+03	2,702E-13	3,946E-02	9,242E-03
XLAM	6,784E+03	1,018E-05	5,972E-05	5,039E-03
Wall frame	3,185E+02	7,902E-14	1,154E-02	2,703E-03
Insulation	1,577E-01	2,759E-08	9,855E-05	2,661E-05
Gypsum board	1,152E+01	1,489E-06	8,727E-02	1,975E-02
Cladding	6,643E+02	1,648E-13	2,407E-02	5,638E-03
Floor finish	4,736E+03	1,175E-12	1,716E-01	4,020E-02
TOTAL	1,360E+04	1,170E-05	3,341E-01	8,260E-02

WASTE	Disposal - Stage C4			
	GWP [KgCO2e]	**ODP** [KgCFC11e]	**AP** [KgSO2e]	**EP** [Kg(PO4)3e]
OSB	3,708E+02	2,265E-11	1,499E-01	1,967E-02
XLAM	2,632E+03	1,608E-10	1,064E+00	1,396E-01
Wall frame	1,084E+02	6,625E-12	4,385E-02	5,752E-03
Insulation	1,528E+00	3,449E-07	1,281E-03	3,548E-04
Gypsum board	0,000E+00	0,000E+00	0,000E+00	6,950E-02
Cladding	2,262E+02	1,382E-11	9,146E-02	1,200E-02
Floor finish	1,613E+03	9,852E-11	6,521E-01	8,555E-02
TOTAL	4,952E+03	3,452E-07	2,003E+00	3,325E-01

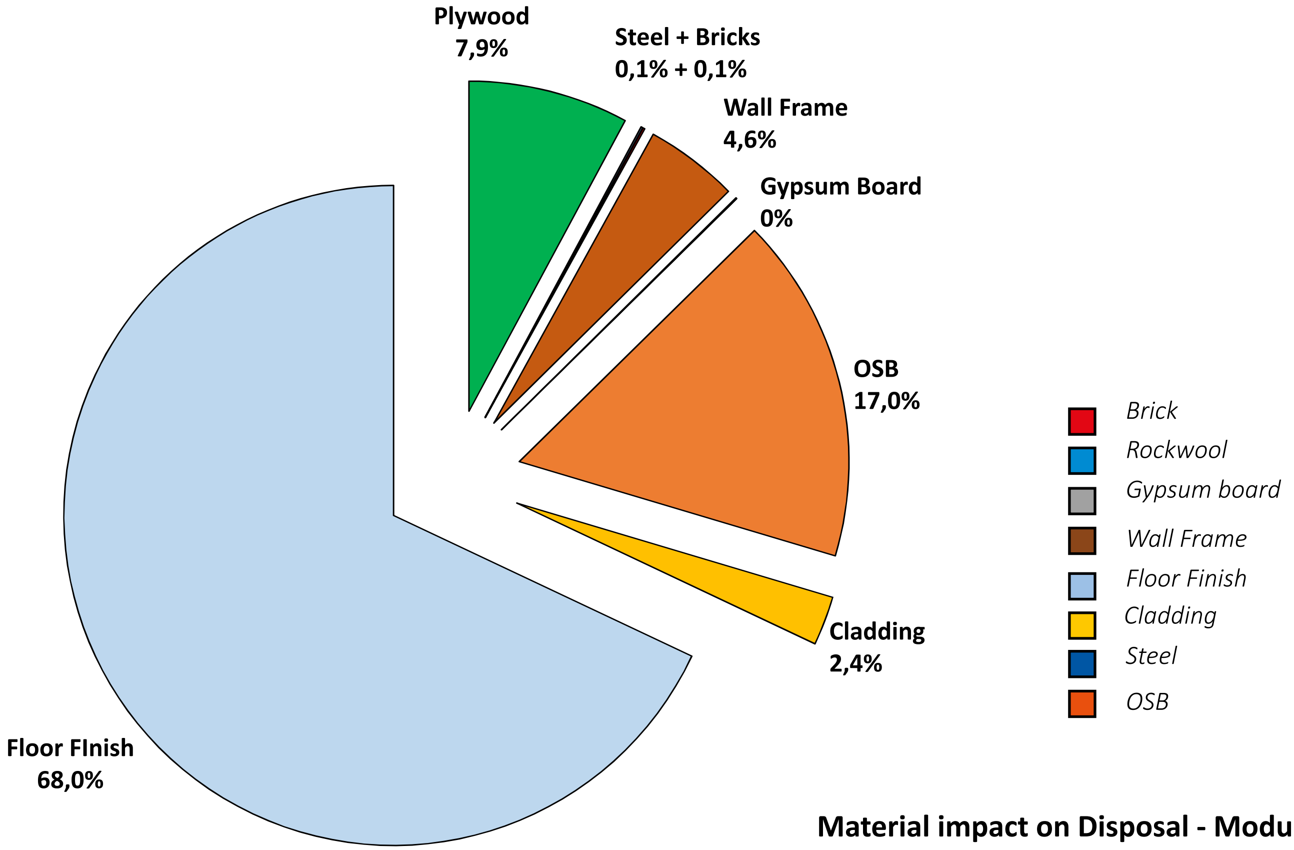


Material impact on Disposal - Module C4
[GWP]

CONTAINER STRUCTURE - *Chennai*

WASTE	Waste processing - Stage C3			
	GWP [KgCO2e]	**ODP** [KgCFC11e]	**AP** [KgSO2e]	**EP** [Kg(PO4)3e]
Plywood (floor)	5,471E+02	1,357E-13	1,982E-02	4,643E-03
Steel	0,000E+00	0,000E+00	0,000E+00	0,000E+00
Brick	2,073E+00	0,000E+00	8,462E-03	0,000E+00
Wall frame	3,185E+02	7,902E-14	1,154E-02	2,703E-03
Insulation	1,041E-01	1,821E-08	6,504E-05	1,756E-05
Gypsum board	6,354E+00	8,209E-07	4,812E-02	1,089E-02
OSB	1,182E+03	2,932E-13	4,283E-02	1,003E-02
Cladding	1,674E+02	4,154E-14	6,067E-03	1,421E-03
Floor finish	4,736E+03	1,175E-12	1,716E-01	4,020E-02
TOTAL	6,960E+03	8,391E-07	3,085E-01	6,991E-02

WASTE	Disposal - Stage C4			
	GWP [KgCO2e]	**ODP** [KgCFC11e]	**AP** [KgSO2e]	**EP** [Kg(PO4)3e]
Plywood (floor)	1,863E+02	1,138E-11	7,532E-02	9,881E-03
Steel	2,171E+00	2,391E-11	1,187E-02	1,781E-03
Brick	0,000E+00	2,031E+00	0,000E+00	-2,708E-01
Wall frame	1,084E+02	6,625E-12	4,385E-02	5,752E-03
Insulation	1,008E+00	2,276E-07	8,455E-04	2,341E-04
Gypsum board	0,000E+00	0,000E+00	0,000E+00	3,832E-02
OSB	4,024E+02	2,458E-11	1,627E-01	2,135E-02
Cladding	5,701E+01	3,483E-12	2,305E-02	3,024E-03
Floor finish	1,613E+03	9,852E-11	6,521E-01	8,555E-02
TOTAL	2,370E+03	2,031E+00	9,698E-01	-1,049E-01

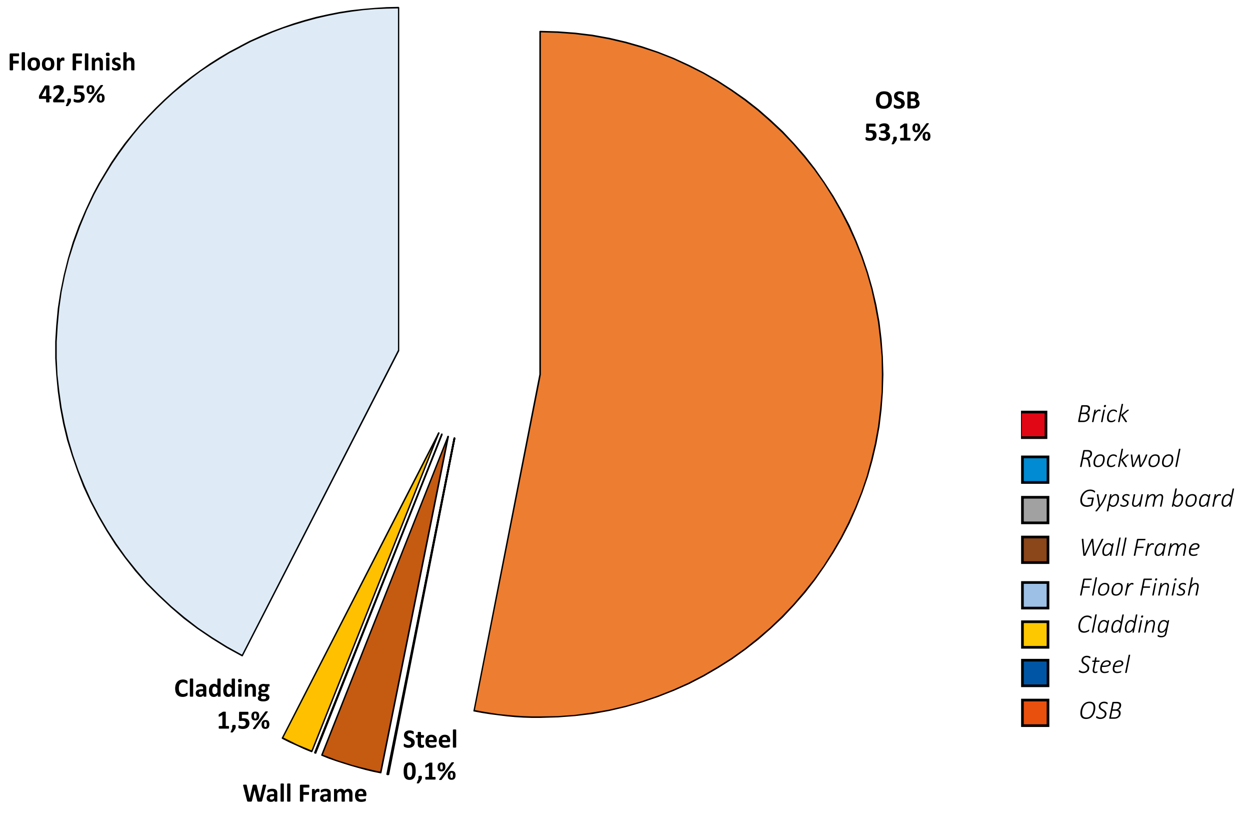


Material impact on Disposal - Module C4
[GWP]

STEEL FRAME - *Chennai*

WASTE	Waste processing - Stage C3			
	GWP [KgCO2e]	**ODP** [KgCFC11e]	**AP** [KgSO2e]	**EP** [Kg(PO4)3e]
OSB	5,922E+03	1,469E-12	2,146E-01	5,027E-02
Steel	0,000E+00	0,000E+00	0,000E+00	0,000E+00
Brick	1,123E+00	0,000E+00	4,586E-03	0,000E+00
Wall frame	3,185E+02	7,902E-14	1,154E-02	2,703E-03
Insulation	1,422E-01	2,489E-08	8,890E-05	2,400E-05
Gypsum board	1,152E+01	1,489E-06	8,727E-02	1,975E-02
Cladding	1,674E+02	4,154E-14	6,067E-03	1,421E-03
Floor finish	4,736E+03	1,175E-12	1,716E-01	4,020E-02
TOTAL	1,116E+04	1,514E-06	4,958E-01	1,144E-01

WASTE	Disposal - Stage C4			
	GWP [KgCO2e]	**ODP** [KgCFC11e]	**AP** [KgSO2e]	**EP** [Kg(PO4)3e]
OSB	2,017E+03	1,232E-10	8,154E-01	1,070E-01
Steel	1,285E+00	1,416E-11	7,029E-03	1,054E-03
Brick	0,000E+00	1,101E+00	0,000E+00	-1,467E-01
Wall frame	1,084E+02	6,625E-12	4,385E-02	5,752E-03
Insulation	1,378E+00	3,112E-07	1,156E-03	3,201E-04
Gypsum board	0,000E+00	0,000E+00	0,000E+00	6,950E-02
Cladding	5,701E+01	3,483E-12	2,305E-02	3,024E-03
Floor finish	1,613E+03	9,852E-11	6,521E-01	8,555E-02
TOTAL	3,797E+03	1,101E+00	1,543E+00	1,254E-01

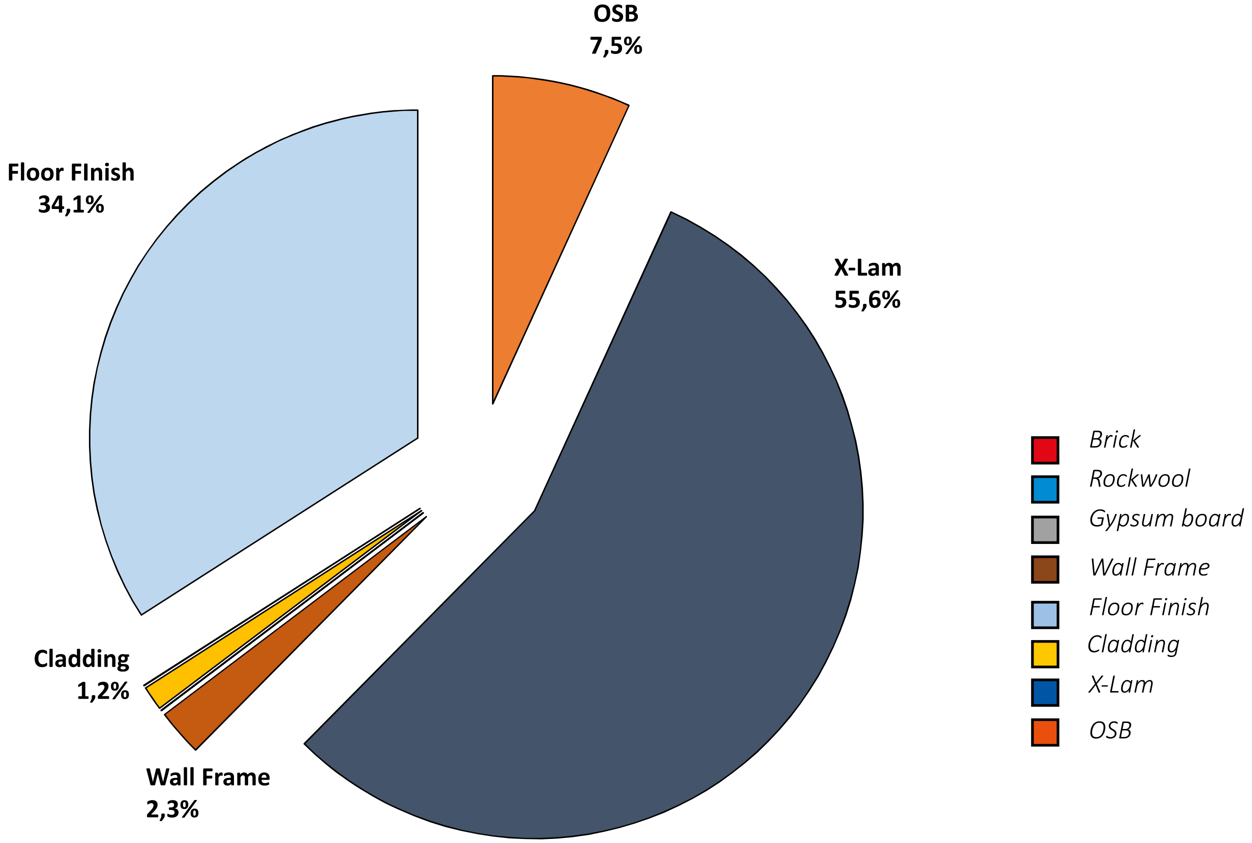


Material impact on Disposal - Module C4
[GWP]

X-LAM STRUCTURE - *Chennai*

WASTE	Waste processing - Stage C3			
	GWP [KgCO2e]	**ODP** [KgCFC11e]	**AP** [KgSO2e]	**EP** [Kg(PO4)3e]
OSB	9,476E+02	2,351E-13	3,434E-02	8,043E-03
XLAM	6,784E+03	1,018E-05	5,972E-05	5,039E-03
Wall frame	3,185E+02	7,902E-14	1,154E-02	2,703E-03
Insulation	8,036E-02	1,406E-08	5,023E-05	1,356E-05
Gypsum board	1,152E+01	1,489E-06	8,727E-02	1,975E-02
Cladding	1,674E+02	4,154E-14	6,067E-03	1,421E-03
Brick	1,037E+00	0,000E+00	4,231E-03	0,000E+00
Floor finish	4,736E+03	1,175E-12	1,716E-01	4,020E-02
TOTAL	1,297E+04	1,168E-05	3,152E-01	7,717E-02

WASTE	Disposal - Stage C4			
	GWP [KgCO2e]	**ODP** [KgCFC11e]	**AP** [KgSO2e]	**EP** [Kg(PO4)3e]
OSB	3,227E+02	1,971E-11	1,305E-01	1,712E-02
XLAM	2,632E+03	1,608E-10	1,064E+00	1,396E-01
Wall frame	1,084E+02	6,625E-12	4,385E-02	5,752E-03
Insulation	7,785E-01	1,758E-07	6,530E-04	1,808E-04
Gypsum board	0,000E+00	0,000E+00	0,000E+00	6,950E-02
Cladding	5,701E+01	3,483E-12	2,305E-02	3,024E-03
Brick	0,000E+00	1,015E+00	0,000E+00	-1,354E-01
Floor finish	1,613E+03	9,852E-11	6,521E-01	8,555E-02
TOTAL	4,734E+03	1,015E+00	1,915E+00	1,854E-01



Material impact on Disposal - Module C4
[GWP]

WASTE PROCESSING STAGE - C3

Scenario	VANCOUVER		
	CONTAINER	**STEEL**	**XLAM**
GWP [KgCO2e]	5,918E+03	6,674E+03	1,346E+04
ODP [KgCFC11e]	8,997E-07	1,557E-06	1,172E-05
AP [KgSO2e]	2,626E-01	3,289E-01	3,289E-01
EP [Kg(PO4)3e]	6,114E-02	7,636E-02	8,138E-02

Scenario	DURBAN		
	CONTAINER	**STEEL**	**XLAM**
GWP [KgCO2e]	1,134E+04	1,165E+04	1,360E+04
ODP [KgCFC11e]	8,769E-07	1,537E-06	1,170E-05
AP [KgSO2e]	4,590E-01	5,093E-01	3,341E-01
EP [Kg(PO4)3e]	1,072E-01	1,186E-01	8,260E-02

Scenario	CHENNAI		
	CONTAINER	**STEEL**	**XLAM**
GWP [KgCO2e]	6,960E+03	1,116E+04	1,297E+04
ODP [KgCFC11e]	8,391E-07	1,514E-06	1,168E-05
AP [KgSO2e]	3,085E-01	4,958E-01	3,152E-01
EP [Kg(PO4)3e]	6,991E-02	1,144E-01	7,717E-02

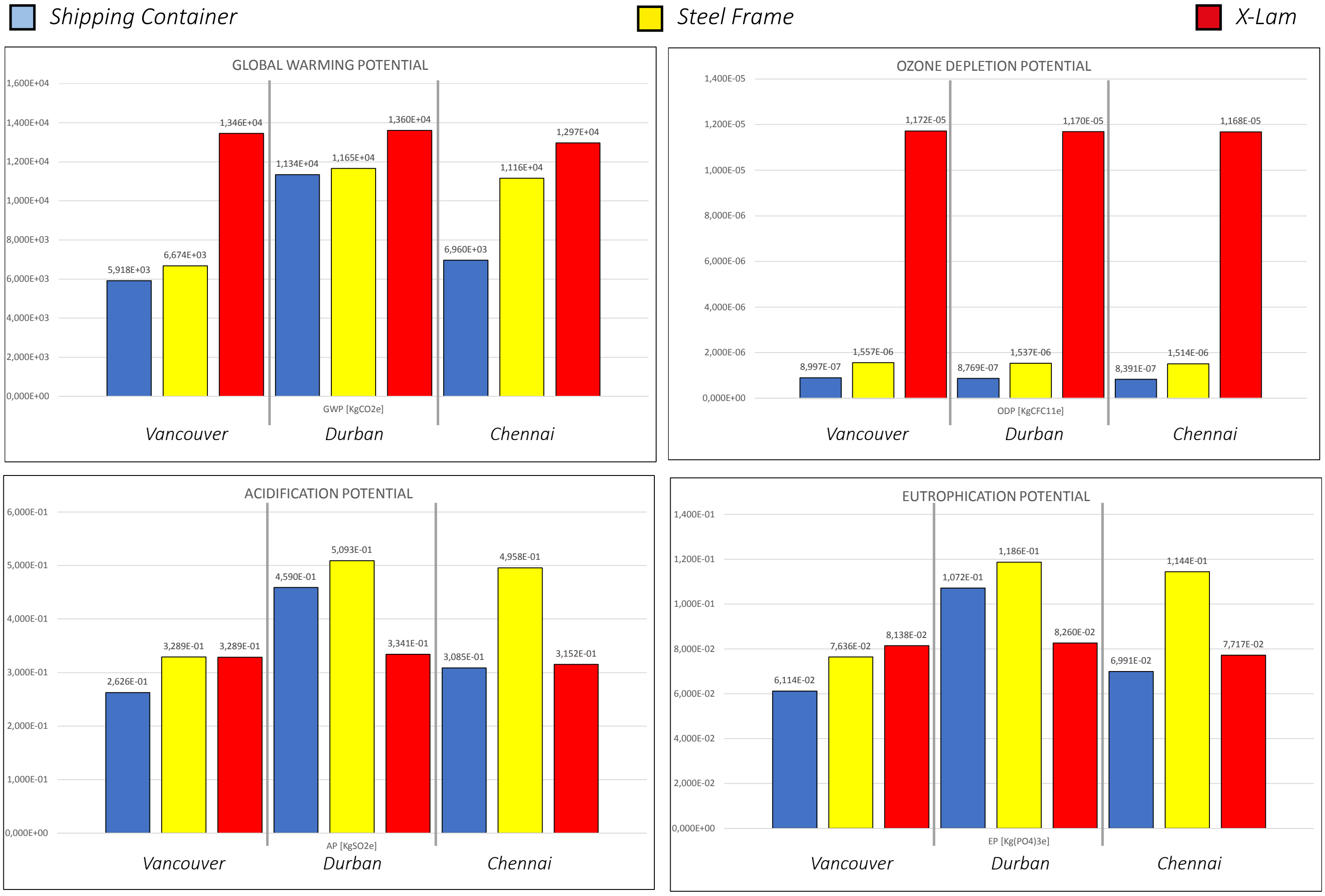


FIGURE 6.14 Waste Processing - Module C3 emissions

LANDFILL EMISSIONS - C4			
Scenario	VANCOUVER		
	CONTAINER	**STEEL**	**XLAM**
GWP [KgCO2e]	2,019E+03	2,273E+03	4,904E+03
ODP [KgCFC11e]	9,848E-07	8,542E-07	6,153E-07
AP [KgSO2e]	8,295E-01	9,274E-01	1,984E+00
EP [Kg(PO4)3e]	1,479E-01	1,918E-01	3,301E-01
Scenario	DURBAN		
	CONTAINER	**STEEL**	**XLAM**
GWP [KgCO2e]	3,865E+03	3,968E+03	4,952E+03
ODP [KgCFC11e]	7,005E-07	6,069E-07	3,452E-07
AP [KgSO2e]	1,575E+00	1,612E+00	2,003E+00
EP [Kg(PO4)3e]	2,455E-01	2,814E-01	3,325E-01
Scenario	CHENNAI		
	CONTAINER	**STEEL**	**XLAM**
GWP [KgCO2e]	2,370E+03	3,797E+03	4,734E+03
ODP [KgCFC11e]	2,031E+00	1,101E+00	1,015E+00
AP [KgSO2e]	9,698E-01	1,543E+00	1,915E+00
EP [Kg(PO4)3e]	-1,049E-01	1,254E-01	1,854E-01

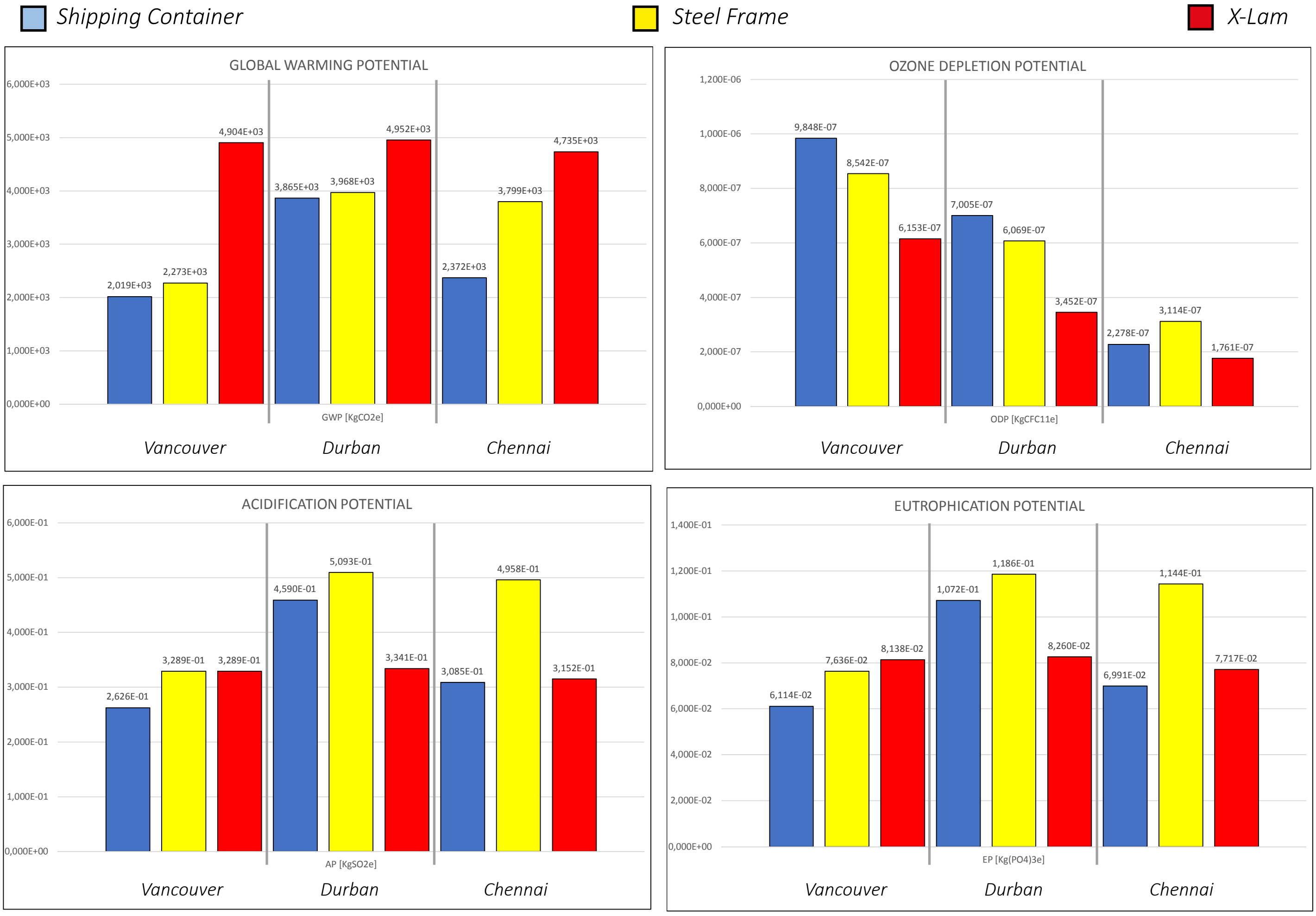


FIGURE 6.15 -Disposal Stage - Module C4 emissions

6.4 Module C : results

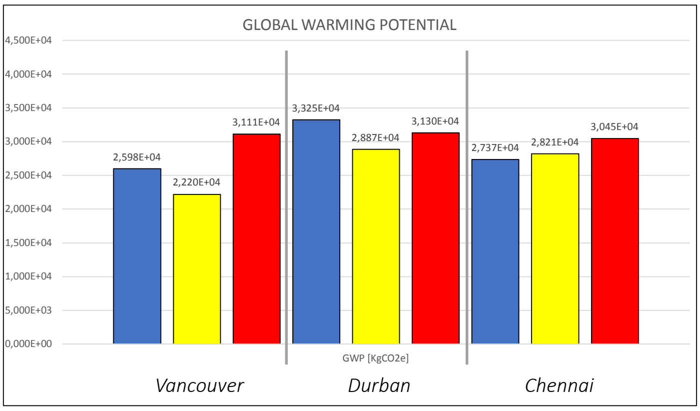
End f Life stage

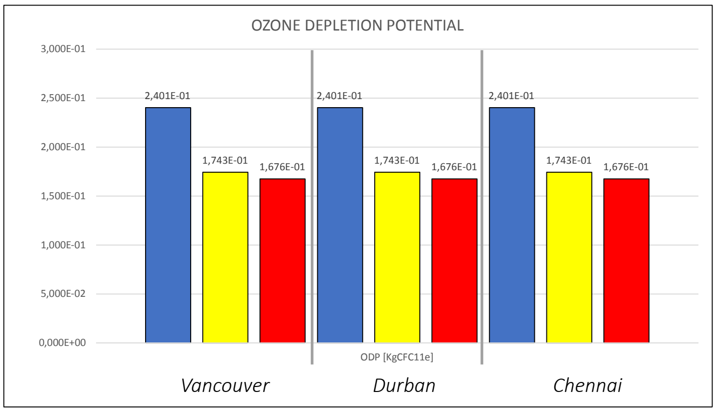
Scenario	VANCOUVER		
	CONTAINER	**STEEL**	**XLAM**
GWP [KgCO2e]	2,598E+04	2,220E+04	3,111E+04
ODP [KgCFC11e]	2,401E-01	1,743E-01	1,676E-01
AP [KgSO2e]	3,554E+01	2,646E+01	2,655E+01
EP [Kg(PO4)3e]	1,446E+01	1,078E+01	1,052E+01

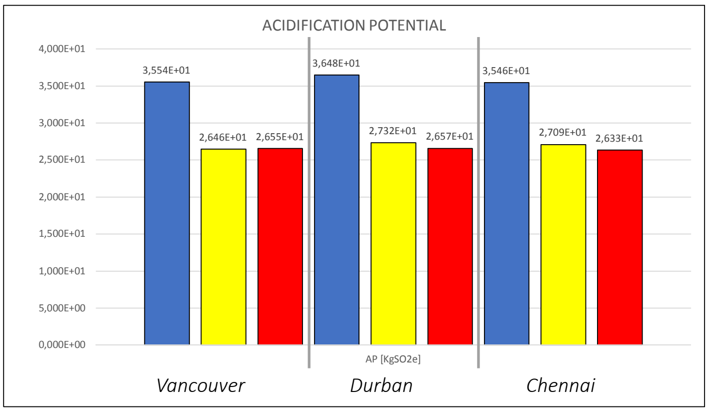
Scenario	DURBAN		
	CONTAINER	**STEEL**	**XLAM**
GWP [KgCO2e]	3,325E+04	2,887E+04	3,130E+04
ODP [KgCFC11e]	2,401E-01	1,743E-01	1,676E-01
AP [KgSO2e]	3,648E+01	2,732E+01	2,657E+01
EP [Kg(PO4)3e]	1,461E+01	1,091E+01	1,052E+01

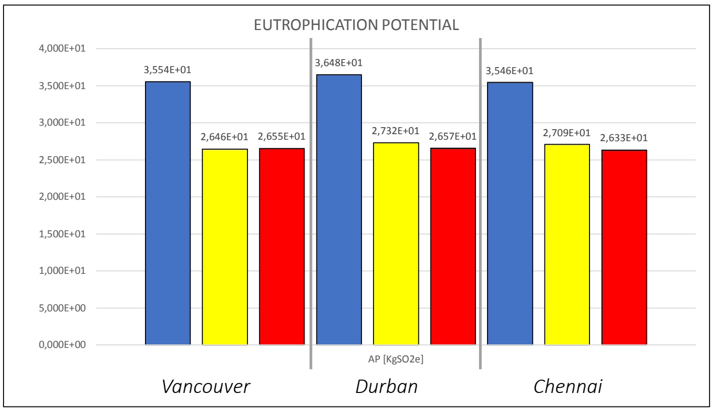
Scenario	CHENNAI		
	CONTAINER	**STEEL**	**XLAM**
GWP [KgCO2e]	2,737E+04	2,821E+04	3,045E+04
ODP [KgCFC11e]	2,401E-01	1,743E-01	1,676E-01
AP [KgSO2e]	3,546E+01	2,709E+01	2,633E+01
EP [Kg(PO4)3e]	1,443E+01	1,086E+01	1,048E+01

🟦 *Shipping Container* 🟨 *Steel Frame* 🟥 *X-Lam*









6.5 System outputs: Reuse-Recovery-Recycling

Material which are not disposed in landfill can be either Reused or Recycled.
Reuse of products means that elements are inputs of the next life cycle, or system, without any operation of reprocessing.
Recovery can be assumed as a partial reprocessing of materias to allow their integral Reuse. This flow has not been considered in the Life Cycle Assessment.
Finally Recycling means that material outputs from a system, in this case a building, are used as input for another life cycle.
When materials are recycled, impacts associated with recovery and reprocessing are included, including material losses during manufacturing, less a credit for avoided extraction of virgin product. When reprocessing is lower than virgin material extraction, Module D for Recycling can lead to negative impact categories which lower the overall impact assessment result.

There are two different recycling processes which have to be taken into account when modelling outputs flows.
On the one hand some material flows are reprocessed preserving their properties in the next life cycle, this is the case of structural steel. A Closed Loop Cycle can be considered for the allocation of recycling credits. ISO 14044 standard suggest the use of closed loop allocation when recycled materials go back into the original product.
On the other hand, when materials experience significant degradation of their properties, during the reprocessing stage, an Open Loop Cycle has to be considered. Open Loop Cycles are also known as Downcycling of products, where recycled materials are used as input for a different process than its original, this is the case of structural timber. Although materials are not disposed in landfil, they cannot be used for the same purpose, for instance structural. Therefore it is evident that emissions for the extraction of virgin material is not avoided for the manufacturing of products within the same purpose.
While the calculation of Close Loop Cycles is widely available in literature and EPDs, greater effort has to be made in modelling Open Loop Cycles.

Material	**GWP** *[kg CO2-eq/kg]*	**ODP** *[kg CFC11-eq/kg]*	**AP** *[kg SO2-eq]*	**EP** *[kg (PO$_4$)$_3$-eq]*
Structural steel	-1.89	-1.18x10^$^{-11}$	6.35x10^$^{-3}$	-5.36x10^$^{-4}$
X-Lam panels	0.603	-5.6x10^$^{-8}$	-1.008x10^$^{-3}$	-2.833x10^$^{-5}$
Hardwood timber	0.603	-5.6x10^$^{-8}$	-1.008x10^$^{-3}$	-2.833x10^$^{-5}$
OSB	0	0	0	0
Gypsum	4.0*10^-8	0	0	1.6x10^$^{-5}$
Timber finishes	0.603	-5.6x10^$^{-8}$	-1.008x10^$^{-3}$	-2.833x10^$^{-5}$
Rockwool insulation	-0.04	-3.1x10^$^{-10}$	-1.8x10^$^{-4}$	-1.3x10^$^{-5}$
Bricks	-0.0017	0	-3.2x10^$^{-5}$	-7.0x10^$^{-6}$

FIGURE 6.16 - Recycling emissions - Module D

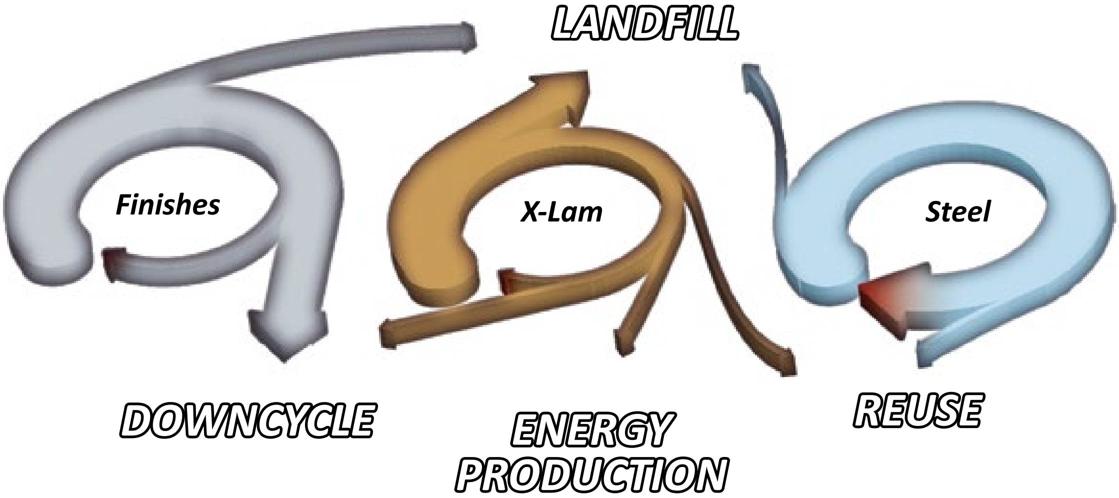


FIGURE 6.17 - End of Life scenarios

Emissions shown in *figure 6.16* are related to average data based on typical End of Life scenarios for each building material.
In the case of Timber products, excluded OSB, recycled flows are consedered to be recycled in an open loop cycle which partially consist on energetic production and chipboard/OSB production.
Credits for recycling are not allocated to OSB panels in order to avoid double counting, since the use of scrap material is included in the production process from the very beginning of its life cycle, therefore credits are already included in its Embodied Engies, using the 100-0 method described below.

International pubblications have defined three methods to address recycling and the allocation of recycling credits outside system boundaries. They all consist on the definition of the phase to which assign credits for the avoided extraction of virgin materials, all based on the fundamental criteria of avoiding the double counting of benefits for recycling.

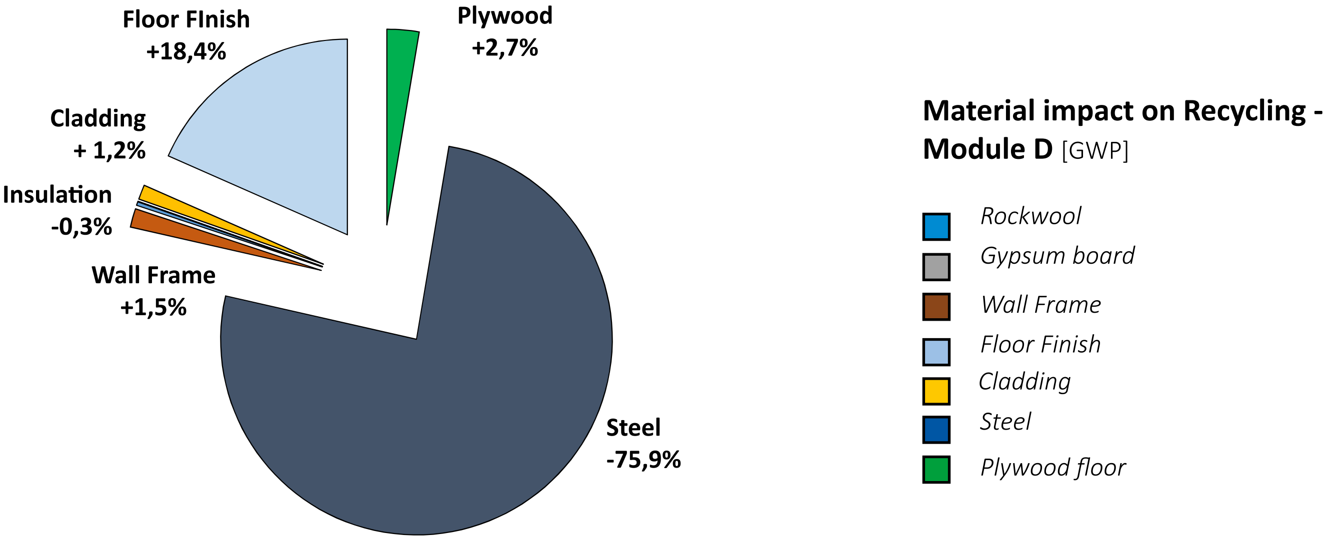
The first method is called 100-0 and gives credits for recycling in the Product Stage, for the calculation of Embodied Eergies.
The second, defined 0-100, allocates credits entirely after the End of Life. This is the method used for this research in order to correctly confront the different emissions of Module D throughout the three case studies.
A Sensitivity Analysis has been included to understand the impact that recycling has on the overall LCA results: two different scenarios have been analyzed including or excluding Module D from the calculation.
Finally european recommendations have been extended to a third approach, called 50-50, which consists on allocating half of the total credits both in input and output of the system.

Follows a summary of Recycling credits for each case study and scenario considered with a representation of the impact of each material on the total Global Warming Potential for Module D.

CONTAINER STRUCTURE - *Vancouver*

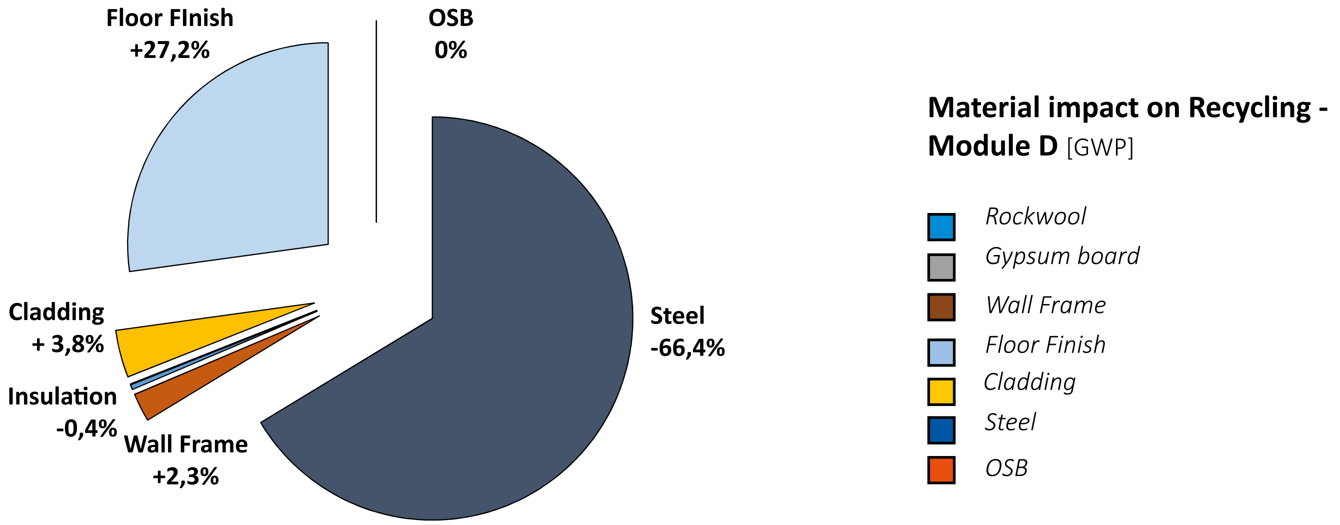
Recycling Credits - total

WASTE	Precycle [Kg]	**GWP** [KgCO2e/kg]	**ODP** [KgCFC11e/kg]	**AP** [KgSO2e/kg]	**EP** [Kg(PO4)3e/kg]
Plywood (floor)	**1488,209**	8,97E+02	-8,33E-05	-1,50E+00	-4,22E-02
Steel	**13566,248**	-2,56E+04	-1,60E-07	8,61E+01	-7,27E+00
Wall frame	**866,397**	5,22E+02	-4,85E-05	-8,74E-01	-2,45E-02
Insulation	**2532,037**	-1,02E+02	-7,85E-07	-4,56E-01	-3,29E-02
Gypsum board	**0,000**	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Cladding	**674,112**	4,06E+02	-3,78E-05	-6,80E-01	-1,91E-02
Floor finish	**10307,498**	6,21E+03	-5,77E-04	-1,04E+01	-2,92E-01
TOTAL		**-1,77E+04**	**-7,48E-04**	**7,22E+01**	**-7,68E+00**



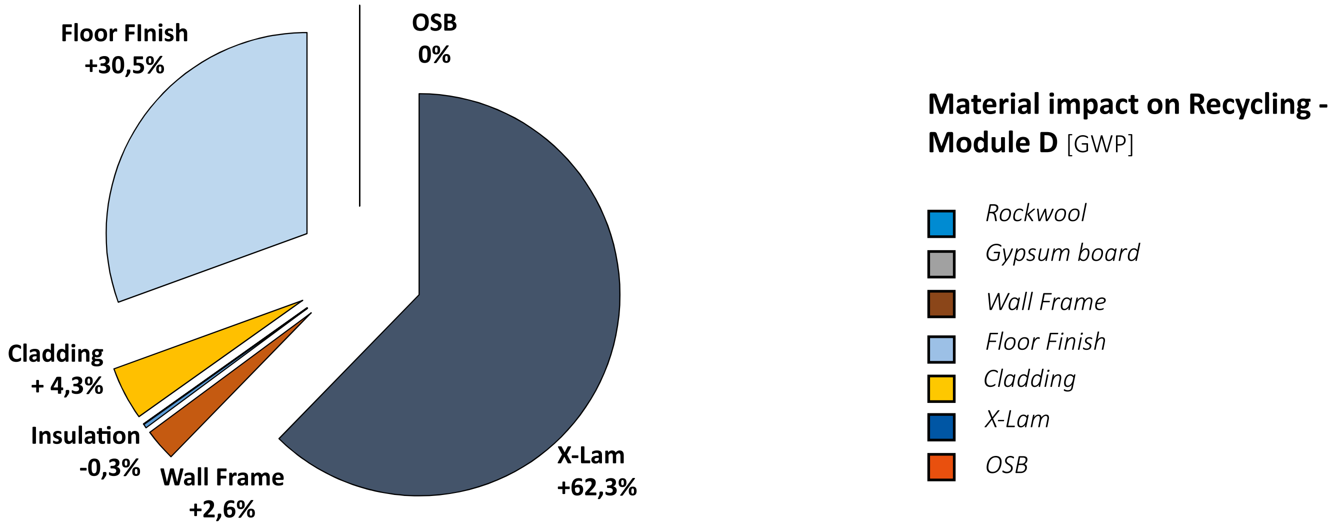
STEEL FRAME - *Vancouver*

Recycling Credits - total					
WASTE	**Precycle** [Kg]	**GWP** [KgCO2e/kg]	**ODP** [KgCFC11e/kg]	**AP** [KgSO2e/kg]	**EP** [Kg(PO4)3e/kg]
OSB	**2564,699**	0,000	0,000	0,000	0,000
Steel	**8032,977**	-1,52E+04	-9,48E-08	5,10E+01	-4,31E+00
Wall frame	**866,397**	5,22E+02	-4,85E-05	-8,74E-01	-2,45E-02
Insulation	**2196,007**	-8,83E+01	-6,81E-07	-3,95E-01	-2,85E-02
Gypsum board	**0,000**	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Cladding	**1445,598**	8,71E+02	-8,10E-05	-1,46E+00	-4,10E-02
Floor finish	**10307,498**	6,21E+03	-5,77E-04	-1,04E+01	-2,92E-01
TOTAL		**-7,663E+03**	**-7,075E-04**	**3,789E+01**	**-4,692E+00**


Material impact on Recycling - Module D [GWP]

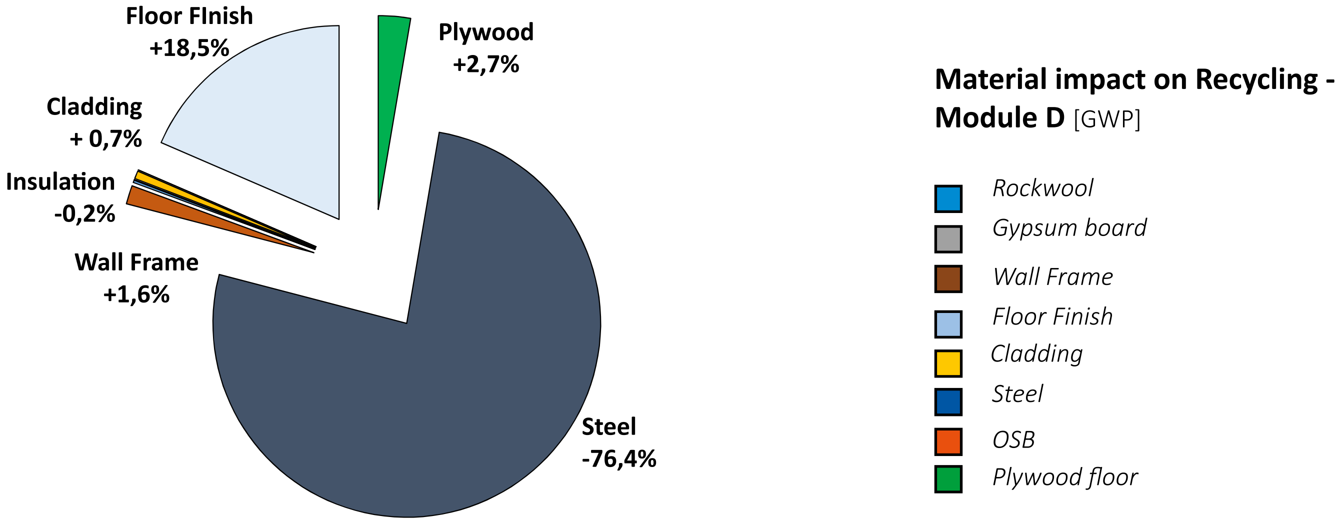
X-LAM STRUCTURE - *Vancouver*

Recycling Credits - total					
WASTE	**Precycle** [Kg]	**GWP** [KgCO2e/kg]	**ODP** [KgCFC11e/kg]	**AP** [KgSO2e/kg]	**EP** [Kg(PO4)3e/kg]
OSB	**2564,699**	0,000	0,000	0,000	0,000
XLAM	**21030,535**	1,27E+04	-1,18E-03	-2,12E+01	-5,96E-01
Wall frame	**866,397**	5,22E+02	-4,85E-05	-8,74E-01	-2,45E-02
Insulation	**1581,424**	-6,36E+01	-4,90E-07	-2,85E-01	-2,06E-02
Gypsum board	**0,000**	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Cladding	**1445,598**	8,71E+02	-8,10E-05	-1,46E+00	-4,10E-02
Floor finish	**10307,498**	6,21E+03	-5,77E-04	-1,04E+01	-2,92E-01
TOTAL		**2,022E+04**	**-1,885E-03**	**-3,422E+01**	**-9,740E-01**


Material impact on Recycling - Module D [GWP]

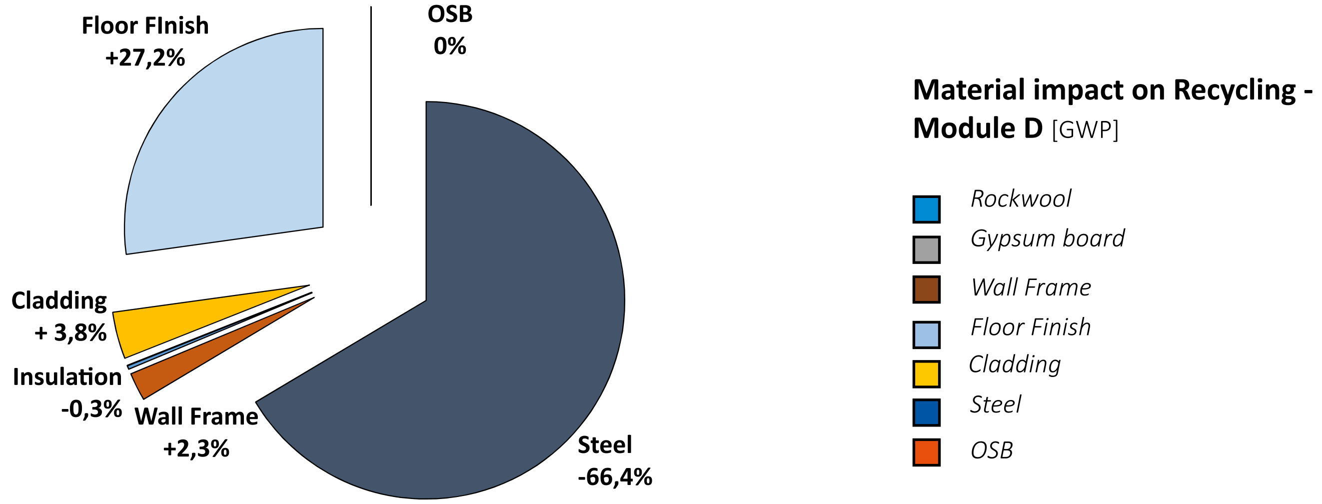
CONTAINER STRUCTURE - *Durban*

Recycling Credits - total					
WASTE	**Precycle** [Kg]	**GWP** [KgCO2e/kg]	**ODP** [KgCFC11e/kg]	**AP** [KgSO2e/kg]	**EP** [Kg(PO4)3e/kg]
Plywood (floor)	**1488,209**	8,97E+02	-8,33E-05	-1,50E+00	-4,22E-02
Steel	**13566,248**	-2,56E+04	-1,60E-07	8,61E+01	-7,27E+00
Wall frame	**866,397**	5,22E+02	-4,85E-05	-8,74E-01	-2,45E-02
Insulation	**1800,727**	-7,24E+01	-5,58E-07	-3,24E-01	-2,34E-02
Gypsum board	**0,000**	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Cladding	**364,385**	2,20E+02	-2,04E-05	-3,67E-01	-1,03E-02
OSB	**15140,304**	0,000	0,000	0,000	0,000
Floor finish	**10307,498**	6,21E+03	-5,77E-04	-1,04E+01	-2,92E-01
TOTAL		**-17859,796**	**-0,001**	**72,686**	**-7,664**



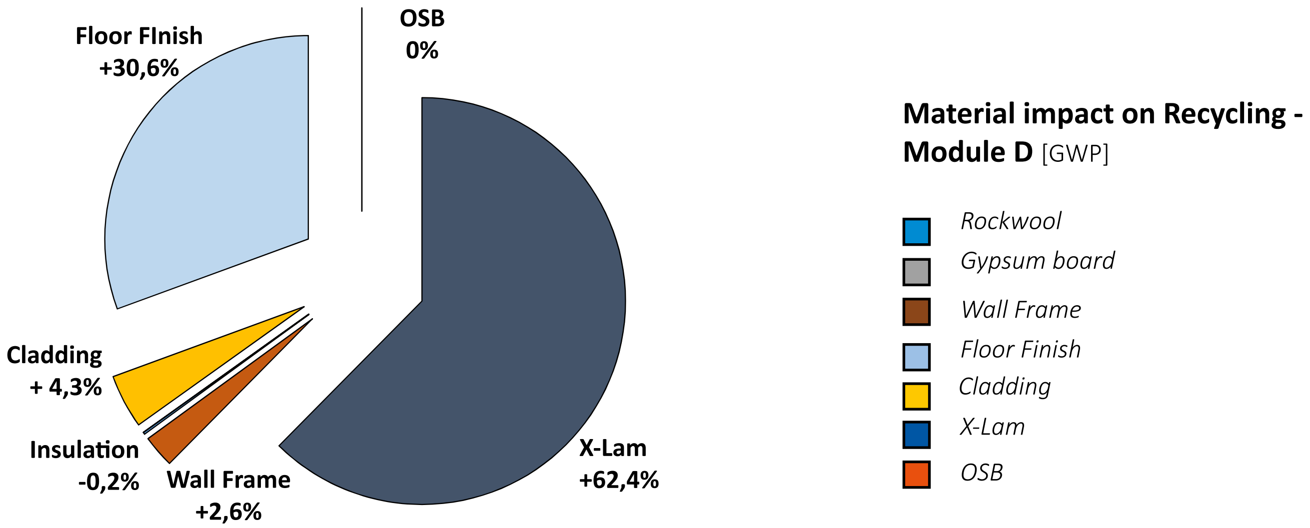
STEEL FRAME - *Durban*

Recycling Credits - total					
WASTE	**Precycle** [Kg]	**GWP** [KgCO2e/kg]	**ODP** [KgCFC11e/kg]	**AP** [KgSO2e/kg]	**EP** [Kg(PO4)3e/kg]
OSB	**16110,594**	0,000	0,000	0,000	0,000
Steel	**8032,977**	-1,52E+04	-9,48E-08	5,10E+01	-4,31E+00
Wall frame	**866,397**	5,22E+02	-4,85E-05	-8,74E-01	-2,45E-02
Insulation	**1559,961**	-6,27E+01	-4,84E-07	-2,81E-01	-2,03E-02
Gypsum board	**0,000**	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Cladding	**1445,598**	8,71E+02	-8,10E-05	-1,46E+00	-4,10E-02
Floor finish	**10307,498**	6,21E+03	-5,77E-04	-1,04E+01	-2,92E-01
TOTAL		**-7,638E+03**	**-7,073E-04**	**3,800E+01**	**-4,684E+00**



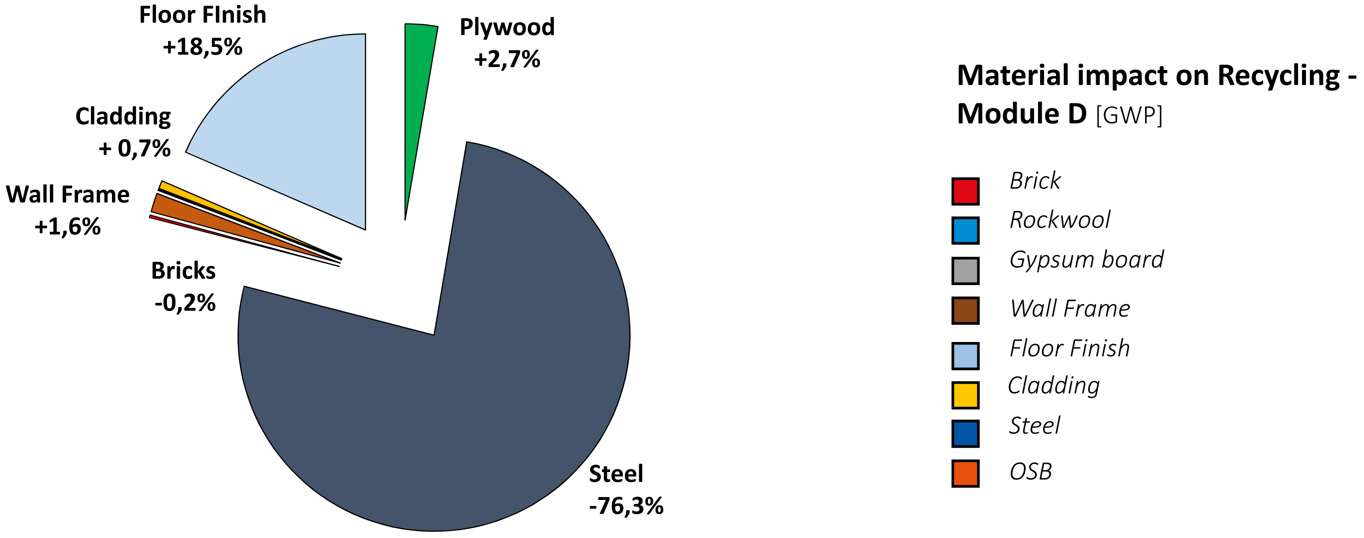
X-LAM STRUCTURE - *Durban*

Recycling Credits - total					
WASTE	Precycle [Kg]	**GWP** [KgCO2e/kg]	**ODP** [KgCFC11e/kg]	**AP** [KgSO2e/kg]	**EP** [Kg(PO4)3e/kg]
OSB	**2962,204**	0,000	0,000	0,000	0,000
XLAM	**21030,535**	1,27E+04	-1,18E-03	-2,12E+01	-5,96E-01
Wall frame	**866,397**	5,22E+02	-4,85E-05	-8,74E-01	-2,45E-02
Insulation	**788,398**	-3,17E+01	-2,44E-07	-1,42E-01	-1,02E-02
Gypsum board	**0,000**	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Cladding	**1445,598**	8,71E+02	-8,10E-05	-1,46E+00	-4,10E-02
Floor finish	**10307,498**	6,21E+03	-5,77E-04	-1,04E+01	-2,92E-01
TOTAL		**2,025E+04**	**-1,885E-03**	**-3,407E+01**	**-9,637E-01**



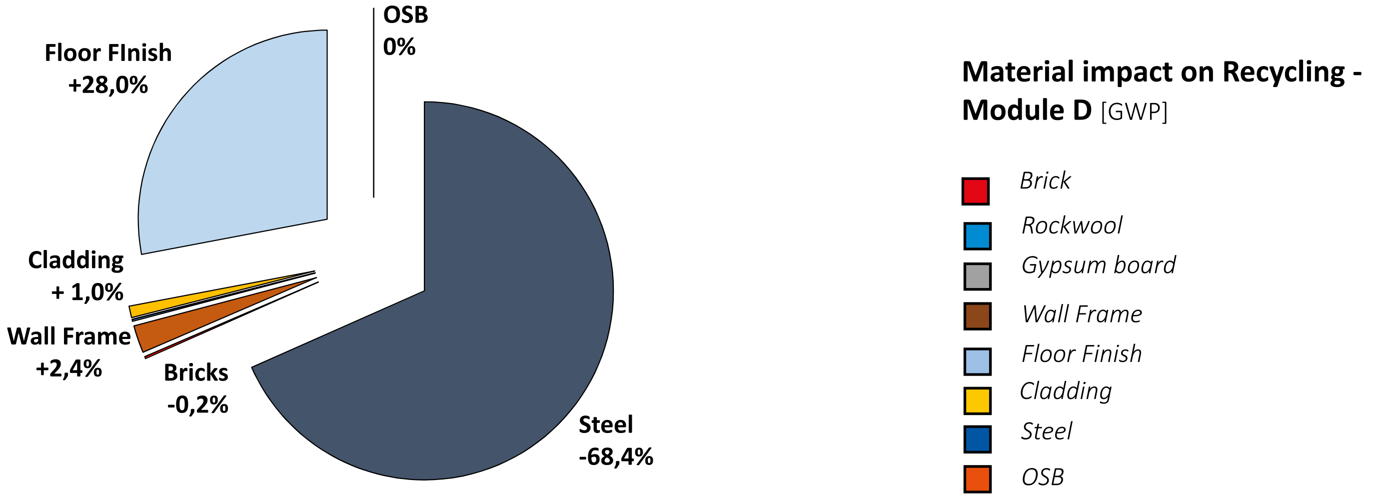
CONTAINER STRUCTURE - *Chennai*

Recycling Credits - total					
WASTE	Precycle [Kg]	**GWP** [KgCO2e/kg]	**ODP** [KgCFC11e/kg]	**AP** [KgSO2e/kg]	**EP** [Kg(PO4)3e/kg]
Plywood (floor)	**1488,209**	8,97E+02	-8,33E-05	-1,50E+00	-4,22E-02
Steel	**13566,248**	-2,56E+04	-1,60E-07	8,61E+01	-7,27E+00
Brick	**42307,761**	-69,808	0,000	-1,354	-0,296
Wall frame	**866,397**	5,22E+02	-4,85E-05	-8,74E-01	-2,45E-02
Insulation	**585,320**	-2,35E+01	-1,81E-07	-1,05E-01	-7,61E-03
OSB	**3215,160**	0,000	0,000	0,000	0,000
Gypsum board	**0,000**	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Cladding	**364,385**	2,20E+02	-2,04E-05	-3,67E-01	-1,03E-02
Floor finish	**10307,498**	6,21E+03	-5,77E-04	-1,04E+01	-2,92E-01
TOTAL		**-17880,744**	**-0,001**	**71,551**	**-7,944**



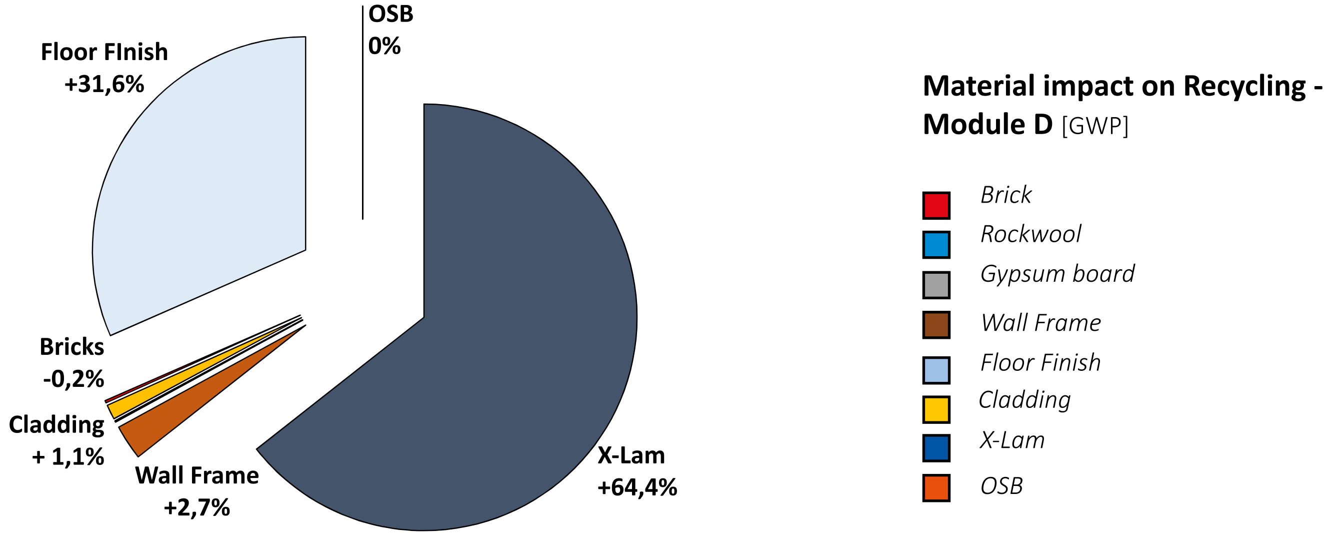
STEEL FRAME - *Chennai*

Recycling Credits - total					
WASTE	**Precycle** [Kg]	**GWP** [KgCO2e/kg]	**ODP** [KgCFC11e/kg]	**AP** [KgSO2e/kg]	**EP** [Kg(PO4)3e/kg]
OSB	**16110,594**	0,000	0,000	0,000	0,000
Steel	**8032,977**	-1,52E+04	-9,48E-08	5,10E+01	-4,31E+00
Brick	**22928,077**	-37,831	0,000	-0,734	-0,160
Wall frame	**866,397**	5,22E+02	-4,85E-05	-8,74E-01	-2,45E-02
Insulation	**800,145**	-3,22E+01	-2,48E-07	-1,44E-01	-1,04E-02
Gypsum board	**0,000**	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Cladding	**364,385**	2,20E+02	-2,04E-05	-3,67E-01	-1,03E-02
Floor finish	**10307,498**	6,21E+03	-5,77E-04	-1,04E+01	-2,92E-01
TOTAL		**-8296,664**	**-0,001**	**38,497**	**-4,803**



X-LAM STRUCTURE - *Chennai*

Recycling Credits - total					
WASTE	**Precycle** [Kg]	**GWP** [KgCO2e/kg]	**ODP** [KgCFC11e/kg]	**AP** [KgSO2e/kg]	**EP** [Kg(PO4)3e/kg]
OSB	**2577,870**	0,000	0,000	0,000	0,000
XLAM	**21030,535**	1,27E+04	-1,18E-03	-2,12E+01	-5,96E-01
Wall frame	**866,397**	5,22E+02	-4,85E-05	-8,74E-01	-2,45E-02
Insulation	**452,043**	-1,82E+01	-1,40E-07	-8,14E-02	-5,88E-03
Gypsum board	**0,000**	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Cladding	**364,385**	2,20E+02	-2,04E-05	-3,67E-01	-1,03E-02
Brick	**21153,880**	-34,904	0,000	-0,677	-0,148
Floor finish	**10307,498**	6,21E+03	-5,77E-04	-1,04E+01	-2,92E-01
TOTAL		**19580,491**	**-0,002**	**-33,599**	**-1,077**



6.6 Module D : results

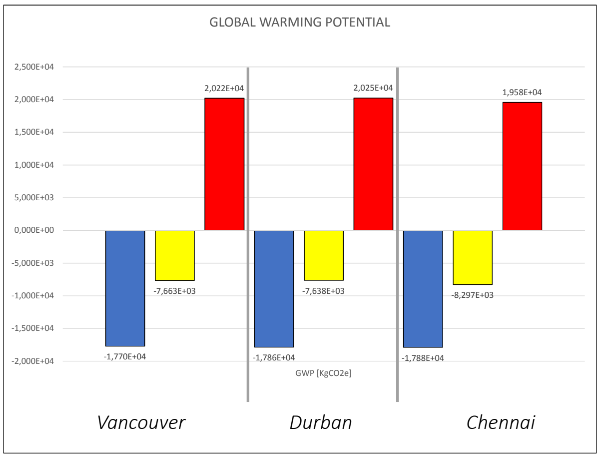
Recycling credits

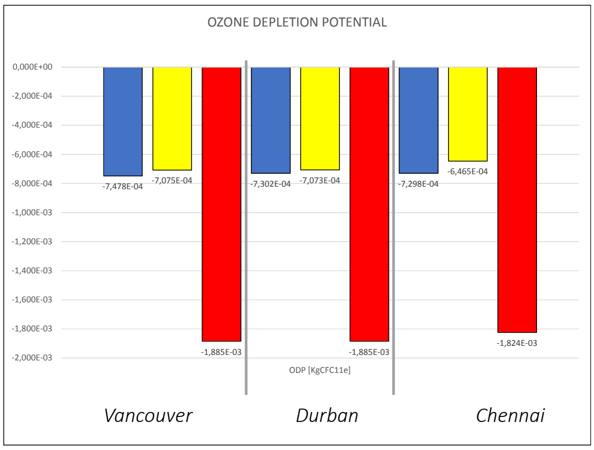
	VANCOUVER		
	CONTAINER	**STEEL**	**XLAM**
GWP [KgCO2e]	-1,770E+04	-7,663E+03	2,022E+04
ODP [KgCFC11e]	-7,478E-04	-7,075E-04	-1,885E-03
AP [KgSO2e]	7,224E+01	3,789E+01	-3,422E+01
EP [Kg(PO4)3e]	-7,682E+00	-4,692E+00	-9,740E-01

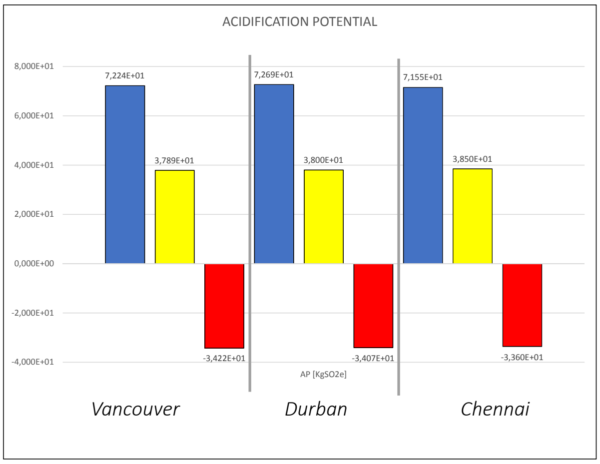
	DURBAN		
	CONTAINER	**STEEL**	**XLAM**
GWP [KgCO2e]	-1,786E+04	-7,638E+03	2,025E+04
ODP [KgCFC11e]	-7,302E-04	-7,073E-04	-1,885E-03
AP [KgSO2e]	7,269E+01	3,800E+01	-3,407E+01
EP [Kg(PO4)3e]	-7,664E+00	-4,684E+00	-9,637E-01

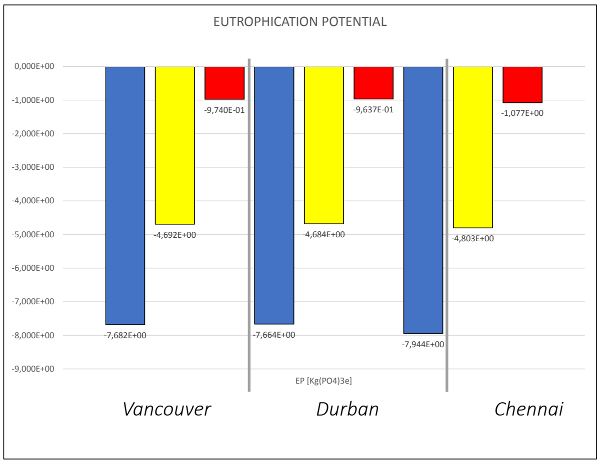
	CHENNAI		
	CONTAINER	**STEEL**	**XLAM**
GWP [KgCO2e]	-1,788E+04	-8,297E+03	1,958E+04
ODP [KgCFC11e]	-7,298E-04	-6,465E-04	-1,824E-03
AP [KgSO2e]	7,155E+01	3,850E+01	-3,360E+01
EP [Kg(PO4)3e]	-7,944E+00	-4,803E+00	-1,077E+00

🟦 *Shipping Container* 🟨 *Steel Frame* 🟥 *X-Lam*









6.7 Summary and observations

The End of Life stage highlights the ultimate impact of shipping containers in the construction sector. From all the above data is evident that demolition and waste processing of a container structure produce higher emissions compared to steel and x-lam structures. This result is mainly caused by demolition itself due to the high amount of steel contained in a container structure: the ratio of steel within a container building is 2,33 times the amount of steel required for a comparable steel frame.
Moving only from these results, it could be incorrectly stated that the use of freight container as building materials does require a larger amount of material and therefore leads to higher emissions.
The inclusion of module D, where recycling credits are allocated to each structure, demonstrates that the use of shipping containers have a double environmental benefit.
On the one hand it addresses the issue of container repositioning, upcycling waste material from one sector, the trade industry, and using it as an input of a "circular economy", the building sector. Raw material extraction is avoided at the beginning of the life cycle, and later on, at the End of Life, a large amount of material becomes available.
On the other hand, the upcycling of intermodal containers releases steel that was "stored" in empty containers, which will be later available for production. In fact difficulties in the management of empty containers testify that in practice the trade industry is not able to recycle its "waste products" and leaves them to rot in depots.
In conclusion, after one life cycle as building components, shipping containers set free 2,33 times the amount of material of a comparable steel structure, material that on the contrary of what happens for steel frames, was not available at the beginning of the process.

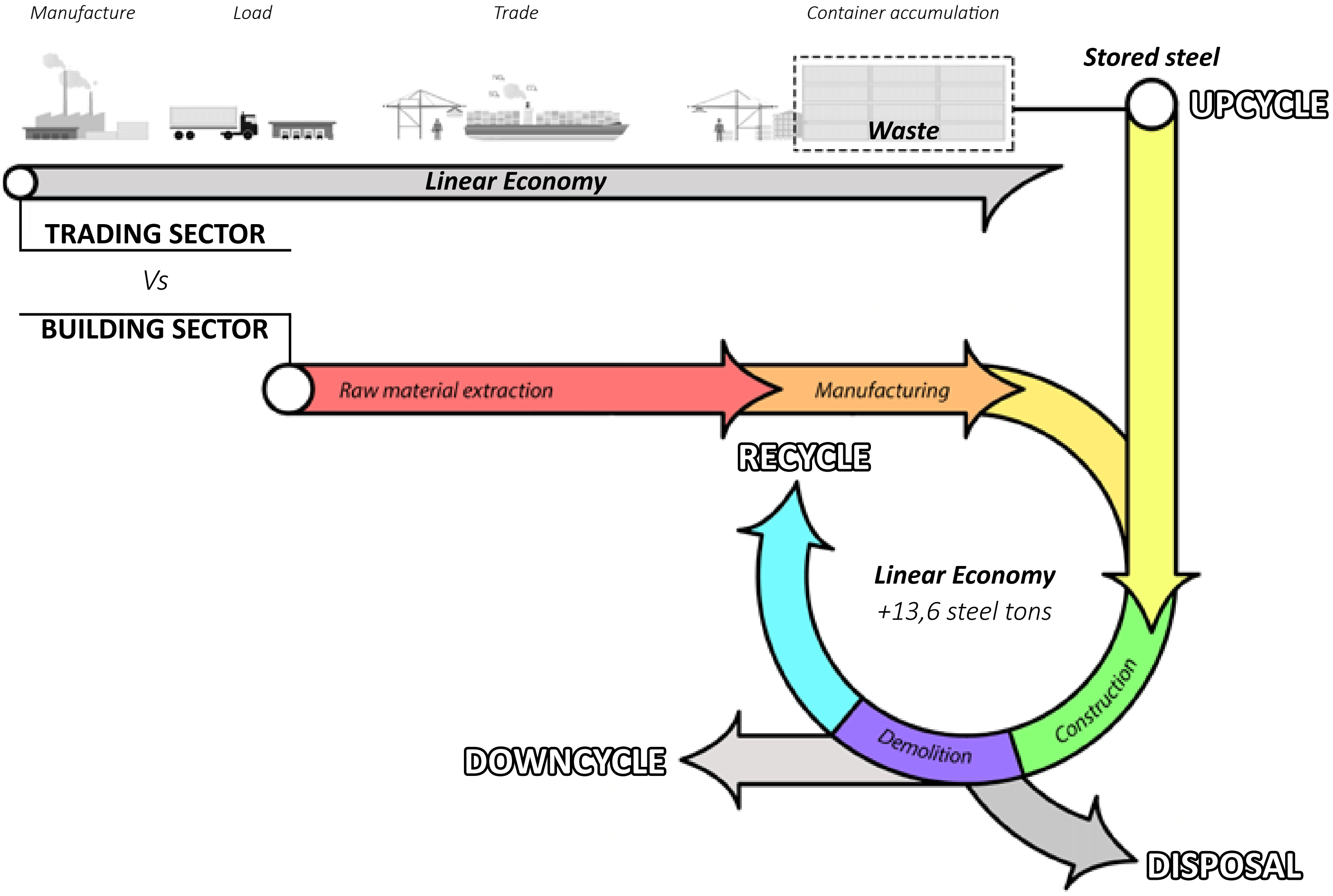


FIGURE 6.18 - Life Cyle of Shipping Container structures

CHAPTER

VII

Cradle to Cradle

7.1 LCA Results

The present chapter aims to show results for the whole Life Cycle of considered structures. Results have been organized in order to draw conclusions from comparisons, structure specific or for by climate zone.

It is important now to introduce the last step of the Life Cycle Assessment: weighting.
This step is defined as optional by the International Standard since it is highly subjective, and if considered alone leads to a difficult interpretation of results. In fact, the weighting step consist in providing a unique index for all impact categories.
It can be useful to give an overall indication of the performance of different buildings. Thus it is not able to provide the same detailed information showed by the use of different impact categories.
Previous chapters clearly show how lower emissions related to some impact categories, for instance GWP, can go along with higher resuts on others, for example AP. Module D is a clear example of this effect. Recycling of steel provides “subtractive credits” for the avoided extraction of virgin material. However, the EAF remelting process leads to the emission of high sulphates, increasing the Acidification Potential. It would have been impossible to draw all of these conclusions with the use of a unique index. For this reason weighting is often considered to be “a reduction of complex inventory data”. This is true only on a superficial level.

Weighting processes can even be regarded as methods that contribute with additional information to an LCA study or a decision making process. The use of such methods can inform on environental priorities, but definitely not replace discussions of environmental values. There is still a need for interpretation, deliberation, and judgement. Therefore there is still a need of representing impact categories separately. It is important to understand that “environmental priorities” are strictly related to “social actors” (for example scientists, policy makers, general public) to whom the index are to be shown and the relative importance that each indicator has for their scope. Weighting is therefore strictly related to audience and goal of the study.
It is also important to underline that the weighting process is not particularly problematic when involved in the comparison of assessments within the same study. As demonstrated in many stages of this study, for example during the Operational Stage, exclusions or interpretations won’t lead to a variation of the relative discrepancy of results within compared assessments, as long as methods are applied uniformously to all projects considered.

Weighting has been defined by the ISO as an optional step and it is described as “the process of converting indicator results by using numerical factors based on value choices”. A reasonable interpretation is that weighting is the application of quantitative measures of the relative severity of different environmental changes. This is also what makes weighting a matter of constroversity.
The weighting process requires some kind of modelling of the consequences that each impact category have to an “end-point”. End points are defined as environmental problems: harm to human health, harm to biodiversity, productivity losses, resource depletion, and so on. Widely diffused models try to predict the degree to which a certain substance or intervention can contribute to a recognized environmental problem.
This study is not the place for a comprehensive description of the weighting method that have been developed up to date.
A wide variety of pubblications draw comparisons on different weighting methods. It is importaant to highlight that different methods may lead to very different results. This is the main reson why weightings presented in this study are always reported along with the overall impact categories .

The weighting method used in this study has been developed by the Science Advisory Board.

Developer	GWP	ODP	AP	EP
Science Advisory Board	16	5	5	5
Harvard University	11	11	9	9
BEES software	29,3	2,1	3	6,2

FIGURE 7.1 - Examples of weighting procedures

For each scenario and structural system, results will be also reported with a sensitivity analysis that excludes Transport and Use Stage.

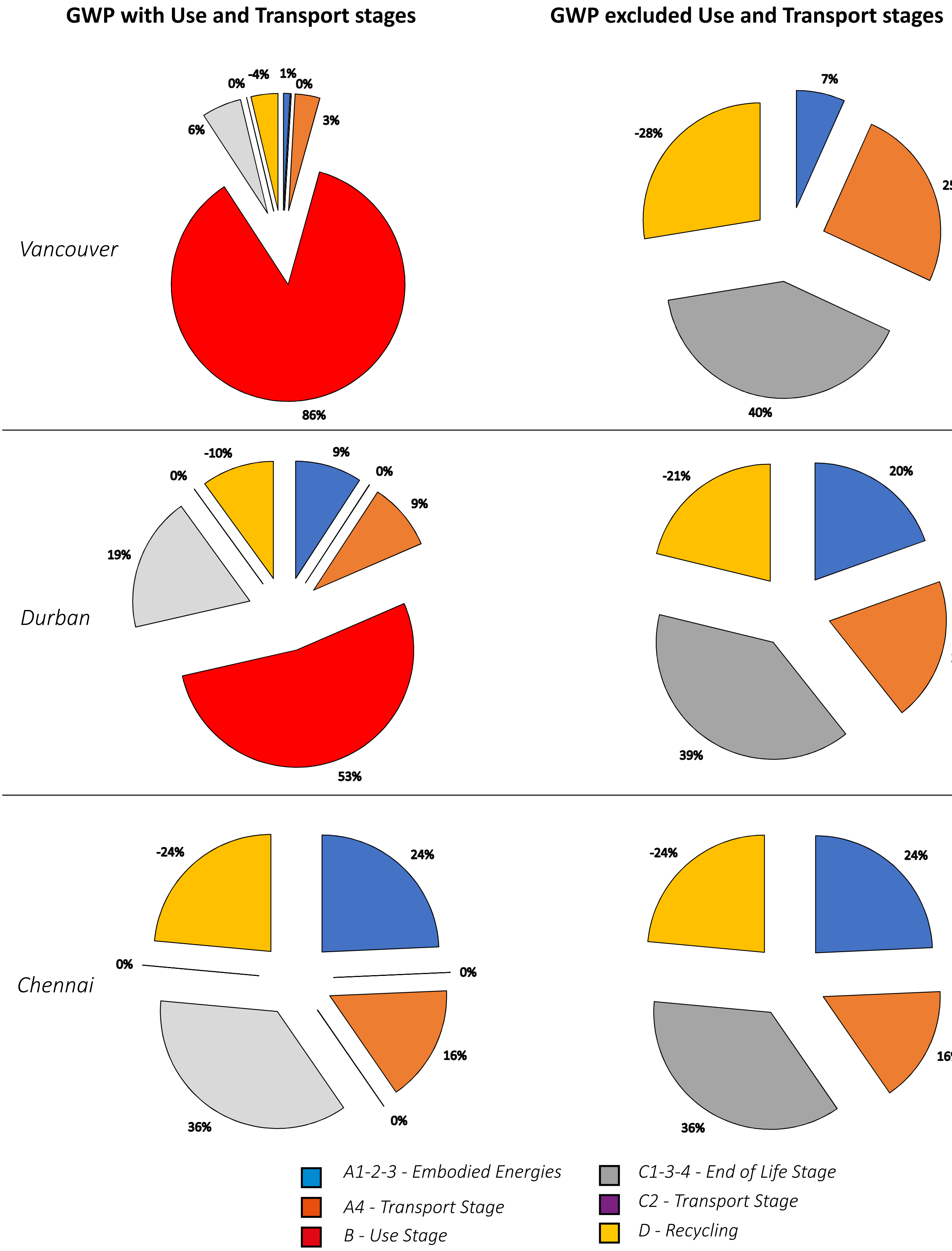


FIGURE 7.2 - Stage's impact on GWP

Figure 7.2 shows results of the impact of each Life Cycle Stage on the GWP of a Container Structure, compared with a sensitivity analysis which excludes Operational and Transport stages.

Reasons for this exclusions are on the one hand, that it allows a better comparison of climate zones. On the other hand emissions from the use stage are “flattened” throughout the different structural types. Operational energy is exactly the same for each structural type due to the inclusion of thermal requirements in the functional unit.
Moreover each transport stage, from gate to site and from site to landfill, are normalized on a “per km” basis, therefore not equally comparable to the other stages.They appear in *figure 7.2* to be not relevant in the overall emissions in this study.

Final results are reported with a sensitivity analysis which excludes module D from the calculation.

VANCOUVER - *LCA results*

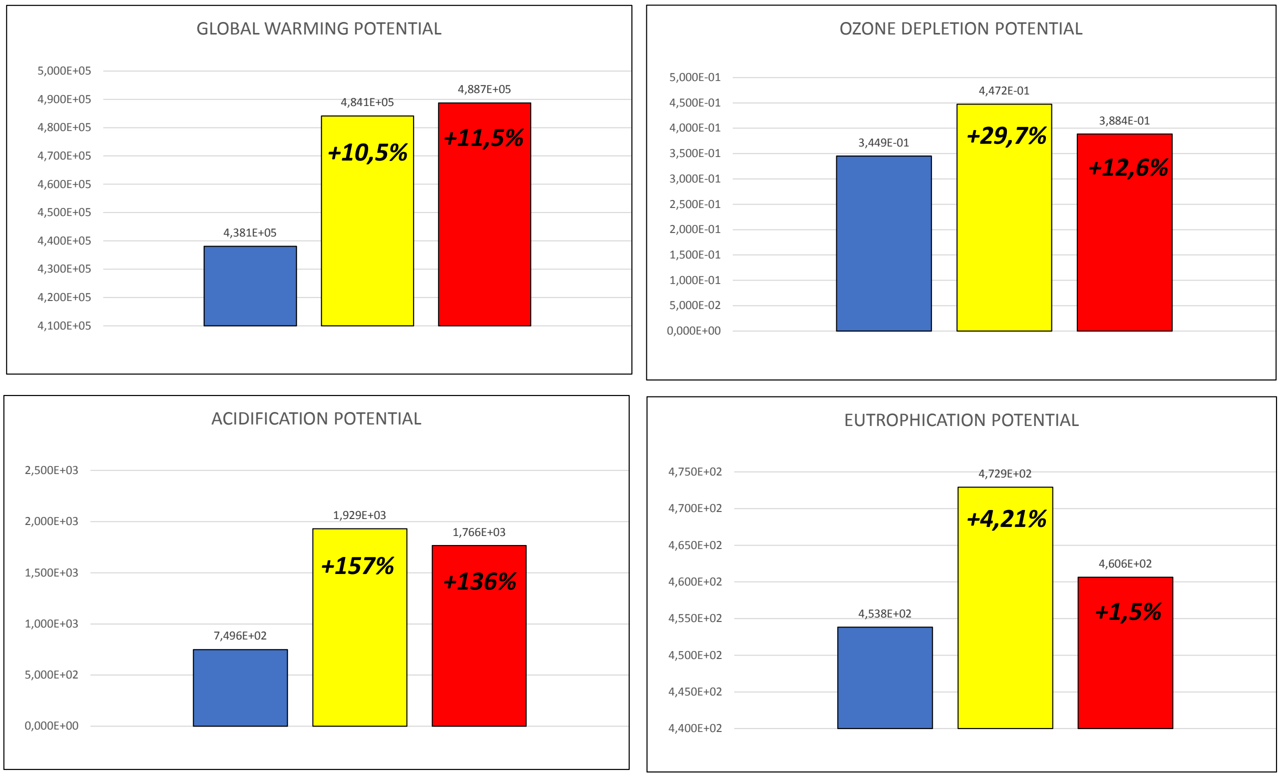
VANCOUVER

	GWP [KgCO2e]			ODP [KgCFC11e]		
	CONTAINER	**STEEL**	**XLAM**	**CONTAINER**	**STEEL**	**XLAM**
A1, A2 , A3	4,295E+03	3,201E+04	1,063E+04	5,046E-04	8,867E-04	1,132E-03
A4	2,772E+00	2,379E+00	3,869E+00	9,810E-05	8,417E-05	1,369E-04
A5	1,620E+04	3,355E+04	2,037E+04	9,947E-02	2,672E-01	2,160E-01
B	4,094E+05	4,040E+05	4,063E+05	5,505E-03	5,433E-03	5,465E-03
C1	1,804E+04	1,325E+04	1,274E+04	2,401E-01	1,743E-01	1,676E-01
C2	3,480E-01	4,229E-01	5,665E-01	1,232E-05	1,496E-05	2,004E-05
C3	5,918E+03	6,674E+03	1,346E+04	8,997E-07	1,557E-06	1,172E-05
C4	2,019E+03	2,273E+03	4,904E+03	9,848E-07	8,542E-07	6,153E-07
D	-1,770E+04	-7,663E+03	2,022E+04	-7,478E-04	-7,075E-04	-1,885E-03
Total	**4,381E+05**	**4,841E+05**	**4,887E+05**	**3,449E-01**	**4,472E-01**	**3,884E-01**
Total without D	*4,558E+05*	*4,918E+05*	*4,685E+05*	*3,456E-01*	*4,479E-01*	*3,903E-01*

	AP [KgSO2e]			EP [Kg(PO4)3e]		
	CONTAINER	**STEEL**	**XLAM**	**CONTAINER**	**STEEL**	**XLAM**
A1, A2 , A3	1,229E+02	1,323E+03	1,247E+03	8,632E+00	1,912E+01	1,362E+01
A4	8,530E-03	7,319E-03	1,190E-02	1,066E-03	1,066E-03	1,488E-03
A5	2,479E+01	5,460E+01	3,599E+01	1,493E+01	2,981E+01	1,711E+01
B	4,941E+02	4,876E+02	4,904E+02	4,235E+02	4,179E+02	4,204E+02
C1	3,445E+01	2,520E+01	2,423E+01	1,425E+01	1,051E+01	1,011E+01
C2	1,071E-03	1,301E-03	1,743E-03	1,339E-04	1,626E-04	2,179E-04
C3	2,626E-01	3,289E-01	3,289E-01	6,114E-02	7,636E-02	8,138E-02
C4	8,295E-01	9,274E-01	1,984E+00	1,479E-01	1,918E-01	3,301E-01
D	7,224E+01	3,789E+01	-3,422E+01	-7,682E+00	-4,692E+00	-9,740E-01
Total	**7,496E+02**	**1,929E+03**	**1,766E+03**	**4,538E+02**	**4,729E+02**	**4,606E+02**
Total without D	*6,773E+02*	*1,892E+03*	*1,800E+03*	*4,615E+02*	*4,776E+02*	*4,616E+02*

VANCOUVER - *LCA results with module D*

🟦 *Shipping Container* 🟨 *Steel Frame* 🟥 *X-Lam*



Percentages indicate the relative difference compared to container structures

FIGURE 7.3 - Vancouver - Impact Categories results

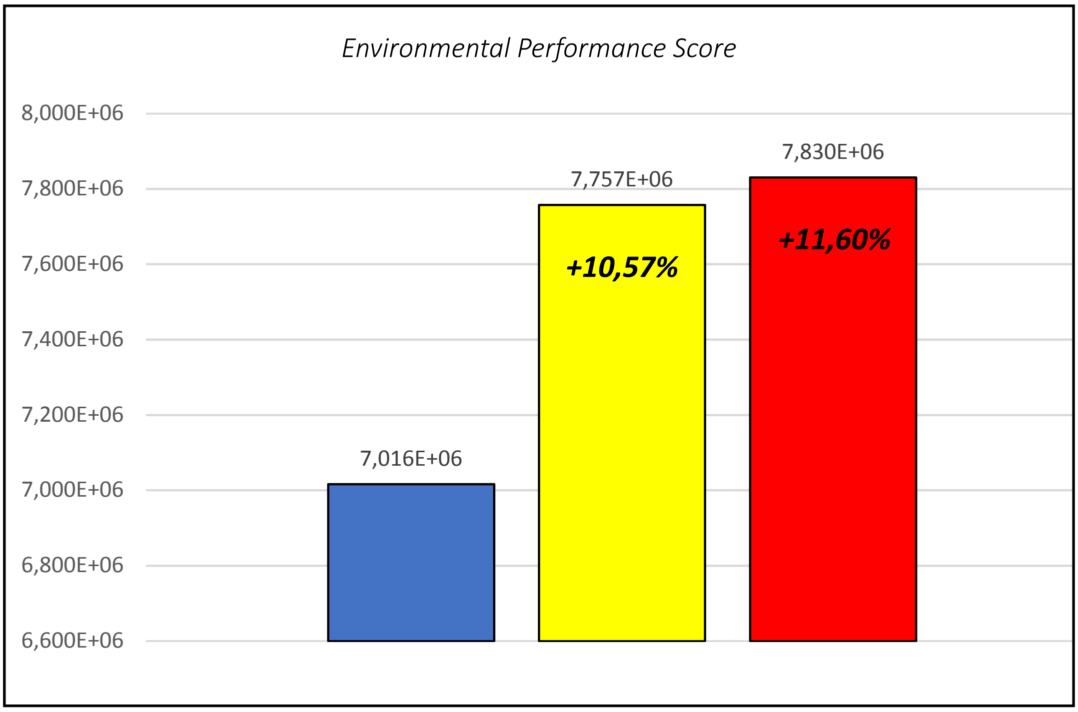
VANCOUVER - *LCA results excluding module D*

Percentages indicate the relative difference compared to container structures

FIGURE 7.4 - Vancouver - Impact Categories results without module D

VANCOUVER - *Weighted results with module D*

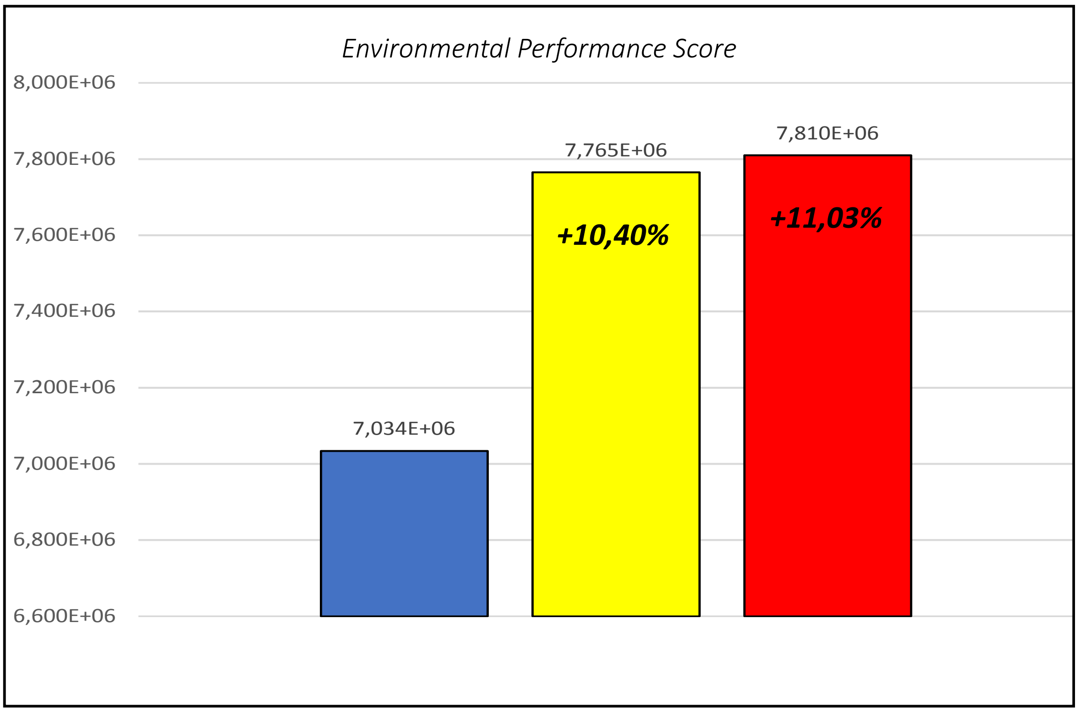
🟦 *Shipping Container* 🟨 *Steel Frame* 🟥 *X-Lam*



Percentages indicate the relative difference compared to container structures

FIGURE 7.5 - Vancouver - Weighted indexes

VANCOUVER - *Weighted results excluding module D*



Percentages indicate the relative difference compared to container structures

FIGURE 7.6 - Vancouver - Weighted indexes without module D

FIGURE 7.7 - Vancouver - GWP percentual impact of Stages

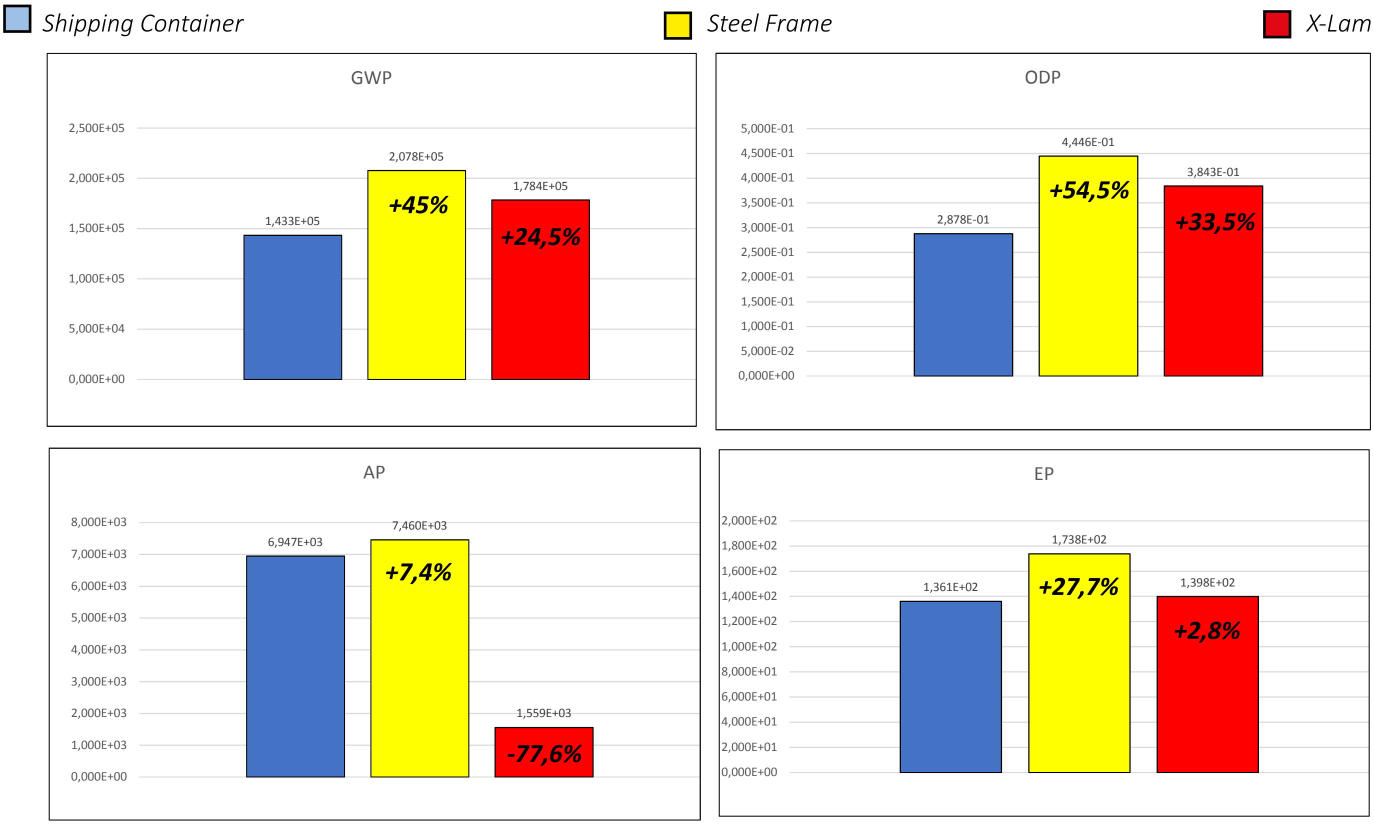
DURBAN - *LCA results*

DURBAN

	GWP [KgCO2e]			ODP [KgCFC11e]		
	CONTAINER	**STEEL**	**XLAM**	**CONTAINER**	**STEEL**	**XLAM**
A1, A2 , A3	1,646E+04	4,243E+04	1,010E+04	1,754E-03	1,998E-03	1,132E-03
A4	2,947E+00	3,668E+00	3,870E+00	1,043E-04	1,298E-04	1,369E-04
A5	1,668E+04	5,108E+04	2,037E+04	4,537E-02	2,676E-01	2,160E-01
B	9,475E+04	9,300E+04	9,637E+04	1,274E-03	1,251E-03	1,296E-03
C1	1,804E+04	1,325E+04	1,274E+04	2,401E-01	1,743E-01	1,676E-01
C2	4,795E-01	5,438E-01	5,666E-01	1,697E-05	1,924E-05	2,005E-05
C3	1,134E+04	1,165E+04	1,360E+04	8,769E-07	1,537E-06	1,170E-05
C4	3,865E+03	3,968E+03	4,952E+03	7,005E-07	6,069E-07	3,452E-07
D	-1,786E+04	-7,638E+03	2,025E+04	-7,302E-04	-7,073E-04	-1,885E-03
Total	**1,433E+05**	**2,078E+05**	**1,784E+05**	**2,878E-01**	**4,446E-01**	**3,843E-01**
Total without D	*1,611E+05*	*2,154E+05*	*1,582E+05*	*2,886E-01*	*4,453E-01*	*3,861E-01*

	AP [KgSO2e]			EP [Kg(PO4)3e]		
	CONTAINER	**STEEL**	**XLAM**	**CONTAINER**	**STEEL**	**XLAM**
A1, A2 , A3	6,701E+03	7,207E+03	1,414E+03	1,470E+01	2,346E+01	1,346E+01
A4	9,067E-03	1,129E-02	1,191E-02	1,133E-03	1,411E-03	1,488E-03
A5	2,252E+01	7,576E+01	3,599E+01	1,643E+01	4,794E+01	1,711E+01
B	1,144E+02	1,122E+02	1,163E+02	9,802E+01	9,621E+01	9,970E+01
C1	3,445E+01	2,520E+01	2,423E+01	1,425E+01	1,051E+01	1,011E+01
C2	1,475E-03	1,673E-03	1,743E-03	1,844E-04	2,091E-04	2,179E-04
C3	4,590E-01	5,093E-01	3,341E-01	1,072E-01	1,186E-01	8,260E-02
C4	1,575E+00	1,612E+00	2,003E+00	2,455E-01	2,814E-01	3,325E-01
D	7,269E+01	3,800E+01	-3,407E+01	-7,664E+00	-4,684E+00	-9,637E-01
Total	**6,947E+03**	**7,460E+03**	**1,559E+03**	**1,361E+02**	**1,738E+02**	**1,398E+02**
Total without D	*6,875E+03*	*7,422E+03*	*1,593E+03*	*1,438E+02*	*1,785E+02*	*1,408E+02*

DURBAN - *LCA results with module D*



Percentages indicate the relative difference compared to container structures

FIGURE 7.8 - Durban - Impact Categories results

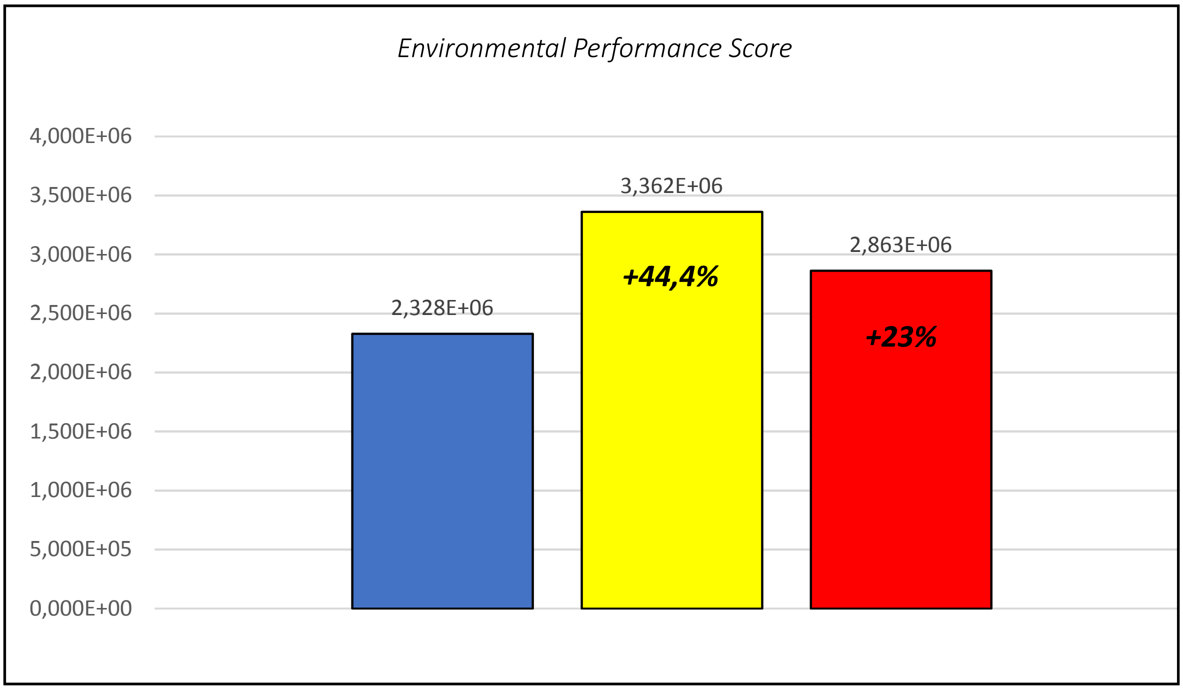
DURBAN - *LCA results excluding module D*

Percentages indicate the relative difference compared to container structures

FIGURE 7.9 - Durban - Impact Categories results without module D

DURBAN - *Weighted results with module D*

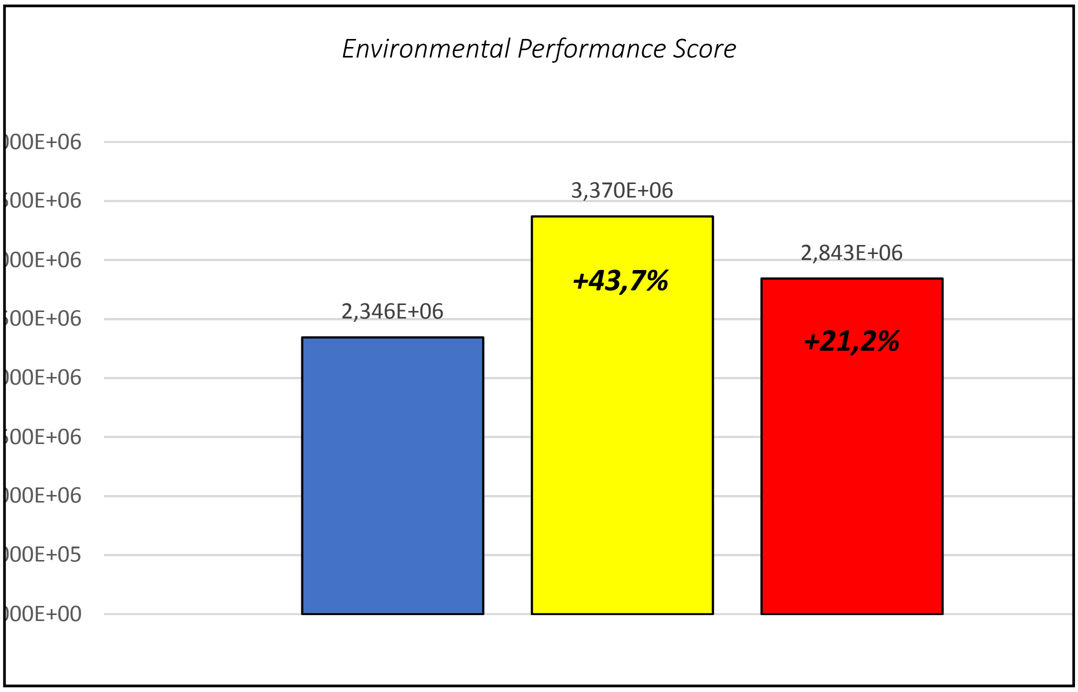
🟦 *Shipping Container* 🟨 *Steel Frame* 🟥 *X-Lam*



Percentages indicate the relative difference compared to container structures

FIGURE 7.10 - Durban - Weighted indexes

DURBAN - *Weighted results excluding module D*



Percentages indicate the relative difference compared to container structures

FIGURE 7.11 - Durban - Weighted indexes without module D

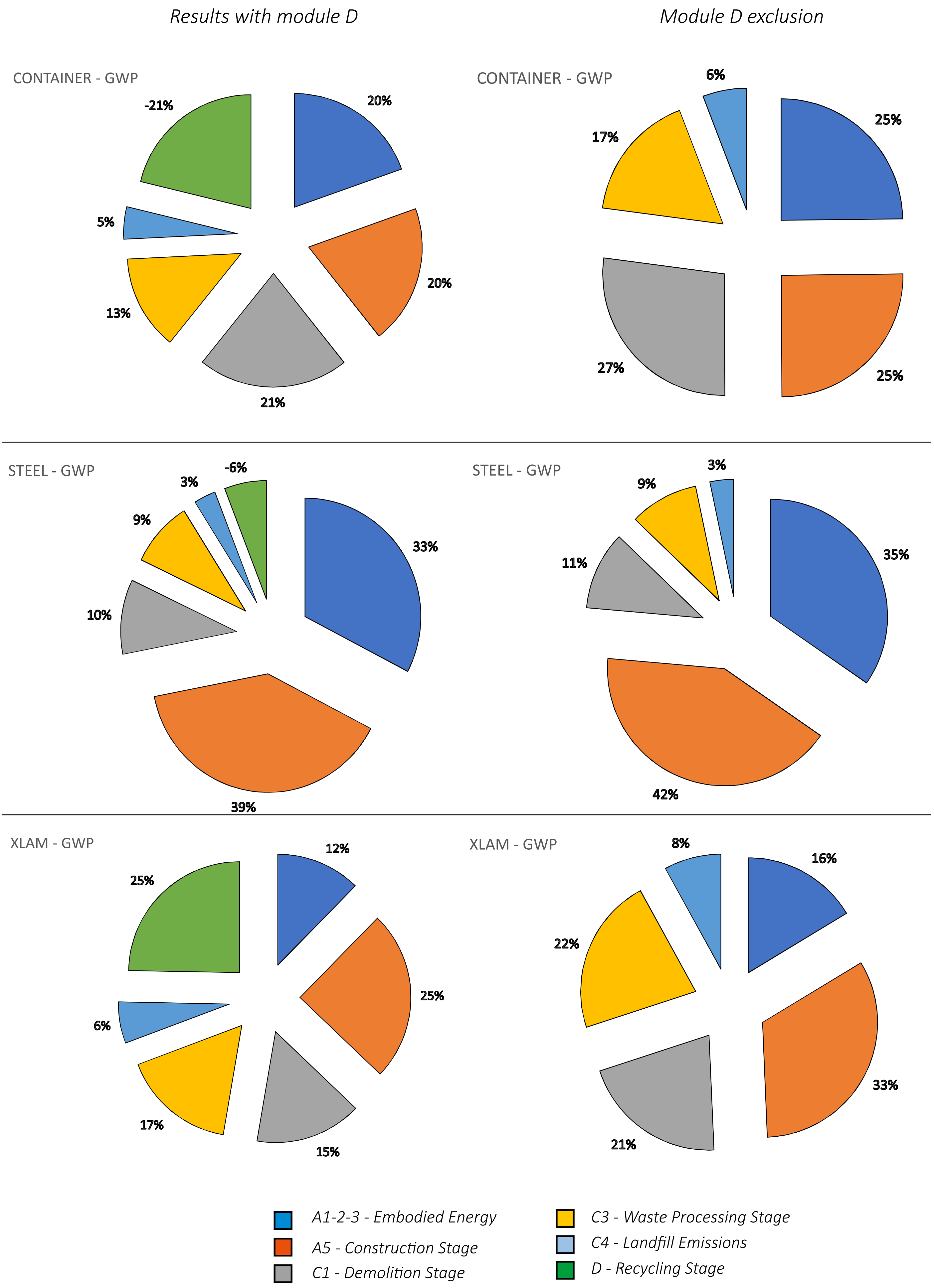


FIGURE 7.12 - Durban - GWP percentual impact of Stages

CHENNAI - *LCA results*

CHENNAI

	GWP [KgCO2e]			ODP [KgCFC11e]		
	CONTAINER	**STEEL**	**XLAM**	**CONTAINER**	**STEEL**	**XLAM**
A1, A2 , A3	1,845E+04	4,175E+04	1,552E+04	7,340E-04	1,196E-03	9,814E-04
A4	5,823E+00	4,798E+00	5,627E+00	2,061E-04	1,698E-04	1,991E-04
A5	1,221E+04	3,844E+04	2,306E+04	4,530E-02	2,674E-01	2,160E-01
B	0,000E+00	0,000E+00	0,000E+00	0,000E+00	0,000E+00	0,000E+00
C1	1,804E+04	1,325E+04	1,274E+04	2,401E-01	1,743E-01	1,676E-01
C2	7,518E-01	7,377E-01	7,423E-01	2,660E-05	2,610E-05	2,627E-05
C3	6,960E+03	1,116E+04	1,297E+04	8,391E-07	1,514E-06	1,168E-05
C4	2,372E+03	3,799E+03	4,735E+03	2,278E-07	3,114E-07	1,761E-07
D	-1,788E+04	-8,297E+03	1,958E+04	-7,298E-04	-6,465E-04	-1,824E-03
Total	**4,016E+04**	**1,001E+05**	**8,861E+04**	**2,856E-01**	**4,425E-01**	**3,830E-01**
Total without D	*5,804E+04*	*1,084E+05*	*6,903E+04*	*2,863E-01*	*4,432E-01*	*3,848E-01*

	AP [KgSO2e]			EP [Kg(PO4)3e]		
	CONTAINER	**STEEL**	**XLAM**	**CONTAINER**	**STEEL**	**XLAM**
A1, A2 , A3	1,620E+03	3,800E+03	1,295E+03	1,436E+01	2,227E+01	1,481E+01
A4	1,792E-02	1,476E-02	1,731E-02	2,240E-03	1,845E-03	2,164E-03
A5	1,712E+01	6,051E+01	3,923E+01	1,180E+01	3,487E+01	1,989E+01
B	0,000E+00	0,000E+00	0,000E+00	0,000E+00	0,000E+00	0,000E+00
C1	3,445E+01	2,520E+01	2,423E+01	1,425E+01	1,051E+01	1,011E+01
C2	2,313E-03	2,270E-03	2,284E-03	2,892E-04	2,837E-04	2,855E-04
C3	3,085E-01	4,958E-01	3,152E-01	6,991E-02	1,144E-01	7,717E-02
C4	6,990E-01	1,396E+00	1,779E+00	1,067E-01	2,401E-01	2,911E-01
D	7,155E+01	3,850E+01	-3,360E+01	-7,944E+00	-4,803E+00	-1,077E+00
Total	**1,744E+03**	**3,926E+03**	**1,327E+03**	**3,265E+01**	**6,320E+01**	**4,410E+01**
Total without D	*1,672E+03*	*3,888E+03*	*1,360E+03*	*4,060E+01*	*6,800E+01*	*4,518E+01*

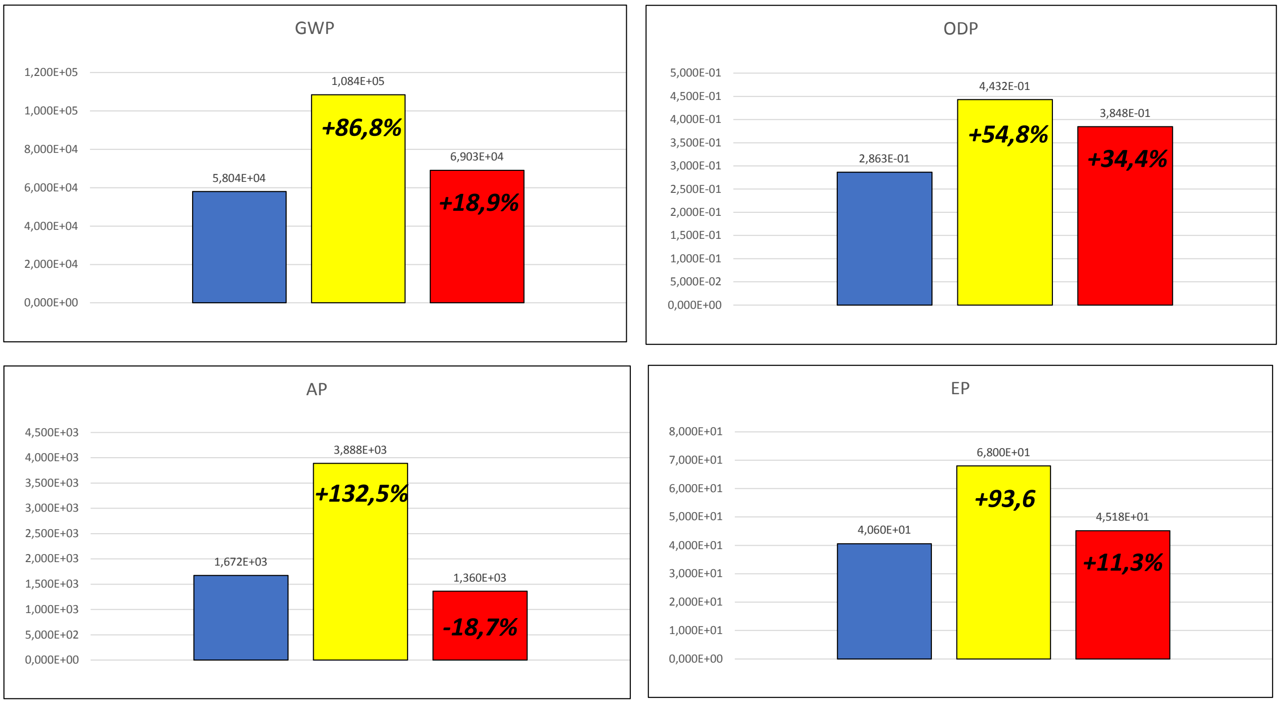
CHENNAI - *LCA results with module D*

🟦 *Shipping Container* 🟨 *Steel Frame* 🟥 *X-Lam*

Percentages indicate the relative difference compared to container structures

FIGURE 7.13 - Chennai - Impact Categories results

CHENNAI - *LCA results excluding module D*

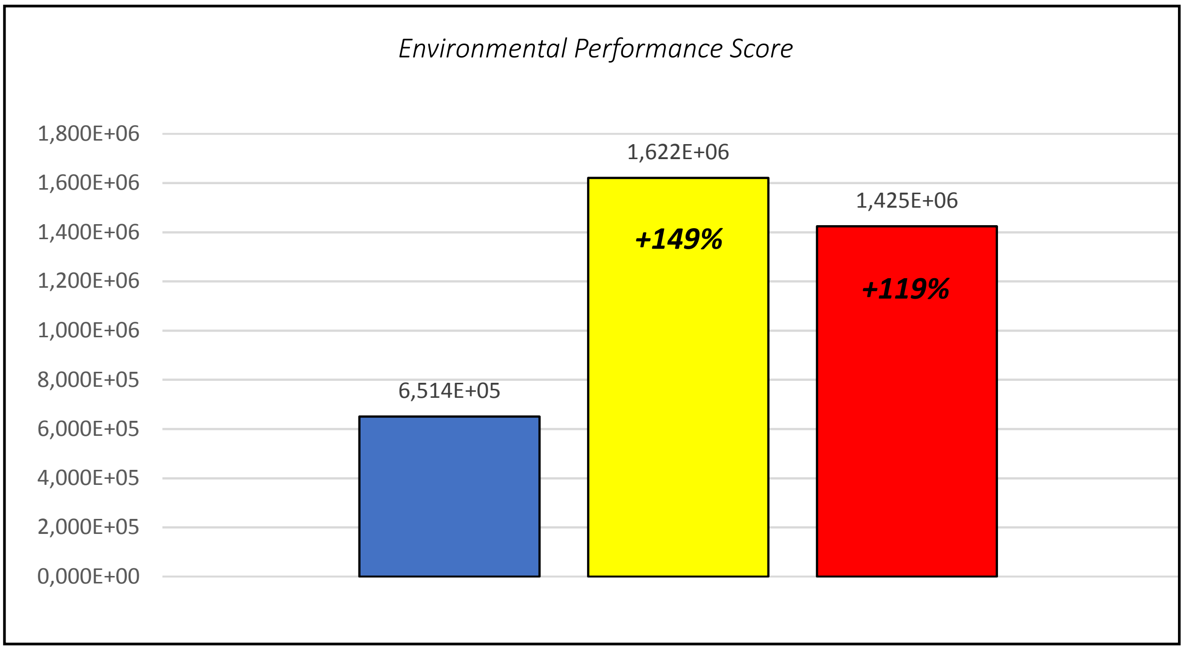


Percentages indicate the relative difference compared to container structures

FIGURE 7.14 - Chennai - Impact Categories results without module D

CHENNAI - *Weighted results with module D*

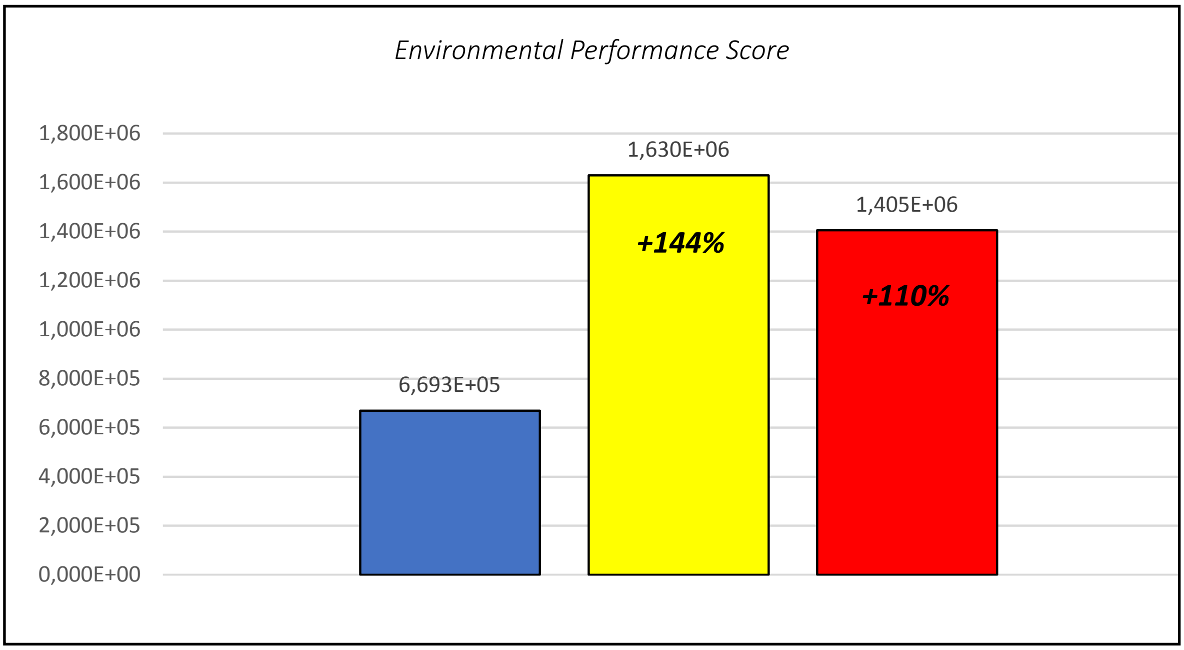
🟦 *Shipping Container* 🟨 *Steel Frame* 🟥 *X-Lam*



Percentages indicate the relative difference compared to container structures

FIGURE 7.15 - Chennai- Weighted indexes

CHENNAI - *Weighted results excluding module D*



Percentages indicate the relative difference compared to container structures

FIGURE 7.16 - Chenanai - Weighted indexes without module D

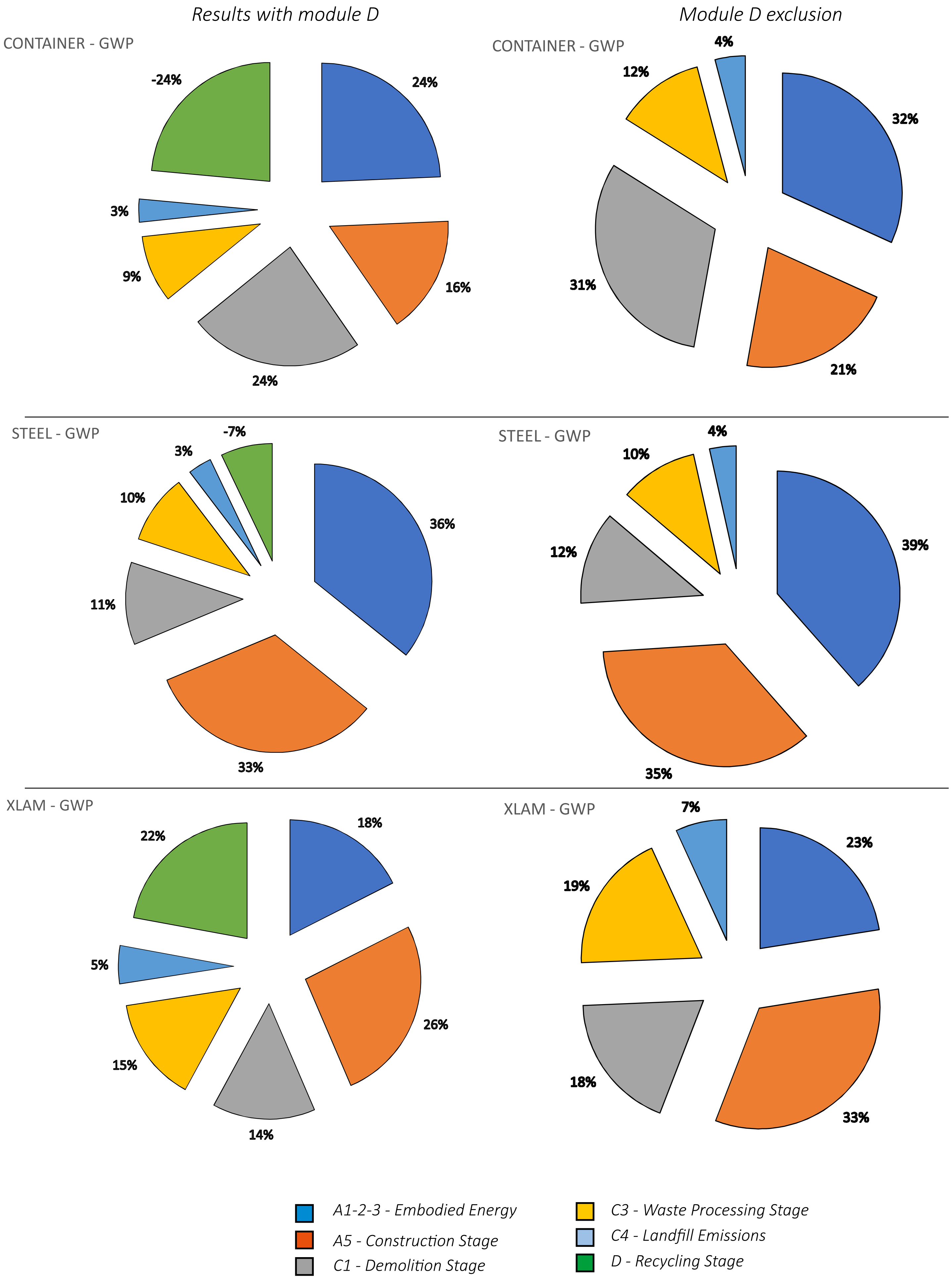


FIGURE 7.17 - Chennai - GWP percentual impact of Stages

CONTAINER STRUCTURE - *Results comparison*

The following pargraph is focused on filtering and grouping any result presented focusing on shipping containers.

	VANCOUVER			
	GWP [KgCO2e]	ODP [KgCFC11e]	AP [KgSO2e]	EP [Kg(PO4)3e]
A1-2-3	4,295E+03	5,046E-04	1,229E+02	8,632E+00
A4	2,772E+00	9,810E-05	8,530E-03	1,066E-03
A5	1,620E+04	9,947E-02	2,479E+01	1,493E+01
B	4,094E+05	5,505E-03	4,941E+02	4,235E+02
C1	2,598E+04	2,401E-01	3,554E+01	1,446E+01
C2	3,480E-01	1,232E-05	1,071E-03	1,339E-04
C3	5,918E+03	8,997E-07	2,626E-01	6,114E-02
C4	2,019E+03	9,848E-07	8,295E-01	1,479E-01
D	-1,770E+04	-7,478E-04	7,224E+01	-7,682E+00
Total	**4,461E+05**	**3,449E-01**	**7,507E+02**	**4,540E+02**

	DURBAN			
	GWP [KgCO2e]	ODP [KgCFC11e]	AP [KgSO2e]	EP [Kg(PO4)3e]
A1-2-3	1,646E+04	1,754E-03	6,701E+03	1,470E+01
A4	2,947E+00	1,043E-04	9,067E-03	1,133E-03
A5	1,668E+04	4,537E-02	2,252E+01	1,643E+01
B	9,475E+04	1,274E-03	1,144E+02	9,802E+01
C1	3,325E+04	2,401E-01	3,648E+01	1,461E+01
C2	4,795E-01	1,697E-05	1,475E-03	1,844E-04
C3	1,134E+04	8,769E-07	4,590E-01	6,114E-02
C4	3,865E+03	7,005E-07	1,575E+00	2,455E-01
D	-1,786E+04	-7,302E-04	7,269E+01	-7,664E+00
Total	**1,585E+05**	**2,878E-01**	**6,949E+03**	**1,364E+02**

	CHENNAI			
	GWP [KgCO2e]	ODP [KgCFC11e]	AP [KgSO2e]	EP [Kg(PO4)3e]
A1-2-3	1,845E+04	7,340E-04	1,620E+03	1,436E+01
A4	5,823E+00	2,061E-04	1,792E-02	2,240E-03
A5	1,221E+04	4,530E-02	1,712E+01	1,180E+01
B	0,000E+00	0,000E+00	0,000E+00	0,000E+00
C1	2,737E+04	2,401E-01	3,546E+01	1,443E+01
C2	7,518E-01	2,660E-05	2,313E-03	2,892E-04
C3	6,960E+03	8,391E-07	3,085E-01	6,991E-02
C4	2,372E+03	2,278E-07	6,990E-01	1,067E-01
D	-1,788E+04	-7,298E-04	7,155E+01	-7,944E+00
Total	**4,949E+04**	**2,856E-01**	**1,745E+03**	**3,283E+01**

FIGURE 7.18 - Chennai - Container structure LCA results

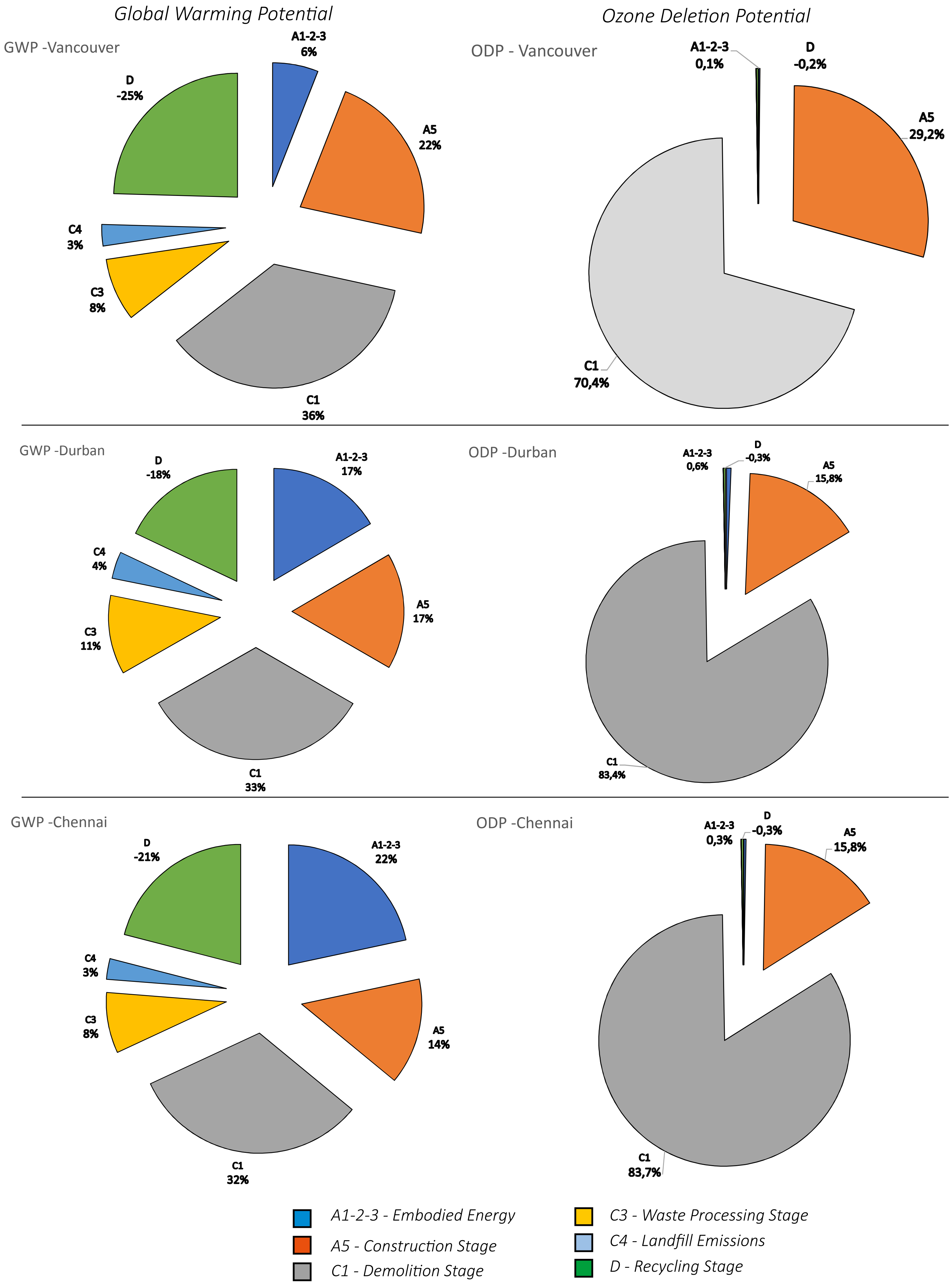


FIGURE 7.19 - Chennai - GWP-ODP percentual impact of Stages

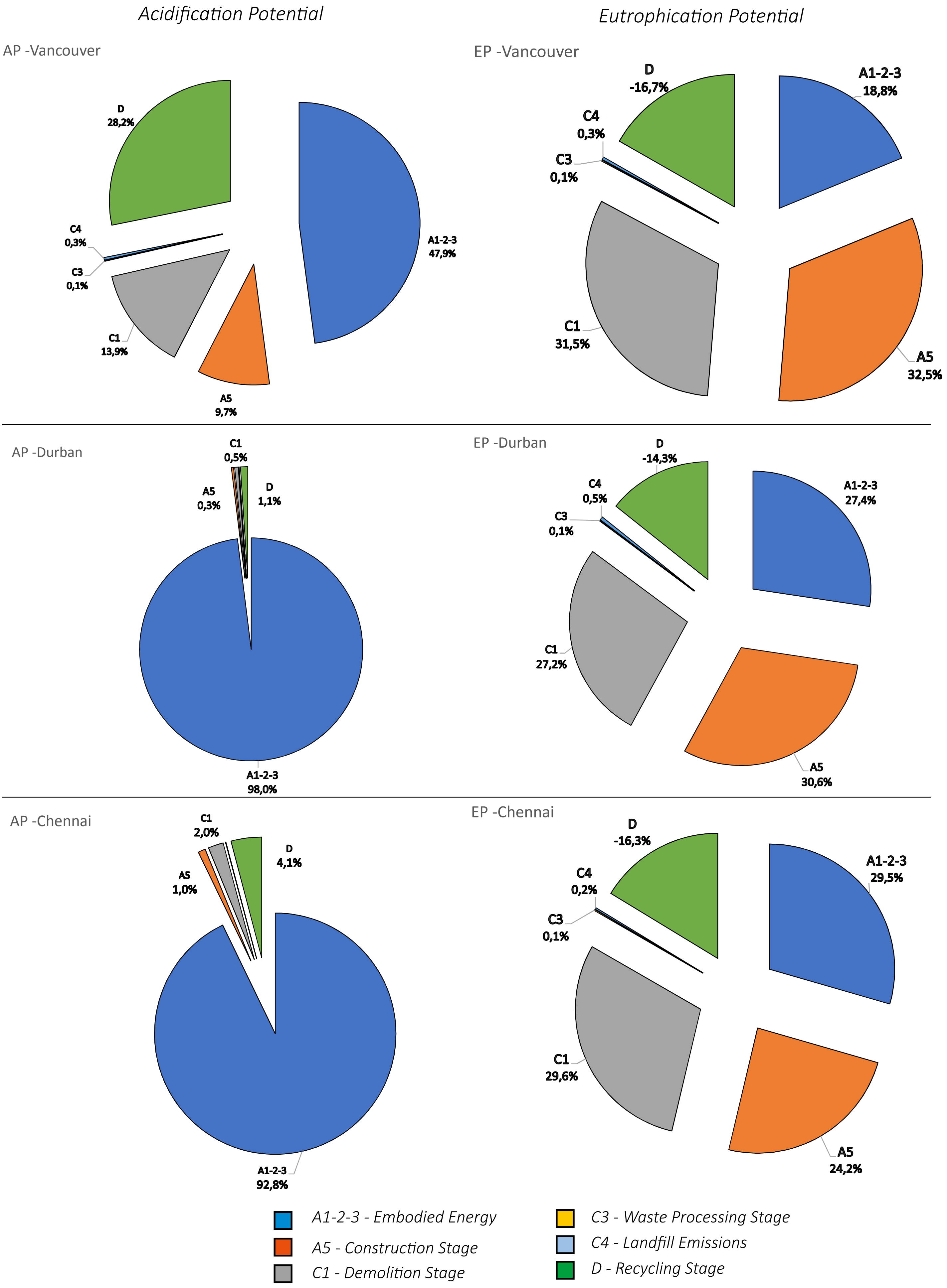
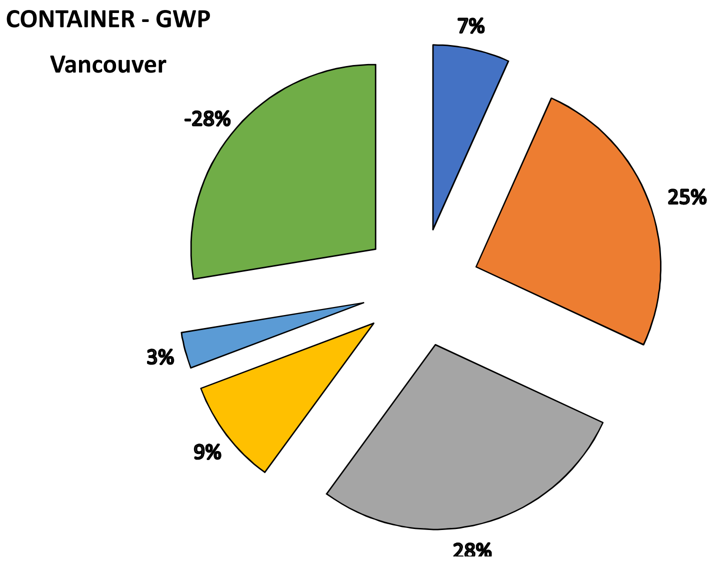


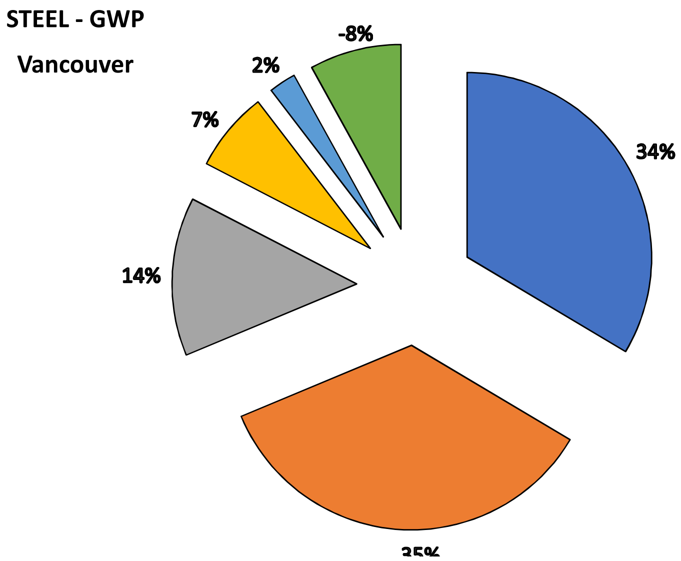
FIGURE 7.20 - Chennai - AP-EP percentual impact of Stages

7.2 Conclusions

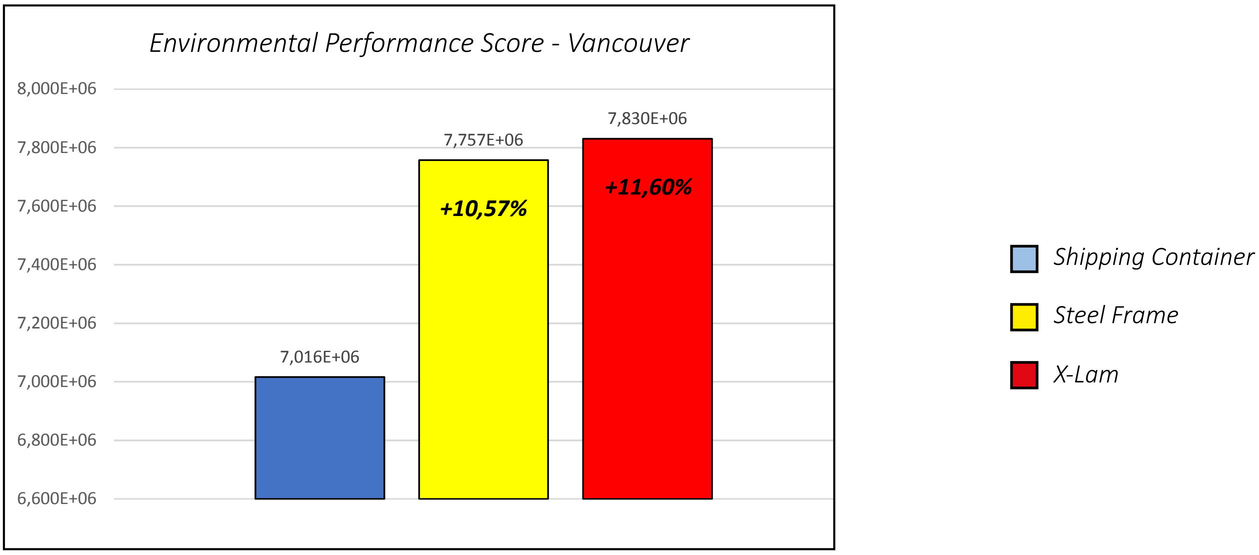
All of the following conclusions come from the exclusion of transport and operational energy from the system: as already demonstrated, these stages do not provide any additional information for this comparative analysis. Moreover the operational energy has already widely been addressed in literature and it is well know the main relavance that has in the life cycle of a building. A great deal of effort has been put in lowering operational emissions. Therefore it can be assumed that with a progressive reduction of emissions related to this stage, the relative relevance of any other stage will increase. Finally it is important to stress that operational energy is not directly linked with the particular structural technology chosen, which is the primary scope of this thesis.

Generally the inclusion of module D is favourable for the container structure due to the large amount of steel that is made available for recycling: 2,33 times the amount of steel of a comparable steel frame are recycled from the structure. Considering that timber products are not recyclable in closed loop, Module D leads to a great environmental benefit towards structures with freight containers as building components.
The following graphs from Vancouver's scenario highlight the great relevance of recycling - Module D, green - in container structures.

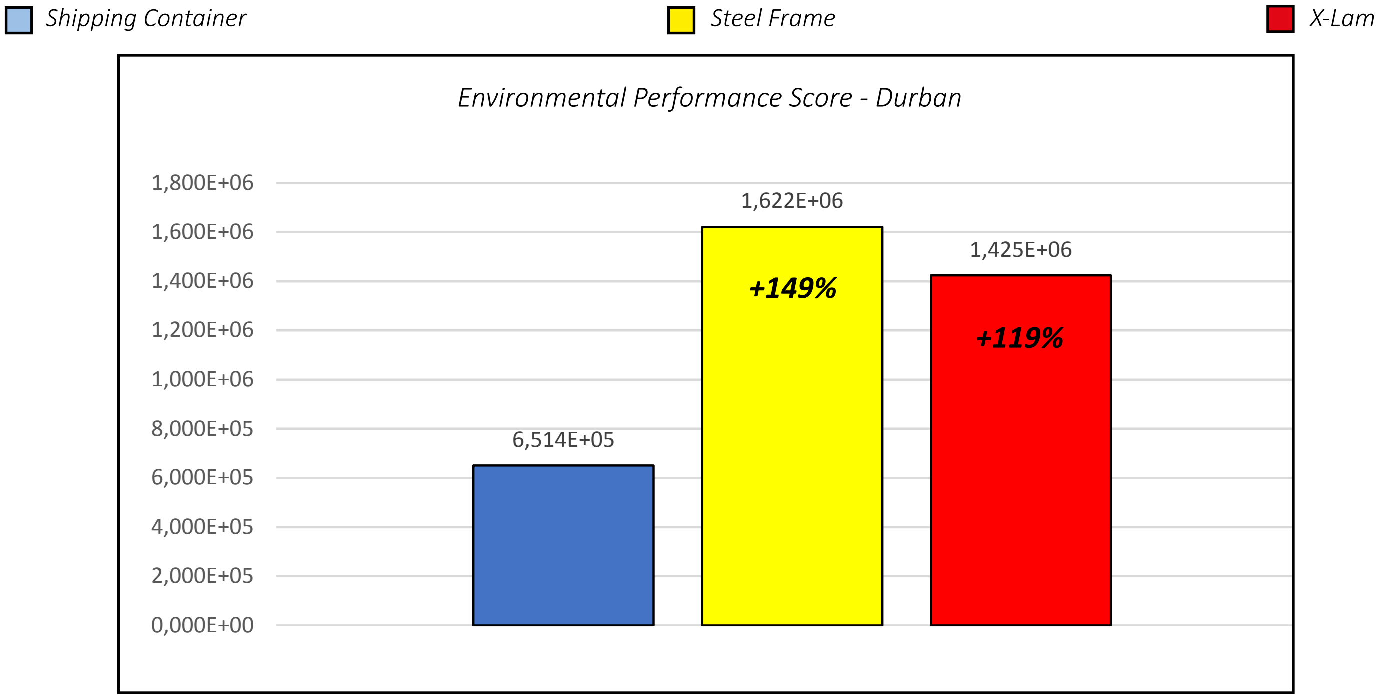




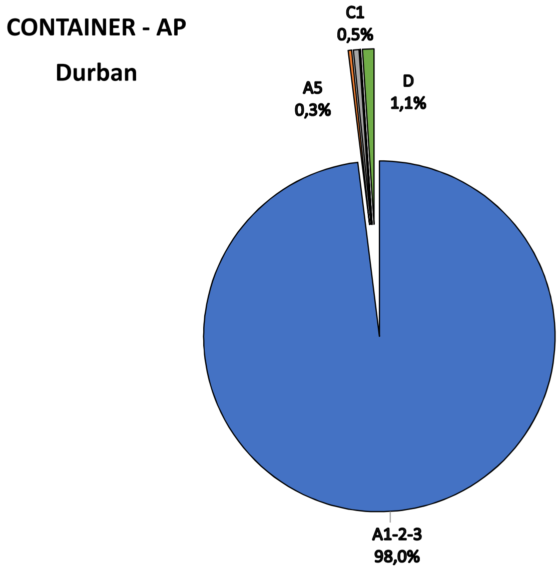
The scenario with high insulation requirements, Vancouver, shows that shipping containers provide environmental benefits for each impact category considered. This is mainly due to avoided emissions in the manufacturing stage, and faster construction schedules.



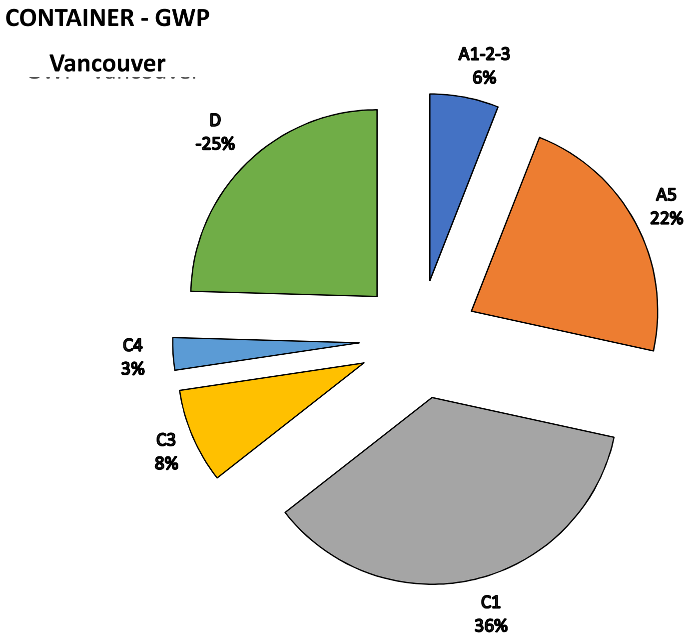
The scenario representative of the need of insulation along with superficial mass walls, Durban, reports an overall environmental benefit of freight containers. Emissions are even lower than reported in colder climates. This is mainly due to the difference of emissions during the construction stage. In fact, as described in the Construction stage section, the presence of a sloped roof highly intensifies emissions of the shipping container structure, therefore partially flattening differences with other structures. A reduction of emissions is true regarding weighting, with an increase of the gap within Global Warming Potential and Ozone Depletion.



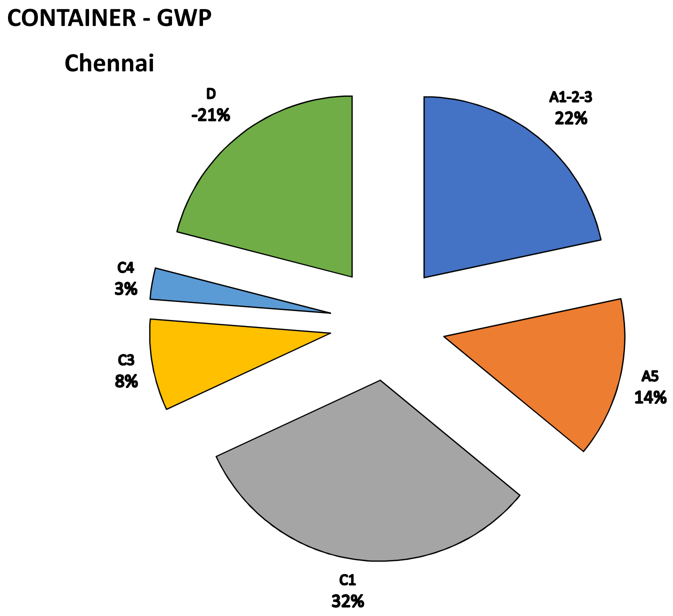
The need of additional superficial mass, which in this case was created with the use of OSB panels, leads to higher emissions from the point of view of Acidification and Eutrophication. As shown in the Embodied Energy stage, the use of great amounts of OSB as partitioning material highly increases impacts, due to the emission of Solphates. Therefore with a decision-making process, which evaluates the use of building materials with low emissions to add thermal mass, impacts can be highly contained. The following graph underlines the massive impact of embodied energies for the container structure due to the use of OSB panels.



The hot climate scenario, Chennai, deepens the gap between container and steel/xlam emissions. This is mainly caused by the use a much more sustainable material to add superficial mass in the envelope, such as bricks. It can be concluded that for container structures, mass materials are the most impactant of the whole life cycle. The following graphs clearly show the increasing impact of embodied energy in hot climates.


CONTAINER - GWP

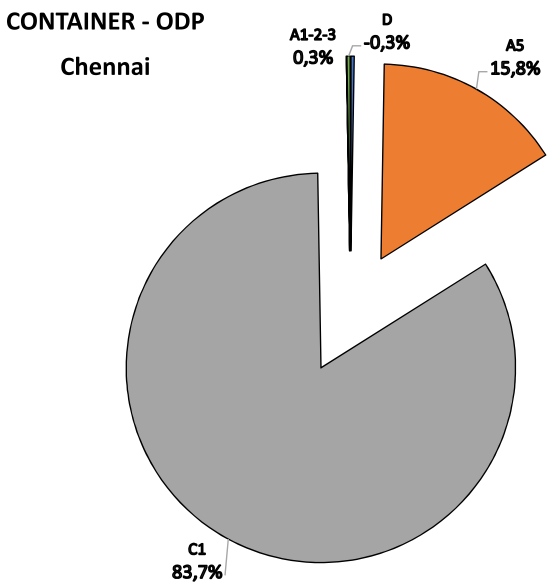
Vancouver


CONTAINER - GWP

Chennai

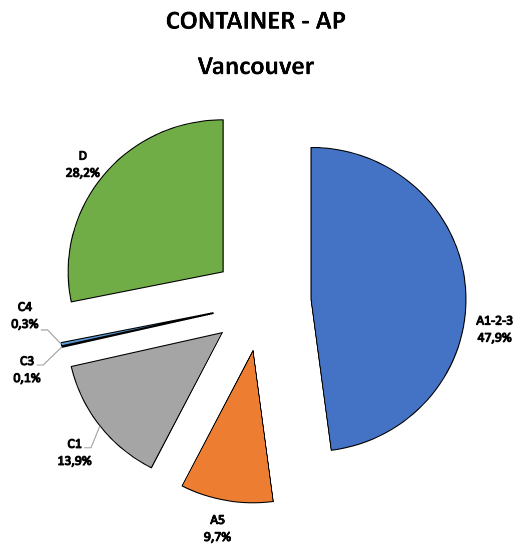
The Global Warming potential is the impact category mostly influenced by recycling credits and therefore by boundaries and interpretations of module D. In general Embodied Energy and Construction/Demolition stages have a comaprable impact on Greenhouse Gas emissions.
Eutrophication Potential appears to move along with Global Warming Potential. Each stage have comparable impacts on both environmental categories.

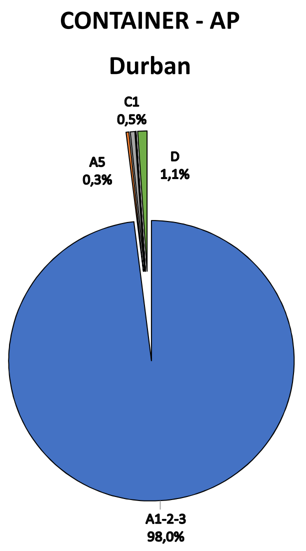
Ozone Depletion Potential is mainly dominated by construction stages, including demolition. This is due to the strict connection of this midpoint effect to fuel-related emissions. In fact these two stages are mainly characterized by emissions from equipment and vehicles. One more time, this aspect underlines that short construction schedules along with light-weight equipment lead to lower emissions. It is also important to stress that the inclusion of distances for transport stages will increase overall emissions and therefore higly impact ODP.
The following graph clearly quantifies this conclusion. Similar results have been obtained in each location.

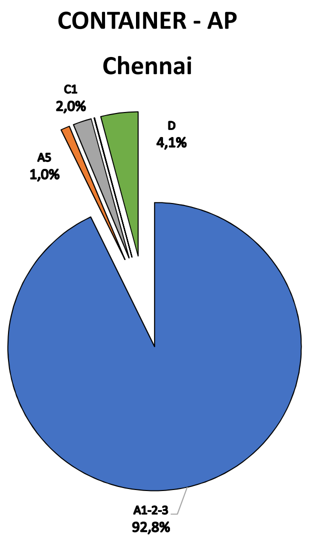

CONTAINER - ODP

Chennai

The Acidification Potential impact is the most “vulnerable” among impacts addressed. This is mainly due to the manufacturing of building materials, especially when a large amount of mass material is needed to ensure good thermal performance in hot climates. Particular attention has to be palced in the selection of these materials, since they will highly affect the overall impact of the container structure. Following results show the increasing dependece of AP when a large amount of material is needed.



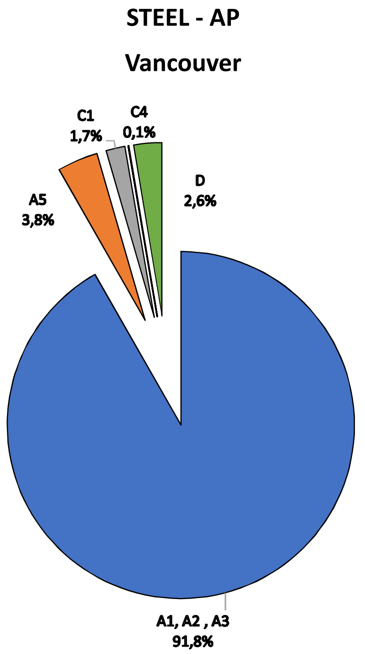


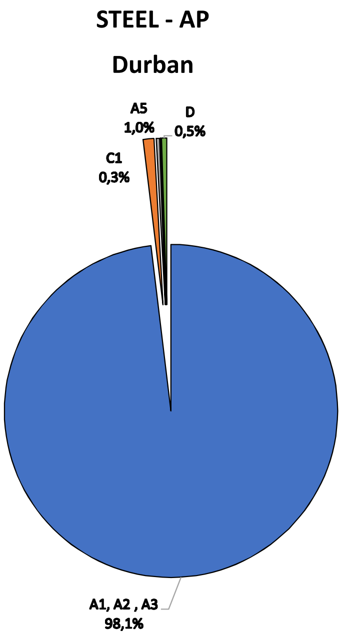


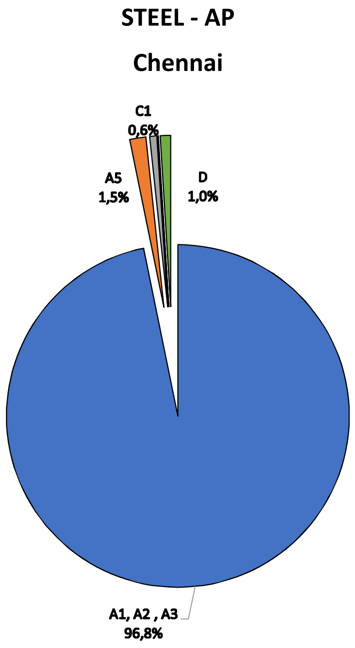
Comparing results from the shipping container structure with the steel frame lead to another relevant conclusion. The great environmental benefit of containers used as building components lays primarly in:

- avoided extraction of structural material;
- short construction schedules;
- great recycling potential.

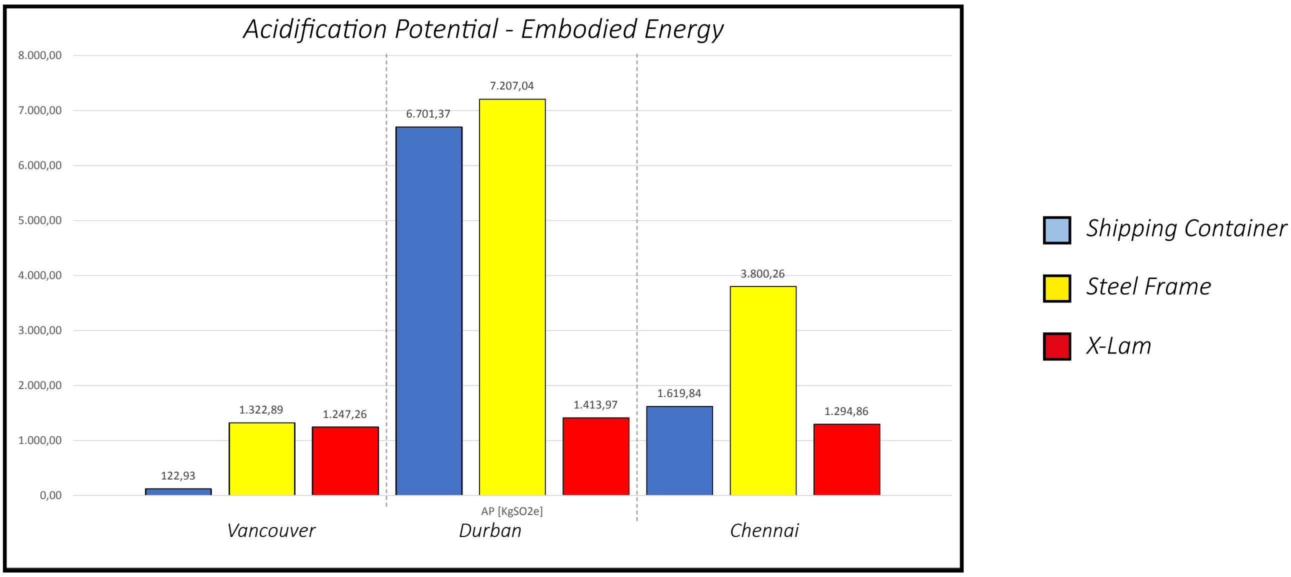
Regarding the impact of life cycle stages, when large amounts of materials are required, container structures tend to behave as a traditional steel frame. Results from the AP impact of the steel frame clearly show this similarity.







Nevertheless it is important to note that this conclusion is true only regarding the percentual impact of each stage. However, the overall embodied energy of shipping containers is of reduced magnitude than steel frames.
As previously stated, the use of OSB in Durban's scenario leads to a peak in emissions while bricks lead to a container's Acidification Potential similar to the X-Lam structure.



It can be generally stated that the use of Shipping Containers as building components leads to environmental benefits compared to steel frames or X-Lam structures within the boundaries and conditions set by this study.
This can be concluded mainly for two important characteristics that freight containes introduce in the building sector: Upcycling and short-scheduled construction sites. This can't be obviously considered an absolute conclusion. The introduction of the concept of environental advantage should be further developed including distances for each transport stage in order to guarantee benefits for local materials and tehnologies.
As stated in the analysis of the End of Life stage, an important conclusion can be drawn from the results of recycling credits. There are two fundamental environental advantages in the use of shipping containers as building components.
On the one hand there is the ethical intention of addressing the empty container repositioning issue by upcycling containers as buiolding components. On the other hand the introduction of intermodal containers in the building sector finally leads to the release of "stored" structural steel.

A final consideration can be made regarding the method used to compare emissions from different building structures. As stated in the description of the functional unit, to ensure an equal comparison it is necessary to take into account much more properties than simple geometry, or "per square meter" requirements.
The great differences of results showed by the temperate scenario, Durban, and hot scenario, Chennai, are a clear example of this assumption. This conclusion is stressed by the peak shown by the Acidification Potential graph above. Both scenarios included the need of thermal mass in order to comply with thermal requirements of the functional unit. Nevertheless, in each scenario it has been used a different material to ensure the required time shift. The use of OSB showed a relevant increase in emissions, which in even overcome the environmental benefit of the shipping containers' reuse. On the other hand, the use of bricks, which emissions are much lower, didn't affect in such a manner overall results.
Therefore conclusions drawn from comparisons of buildings using only spatial functional units but different materials can lead to unequal results. The consistence of results showed in the present study is guaranteed by the use of a unique material for each purpose in every building compared.

7.3 Further development

Further research should be focused on the inclusion of more technologies to compare: concrete, hardwood timber, bricks, prefabricated structures and so on. Moving from results of the present thesis, it can be assumed that timber frames would add more information to the debate. In fact the inclusion of hardwood timber could open up the comparison to a near-zero embodied energy structure, shipping containers, and subtractive product stage emissions, wood (due to carbon sequestration).

A key limitation of the study is the availability of a wide range of data to create a reliable invetory database. LCI data should be extended and further developed, including quality data matrixes. Detailed analysis of EPD's compatibility within system boundaries should be conducted.

Furthermore, scenarios could be improved, addressing real life locations. Transport impacts have been estimated normalizing in a "per km" basis, leading to a near 0% impact on the overall life cycle. Accurate site information may lead to much detailed information on transport stages and recycling possibilities of each location.

It is evident that the discussion has been limited to environmental considerations. In order to finally state the impact of shipping containers in the building sector, further research should analyze social and economical aspects. When addressing economical aspects, the choice of 20-foot or 40-foot containers might highly affect the transportation stage. Moreover the use of shorter units, 20-foot containers, may affect the social impact of shipping container structures due to the possibility of reaching much isolated locations, compared to the transportation of 12 meter long containers.

Moving from the results and the mothodology shown, the comparison could be conducucted solely within shipping container structures, analyzing the possibilities from the point of view of design. Since the main vulnerabilities of each stage have been reported, the next step of this study might be the analysis on which design decisions produce overall environmental benefits.

Module A5 points out benefits of a short construction schedule. Further development of this study may be in the analysis of high raised structures which involve a larger amount of material. High raised structures may draw attention to different aspects or stress conclusion partially visible from the results of this study.

As described in the introductionary chapter, container's repositioning is a major issue regarding the global trading system. Further research should aim to quantify the upcycling potential of the reuse of shipping containers. In the present thesis, environmental benefits for the reuse of containers as building components are coming mostly from the avoided extraction of virgin materials. It can be argued though that the reuse of containers actually avoids repositioning costs and emissions. The quantification of emissions from repositioning is an highly predictive work, which can however help understanding and quantifying the constribution of the building sector in reducing the overall empty container accumulation's issue.

Moreover, results from the End of Life highlight that containers can be addressed as stored steel, rather than objects. Steel that by means of upcycling is released back. Further research might aim to understand the environmental benefit of these release-effect considering the process of corrosion to which abandoned containers are subjected. In fact it has been estimated that, in part due to ongoing corrosion losses, a great portion of steel will never become available for recycling at 0,5% rate per year. The more containers are left to rot, the more their stored steel will be corroded.
Therefore the safeguard and release of this stored steel by means of its use as building component might be considered as avoided corrosion and hence improvement in global availability of materials.
The correct way of modelling and addressing these conceptual topics could be the main scope of a study focused on quantifying the environmental benefits of upcycling

CHAPTER

VIII

References

8. References

Chapther 1. Shipping Containers

[1] M.Levinson (2002). *"The Box - How the Shipping Container Made the World Smaller and the World Economy Bigger"*. Princeton University press

[2]] A.A. Palma Olivares (2010). "*Sustainability in prefabricated architecture. A comparative life cycle analysis of container architecture for residential structures".* Master in architecture, Victoria University of Wellington

[3] J.P. Rodriguez (2013). *"The geography of transportation system".* London-New York

[4] K.A.Giriunas (2012). *"Evaluation, modelling and analysis of shipping container building structures"*. Ohio State University

[5] Y.Guo, W.Wang (2013). *"Study on carbon footprint of container transportation system".* Advanced materials research review, Switzerland

[6] M.Boile et al. (2008). *"Regional repositioning of empty containers - case of inland depots"*. School of Business, Rutgers University

[7] J.Karmelic et al. (2012). *"Empty container logistics".* Transport logistics review

[8] N.S. Bernat et al.(2016) . *"Empty Container Management at Ports Considering Pollution, Repair Options, and Street-Turns".* Hindawi pubblications

[9] S.Theofanis,M.Bolle (2008) . *"Empty marine container logistics: facts, issues and management strategies". GeoJournal, review*

[10] D.P. Song, J.Carter (2009) . *"Empty container repositioning in the liner shipping". Maritime Policy & Management, London*

[11] A.Cimino et al.(2010) . *"Empty containers repositioning: a state of the art overview". University of calabria, Old Dominion University, Virginia*

[12] R.Diaz et al.(2011) . *"Forecasting Empty Container Volumes". The Asian journal of shipping logistics*

[13] www.shippingwatch.com/articles

Chapther 2. LCA

[14] J.M.Khatib (2016). "*Sustainability of Construction Materials"*. United Kingdom

[15] European Environment Agency (1997). "*LCA. A guide to approaches, experiences and information sources".* Denmark

[16] Athena (2014)*. "Athena Guide to Whole-Building. LCA in Green Building Programs".* Ottawa

[17] International Energy Agency (2004).*"Energy-Related Environmental Impact of Buildings".* Annex 31. Canada

[18] J.Anderson,J.Thornback (2012).*"A guide to understanding the embodied impacts of construction products".* Construction Products Assosiacion, United Kingdom

[18] www.steelconstruction.info

Chapther 2. Standards

[19] ISO 14040 (2006). ***"Environmental management. Life Cycle assessment. Principles and framework".*** International Standards Organization

[20] ISO 14044 (2006). ***"Environmental management. Life Cycle assessment. Requirements and guidelines".*** International Standards Organization

[21] BS EN 15643 (2012). *"Sustainability of Construction Works. Assessment of Buildings. Framework"*. United Kingdom

[22] BS EN 15978 (2012). *"Sustainability of Construction Works. Assessment of Buildings. Calculation method"*. United Kingdom

[23] BS EN 15804 (2014). *"Sustainability of Construction Works. Environmental Product Declarations."*. United Kingdom

[24] G..Krigsvoll, M.Fumo, R.Morbiducci (2010). *"National and International Standardization (ISo and ECS) Relevant for Sustainability in Construction"*. Sustanability 2010, 2, 3777-3791 issue

[25] www.breeam.org.uk

Chapther 2. LCA for Buildings

[26] A. Carre (2011). "***A Comparative Life Cycle Assessment of Alternative Constructions of a Typical Australian House Design"***. Forests and wood products. Australia

[27] J.Gajda (2001). "***Energy use of single-family houses with varoius exterior walls"***. Portland Cement Assosiacion

[28] Ashraf F.Ragheb (2011). ***"Towards environmental profiling for office buildings using life cycle assessment (LCA)".*** PhD Architecture, University of Michigan

[29] Hamidul Isalam et al. (2014). ***"Life cycle assessment and life cycle cost implication of residential buildings. A review".*** Renewable and Sustainable Energy reviews

[30] Hamidul Isalam et al. (2014). ***"Life cycle assessment and life cycle cost implication of wall assemblages design".*** Renewable and Sustainable Energy reviews

[31] Maurizio Cellura (2017). "***Life Cycle Assessment Appliata all'Edificio. Metodologia e casi di studio sul sistema fabbricato-impianto".*** Milano

[32] T.Scalet (2015). *"Cross Laminated Timber as sustainable technology for the future".* Helsinki Metropolia University

[33] C.L.Thiel et al.(2013). *"A materials life cycle assessment of a net zero energy building".* Energies 2013, 6,1125-1141 issue

Chapther 3.Shipping Containers Companies

[34] https://comtrade.un.org

[35] https://www.shipmap.org

[36] Structural specifications. *"Pannello strutturale in legno. Comportamento statico e sismico".* Diemme legno, Italy

[37] D.P.Song et al.(2011). *"An operational activity-based method to estimate CO2 emissions from container shipping considering empty container repositioning"* Pubblication, Elsevier.

[38] Maersk Line, Annual Sustainability Report - 2013.

Chapther 2. LCA for shipping containers

[39] D.S.da Silva Urbano (2015). *"Environmental footprint of modular building solution using LCA approach"*. Instituto Superior Tecnico, Universidade de Lisboa

[40] C.Ulloa,E.Arce,G.Rey,J.L.Miguez (2017). *"Recycling COR-TEN sea containers into service modules for military applications".* Energies, article

[41] A.A. Palma Olivares (2010). "*Sustainability in prefabricated architecture. A comparative life cycle analysis of container architecture for residential structures".* Master in architecture, Victoria University of Wellington

[42] Hamidul Isalam et al. (2016). "*Life cycle assessment of shipping container home: a sustainable construction".* Australia

[43] J.D.Smith (2006). *Shipping Containers as Building Components".* University of Brighton

[44] J.Vijayalaxmi (2010). *"Towards sustainable architecture. A case with Greentainer".* Local Environment, vol.15 no.3, 245-259 issue

[45] A.Ringvold (2017). *"Prospective Life Cycle Assessment of Container Shipping".* NTNU, Norway

Chapther 3. Climate zones

[46] DM 26/06/2015. *"Criteri generali e requisiti delle prestazioni energetiche degli edifici".* Italy

[47] www.weatherbase.com

[48] http://koeppen-geiger.vu-wien.ac.at

Chapther 3. Thermal performance

[49] AHSRAE (2006). *"Green Guide Handbook".*

[50] AHSRAE (2008). *"ASHRAE Addenda. Sandard 90.1".*

[51] IECC 2006 Prescriptive Requirements

[52] IECC 2015, Chapter 4 - Residential Energy Efficiency

[53] ISO *6946* (2007). *"Building components and building elements. Thermal resistance and thermal transmittance. Calculation method.".* International Standards Organization

[54] ISO *13786* (2007). *"Thermal performance of building components. Dynamic thermal characteristics. Calculation methods.".* International Standards Organization

[55] DM 26/06/2015. *"Criteri generali e requisiti delle prestazioni energetiche degli edifici".* Italy

[56] DM n. 162 15/06/2015. *"Descrizione dell'edificio di riferimento e parametri di verifica".* Italy

Chapther 3. X-Lam structures

[57] A.Bernasconi (2007). *"Calcolo dell'X-Lam. Basi, normative, progettazione, applicazione".* Promolegno, Italy

[58] Structural specifications. *"Pannello strutturale in legno. Comportamento statico e sismico".* Diemme legno, Italy

Chapther 4. Life Cycle Inventory

[59] G.Hammond, C.Jones (2011). *"Embodied Carbon - The Inventory of Carbon and Energy (ICE)".* BSRIA, Bath University, United Kingdom

[60] Environmental Product Declaration. *"Cold-formed aluminium sheet for exterior applications".* German Aluminium Association

[61] Environmental Product Declaration. *"Oriented Strand Board".* North American Wood Council

[62] Environmental Product Declaration. *"Kronoply Oriented Strand Board".* Institute of Construction and Environment

[63] Environmental Product Declaration. *"Plywood".* WoodSolutions

[64] Environmental Product Declaration. *"Accoya wood cladding".* Accoya

[65] Environmental Product Declaration. *"Wall panels".* Kingspan

[66] Environmental Product Declaration. *"Timber weatherboaard".* Accoya

[67] Environmental Product Declaration. *"Rockwool". Rockfan, epd-norge*

[68] Environmental Product Declaration. *"Mineral wool".* Knauf insulation

[69] Environmental Product Declaration. *"Rockwool". Rockwool*

[70] Environmental Product Declaration. *"EPS". EUMEPS*

[71] Environmental Product Declaration. *"PU".* Institute of Construction and Environment

[72] Environmental Product Declaration. *"XPS foam".* Institute of Construction and Environment

[73] Environmental Product Declaration. *"Gyproc wallboard".* Gyproc

[74] Environmental Product Declaration. *"Waterborne floor paint".* PPG

[75] Environmental Product Declaration. *"Ceraamic tiles".* Marazzi Group

[76] Environmental Product Declaration. *"Hardwood strips flooring".* FP innovations

[77] Environmental Product Declaration. *"Fire proctection paint".* Rudolf Hensel GmbH

[78] Environmental Product Declaration. *"Concrete".* Argos

[79] Environmental Product Declaration. *"Hardwood timber".* Woodsolutions

[80] Environmental Product Declaration. *"X-Lam".* Institute of Construction and Environment

[81] Environmental Product Declaration. *"X-Lam". Nordic*

[82] Environmental Product Declaration. *" Structural steel".* Bre

[83] Environmental Product Declaration. *"Hollow structural steels ections".* Steel Tube Institute

[84] Environmental Product Declaration. *"Structural steel: sections and plates".* Institute of Construction and Environment

[85] Environmental Product Declaration. *"Generic brick".* Bre

[86] Environmental Product Declaration. *"Bricks".* Cendec

Chapther 4. Gate to Site

[87] J. Anderson, N. Howard (2000). *"The Green Guide to Housing Specification"* . BRE Report 390. UK: BRE, 2000

[88] P.Hradil, A.Talja, M.Wahlström (2014).*"Re-use of structural elements - Environmentally efficient recovery of building components".* VTT-Technical Reseacrh Center, Tampere, Finland

Chapther 5. Construction Stage

[89] L.Grosso (2004). *"Tempario per opere edili civili"* . Il Sole 24 Ore, Milano.

[90] S-H.Li et al. (2017). *"An application of Life Cycle Assessment in carbon emissions during construction phase: a case study of newly built dormitory in Shenzen University"*. College of Civil Engineering, Shenzen University

[91] A.Takano et al.(2014). "*Greenhouse gas emissions from construction stage of wooden buildings"* . Article in International Wood Products Journal.

Chapther 6. Demolition and landfill emissions

[92] F.P. Torgal, S.Jalali (2011). *"Eco-efficcient onstruction and building materials"*. University of Minho. Guimaraes

[93] Department of Climate Change (2006). *"Australian Methodology for the Estimation of greenhouse gas emissions and sinks - Waste"*. National Greehouse Gas Commitee. Australia.

[94] EPA (2015). *"Waste Reduction Model (WARM) - Landfilling"*. United States Environmental Protection Agency.

[95] O.Parkes et al. (2014). *"Life cycle assessment of integrated waste management systems for alternative legacy scenarios of the London Olympic Park"*. Waste Management Journal.

Chapther 6. Recycling

[96] J.Bowyer et al. (2015). *"Understanding steel recovery and recycling rates and limitations to recycling"*. Dovetails Partens

[97] A.Schmidt et al. (2010). *"Life cycle assessment of three insulation materials: stone wool, paper wool and flax celluulose"*. Denmark

Chapther 7. Weighting

[98] M.Bengtsson et al. (2000). *"Weighting in LCA - Approaches and applications"*. Chalmers University of Technology, Sweden.

[99] T.P.Gloria et al. (2007). *"Life Cycle Impact Assessment Weights to Support Environmentally Preferable Purchasing in the United States"*. Environent and Science Technology review, USA.

[100] T.Kim et al. (2016). *"LAnalysis of Environmental Impact for Concrete Using LCA by Varying the Recycling Components, the Compressive Strength and the Admixture Material Mixing"*. MDPI, Sustainability review, article.

General

[101] W. McDonough, M.Braungart (2002). *"Cradle to cradle : remaking the way we make things"*. North Point press

[102] M.Raim et al. (2015). *"Regulating global shipping corporations' accountability fro reducing greenhouse gas emiisions in the seas"*. Marine Policy, review

[103] A.W.Botes (2013). *"A feasibility study of utilising shipping containers to address the housing backlog in South Africa"*. Stellenbosch University

[104] X.Zha, Y.Zuo (2015). *"Finite element study of container structure under normal and high temperature"*. Harbin Institute of Technology, Shenzen

[105] U.Sanders et al. (2015). *"Think outside your boxes".* Boston Consulting Group