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Upcycling shipping containers as building components: *an environmental impact assessment*

Mattia Bertolini, Luca Guardigli

Abstract

Purpose. The introduction of shipping containers in the trading system has increased world economic growth exponentially. The main drawback of this linear economy is the accumulation of empty containers in import-based countries. Designers throughout the world are working with intermodal containers for environmental purposes, often employing them as building components. This research aims to evaluate the environmental impact of a container dwelling in comparison with similar steel and X-Lam structures.

Methods. In order to estimate the effective sustainability of container structures, a comparative LCA has been undertaken. A mid-point approach was adopted focusing on Global Warming Potential (GWP), Ozone Depletion Potential (ODP), Acidification Potential (AP) and Eutrophication Potential (EP).

To ensure reliable comparisons a functional unit with combined spatial and thermal requirements has been defined. The proposed unit includes a total floor surface of 206,6 m^2 and transmittance requirements in accordance with IECC and ASHRAE standards. Three representative scenarios have been identified to address cold, temperate and hot climates within import-oriented places: Vancouver, Durban and Chennai. For hot climates the functional unit has been implemented with a minimum Periodic Thermal Transmittance to ensure interior thermal comfort.

Results and discussion. It can be generally stated that the use of shipping containers as building components leads to overall environmental benefits compared to steel and X-Lam structures within the boundaries of this analysis. The main advantages of container structures are related to avoided extraction of structural materials, shorter construction schedules and high recycling potential at their end of life. Instead, the use of a combined functional unit leads to equal results on transport and operational stages which can be excluded from a whole life cycle comparison. The use of high thermal mass materials is particularly relevant for container homes in hot climates, and superficial mass is very incisive in whole life cycle assessment.

Conclusions. Empty containers are accumulated worldwide as a result of the linear nature of the trading system. A container building presents 2,33 times the amount of structural material of a functionally comparable steel frame. With an upcycling process, the "stored" steel contained within freight containers is introduced into the circular economy of the building sector. After the End of Life stage, this leads to the "release" of 13,6 tons of structural steel for a 200 m^2 house.

Recommendations. Results and conclusions of this article are strictly connected to the availability of empty and used containers in the study location. Shipping containers are outputs of a linear system, the trading economy, and intended to be used as input of a different system, the building sector, which aims to be circular. Therefore, the use of newly manufactured containers has not been considered, and emissions for their production, related to the trading sector, are not allocated to the building footprint.

Keywords

Shipping Containers, Steel, X-Lam, LCA, Comparative LCA, Functional Unit, Upcycling, Environmental Advantage, Recycling

1 Introduction

The introduction of standardized shipping containers in the middle of the twentieth century into the transportation system increased world economic growth exponentially (Levinson 2002). However, this revolution also brought unlikely consequences due to trade imbalances in many countries throughout the world. The trade industry can be modelled as a linear economy where goods move from export-oriented to import-oriented countries. The core of the transportation system is formed by shipping containers, which constantly guarantee the intermodal nature of trade. This system has created a double dilemma: while it is too expensive to retrieve empty containers back to their origin, leaving them in depots occupies a large amount of space and requires a great deal of effort for their repositioning (Rodriguez 2013).

According to a report of the United Nations (UNCTAD 2008), since 1990 container trade is estimated to have increased five times, which is equivalent to an average annual growth of 9,8%. This means that the actual empty container accumulation, with the present growth rate, is likely to be much more piercing in the future. Containers are defined within the trading system as both transport and production units. They can be moved as an export, import or repositioning flow. Trade imbalances are probably the most important cause of accumulation of empty containers because import-oriented regions systematically face an accumulation of empties (Rodriguez 2013). Once a container has been unloaded, it has to be moved empty back to its origin, because cargo cannot be arranged for another destination. Since this collateral transport stage is almost as costly as moving a fully loaded container, the manufacturing of new containers becomes the cheapest solution. This problem is underlined by the fact that today about 2,5 million of TEUs (Twenty-Foot Equivalent Units) are being stored empty (Karmelić et al. 2012) This number corresponds to the 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 (Rodriguez 2013).

The surplus of empty containers worldwide has drawn the attention of many designers focused on minimizing resource extraction (Botes 2013, Kotnik 2013, Vijayalaxmi 2010). Moreover, many designers find in containers a suitable method of construction: they are modular in shape, structurally strong and widely available (Smith 2005). While designers claim from an ethical point of view the environmental benefits deriving from the use of freight containers as building components, the discussion from a Life Cycle perspective is still open and uncertain (Olivares 2010, da Silva Urbano 2015, Islam et al. 2016).

2 Method

2.1 Goal and Scope.

The primary goal of this article is to evaluate the environmental benefits coming from the use of shipping containers upcycled into building components. The starting point is the existence of a container accumulation issue in the world trading economy. Similar studies and further research should be conducted only considering the availability and reuse of empty containers in the study location.

The following LCA has been conceived as a desktop study and is therefore intended to use only published data to undertake the assessment (Bengtsson 2013). Thus, the study does not specifically address an actual building, but proposes a theoretical design for a single family, double storey dwelling, which serves as a common basis for three different structural technologies to be compared: a container building, a steel frame and an X-Lam structure.

2.2 System boundaries and allocation procedures

Moving from the comparative nature of the analysis, system boundaries have been set in order to exclude elements that are not directly affected by changes of structural material. It has been assumed that emissions related to foundations, stairs, doors, windows, fixtures, skirtings, electrical and plumbing fit-outs, garden and mechanical systems are equal to every different structural material and therefore they do not affect the overall comparison. Final results have to be interpreted carefully since they provide a relative impact for each structural technology, rather than an absolute evaluation of the environmental performance. The only allocation procedure used within the study is related to the apportion of recycling credits to the steel frame structure. In order to avoid double counting of credits, steel is considered virgin as input of the system in the Product stage. Then credits are allocated after the End of Life stage in the Reuse-Recovery-Recycle module. This 0-100 procedure has been chosen in order guarantee an equal comparison of the recycling output for each technology (Cellura 2017).

2.3 Functional Unit and comparability

Main purpose of the Functional Unit is to provide an equitable measure to compare products, in this case buildings, exclusively based on the service provided by the product itself. Due to the complexity and variety of purposes provided by a house, defining its core function is not straightforward. Building's outputs are produced by systems and mechanisms that depend on multiple factors: geometry, location, performance, use and materials. Among the different functions of a house, human shelter and interior comfort are arguably its priorities.

The outcome determined considering a Functional Unit resulting from a combination of interior comfort and spatial requirements strikes the conservative definition of *per square meter* or *per total house*, which both consist solely in geometrical requirements; in fact, the normalization of impact results *per square meter* could be appropriate only when comparing simple systems.

The present article argues that in order to compare buildings, the use of a simple spatial functions is not sufficient to ensure an equal base of comparison. The scope of this study is to understand the sustainability of shipping containers upcycling in the building sector. When a comparative scope is defined, it is important to assess buildings which differ mainly on the subject of analysis, in this case the core structure, keeping every other independent variable, such as wall frames and insulation, strictly equal in each case study, corresponding to a specific location.

For instance, if a simple element, such as insulation, differs among the compared buildings, the results of the entire analysis will be highly affected by this variation (Schmidt et al.). Hence the outcomes of the study will be dependent on the combined impact of structure and insulation, leading to a difficult interpretation of results. For this reason, the following comparative LCA has been developed selecting building materials before the design stage of each case study. Then, depending on the desired thermal performance of the envelope, defined by IECC and ASHRAE requirements, different construction details have been developed for each structural type, leading to different bill of quantities for each case study.

While thermal comfort is guided by international minimum requirements (IECC 2015), spatial requirements are defined in relation to the limitations imposed by the ISO standardization of shipping containers (ISO 1496-1 Series 1 1990). Benchmark technologies compared will represent alternative structural frames fitting with the design composition of a six-container-double-storey house. The design results in a total 206,12 m^2 floor area (including balconies) with 84,31 m^2 for each level (Fig. 1, Fig. 2).

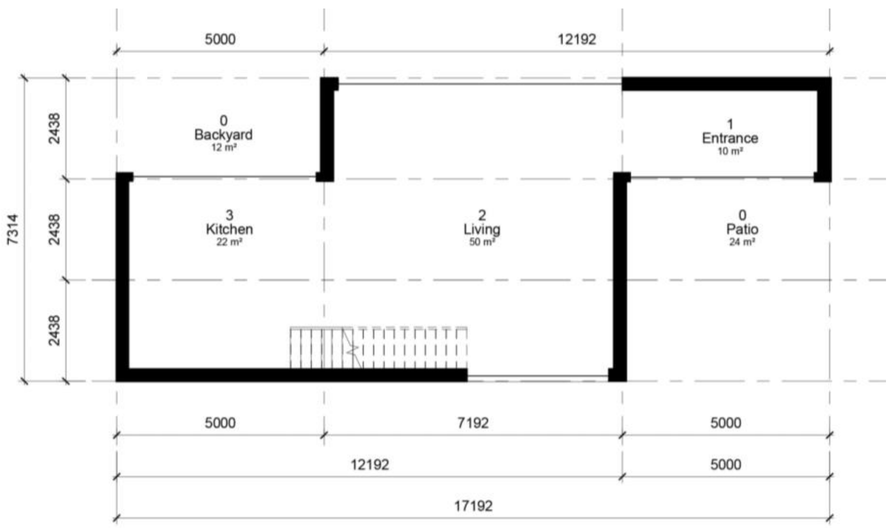

Fig. 1 Six-container-double-storey house, ground floor plan

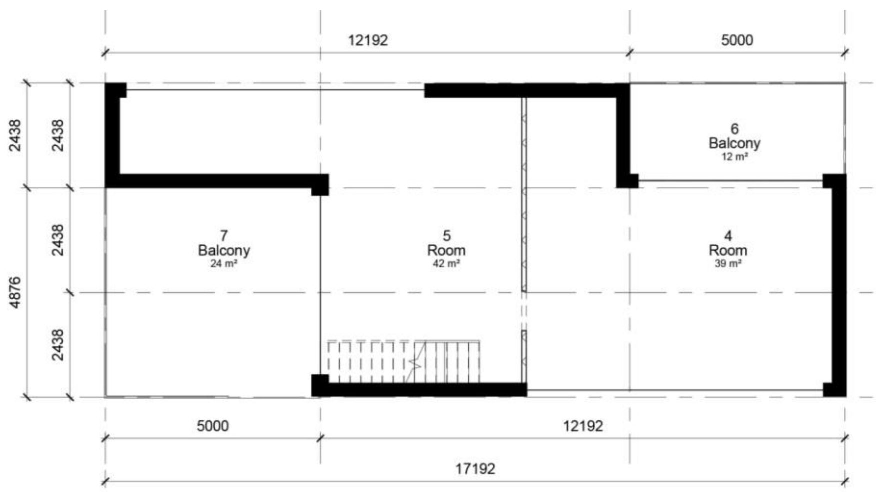

Fig. 2 Six-container-double-storey house, first floor plan

2.4 Benchmark technologies.

To evaluate the impact of freight containers as building components it is necessary to define reference technologies from which draw conclusions. Structural steel is the most straightforward technology to compare with container components from the point of view of materials. The steel frame designed is composed by HEA120 columns, IPE100 beams, C76x38 C-channel joists and T-tees 152x76x12 bracings as described in Table 1.

Table 1 Structural materials for the steel frame structure

	Profile	**Total length** *[m]*	**Volume***[m³]*	**Total weight** *[Kg]*
Beams	*IPE 100*	*266,62*	*0,275*	*2155,64*
Columns	*HEA 120*	*74,24*	*0,188*	*1474,48*
Joists	*C 76x38*	*635,41*	*0,642*	*5037,35*
Bracings	*T 152x76*	*122,90*	*0,175*	*1373,75*

Nevertheless, steel frames differ completely from the point of view of construction operations and assemblies design (Giriunas et al. 2012); the construction of container homes is much closer to prefabricated buildings. Its box-like behaviour is addressed in comparison with a CLT (Cross Laminated Timber) structure (Table 2). CLT (or X-Lam) structures have similar on site practices and construction details.

Table 2 Structural materials for the X-Lam structure

	Dimensions *[mm]*	**Unit**	**Volume** *[m³]*	**Total weight** *[Kg]*
X-Lam	*150*	*569,93 m²*	*0,074*	*580,25*
Hardwood Columns	*150x150*	*8,70 m*	*0,196*	*47,78*

2.5 Scenarios

As stated above, thermal performances for the functional unit are defined following the requirements of the International Energy Conservation Code (IECC 2015). Thermal transmittance is indicated for each assembly depending on the climate zone in which the building is located. The study has been carried out for three different scenarios representing contrasting thermal requirements. Since the scope of the study is strictly related to the container accumulation issue, each location has been defined combining container depots and climate zones. The whole repositioning matter begins with the accumulation of containers in intermodal depots, located in import-oriented countries, where they are unloaded and then left empty. Evaluating the trade balance of economies worldwide (Fig. 3), it is possible to determine the availability of empty containers in most locations (WTO 2017). Within import-oriented countries, three maritime depots have been selected as scenarios representative of cold, temperate and hot climates (Fig. 4): Vancouver in Canada, Durban in South Africa and Chennai in India.

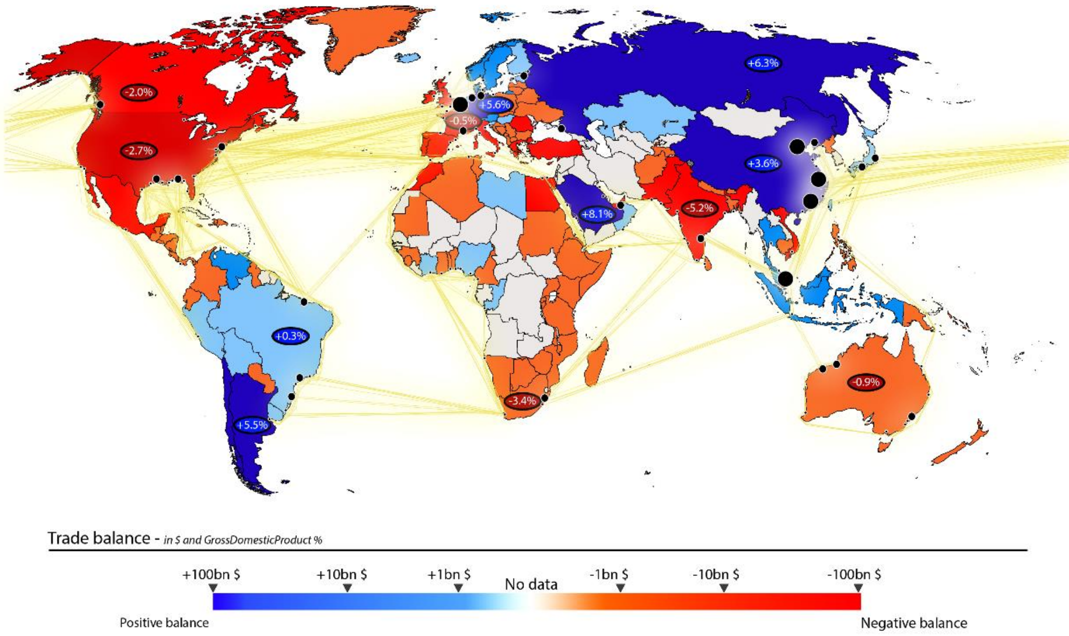

Fig. 3 Goods and services trade balance in $ and as percentage of the Gross Domestic Product

Scenarios of Durban and Chennai present monthly solar radiations which can be higher than 290 W/m^2. In order to ensure an adequate interior comfort for cooling necessities, it has been imposed an additional Periodic Thermal Transmittance of 0,18 W/m^2-K for each horizontal or inclined assembly and 0,10 W/m^2-K for vertical assemblies, along with a minimum time shift of 10 hours (Tab. 3). To achieve these performances, superficial mass has been added to the assemblies with OSB panels for the Durban scenario and bricks for Chennai.

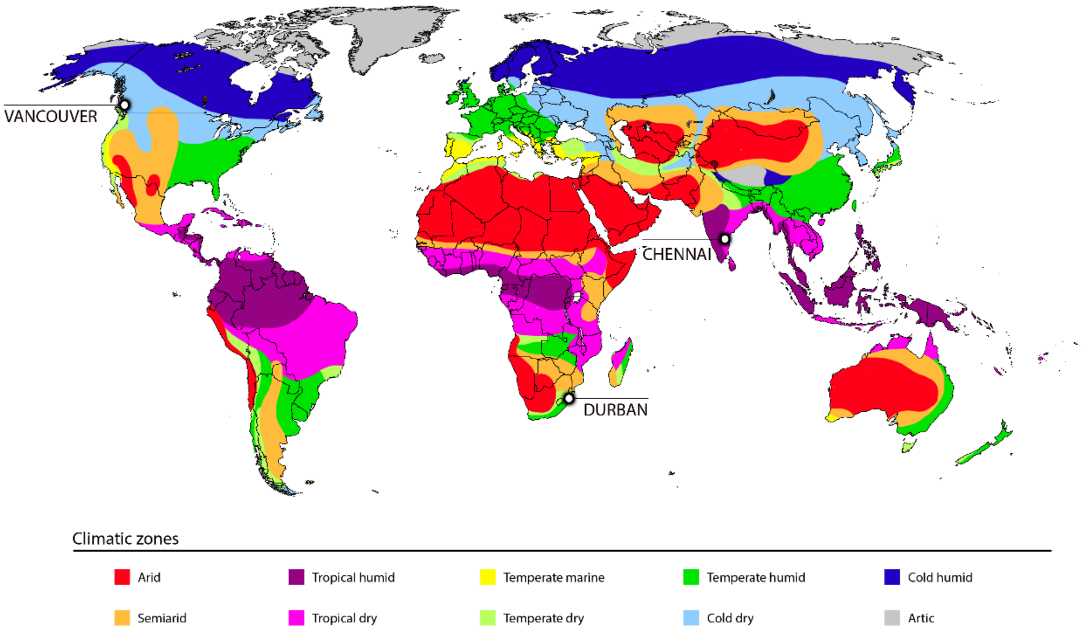

Fig. 4 Worldwide climate zone classification defined with the Köppen-Geiger system

Table 3 Thermal transmittance for each building assembly, expressed in W/m^2-K, as defined by the International Energy Conservation Code – Chapter 4 for Residential Energy Efficiency

	Climate Zone	Heating Degree Days	Cooling Degree Days	Ceiling U-factor	Frame Wall U-factor	Floor U-factor
Vancouver	*Cold*	*4251°*	-	*0,147*	*0,255*	*0,187*
Durban	*Temperate*	*184°*	*1924°*	*0,170*	*0,340*	*0,266*
Chennai	*Hot*	-	*6779°*	*0,198*	*0,476*	*0,363*

2.6 Life Cycle Inventory

Databases for LCI have been developed using information from the ICE guide published by BSRIA and Bath University along with Environmental Product Declarations (Hammond and Jones 2011). While these estimates are believed to be sufficient to compare alternative construction methods, they could be further developed including a Data Quality Assessment or actual measurements, especially when it comes to construction, demolition, waste processing and reuse-recycling considerations.

3 Results

The study has been carried out following every stage of a building's life cycle, from Cradle to Cradle (Torgal et al. 2011). The whole life cycle of a building has been subdivided into modules as defined by the standard UNI EN 15978:2011.

3.1 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 include 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, 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. The cradle-to-gate stage includes modules A1-2-3 and is defined the Product Stage within the life cycle of a building.

Following results have been defined computing Global Warming Potential (GWP), Ozone Depletion Potential (ODP), Acidification Potential (AP) and Eutrophication Potential of each building material, collected in Table 4 with the Bill of Quantity shown in Table 5. It is important to stress that the use of OSB or bricks as superficial mass for passive cooling purposes highly affects partial results shown in Table 6. This is particularly relevant for the Acidification Potential due to the massive use of glues for the production of OSB panels. One more time the importance of a functional unit that allows an equal confrontation of each technology becomes evident**:** in fact, mass materials have been changed only among different scenarios. This evidence has to be carefully considered when comparing results between scenarios involving the use of different materials within the assemblies.

Results show that shipping container structures have always lower environmental impacts than steel structures (Fig. 5). However, while colder climates enhance the environmental advantage of intermodal containers, tropical zones are much favourable to X-Lam technologies due to the general need of superficial mass for passive cooling. The peak of emissions for ODP and AP show that mass materials are the main contributors for emissions of a container structure.

Table 4 GWP, ODP, AP and EP of each selected material, including modules A1, A2, A3 as for UNI EN 15978.

Material	**GWP** [$KgCO_2e$ / Kg]	**ODP** [$KgCFC_{11}e$ / Kg]	**AP** [$KgSO_2e$ / Kg]	**EP** [$Kg(PO_4)_3e$ / Kg]
Rockwool	1,28	1,164 E-9	9,8 E-3	2,036 E-3
Steel S235	2,61	2,72 E-11	8,32 E-3	7,29 E-4
Avg. recycled steel S235	0,72	3,9 E-11	1,97 E-3	1,93 E-4
Plywood flooring -*15mm*	-0,737	2,351 E-12	3,96 E-3	1,03 E-3
Plywood panel -*7mm*	-1,467	9,97 E-12	1,27 E-2	3,71 E-3
Hardwood finish	-0,093	1,189 E-9	3,24 E-3	2,13 E-4
X-Lam panel – *150mm*	0,167	8,726 E-9	4,902 E-4	1,186 E-4
Timber wall frame	0,0983	1,26 E-7	2,218 E-3	2,16 E-4
Radiata pine weatherboard	0,466	1,54 E-7	6,772 E-3	5,99 E-4
OSB panel – *12mm*	0,4138	4,217 E-8	2,174 E-1	1,702 E-4
Brick – *215 x 102,5 x 65mm*	0,158	5,37 E-10	1,35 E-3	5,00 E-5
Gypsum board - *13mm*	0,276	1,03 E-8	7,277 E-4	1,433 E-4
Fire protection paint -*120min*	2,51	1,6 E-7	1,28 E-2	5,1 E-3

Table 5 Bill of Quantities for the case studies in each scenario.

Material [Kg]	**Vancouver**			**Durban**			**Chennai**		
	Container	*Steel*	*X-Lam*	*Container*	*Steel*	*X-Lam*	*Container*	*Steel*	*X-Lam*
Rockwool	2813,37	2440,01	1757,14	2000,81	1733,29	985,50	650,36	899,05	502,27
Steel *S235*	854,21	10041,22	/	854,21	10041,22	/	854,21	10041,22	/
Hardwood finish	25768,75	25768,75	25768,75	25768,75	25768,75	25768,75	25768,75	25768,75	25768,75
X-Lam panel *150mm*	/	/	42061,07	/	/	42061,07	/	/	42061,07
Timber wall frame	1732,79	1732,79	1732,79	1732,79	1732,79	1732,79	1732,79	1732,79	1732,79
Radiata pine weatherboard	1685,28	3613,98	3613,98	910,96	3613,98	3613,98	910,96	910,96	910,96
OSB panel *12mm*	/	5129,40	5129,40	30280,61	32221,19	5924,41	6430,32	16321,00	5155,74
Brick *215x102,5x65mm*	/	/	/	/	/	/	84615,52	45856,15	42307,76
Gypsum board *13mm*	2401,19	4354,93	4354,93	2401,19	4354,93	4354,93	2401,19	4354,93	4354,93
Fire protection paint *120min*	89,31	569,93	/	354,31	569,93	/	354,31	569,93	/

Table 6 Product Stage emissions for each scenario and technology.

Impact Category	Vancouver			Durban			Chennai		
	Container	*Steel*	*X-Lam*	*Container*	*Steel*	*X-Lam*	*Container*	*Steel*	*X-Lam*
GWP [KgCO_2e]	4’295	32’010	10’630	16’460	42’430	10’100	18’450	41’750	15’520
ODP [KgCFC_{11}e]	5,05 E-4	8,87 E-4	1,13 E-3	1,75 E-3	2,00 E-3	1,13 E-3	7,34 E-4	1,20 E-3	9,81 E-4
AP [KgSO_2e]	123	1’323	1’247	6’701	7’207	1’414	1’620	3’800	1’295
EP [Kg$(PO_4)_3$e]	8,632	19,12	13,62	14,70	23,46	13,46	14,36	22,27	14,81

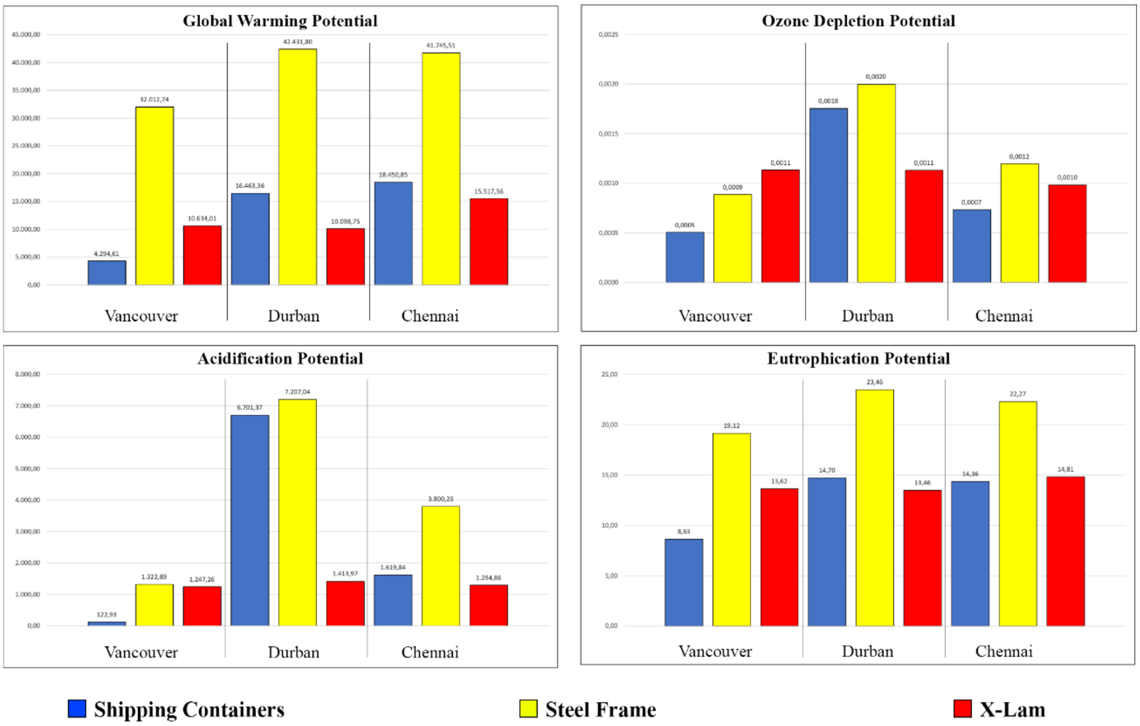

Fig. 5 Module A1-2-3 results: comparison for each scenario and technology.

The use of a 0-100 allocation procedure for the steel frame leads to much higher emissions on this stage. Therefore, to have a fair comparison of container and steel technologies is necessary to include Module D for recycling. In this case, even considering a 100-0 allocation procedure, including credits for the recycling of steel at the beginning of its lifecycle, leads to an environmental advantage of container structures (Cellura 2017).

3.2 Gate to Site

It is necessary to underline that the main limitation of the present study is related to the use of abstract scenarios rather than real buildings. Data regarding actual distances from gate to site are not available and therefore emissions for each transportation stage have been expressed with a *per km* normalization.

For this calculation average values available worldwide have been assumed as follows:

Engine power	*380 kW*	**Fuel tank**	*184 l*
Maximum load	*36'500 kg*	**Fuel type**	*Diesel*
Full load speed	*60 km/h*		

Average Diesel emissions

GWP	[kgCO_2e / kW-h]	*0,26*
ODP	[kgCFC_{11}e / kW-h]	*9,2 E-6*
AP	[kgSO_2e / kW-h]	*8,0 E-4*
EP	[kg$(PO_4)_3$e / kW-h]	*1,0 E-4*

In order to express the total emissions results in mass of impact equivalent per km, it has been used a *Conversion Factor* to transform kWh power-emissions to km distance-emissions:

Conversion Factor = *[**Engine power**]* / *[**Full load speed**]* = 380 / 60 = 6,43 *[kWh/km]*

Then a *Load Factor* has been introduced to include the assumption that empty vehicles produce lower emissions than fully loaded trucks. This factor is represented by the percentage of weighted building material compared to the maximum load allowed by the truck:

Load Factor = *[**kg of building material**]* / *[**Max load**]*

In order to calculate normalized emissions, per km, for the transportation of building materials, average diesel emissions have to be multiplied for the *Conversion Factor* and *Load Factor*:

Emission *[kg impact-e / km] = [**Unitarian emission**]*[**Conversion Factor**]*[**Load Factor**]*

Table 7 shows the results of this calculation for each scenario and technology based on Bills of Quantities reported in Table 5. It is evident that emissions related to each transport stage are strictly linked to the whole weight of building materials involved in the construction. Further research should be done by assessing real scenarios including actual distances measurements into the calculation in order to correctly address the relevance of these stages within the life cycle of a building.

Table 7 Gate to Site normalized emissions

Impact Category	Vancouver			Durban			Chennai		
	Container	*Steel*	*X-Lam*	*Container*	*Steel*	*X-Lam*	*Container*	*Steel*	*X-Lam*
GWP [$KgCO_2e$ / km]	2,77	2,38	3,87	3,10	3,59	3,87	5,82	4,80	5,63
ODP [$KgCFC_{11}e$ / km]	9,8 E-5	8,4 E-5	13,7 E-5	11,0 E-5	12,7 E-5	13,7 E-5	20,6 E-5	18,0 E-5	19,9 E-5
AP [$KgSO_2e$ / km]	8,5 E-3	7,3 E-3	11,9 E-3	9,5 E-3	11,0 E-3	11,9 E-3	17,9 E-3	14,8 E-3	17,3 E-3
EP [$Kg(PO_4)_3e$ / km]	10,7 E-4	10,7 E-4	14,9 E-4	11,9 E-4	13,8 E-4	14,9 E-4	22,4 E-4	18,8 E-4	21,6 E-4

The actual relevance of the proposed calculation lays on the inherent possibility of determining the Environmental Advantage of two compared technologies. In fact, results of the embodied energy for shipping container structure clearly show an environmental advantage when compared to steel frames. Moving from a *per km* normalization of the Site to Gate stage, it is possible to define the maximum distance within which containers can be displaced *before environmental advantage is lost*. This distance is defined comparing the embodied energy for the production of newly manufactured steel profiles to normalized transport emissions of shipping containers necessary to build a functionally equivalent building of 6 modules. This leads to the boundary distance where emissions coming from the transportation of containers equal the embodied energy of virgin steel profiles:

Boundary Distance *[km]* = ***Embodied Energy [****Steel****] / Transport Emissions [****Containers****]*** = **1700** km

This result is consistent with data published by the BRE Group in the Green Guide to Specification, where the environmental advantage was related to the comparison of recycled and virgin steel profiles (Anderson, Howard 2000). Moreover, it has to be noted that this result is conservative since emissions for the transportation of the steel frame from gate to site are not included into the calculation. Further study of real case scenarios would help contextualizing the extents of this concept.

Map in Figure 6 displays the impact of a 1700 km transport distance from seaport depots. To have a more detailed overview of this concept, further research should be done including even continental depots.

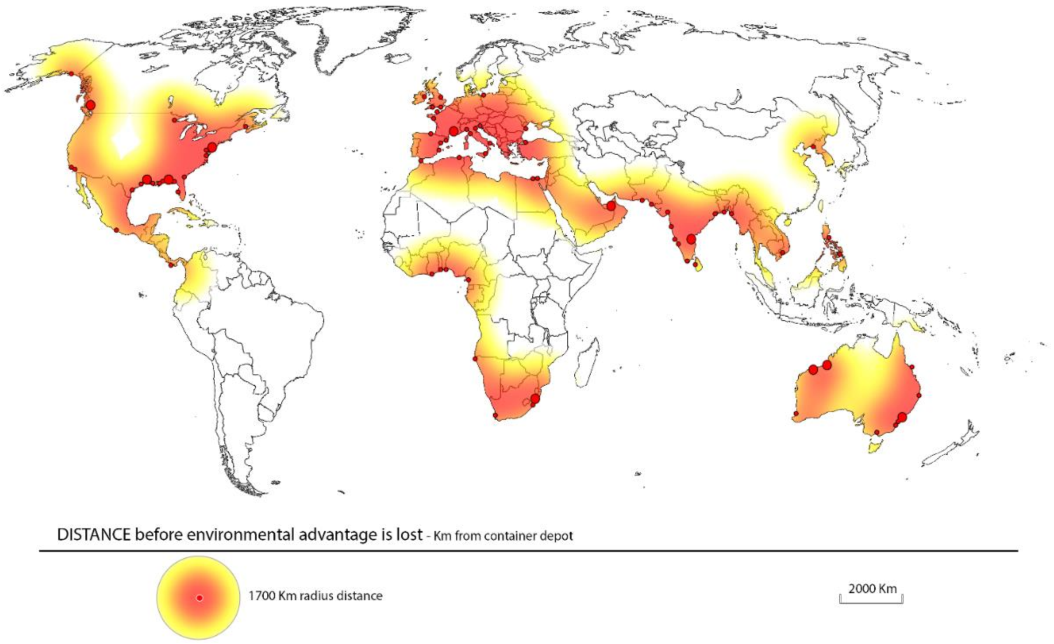

Fig. 6 Distance for environmental advantage of shipping containers

3.3 Construction Stage

Module A5, related to the Construction Stage, can be seen as an additional manufacturing phase in which building materials, considered as individual products, come together in the manufacturing of the entire building. Generally speaking, emissions occurring on this stage are the result of machinery operation, strictly linked to the consumption of fuels and electricity.

Current literature often ignores onsite fabrication impacts, assuming them to be minimal on the whole life cycle of a building. Nevertheless, with the progressive mitigation of the Operations Energies, emissions of other stages, including construction are becoming increasingly relevant. Moreover, to correctly address the impact of Shipping Containers within the building sector, it is necessary to take into account the prefabricated nature of its inherent technology, which leads to faster onsite activities and therefore lower emissions (Takano et al. 2014).

In order to address the amount of emissions for each technology, the calculation has been conducted using a time chart of building operations (Grosso 2007). For each operation needed the duration of the construction process, the equipment necessary and its overall emissions were defined. Operations have been considered non-overlapping during the construction process due to the lack of data regarding this topic.

Time schedules for the container structure have been defined from on-site experience and verified with the methodology developed in the present study to ensure consistency. In each construction site 8 labour hours per day of 5 workers (2 basic, 1 qualified and 1 specialized) were considered. Specifications for the machinery involved in the construction process are listed in Table 8. Fuel and electricity emissions per kWh are listed in Table 9.

Table 8 Machinery specification for on-site emissions calculations

Machinery involved	**Engine Power** [Hp]	**Engine Power** [kW]	**Engine type**
Cement mixer	11	8,2	Diesel
Excavator	180	134,2	Diesel
End cutter	34	25,4	Electric
Welder	35	26,1	Electric
Forklift	83	61,9	Diesel
Crane	175	130,5	Diesel
Saw blade	3	1,8	Electric
Generic light sets	110	82,0	Electric
Generator/Compressor	37	27,6	Diesel
Sander	1	0,8	Electric
Dump truck	518	386	Diesel

Table 9 Power emissions for fuels and electricity in each scenario considered.

Fuel Type	**GWP** [kgCO_2e / kWh]	**ODP** [kgCFC_{11}e / kWh]	**AP** [kgSO_2e / kWh]	**EP** [kg$(PO_4)_3$e / kWh]
Diesel	0,26	9,2 E-6	8,0 E-4	1,0 E-4
Gasoline	0,31	9,2 E-6	8,0 E-4	1,0 E-4
Electricity	0,78	11,0 E-10	9,4 E-4	8,1 E-4

Operations for the arrangement of the construction site, such as demolitions, earthworks, foundations and crane positioning have been excluded from the study, considering their consistency for each structural technology. Overall time schedules, energy consumption and emissions are resumed in Table 10. It has to be noted that the location of each building does not directly affect the duration of each construction.

Construction Stage's emissions show that the prefabricated nature of shipping containers leads to shorter schedules and therefore an environmental benefit compared to steel and X-Lam technologies.

Table 10 Construction sites calculation results

	Container	Steel frame	X-Lam
Total duration [hours]	445,19	1124,03	879,99
Total duration [days]	12	28	22
Diesel consumption [kW-h]	4908,46	29001,39	23452,20
Electricity consumption [kW-h]	13978,39	39504,86	26681,89
GWP [KgCO_2e]	1,67 E+4	5,11 E+4	2,0 E+4
ODP [KgCFC_{11}e]	0,45 E-1	2,68 E-1	2,2 E-1
AP [KgSO_2e]	2,25 E+1	7,58 E+1	3,60 E+1
EP [Kg$(PO_4)_3$e]	1,64 E+1	4,79 E+1	1,71 E+1

3.4 Use Stage

Commonly, the occupancy stage is evaluated by means of its energy use. Annual energy is calculated taking into account use and occupancy patterns of each space, mechanical features of the building and local climate. Moreover, in recent years a great deal of effort has been put on reducing the operational energy of buildings; as a result of this mitigation, the relative importance of each other life cycle stage has increased. The study presented in this paper is a comparative analysis and its results are intended to be relative to the confronted technologies, rather than being absolute. Since the developed functional unit includes properties of thermal performance, the amount of energy involved in the use stage is the same for each technology compared. Moving from these considerations becomes evident that the operational stage is highly related to design and technical decisions, which are completely independent from the structural material selected. Therefore, the whole Use Stage does not affect the scope of this study. A sensitivity analysis result has been used to exclude the operational energy from the overall comparison of each technology life cycle.

3.5 End of Life

The End of Life of a building is marked by the demolition stage, although it is not the end of life for each individual building material, which should face a subsequent phase of Reuse-Recovery-Recycling (Hradil et al. 2014). Several sub-stages constitute the entire End of Life of a building, including Waste Processing, Waste Transport and Landfilling. 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 using the same method of the construction stage: defining operations and time charts, computing the hourly usage of machinery and converting the energy consumption into environmental emissions. As an output of the demolition phase, building materials are computed as different waste flows. Table 11 resumes recovery, recycle and disposal rates for each building material. Material flows have been defined with the information included in each EPD provided by producers.

Table 11 Recovery, Recycling and Disposal average rates according to selected EPDs

Material	**Recycle**	**Reuse**	**Disposal**
Structural steel (Bre, Steel Tube Institute)	80%	10%	10%
X-Lam panels (Institut Bauen und Umwelt e.V., Institute of Construction)	50%	40%	10%
Hardwood timber (Woodsolutions)	50%	40%	10%
OSB (North American Wood Council, Kronoply – Institute of Construction and Environment)	100%	/	/
Gypsum (Gyproc)	/	/	100%
Timber finishes (Accoya, Kingspan, PPG, FP Innovation)	40%	50%	10%
Rockwool insulation (Rockfan, epd-norge, Rockwool)	90%	/	10%
Bricks (Bre, Cendec)	50%	40%	10%

Very little variation has been found within calculations for Demolition Stages in different climate zones and therefore Table 12 shows a unique value for each technology.

Table 12 Emissions for the Demolition Stage.

	Container	*Steel*	*X-Lam*
Total duration [hours]	675,91	500,98	482,27
Total duration [days]	17	13	12
Diesel consumption [kW-h]	26076,35	18938,58	18204,49
Electricity consumption [kW-h]	17098,10	12644,02	12166,63
GWP [$KgCO_2e$]	1,81 E+4	1,33 E+4	1,27 E+4
ODP [$KgCFC_{11}e$]	0,24	0,17	0,17
AP [$KgSO_2e$]	34,44	25,20	24,23
EP [$Kg(PO_4)_3e$]	14,25	10,51	10,11

The large amount of steel contained in a container structure leads to longer demolition schedules and therefore higher emissions. The next paragraph highlights the importance of steel flows after demolition in a container structure, partially accounting for higher emissions on this stage (Bowyer 2015). Although demolition waste is a problem of increasing relevance, there is little statistic and literature available on the subject to address its magnitude in detail (Parker et al. 2015).

When organic materials are landfilled, anaerobic bacteria degrade them, producing both Carbon Dioxide (CO_2) and Methane (CH_4), along with other gases (US EPA 2015). Among them Methane is the most significant from a Global Warming perspective due to its high potential, considered around 21-25 times CO_2-equivalents. Carbon entering the landfill can have several outputs: exit as CH_4, CO_2, Volatile Organic Compounds (VOCs), dissolve into leachate, or remain stored in the landfill. Generally, literature agrees with the assumption that CO_2 emitted in the process of degradation is not cause of environmental harm, because it 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 an anthropogenic environmental harm.

For this calculation, each material flow resumed in Table 13, has been accounted for its emissions of waste processing and landfilling, defined by EPDs and resumed in Table 14.

It has to be noted that material flows are slightly different for each scenario, nevertheless they have been reported in a single table to avoid repetitions.

Whole emissions for Module C, End of Life, including Demolition, Waste processing and Disposal, are resumed in Table 15 and represented in Fig. 7.

Table 13 Material flows after demolition.

Material [Kg]	**Container**			**Steel**			**X-lam**		
	Recycled	*Reused*	*Landfilled*	*Recycled*	*Reused*	*Landfilled*	*Recycled*	*Reused*	*Landfilled*
Rockwool	2532,04	/	281,34	2196,01	/	244,00	1581,42	/	175,71
Steel	13566,25	1695,78	1695,78	9037,10	502,06	502,06	/	/	/
Hardwood finish	10307,50	12884,37	2576,88	10307,50	12884,37	2576,88	10307,50	12884,37	2576,88
X-Lam panel	/	/	/	/	/	/	21030,535	16824,43	4206,11
Timber wall frame	866,40	866,40	/	866,40	866,40	/	866,40	866,40	/
Radiata pine weatherboard	674,11	842,64	168,53	1445,60	1807,00	361,40	1445,60	1807,00	361,40
OSB panels	15140,30	12112,24	3028,06	5129,40	/	/	5129,40	/	/
Brick	42307,76	33846,21	8461,55	22928,08	18342,46	4585,62	21030,54	16824,43	4206,11
Gypsum board	/	/	2401,19	/	/	4354,93	/	/	4354,93

Table 14 Module C3 and C4 – Waste Processing and Landfill emissions

Material	**GWP** [$KgCO_2e$ / Kg]		**ODP** [$KgCFC_{11}e$ / Kg]		**AP** [$KgSO_2e$ / Kg]		**EP** [$Kg(PO_4)_3e$ / Kg]	
	Waste Processing	*Landfill*	*Waste Processing*	*Landfill*	*Waste Processing*	*Landfill*	*Waste Processing*	*Landfill*
Steel members	/	1,28 E-4	/	1,41 E-14	/	7,00 E-6	/	1,05 E-6
Timber products	1,61	0,626	2,42 E-9	3,82 E-14	1,42 E-8	2,53 E-4	1,20 E-6	3,32 E-5
Gypsum	2,65 E-3	/	3,42 E-10	/	2,00 E-5	/	4,54 E-6	1,6 E-5
Rockwool insulation	1,6 E-3	0,0155	3,42 E-10	3,5 E-9	1,00 E-6	1,3 E-5	2,7 E-7	3,6 E-6
Bricks	2,45 E-4	2,4 E-4	/	/	1,00 E-6	-3,2 E-5	/	-7,0 E-6

Table 15 End of Life emissions for each scenario and technology

Impact Category	**Vancouver**			**Durban**			**Chennai**		
	Container	*Steel*	*X-Lam*	*Container*	*Steel*	*X-Lam*	*Container*	*Steel*	*X-Lam*
GWP [$KgCO_2e$]	25’980	22’200	31’110	33’250	28’870	31’300	27’370	28’210	30’450
ODP [$KgCFC_{11}e$]	0,240	0,174	0,168	0,240	0,174	0,168	0,240	0,174	0,168
AP [$KgSO_2e$]	35,54	26,46	26,55	36,48	27,32	26,57	35,46	27,09	26,33
EP [$Kg(PO_4)_3e$]	14,46	10,78	10,52	14,61	10,91	10,52	14,43	10,86	10,48

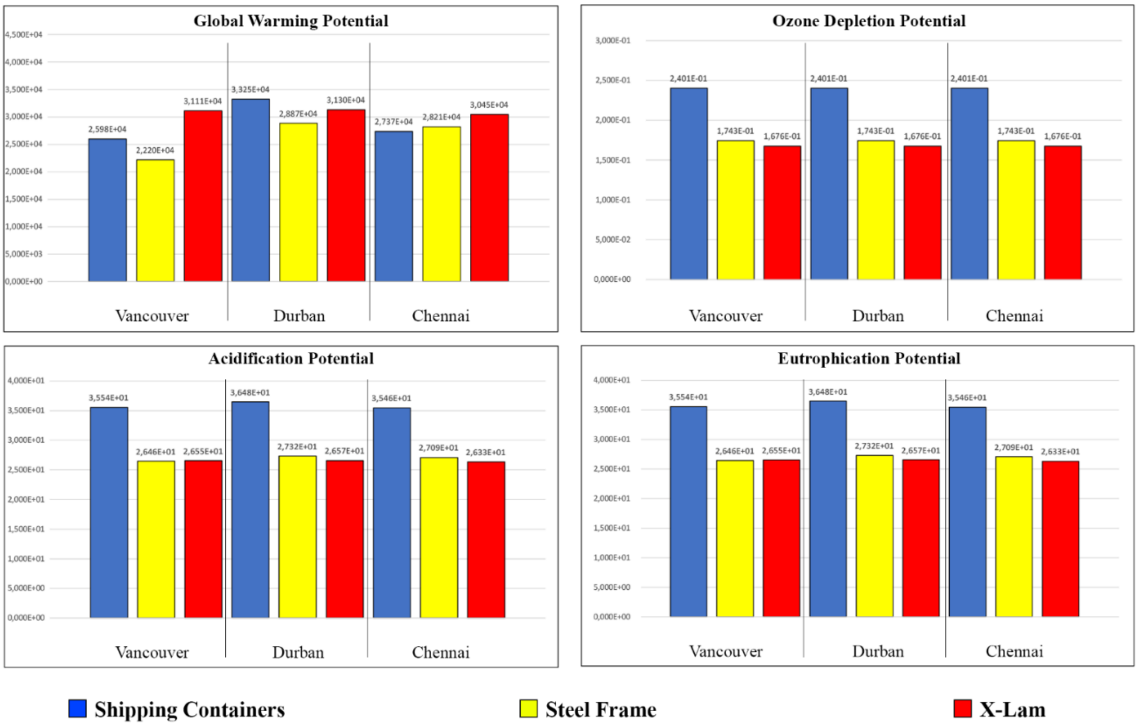

Fig. 7 Module C, End of Life emissions for each scenario and technology

3.7 Reuse-Recovery-Recycling

Materials which are not disposed in landfill can be either Reused or Recycled. The reuse of products means that outputs materials are used as input of another lifecycle, or system, without any operation of reprocessing. Recovery can be assumed as a partial reprocessing of material to allow its integral reuse. This material flow has not been considered in the present LCA.

Finally, Recycling means that output materials are recovered and reprocessed, avoiding extraction of virgin resources. This process might include material losses during manufacturing and processing. Two different recycling processes have to be accounted when modelling output flows. On the one hand, materials are reprocessed preserving their inherent qualities for the next life cycle. When a recycled material goes back into the original product, for instance steel members, ISO 14044 suggests the use of a Closed Loop Cycle model: credits for the avoided extraction of virgin material are subtracted from the overall impact of the whole lifecycle, with the addition of emissions related to reprocessing. On the other hand, when materials experience significant degradation of their properties during their reprocessing, an Open Loop Cycle has to be considered. Open Loop Cycles are also defined as Downcyclings, where recycled materials are converted into inputs of a different process: this is the case of structural timber, which usually can’t be recycled as structural material after its demolition. Although materials are not landfilled, they cannot be used for structural purposes, and therefore emissions for the extraction of virgin material are not actually avoided. In the case of timber products, material outputs are considered to be partially used for energy production or as input for chipboard and OSB panels. Credits for recycling are not allocated to OSB panels in order to avoid double counting since the use of downcycled material is considered in its Product Stage using a 100-0 allocation procedure.

Table 16 reports the recycling impact of each building material considered. Overall results for the calculation of all out of boundaries recycling credits are reported in Table 17 and represented in Fig. 8.

Table 16 Recycling credits database

Material	**GWP** [KgCO_2e / Kg]	**ODP** [KgCFC_{11}e / Kg]	**AP** [KgSO_2e / Kg]	**EP** [Kg$(PO_4)_3$e / Kg]
Steel members	-1,89	-1,18 E-11	6,35 E-3	-5,36 E4
Timber products	0,60	-5,6 E-8	-1,01 E-3	-2,83 E-5
OSB	/	/	/	/
Gypsum	4,0 E-8	/	/	/
Rockwool insulation	-0,04	3,1 E-10	-1,8 E-4	-1,3 E-5
Bricks	-0,0017	/	-3,2 E-5	-7,0 E-6

Table 17 Module D, Recycling credits for each technology and scenario

Impact Category	**Vancouver**			**Durban**			**Chennai**		
	Container	*Steel*	*X-Lam*	*Container*	*Steel*	*X-Lam*	*Container*	*Steel*	*X-Lam*
GWP [KgCO_2e]	- 17’700	- 7’663	+ 20’220	- 17’860	- 7 ’638	+ 20’250	- 17’880	- 8’297	+ 19’580
ODP [KgCFC_{11}e]	- 7,48 E-4	- 7,08 E-4	- 18,9 E-4	- 7,30 E-4	- 7,07 E-4	- 18,9 E-5	- 7,30 E-4	- 6,47 E-4	- 18,2 E-4
AP [KgSO_2e]	+ 72,24	+ 37,89	- 34,22	+ 72,69	+ 38,00	- 34,07	+ 71, 55	+ 38,85	- 33,60
EP [Kg$(PO_4)_3$e]	- 7,68	- 4,69	- 0,97	- 7,66	- 4,68	- 0,96	- 7,94	- 4,80	- 1,08

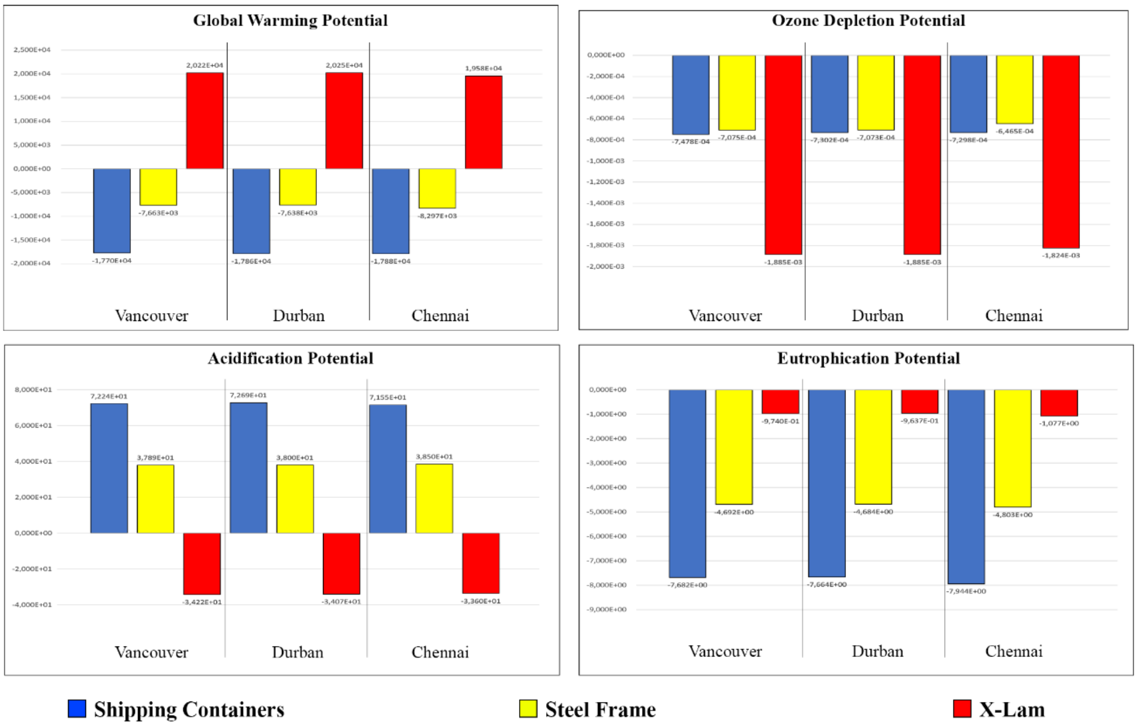

Fig. 8 Module D, out of boundaries Recycling credits.

4 Discussion

As above mentioned, the whole Life Cycle Assessment has been conducted with a sensitivity analysis which aims to exclude Operational energy and transport stages to allow a clear comparison of each technology studied. Table 18 and Figure 9 are intended to report the overall impact of each technology compared. The environmental benefit provided by a proper use of intermodal containers as building components is clearly evident. Generally speaking, it can be concluded that the use of shipping containers provides multiple benefits during the life cycle of a building. Firstly, it has to be reported the advantage related to avoided extraction of a large amount of virgin material for structural purposes. Nevertheless, the comparison of Durban's and Chennai's scenarios points out the importance of a mindful selection of sub-structural material: peaks of emissions within Durban's location are directly linked with the selection of OSB which produces higher emissions when compared, for instance, with bricks used for Chennai's (Fig. 10).

Table 18 Whole Life Cycle Assessment results with the inclusion of Module D for recycling

Impact Category	Vancouver			Durban			Chennai		
	Container	*Steel*	*X-Lam*	*Container*	*Steel*	*X-Lam*	*Container*	*Steel*	*X-Lam*
GWP [KgCO_2e]	28’764,9	80’100,7	82’337,0	48’529,11	114’745,4	82’028,2	40’149,8	100’098,4	88’600,5
ODP [KgCFC_{11}e]	0,339	0,442	0,383	0,286	0,443	0,383	0,285	0,442	0,383
AP [KgSO_2e]	255,51	1’441,83	1’275,58	6’833,06	7’348,13	1’442,46	1’743,98	3’926,36	1’326,82
EP [Kg$(PO_4)_3$e]	30,34	55,01	40,28	38,07	77,62	40,14	32,65	63,20	44,10

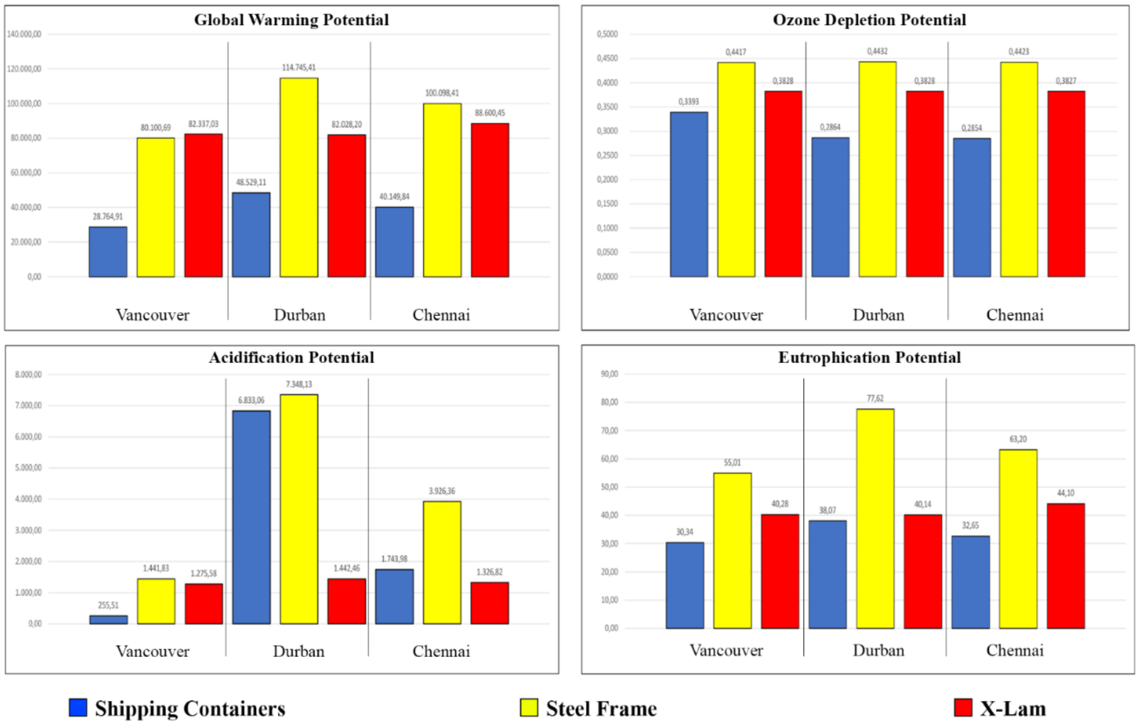

Fig. 9 Whole Life Cycle Assessment results.

Acidification Potential of container homes is the most delicate aspect from the point of view of material selection. Embodied Energies account for 50% to 98% of the AP during the whole lifecycle of a building. The volume of OSB and bricks needed in hot climates ranges from 30% to 40% as reported in Figure 8. This evidence stresses the relevance of a thoughtful choice of mass material for passive cooling purposes in order to keep the environmental benefit of any structural technology. Other environmental benefits are related to the prefabricated nature of container structures which leads to shorter construction schedules. Module A5 and C1, Construction and Demolition, contribute to the 98% of ODP due to the intensive use of ozone depleting machinery. Therefore, short construction schedules lead to lower ODP in container structures. Finally, the overall sustainable nature of container structures lays in the great recycling potential after their End of Life.

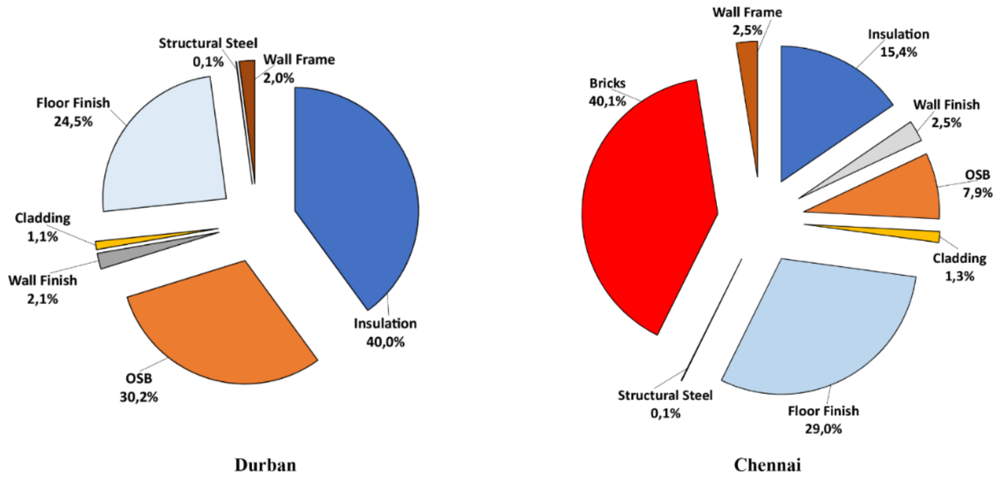

Fig. 10 Volume of materials for a container structure in two different scenarios.

5 Conclusions

The End of Life stage highlights the ultimate impact of shipping containers in the construction sector. All reported calculations show that demolition and waste processing of a container structure produce higher emissions compared to steel and X-Lam technologies. 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 material 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 has actually 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 what aims to be a *circular economy*, the building sector (Fig. 11). 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, again. On the other hand, the process of upcycling intermodal containers releases steel that was "stored" into the abandoned structure of containers, which will later be available for production. In fact, difficulties in the management of empty containers are an evidence that in the current practice the trade industry is not able to recycle its *waste outputs*, leaving them to rot in depots. In conclusion, after one life cycle as building components, shipping containers set free 13,6 steel tons every 6 containers used. Without a proper recycling process of containers, the large amount of resources stored within each unit is left to exhaustion after only a single cycle, one single trip to an import-oriented country, rather than taking advantage of the high recycling potential of steel products.

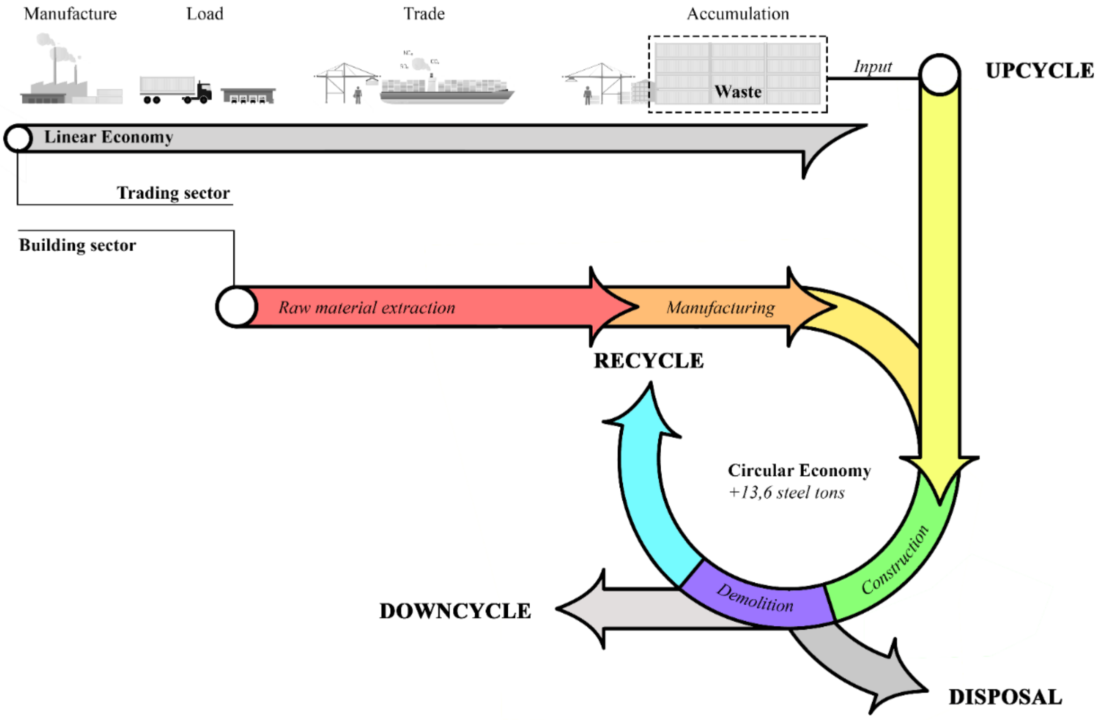

Fig. 11 Life Cycle of a Shipping Container structure.

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