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Mitigating climate change by minimising the carbon footprint and embodied energy of construction materials: A comparative analysis of three South African Bus Rapid Transit (BRT) stations

Peer reviewed

Abstract

This article investigates the role that architecture can play in mitigating climate change by comparing the environmental impact of construction material use in two existing South African Bus Rapid Transit (BRT) stations in Johannesburg and Cape Town and a proposed BRT station for Tshwane. The article will generate guidelines to improve the resource efficiency of future BRT trunk-route stations.

The climate change mitigation potential of BRT stations has been determined by analysing their carbon footprint and embodied energy over the cradle to gate[1] period. The quantity of construction material used in each station was calculated, while the carbon footprint intensity and embodied energy intensity were determined by means of the Inventory of Carbon & Energy (ICE) carbon and embodied energy calculator.

Calculations of embodied energy of structural systems and material use reveal that the Cape Town station is 36.5% more efficient in terms of carbon footprint intensity and embodied energy intensity than the Johannesburg station and 23.2% more efficient than the Tshwane station. The station base is the most energy-intensive component, contributing an average of 38% to the total embodied energy. It was concluded that steel contributes more than 50% to the total carbon footprint and embodied energy of each station.

The analysis determines that lower scaled, spatially economical structures using low embodied energy materials will positively contribute to reduced carbon footprints and thus climate change mitigation strategies. The outcomes of the article also set a benchmark for prospective life-cycle assessments (LCA) and establish design guidelines for the design of future BRT stations.

Keywords: Bus Rapid Transit (BRT), carbon footprint, climate change, construction materials, embodied energy, life-cycle analyses, resource consumption

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[1] 'Cradle to gate' includes the extraction of raw materials, transportation and processing to the point where the product leaves the factory.

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Abstrak

Hierdie artikel spreek die rol van argitektuur in die mitigasie van klimaatsverandering aan. Deur te fokus op die konstruksiemateriaalverbruik van twee bestaande Suid-Afrikaanse '*Bus Rapid Transit*' (BRT)-stasies in Johannesburg en Kaapstad en 'n voorgestelde BRT-stasie vir Tshwane, vergelyk die artikel die omgewingsimpak van elke stasie. Die artikel fokus daarop om riglyne vir energie- en hulpbronverbruik doeltreffende BRT stasies te identifiseer.

Die klimaatsverandering mitigasie potensiaal van argitektuur is gekwantifiseer deur die stasies se koolstofinhoud en ingeslote energie vanaf die 'cradle to gate' periode te analiseer. Deur die hoeveelhede konstruksiematerial verbruik in elke stasie te bereken en gebruik te maak van die '*Inventory of Carbon & Energy'* (ICE) is die koolstofinhoud en ingeslote energie-intensiteite van die elke stasie blootgelê.

Die navorsing op die ingeslote energie van die struktuur en materialgebruik dui daarop dat die Kaapstad-stasie die beste vaar in terme van energie-intensiteit deur 36.5% meer hulpbronverbruikdoeltreffend te wees as die Johannesburg-stasie en 23.2 % as die Tshwane-stasie. Terwyl die stasie basis as mees energie-intensiewe komponent gemiddeld 38% bydra tot die totale ingeslote energie, is staal as die mees energie-ondoeltreffende materiaal geïdentifiseer. Staal dra meer as 50% by tot die totale koolstofinhoud en ingeslote energie.

Hierdie artikel kom tot die gevolgtrekking dat kleiner skaal, ruimtelikdoeltreffende strukture wat lae ingeslote energiematerial gebruik, lei tot strukture met laer koolstofinhoud wat kan bydra tot klimaatsverandering mitigasiestrategieë. Die gevolgtrekkings in hierdie artikel poog om 'n vergelykbare basislyn te stel vir toekomstige lewenssiklusanalises en terselfdertyd ontwerpbeginsels vir die ontwerp van voornemende BRT-stasies te bied.

Sleutelwoorde: Bus Rapid Transit, hulpbronverbruik, ingeslote energie, klimaatsverandering, konstruksiematerial, koolstofinhoud, lewenssiklusanalise.

1. Introduction

The adverse effects of global warming are evident worldwide, especially in the urban environment. Climate change, coupled with rapid urbanisation, population growth and the increasing threat of resource depletion, requires that architects employ new strategies to mitigate and resolve these problems (Fay, Treloar & Lyer-Raniga, 2000: 32, 40; Bennetts, Radford & Williamson, 2003: 121,125-126).

Large sectors, such as the built environment and transport industry, are major contributors to increasing global greenhouse gas emissions which increase the effects of climate change. These sectors contribute 7.9% and 13% to global emissions, respectively (Metz, Ogunlade, Bosch, Dave & Meyer, 2007: 105). South Africa's sprawling cities intensify the consumption of transport energy, which constitutes 26% of the national energy use (IEA, 2002: 20, 210; Department of Energy, 2009: 9), thus accentuating the significance of the built environment and transport industry as critical components to be considered in climate change mitigation strategies.

Being a mass mode of transit, the implementation of Bus Rapid Transit (BRT) systems in South African metropoles will address problems of climate change and the lack of mobility (Tshikalanke, 2010: 15). Unfortunately, these transport systems require large and energy-intensive infrastructural systems. In a life-cycle assessment (LCA) of the BRT system in Xiamen, it was concluded that infrastructure and vehicles contributed a third to the transport system's total embodied energy over a 50-year cycle (Cui, Niu, Wang, Zhang, Gao & Lin 2010: 335). This emphasises the importance of designing resource-efficient infrastructure.

1.1 Study objective

This study forms part of a research project[2] which focused on the role of architecture in mitigating climate change, addressing issues such as carbon footprints and embodied energy of construction materials in a design process (Hugo, 2010). With the current implementation of the BRT systems within South African cities, the study identified an opportunity to research the design of BRT infrastructure and, in particular, BRT trunk-route stations.

This study identifies specific architectural design guidelines to decrease the carbon footprint and embodied energy intensities of trunk-route stations. In addition to identifying effective architectural design strategies, this analysis also aims to act as a datum for the LCA studies of future BRT stations.

1.2 Current knowledge base

Several international studies (Cole, 1999: 335-336; Bennets *et al*., 2003: 98, 126; Mitraratne & Vale, 2003: 483-484; Hacker, De Saulles, Minson & Holmes, 2008: 376) have identified the value of life-cycle assessments in addressing resource consumption and the mitigating potential of architecture in an objective quantitative manner. In the process, the studies have identified and proven various successful sustainable structural systems, materials and strategies within the built environment.

The first knowledge issue this study addresses is the lack of quantitative research available in South Africa regarding the embodied energy and carbon footprint of architecture. The singular

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[2] This study forms part of a larger South Africa climate change mitigation project developed by the United Nations Development Programme (UNDP) and Global Environment Facility (GEF).

study by Daniel Irurah[3] (1997) focused on the embodied energy of the built environment and the construction industry, and developed an extensive data set on the energy consumption of the built environment and its various trades as well as a set of algorithms to calculate the embodied energy of these industries.

An additional study conducted by *The Carbon Disclosure Project (CDP)* was undertaken in South Africa over the past five years (Hanks, Dane, Hermanus & Niederhumer, 2011). This project focuses on the carbon footprint of companies listed on the Johannesburg Stock Exchange, but it does not provide any specific insight or data pertaining directly to the built environment. Therefore, the limited research that has been done in South Africa renders additional significance to the research presented in this study.

The second knowledge issue identified during the study addresses resource efficiency of BRT systems. While these systems successfully reduce the carbon footprint of transportation networks within cities by using energy-efficient vehicle and fuel types and minimising the use of private transportation, they require energy-intensive infrastructure to function. The majority of studies focus on the carbon footprint and emission reductions through the use of different fuel and vehicle types associated with the BRT interventions. These studies are significant and well researched (Wright & Fulton, 2005; Vincent & Jerram, 2006; McDonnell, Ferreira & Convey, 2008; Tshikalanke, 2010), but few address BRT 'infrastructure' and associated environmental impact (Cui *et al*., 2010). This article thus focuses on the BRT trunk-route 'stations' as key components within the entire transport network.

2. Research methodology

In order to identify possible guidelines for the design of future trunk-route stations, a comparative life-cycle assessment was made of three selected BRT stations, namely the Rea Vaya in Johannesburg designed by Ikemeleng Architects, MyCiti in Cape Town by ARG Design and Retro Tram in Tshwane by Mashabane Rose Architects. A quantitative analysis of these stations focused on the carbon footprint and embodied energy for the cradle to gate period.

Although the study addresses a multifaceted issue, the research focuses only on initial construction material use and design solutions.

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[3] Daniel Irurah currently teaches at Witwatersrand University, South Africa, as well as being actively involved in the built environment as consultant on the sustainability and energy efficiency of various projects.

It aims to reveal the influence that initial design decisions have on the overall environmental impact of the stations.

The authors of this study acknowledge that the largest portion of resources will be used by the infrastructure of the BRT system and operation. However, in the first phase of Rea Vaya BRT system, a total of 150 trunk-route stations will be constructed (Dlamini, 2008: 1), whereas the Tshwane BRT system plans to construct a total of 46 trunk-route stations for its first phase, with more to follow in future phases (Advance Logistics Group, 2008: 9). Due to the large number of stations that will be constructed, small savings in terms of the materials used in each station could lead to substantive overall savings. These savings can be channelled to building additional stations, increasing the accessibility of the respective transport systems.

2.1 The value of comparative life-cycle assessments

Comparative LCA studies allow one to generate a single figure to compare different products with each other (Fay *et al.*, 2000: 32). Although the process tends to ignore valuable qualitative influences, its strength lies in its ability to generate objective quantitative conclusions from a comparison between different products or processes over a specific time period (Rai, Behzad, Rosi, & Xiao, 2011: 2271).

To ensure a reliable comparison, a series of assumptions or delimitations are made to either develop a base case for comparison or ensure that the separate comparable case studies are established (Fay *et al.*, 2000: 36; Rai *et al.*, 2011: 2273).

Using BRT trunk-route stations as case studies provided the opportunity to compare a series of buildings which function on the same basis, follow similar spatial structures and accommodate similar movement patterns. Furthermore, all the case studies functioned within similar contexts as trunk-route stations within a BRT transport system. This meant that these had to adhere to the same strict design and engineering guidelines as set by South African National Road Agency Limited (SANRAL) and international best practice. Yet, all three designs followed different design processes leading to diverse design solutions.

The BRT stations are thus used as a unit of comparison of embodied energy and carbon footprints concerning the use of construction materials. Although the embodied energy and carbon footprint of BRT stations are substantially less when compared with those of the infrastructure, there are 'few current' comparable building typologies that serve similar functions within the same context (a BRT system) and can provide insight into the embodied energy and carbon footprint associated with the use of building materials, due to certain design solutions. Hence, the use of the BRT trunk-route station is considered appropriate, due to its comparability rather than its actual impact on the complete BRT system.

2.2 Defining the scope of analysis

Greadel (1998: 21-23) argues that it is extremely important to establish the system boundary[4] at the outset of a life-cycle assessment. With the recent increase in efficiency of operational energy in buildings, the focus has shifted to the embodied energy of these buildings (Fay *et al.*, 2000: 39). This is especially pertinent when dealing with buildings with highly efficient operation systems and shortened functional life cycles, such as warehouses or industrial buildings (Rai *et al.*, 2010: 2272). BRT trunk-route stations arguably have the same shortened functional life cycle, due to high use and maintenance, while the operational energy consumption of these stations is already highly efficient.

This prompted the study to focus only on the cradle to gate life-cycle period of the case studies, as the construction material use in each station was identified as an energy-intensive period in the life cycle of BRT systems (Cui *et al*., 2010: 329, 335).

Transport energy was excluded, as most of the materials are manufactured within 400km of the respective sites and constitute less than 1% of their embodied energy (Cole, 1999: 347; Mithraratne & Vale, 2003: 488-489). Furthermore, construction energy was omitted in the calculations, as it contributes less than 3% of the embodied energy over a 20-year period (Cole, 1999: 343; Mithraratne & Vale, 2003: 488-489).

Building operational energy was excluded, even though recent studies reveal that the operational energy of buildings constitutes approximately 50% of their total embodied energy over a 50-year cycle (Fay *et al.*, 2000: 40; Mithraratne & Vale, 2003: 488-489; Jones, 2011a: 15). The BRT stations investigated are generally energy-efficient in operational terms, as large areas (95%) are serviced by natural light and ventilation. Little improvement can be made to operational energy use, as the stations already use minimal electronic equipment, while certain energy-consumptive strategies

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[4] 'System boundary' refers to the specific time period analysed during a LCA study.

such as CCTV systems and high lighting levels at night are deemed necessary to ensure commuter safety.

The recycling of construction materials has been excluded following conclusions made in a study by Fay *et al*. (2000: 34) that energy saving must be accredited to the second-phase project, referring to the project which actually uses recycled content. Thus, no energy savings were included, due to the recycling potential of construction materials.

2.3 Choosing an appropriate carbon footprint and embodied energy data set calculator

There are various methods available for accurately calculating the carbon footprint or embodied energy. The first method uses a 'process analysis' approach and is a simple method of collecting site-specific data on products used in the project. This can be very cumbersome (and often impossible) when collecting a large variety of upstream energy inputs. The second method follows an 'in-put out-put analysis' using national statistical information regarding the economic flow between different sectors (Fay *et al.*, 2000: 33). Unfortunately, the data generated with this method is very broad and not site-specific.

In this study, an initial effort to follow the 'process analysis' method proved unsuccessful. The primary data on the carbon footprint and embodied energy from specific manufacturers within South Africa did not cover a wide enough range of materials nor was the same analysis criteria used for all the products. This rendered the information unreliable for a comparative analysis. Furthermore, the 'in-put out-put' method was unsuccessful, as the tables published by Statistics South Africa have been densely aggregated, which made the distinction between different sectors within the construction industry impossible.

This prompted the study to use international data for life-cycle assessments of the respective case studies, due to the limited available primary data and research on the carbon footprint and embodied energy for the construction industry in South Africa.

The study identified the UK-based Inventory of Carbon & Energy (ICE) embodied energy and carbon calculator as an appropriate data set to analyse the different case studies, as it covers a wide range of materials, enabling objective comparisons of materials and construction systems (Jones, 2011b: 33-169).

The ICE calculator primarily uses carbon footprint and embodied energy data captured in Europe. To maintain the applied objectivity of the study, the figures were used in a comparative manner.

2.4 Constituents of the comparative analysis

The selected BRT stations were comparatively analysed according to three parameters. The first parameter analysed the entire station, quantifying the impact of size and spatial efficiency. The second comparison focused on the different station components: the station base, wall, roof structure as well as signage and handrails (see Figure 1). This comparison demonstrated the impact of different structural systems on building form. Note that 'wall' includes the vertical structure and glazing and that 'signage and handrails' also include the signage tower usually positioned outside the stations' structure. In the third comparison, the overall material use was assessed in order to identify energy-intensive materials.

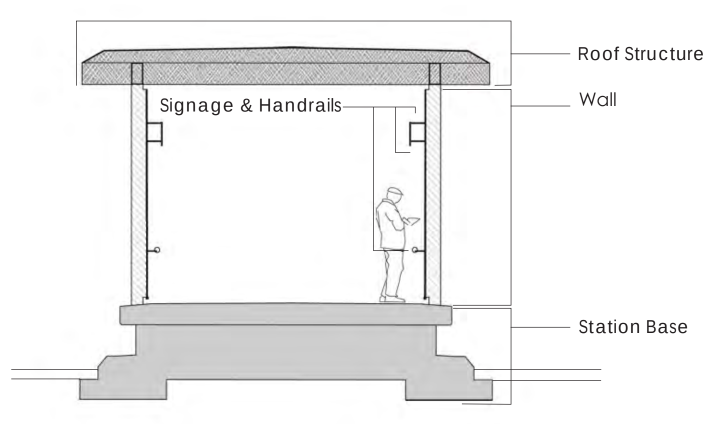

Figure 1: Description of structural components of BRT trunk-route stations
Source: Hugo, 2012: Own drawing

2.5 Quantifying and comparing material use

Technical documentation, photographs, interviews and site visits formed the basis for the assessment of the carbon footprint and embodied energy of each station. All the station components[5] were measured and their weight calculated. Construction material use of each station was analysed according to carbon footprint and embodied energy, using the following equation:

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[5] 'Components' refers to the different station elements being structural or infill.

$M_{volume} \times M_{density} = M_{weight}$ M - Specific material type
$M_{weight} \times EE_{coefficient} = EE_{total}$ EE - Embodied
$M_{weight} \times CF_{coefficient} = CF_{total}$ CF - Carbon footprint

The carbon footprint refers to the carbon dioxide equivalent (CO_2eq) emissions generated during the extraction and processing of a product (Jones, 2011a: 1). Irurah (1997: 10) defines embodied energy as the quantity of energy (joule) consumed during the production of goods or rendering of services; the sum total thereof is assumed to be embodied in the product.

As the floor areas of the various stations differ, 'carbon footprint intensity' and 'embodied energy intensity' were used as comparative units. These quantified the amount of carbon or energy embodied per square meter. These concepts can be summarised with the term 'resource efficiency' referring to the ability of a product to produce the same value with less resources or materials.

2.6 Case studies

2.6.1 The BRT system

The BRT system is a highly efficient and adaptable mass transit system which uses existing road networks (Wright & Hook, 2007: 50-66). It consists of dedicated trunk (main) routes with smaller feeder routes that link isolated neighbourhoods with their respective city centres (Advance Logistics Group, 2008: 4; City of Cape Town, 2010: 15). Currently, planning has been concluded for BRT systems in four South African metropoles,[6] and it is intended to be expanded to other cities.

Various studies have confirmed the success of BRT systems in addressing the reduction of urban transport greenhouse gas emissions (Wright & Fulton, 2005: 710-711; Vincent & Jerram, 2006: 233; Wright & Hook, 2007: 85, 699, 702-705; McDonnell *et al.*, 2008: 750-751; Tshikalanke, 2010: 15). Research done in Zurich revealed that a BRT system only requires 9% of the energy of a light rail system per kilometre and only 3% of an elevated railway system. In comparison to subway systems, the BRT system consumes less than 2% of the required energy per kilometre (Wright & Hook, 2007: 56).

BRT systems also promote corridor development (Pienaar & Motuba, 2007: 426; Wright & Hook, 2007: 87), improve access and passenger

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[6] These 4 cities include Johannesburg, Cape Town, Tshwane and Rustenburg.

safety (Pienaar & Motuba, 2007: 426; Walker & Hook, 2007: 86-87; Advanced Logistics Group, 2008: 15), and increase mobility in urban environments (Advanced Logistics Group, 2008: 2, 4). The success of BRT systems can be primarily attributed to their flexibility in implementation.

2.6.2 Specific trunk-route stations

The three case studies analysed are two completed stations, namely the Rea Vaya and MyCiti stations, and the Retro Tram station that was still in the design phase at the time of this study.

The stations are enclosed structures on raised platforms, are located on the median of the road, and usually have a single entrance. Articulated buses with raised floors service these stations to ensure fast and safe transfer of commuters. The stations are typically located at 500m intervals to accommodate the elderly, children and disabled commuters.[7]

All three case studies are trunk (main)-route stations and are positioned on the road median. All stations are designed to accommodate buses in both directions and house similar functions.

All electrical and security services, kiosks and associated operational energy consumption were excluded from the study. This ensures that all additional variables, prescribed by local councils, have been eliminated, allowing only for assessment of the stations themselves.

Rea Vaya stations in Johannesburg (see Figure 2) are covered with ventilated steel roofs cantilevering from a series of slanted steel columns. A precast concrete base with a smooth cement screed finish forms the station platform. The structure is enclosed with laminated glass panes fixed to a circular steel substructure. A stainless steel kiosk is enclosed within the station envelope.

MyCiti stations in Cape Town (see Figure 3) are small-scaled stations with station and kiosk/entrance components. They are fully enclosed with laminated glazing, while overhead louvers assist with indoor ventilation. A lightweight roof is carried on slanted steel portal frames. The station base is constructed from precast concrete sections with a tiled floor finish.

Retro Tram stations (see Figure 4) are one of four prototypes designed for Tshwane. These slender stations with high roofs are enclosed with a simple slightly curved steel column and beam structure. Similar to

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[7] The average person easily walks 400m in 5 minutes (Thandani, 2010: 735).

the other case studies, the station uses a precast concrete station base with an assumed cement screed finish. A semi-vaulted steel roof covers both the station and the kiosk. The roof is suspended above the laminated glass walls which are fixed to an independent steel substructure.

Figure 2: Rea Vaya station, Old Synagogue Station, Braamfontein, Johannesburg
Source: Hugo, 2010

Figure 3: MyCiti station, Granger Bay station at Cape Town stadium, Cape Town
Source: Hugo, 2012: Own photograph

Figure 4: Proposed Retro Tram station for Tshwane
Source: McClenaghan, 2011: Personal communication

3. Results

3.1 Analysing the entire BRT stations

In the first comparison, the entire stations were calculated and assessed. Although the floor areas of all the stations differ, they are of similar height (see Figures 5 and 6).The Retro Tram station is the only exception, being substantially narrower. The Retro Tram station is the smallest with a floor area of 159m^2, followed by the MyCiti station at 197m^2. The Rea Vaya station is the largest case study with a floor area of 305m^2. The total carbon footprints and embodied energies for the Rea Vaya, MyCiti and Retro Tram stations are 297.8 t CO_2 (3 478 GJ); 129.5 t CO_2 (1 411 GJ); 136.3 t CO_2 (1 485 GJ), respectively (see Table 1).

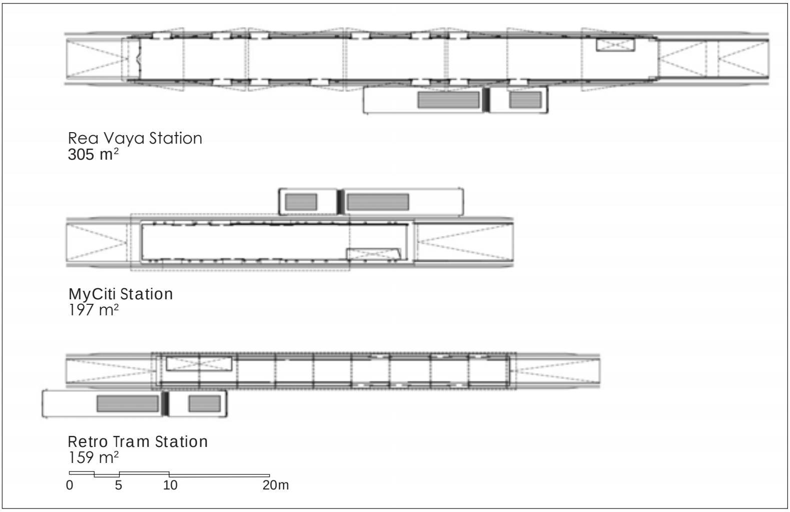

Figure 5: Comparative schematic plans of case studies

Source: Hugo, 2012. Sections redrawn from information supplied by architects: Bhana, 2011: Personal communication; Rendall, 2011: Personal communication; McClenaghan, 2011: Personal communication.

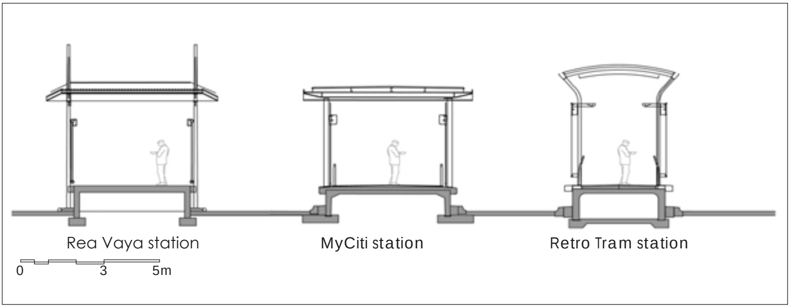

Figure 6: Comparative schematic sections of case studies

Source: Hugo, 2012. Sections redrawn from information supplied by architects: Bhana, 2011: Personal communication; Rendall, 2011: Personal communication; McClenaghan, 2011: Personal communication.

Table 1: Results of life-cycle assessment of case studies

	Rea Vaya				*MyCiti*				*Retro Tram*			
	Element total				*Element total*				*Element total*			
Station component	*EE MJ*		*CF $Kg\ CO_2$*		*EE MJ*		*CF $Kg\ CO_2$*		*EE MJ*		*CF $Kg\ CO_2$*	
Base												
Component total	674351	MJ	73025	Kg	565849	MJ	63882	Kg	821791	MJ	82968	Kg
EI / CI	211	MJ/m2	239	$kgCO_2/m^2$	2872	MJ/m2	1197	$kgCO_2/m^2$	5168	MJ/m2	522	$kgCO_2/m^2$
Wall												
Component total	1832208	MJ	141883	Kg	521970	MJ	39260	Kg	232368	MJ	16855	Kg
EI / CI	6007	MJ/m2	465	$kgCO_2/m^2$	1650	MJ/m2	199	$kgCO_2/m^2$	1461	MJ/m2	106	$kgCO_2/m^2$
Roof structure	727845											
Component total	2386											
EI / CI		MJ	55282	Kg	241800	MJ	18044	Kg	244383	MJ	18505	Kg
		MJ/m2	181	$kgCO_2/m^2$	1227	MJ/m2	92	$kgCO_2/m^2$	1537	MJ/m2	116	$kgCO_2/m^2$
Handrail and signage												
Component total												
EI / CI	203420	MJ	21664	Kg	81818	MJ	8388	Kg	186418	MJ	18045	Kg
	667	MJ/m2	71	$kgCO_2/m^2$	415	MJ/m2	42.6	$kgCO_2/m^2$	1172	MJ/m2	113	$kgCO_2/m^2$
Total weight	501 924	Kg			351 976	Kg			356 792	Kg		
Total	3437824	MJ	291854	$Kg\ CO_2$	1411437	MJ	129574	$Kg\ CO_2$	1484960	MJ	136373	$Kg\ CO_2$
	3437.80	GJ	291.90	$T\ CO_2$	1411.40	GJ	129.60	$T\ CO_2$	1484.70	GJ	1364.00	$T\ CO_2$
Floor area of station	305	M^2	305	m^2	197	M^2	197	m^2	159	M^2	159	m^2
EI / CI	11271.55	MJ/m^2	956.90	$kgCO_2/m^2$	7164.65	MJ/m^2	657.74	$kgCO_2/m^2$	9339.37	MJ/m^2	857.69	$kgCO_2/m^2$

Abbreviations: EE- embodied energy, CF – carbon footprint, EI – energy intensity, CI – carbon intensity
Energy intensity: Joules per square meter/kilogram carbon per square meter

Source: Hugo, 2012: Own table

As the size of each station differs, an assessment of carbon footprint intensity and embodied energy intensity provides comparable results. The most inefficient case study, the Rea Vaya station, is calculated at 11 271 MJ/m² and 956 kgCO$_2$/m², followed by the Retro Tram station with 9 339 MJ/m² and 857 kg CO$_2$/m². This equates to a 10.3% (carbon footprint intensity) and 17.1% (embodied energy intensity) positive difference in carbon footprint and embodied energy per square meter. Leading in resource efficiency is the MyCiti station, which is 31.2% (carbon footprint intensity) and 36.5% (embodied energy intensity) more efficient than the Rea Vaya station at 7 164 MJ/m² and 657 kg CO$_2$/m² (Figures 7 and 8).

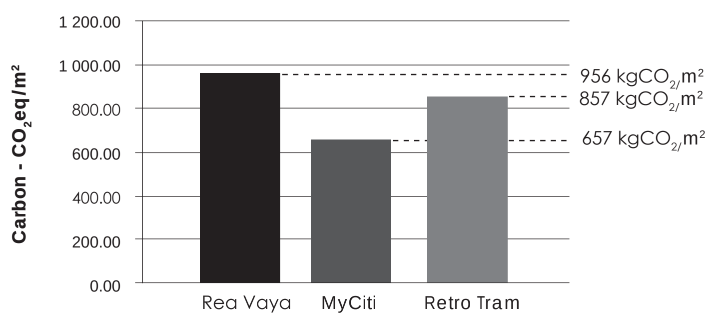

Figure 7: Carbon intensity comparison
Source: Hugo, 2012: Own figure

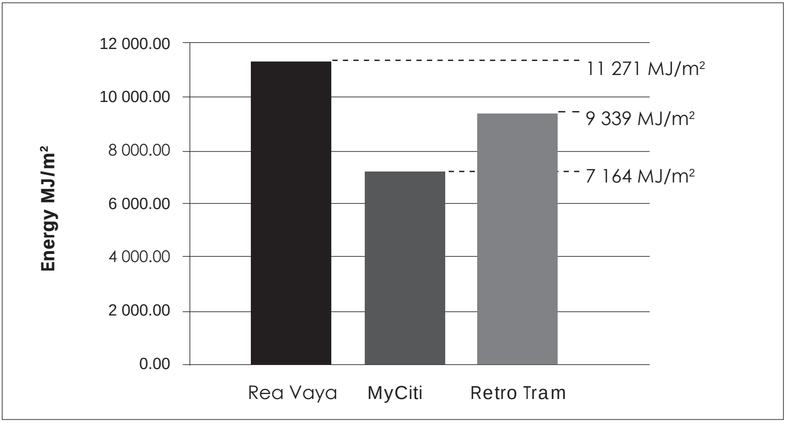

Figure 8: Embodied energy intensity comparison
Source: Hugo, 2012: Own figure

3.2 Comparison of the separate station components

Components were compared in terms of the station base, wall, roof structure and handrails and signage. The results show that the station bases of the MyCiti and Retro Tram stations are the most energy-intensive, contributing 40% (565 GJ, 63.8 tons CO_2) and 55% (822 GJ, 82.9 tons CO_2), respectively, to the total embodied energy (see Figures 10 and 11). Rea Vaya station contains the largest quantity of embodied energy in the wall 53% (1 831 GJ, 141.8 tons CO_2), while only 20% (674 GJ, 73 tons CO_2) is consumed by the substructure (Figure 9).

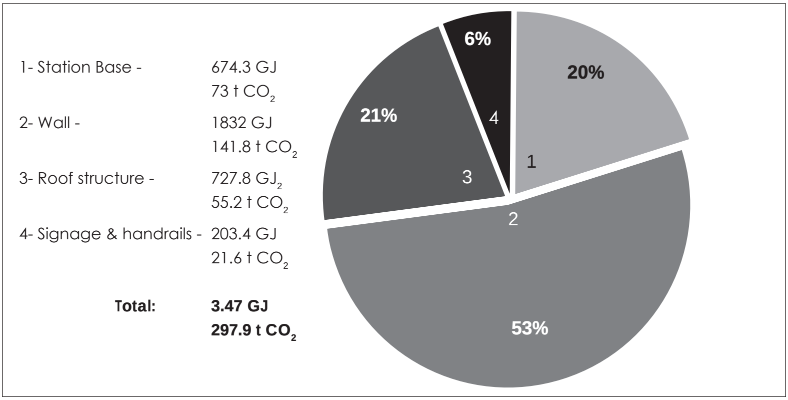

Figure 9: Energy consumption by component - Rea Vaya station
Source: Hugo, 2012: Own figure

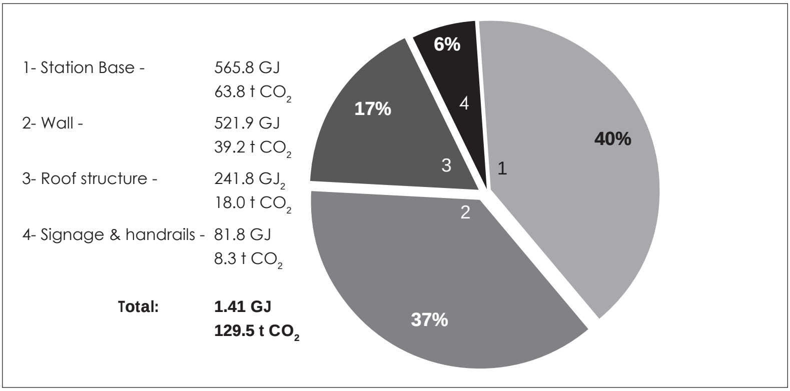

Figure 10: Energy consumption by component - MyCiti station
Source: Hugo, 2012: Own figure

Although signage is generally resource-efficient, in the Retro Tram case study, it constitutes 13% (186 GJ and 17.9 t CO_2) of the total carbon footprint and embodied energy (Figure 11). In the other two stations, it represents an average of 6% of the total carbon footprint and embodied energy (see Figures 9 and 10).

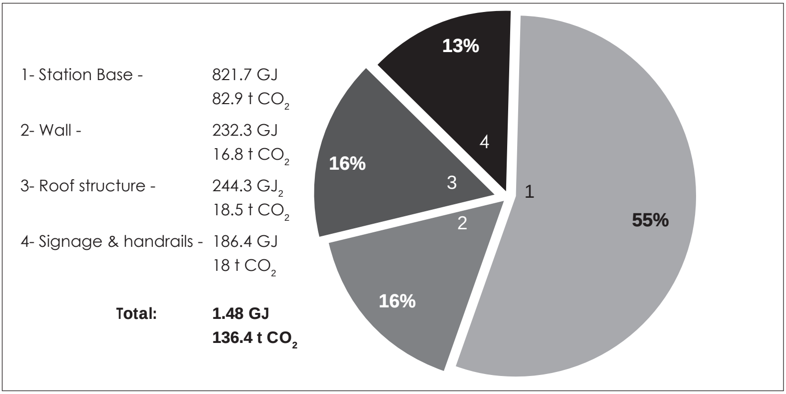

Figure 11: Energy consumption by component - Retro Tram station

Source: Hugo, 2012: Own figure

The wall components display the widest range in terms of energy intensity, ranging from 6 003 MJ/m² (465kgCO_{2eq}/m²) in the Rea Vaya station to 1 455 MJ/m² (106 kgCO_{2eq}/m²) for the Retro Tram station. The wall of Rea Vaya is 53% of the entire structure, whereas in Retro Tram, it is only 16%.This reveals the difference that resource-efficient design can make. The station bases and walls are two areas where large improvements are possible (Table 1 and Figure 12).

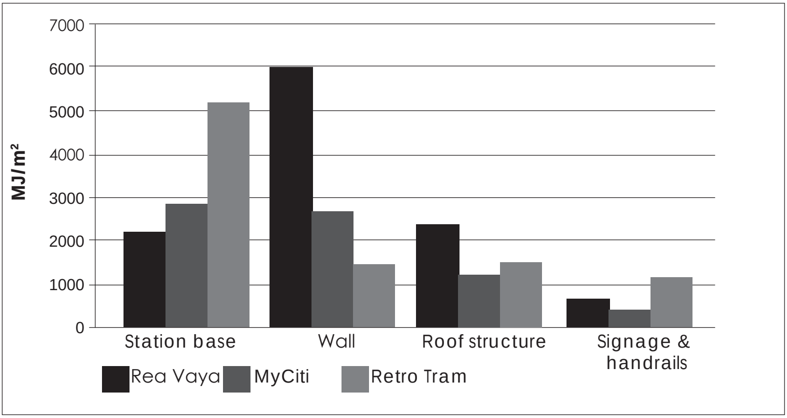

Figure 12: Comparison of embodied energy per component

Source: Hugo, 2012: Own figure

3.3 Material use comparison

In the third comparison, material quantities were calculated and assessed. Concrete, precast concrete and soil constitute an average of 86% (1 057 tonnes) of the total mass of each station (Table 1). Concrete and precast concrete have the largest embodied energy and are used extensively in all the case studies, contributing on average 70% (872 tonnes) to the total mass of each station. Steel is the fourth largest contributor, adding 3% to 5% (137 tonnes) to the total mass of each station. The mass of the remaining materials is relatively insignificant, typically contributing only 1% to the total (see Table 1 and Figure 13).

By contrast, the embodied energy of steel is substantially higher, contributing an average of 54% (305 tonnes CO_2) and 62% (3 928 GJ) to the total carbon footprint and embodied energy, respectively (Figure 14). On average, the embodied energy of steel is 240% (1 626 GJ vs. 3 928 GJ) larger than concrete and precast concrete combined.

Although very little stainless steel has been used in each station, the carbon footprint and embodied energy of this material is very high. Stainless steel represents an average of 5% (326 GJ) of the total embodied energy, yet only contributes 1% (7.1 tonnes) to the total mass (Figures 13 and 14).

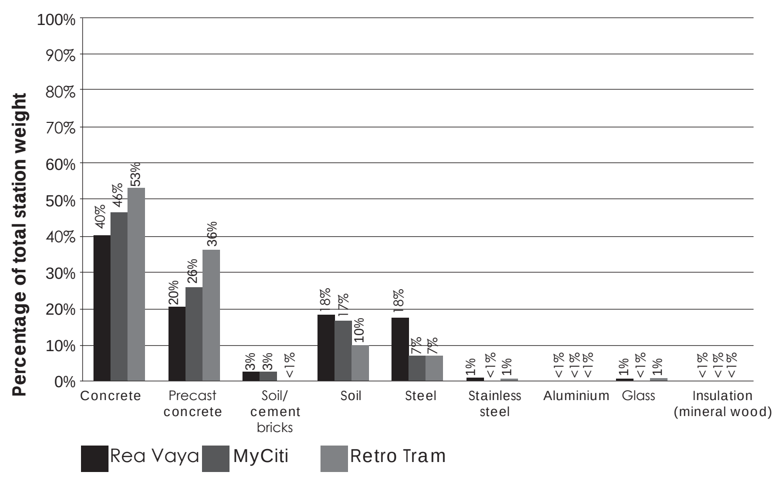

Figure 13: Comparison of type and percentage of materials used in the stations

Source: Hugo, 2012: Own figure

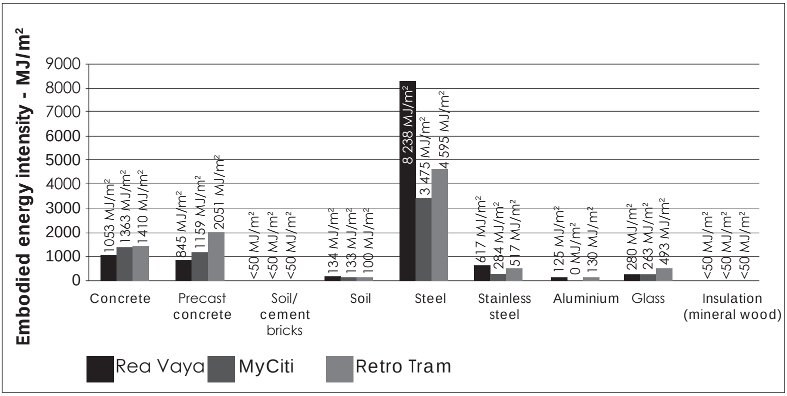

Figure 14: Comparison of embodied energy of specific materials

Source: Hugo, 2012: Own figure

4. Discussion

The analysis reveals that the material types used in the three stations are generally similar. All three case studies comprise large quantities of *in situ* and precast concrete (on average equalling 70% of the total mass). This has been largely utilised for the stations bases, while lightweight steel wall and roof structures enclose these bases, constituting an average of 62% of the total embodied energy.

The different applications of these materials are clearly indicated when analysing the resource efficiency of the stations' components. To a certain extent, all three case studies utilised different structural systems which has led to striking differences in carbon footprint and embodied energy intensities. In both the Retro Tram and MyCiti case studies, the station bases constituted the largest portion of embodied energy, while in the Rea Vaya case, the wall structure has the biggest impact.

The effect of these differences in structural systems is clearly indicated in a comparison between the overall station designs. The Rea Vaya station is revealed as the most resource-inefficient station. This can be attributed to a complex cantilevering roof and wall structure. The Retro Tram station's structure is on average 17.1% more efficient in terms of its carbon footprint intensity and embodied energy intensity than the Rea Vaya station. While the Retro Tram station's roof and walls are resource-efficient solutions, the large quantity of steel in the station's base lowers its overall efficiency. As the most efficient case study, the MyCiti station has a 36.5% and 23.2% lower embodied energy than the respective Rea Vaya and Retro Tram stations. Yet, due to the climatic conditions in Cape Town, the MyCiti station provides the highest level of protection to the external elements of all the case studies, thus providing the highest level of value with the least amount of resources or materials.

Reductions in carbon footprint and embodied energy can be achieved by employing the preceding analyses as four guiding principles at the conception of a project. These principles address station size, structural system, and the selection and use of materials.

4.1 Achieving spatial economy

The Retro Tram station has a total carbon footprint which is only 3% (136.3 T CO_2 vs. 129.5 T CO_2) larger than the MyCiti station; yet its carbon footprint intensity is 21% (857 vs. 657 $kgCO_2/m^2$) larger than the MyCiti station. This can be attributed to the Retro Tram station being more economic in its space utilisation, leading with a footprint (area) which is $38.6m^2$ smaller.[8]

These design regulations specify station length, while station width relates to the number of commuters using the station during its peak occupation hour (pph/m^2).

Spatial economy refers to both the minimisation of floor area and enclosed volume. This calls for a renewed focus on anthropocentric spaces which are multifunctional, merging both functional space with the required movement spaces, simultaneously minimising its spatial use and maximising its adaptability and modularity. It requires a critical understanding of the user numbers, building function, movement circulation and minimum spatial requirements.

This process of minimising the enclosed volume can directly be translated to lowering the quantity of material use and effectively lowering carbon footprint and embodied energy of an intervention.

4.2 Simplifying structural systems

A comparison of case study roofs reveals that the energy intensity of the complex Rea Vaya station (2.36 GJ/m^2 and 179 $kgCO_2/m^2$) is 35% higher than the Retro Tram station (1.52 GJ/m^2 and 115 $kgCO_2/m^2$). This demonstrates the energy efficiency of a single continuous roof structure.

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[8] All the designs needed to adhere to SANRAL regulations and international best practice.

The Rea Vaya station is the least energy-efficient station, as it is constructed with a complex system of columns from which the wall and roof cantilever. This results in a wall-and-column structure which embodies 53% (1 832 GJ, 141.8 t CO_2) of the structure of the entire station, while the columns contribute 35% (1 187GJ, 92.9 t CO_2) to total embodied energy. A smaller, functional, wider spaced column system is utilised in the Retro Tram station, contributing only 6% (86.1GJ, 6.7 t CO_2) to the total embodied energy of this station. Structural systems should, therefore, be appropriately scaled to suit the type and size of project.

4.3 Dematerialising structural components and materials

In all of the stations, the structural systems separate the substructure of the glass envelope from the main structure and columns, leading to a duplication of structure. The Curitiba BRT station prototype dematerialises the envelope structure, using a single plane to act as both main structure and envelope substructure. This concept of dematerialisation can be extended by adding additional functions to a structure or component (Van der Ryn & Pena, 2002: 243-244), thus maximising the structure's functionality while minimising its resource consumption.

In two of the three case studies, signage towers were used to improve the legibility and identity of the stations. The Retro Tram tower contributes substantially to the energy consumption, adding 7% (103 GJ and 9 t CO_2) to the total carbon footprint and embodied energy. It is a composite tower with layers of steel and glass fixed to a precast concrete tower. However, the signage tower of MyCiti Station is a simple painted steel tower with an easily legible signboard and only adds 1% (19.6 GJ and 1.6 T CO_2) to the station's total carbon footprint and embodied energy. This illustrates the importance of designing simple structures through dematerialisation into a single entity while using homogenous materials that allow for easy fixing.

4.4 Choosing appropriate materials

An analysis of material consumption indicates that the main material used in all the stations is concrete. This accounts on average for 70% of the total mass per station. When the embodied energy contribution of each material is compared, the impact of concrete is interestingly low (see Figures 13 and 14). By contrast, the impact of steel and stainless steel is much higher, on average contributing 62% to the total embodied energy of each station.

At a micro scale, the impact of material choice becomes more evident. The station base of the Retro Tram station is 45% more energy-intensive than the MyCiti station. This can be attributed to the large amount of steel used in the base. In the Retro Tram station, steel boarding plates are bolt-fixed to a steel channel, while in the MyCiti station these edges are *in situ* cast concrete with rubber-covered boarding plates fixed on top. Although the steel boarding plates are versatile and adaptable, these constitute 20% (290 GJ) of the total embodied energy, whereas the concrete edge case only contributes 2% (34 GJ) to the MyCiti station's total energy consumption. This emphasises the importance of choosing low embodied energy materials, while taking structural implications into account.

The application of reinforced concrete must be re-evaluated. All three stations have precast concrete culverts as substructures. Although these structural systems minimise construction time, precast concrete is 22% more energy-intensive than *in situ* cast concrete (Jones, 2011b: 56-57). As the precast concrete culverts contribute an average of 43% to the total embodied energy of the substructures, *in situ* casting will lead to substantial savings.

5. Conclusion

In order to address carbon footprint and embodied energy in architecture, the study undertook a cradle to gate life-cycle assessment of three South African BRT trunk-route stations. The comparative analysis, which quantified the construction material use of each station, revealed the impact of resource-efficient design solutions. A series of conclusions have been drawn from the study and are framed as four guidelines. These guidelines address station size, structural systems and the selection and use of materials.

Furthermore, a continuous assessment and calculation of construction material use in these structures during the design process will lead to the lowering of carbon footprints and embodied energy.

In comparison to the greater BRT infrastructure systems, these carbon footprint and embodied energy savings of small BRT trunk-route stations are significant (Cui *et al*., 2010: 335). This becomes clear when applying these energy savings to an entire BRT system. During the first phase of the Rea Vaya BRT system, one hundred and fifty trunk-route stations will be built (Dlamini, 2008: 1). As the MyCiti stations are 36.5% more energy-efficient than the Rea Vaya stations, an additional fifty-four stations can be built with the same quantity of resources used in the Rea Vaya system. It is, therefore, opportune to follow the identified guidelines at the conception of a project.

The study revealed the need for more research on the development of a South African construction material carbon footprint and embodied energy calculator. It is a much needed tool to advance accurate local climate change mitigation strategies.

The study identified benchmarks and design guidelines to test new BRT station proposals, which will challenge designers to aim for low carbon and energy-efficient design solutions. These strategies will go a long way in minimising the impact of architecture and mitigate the negative effects of climate change.

Acknowledgements

Jan Hugo would like to thank David Ingham, Prof. Jannie Hugo, Ilse Hugo, Wilfried Bohm and Pieter Matthews for their advice and assistance while writing this article; ARG design, MRA architects and Ikemeleng architects for giving permission to analyse their designs, and the United Nations Development Programme (UNDP) and Global Environment Facility (GEF) for sponsoring this project.

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