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The carbon footprint and embodied energy of construction material: A comparative analysis of South African BRT stations

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Abstract

This article describes strategic design decisions that architects can make during the initial stages of a project to minimise the use of construction materials, reduce carbon emissions and increase energy efficiency. A proposed prototypical Bus Rapid Transit (BRT) station *Switch* is used as a case study. The investigation focuses on minimising the use of construction materials through an iterative design and assessment process.

This article extends an earlier study which analysed existing BRT stations in South Africa by conducting comparative life-cycle analyses (LCA). The earlier study by Hugo, Stoffberg & Barker (2012) identified a series of guidelines to inform the design of low-carbon and embodied energy BRT stations and determined a specific station, the *MyCiti* station, as the most efficient in terms of its carbon footprint and embodied energy intensity. As a result, the *MyCiti* station was identified as benchmark for future LCAs of station designs.

The *Switch* prototypical BRT station is purpose designed for the Tshwane[1] context and uses the identified guidelines (Hugo, Stoffberg & Barker, 2012) as well as carbon footprint (CF) and embodied energy (EE) of construction systems and materials as design informants generated from a study conducted by Jones (2011b). These informed material choices, use of low-carbon structural systems and integration of multifunctional station components.

A cradle-to-gate[2] life-cycle assessment compares the CF and EE of the *Switch* station and an existing South African precedent, the *MyCiti* station in Cape

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[1] Tshwane, located in the Gauteng province, is the fourth most populated metropolis in South Africa, yet covers the largest area.

[2] Cradle-to-gate refers to the energy consumption of materials that includes extraction, transportation and processing until the product leaves the manufacturing plant.

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Town. The *Switch* station is 35% and 34% (4.08 GJ/m^2 & 378.6kgCO$_2$/m^2 vs 6.28 GJ/m^2 & 574.7kgCO$_2$/m^2) more efficient than the existing *MyCiti* station, in terms of respective embodied energy intensity and carbon-footprint intensity.

This prototype is proposed as a benchmark for prospective life-cycle analyses to inform the material choice and design of future BRT stations in South Africa.

Keywords: Bus Rapid Transit stations, carbon footprint, climate change, embodied energy, life-cycle assessment, construction materials

Abstrak

Hierdie artikel bespreek strategiese besluite wat argitekte kan neem tydens die aanvanklike ontwerpsfase van 'n projek om die gebruik van konstruksie-materiaal te verminder, by te dra tot die mitigasie van klimaatsverandering en energiedoeltreffendheid te verbeter. Deur gebruik te maak van 'n voorgestelde '*Bus Rapid Transit*' (BRT) stasie *Switch*, as gevallestudie, fokus die studie op die vermindering van konstruksie-materiaal verbruik deur iteratiewe ontwerps- en hersieningsprosesse.

Die artikel brei uit op 'n vorige studie waarin bestaande BRT-stasies in Suid-Afrika geanaliseer is. Deur gebruik te maak van 'n vergelykende lewenssiklus-analise (LSA) het die studie deur Hugo, Stoffberg & Barker (2012) 'n reeks riglyne geïdentifiseer wat die ontwerp van 'n lae koolstof en ingeslote energie BRT-stasie kan inlig. Verder het die studie ook 'n spesifieke stasie, die *MyCiti*-stasie, geïdentifiseer as die mees effektiewe stasie in terme van sy koolstofinhoud en ingeslote energie intensiteit. Hierdie stasie is as normtoets vir toekomstige LSA's van stasie-ontwerpe geïdentifiseer.

Die *Switch* prototipiese stasie is spesifiek ontwerp vir die Tshwane-konteks[3] en maak gebruik van spesifieke riglyne (Hugo *et al.,* 2012) sowel as die koolstofinhoud en ingeslote energie van konstruksie-materiaal en -sisteme as ontwerpsinvloede. Hierdie koolstofinhoud en ingeslote energiewaardes bereken van 'n studie onderneem deur Jones (2011b) was die bepalende faktor vir die materiaal keuse, gebruik van lae koolstofkonstruksiesisteme en die integrasie van veeldoelige stasiekomponente.

Die '*cradle-to-gate*'-LSA[4] vergelyk die koolstofinhoud en ingeslote energie van die *Switch*-stasie met 'n bestaande Suid-Afrikaanse stasie, naamlik die *MyCiti*-stasie in Kaapstad. Die navorsing (Hugo *et al.*, 2012) onthul dat die *Switch*-stasie onderskeidelik 'n 35% en 34% (4.08 GJ/m^2 & 378.6 kgCO$_2$/m^2 vs. 6.28 GJ/m^2 & 574.7 kgCO$_2$/m^2) laer ingeslote energie en koolstofinhoudintensiteit het as die bestaande *MyCiti*-stasie.

Hierdie prototipe fokus daarop om as normtoets vir toekomstige lewensiklusanalises, die materiaal keuse en ontwerp van daaropvolgende BRT-stasies te begelei.

Sleutelwoorde: '*Bus Rapid Transit*'-stasies, ingeslote energie, klimaatsverandering, koolstofinhoud, lewensiklusanalise, boumateriale

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[3] Die Tshwane-metropool is geleë in Gauteng. Alhoewel dit slegs die vierde digste populasie huisves, beslaan dit die grootste oppervlakte van alle Suid-Afrikaanse stede.

[4] "Cradle-to-gate" stel die energieverbruik van materiale voor en sluit die ontguning, vervoer, verwerking/vervaardiging in tot by die punt waar die produk die fabriek verlaat.

1. Introduction

Global resource consumption and climate change severely impact on our cities and society[5] and are caused by a series of polluting sectors, of which transportation is one of the main contributors. Transportation pollution has steadily increased since the 1970s. It currently contributes 22% to global greenhouse gas emissions and consumes 19% of global energy consumption (Parry, Canziani, Palutikof, Van der Linden & Hanson, 2007: 105; IEA, 2010: 19; IEA 2013: 9). A further 40% increase in global carbon emissions in this sector can be expected by 2030 (IEA, 2010: 19).

Bus Rapid Transit (BRT) systems have been implemented worldwide to address the problem of increasing greenhouse gas emissions and urban air pollution (Wright & Fulton, 2005: 710-711; Vincent & Jeraam, 2006: 233; McDonnell, Ferreira & Convey, 2008: 750-751; Wöhrnschimmel, Zuk, Martinez-Villa, Cerón, Cárdenas, Rojas-Bracho & Fernández-Bremauntz, 2008: 8194, 8198-8199; Nugroho, Fujiwara & Zhang, 2010: 915, 922-923). In addition to mitigating climate change, BRT systems also promote corridor development (Pienaar, Van Den Berg & Motuba, 2007: 426; Wright & Hook, 2007: 87; Deng & Nelson, 2013: 111), improve access and passenger safety (Pienaar, Van Den Berg & Motuba, 2007: 426; Advanced Logistics Group, 2008: 15; Deng & Nelson, 2013: 109), and increase mobility in urban environments (Advanced Logistics Group, 2008: 2, 4; Deng & Nelson, 2013: 109-110).

This article forms part of a larger research project[6] that focuses on architectural design and its potential to mitigate climate change (Hugo, 2010). Materials selection in architecture is compared as a potential variable to minimise embodied energy (EE),[7] carbon

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[5] Various studies have revealed increases in ambient temperatures, flooding, rising sea level and extreme weather conditions aggravated by climate change. These negatively impact the general living standards, health, economy and resilience of inhabitants within cities globally (Sherbinin, Schiller & Pulsipher, 2007: 39-40; Ramos & Kahla, 2009: 262; Walker & King, 2008: 41-68; Roaf, Crichton & Nicol, 2009: 16-17, 58-90, 134-147; Lui & Deng, 2011: 188; Vijayavenkatarama, Iniyan & Goic, 2012: 879-882, 884).

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

[7] Embodied energy refers to the total amount of energy (Joule) used during the manufacture of a good; this is accepted as embodied in the good (Irurah, 1997: 10).

footprint (CF)[8] and energy efficiency (Hugo, 2010; Hugo *et al.,* 2012; Basbagil, Flager, Lepech & Fischer, 2013: 88-89).

In the light of the conclusions drawn by Cui, Niu, Wang, Zhang, Gao & Lin (2010), who question the energy efficiency of BRT infrastructure, and as BRT systems are currently planned and implemented in a number of South African cities, the study addresses energy efficiency in BRT infrastructure, with particular focus on BRT trunk-route stations (Hugo, 2010; Hugo *et al.,* 2012).

1.1 Objective

This article aims to improve the design of BRT trunk-route stations by using CF and EE as informants and a set of guidelines identified in a previous study (Hugo *et al.*, 2012). This earlier LCA study (Hugo *et al.*, 2012) critically analysed the CF and EE of selected South African BRT stations and generated and identified design guidelines. The current study sets out to test these design principles and methods. Using a single comparable unit from the previous study, namely the BRT stations, allows assessment and quantification of the final design outcome against existing precedents. The proposed *Switch* station aims to specifically act as benchmark for the design of future BRT stations, while generally promoting embodied carbon and energy accountability in the built environment.

1.2 Rationale

Although various international LCA studies analyse a variety of building types (Mithraratne & Vale, 2003; Thormark, 2006; Rai, Sodagar, Fieldson & Hu, 2011; Kofoworola & Gheewala, 2009; Ramesh, Prakash & Shukla, 2012; Varun, Sharma, Shree & Nautiyal, 2012), little research has focused on the environmental efficiency of transportation buildings. In addition, substantial international studies have proved the effectiveness of the BRT systems in mitigating climate change in terms of vehicle designs, fuel consumption and air-pollution minimisation (Wright & Fulton, 2005; Vincent & Jeraam, 2006; McDonnell *et al.,* 2008, Wöhrnschimmel *et al.*, 2008, Nugroho *et al.*, 2010). Yet only one study, undertaken by Cui *et al.* (2010), highlights the high CF and EE inputs of a typical BRT system. In response, this study focuses on the use of construction material of BRT infrastructure, in particular the BRT trunk-route station.

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[8] Carbon footprint refers to the carbon equivalent (CO2eq) emissions emitted during the product's extraction and processing (Jones, 2011a: 1).

The study acknowledges that the modal change from private to public transport use enabled by BRT systems fully justifies their implementation in terms of reducing CO_2 emissions. Furthermore, BRT systems generally require extensive infrastructure, demanding high CF and EE inputs, increasingly more than what is required for trunk-route stations. The value of this research does not necessarily reside in the magnitude of emission reduction in comparison to the larger BRT system. It resides in illustrating that the seemingly conventional choices made during infrastructure development could be positively challenged to resolutely reduce environmental impacts and enhance an environmentally conscious design ethos.

As both the Tshwane and Cape Town BRT systems' first phases require 48 and 43 trunk-route stations, respectively, with more to follow in subsequent phases (Advanced Logistics Group, 2008: 9; City of Cape Town, 2010: 9, 36), any energy savings made in each station will benefit the sustainability of the ever-expanding network, providing design, construction and maintenance benefits over time. At one end of the scale, the study aims to provide 'energy-efficient' design guidelines for future South African BRT stations and, at the other end of the scale, by implication, strategic design decisions for other impending architectural projects.

The current research project's core strength resides in the conclusions drawn from the comparative analysis as example of the environmental impact that definitive choices of alternative materials, design approaches, principles and philosophies have on one key component of the BRT system. This perception illustrates that, should the design of the BRT system follow similar principles in mitigating climate change and reducing its carbon footprint, then substantial reductions in carbon dioxide emissions could be obtained for future decades.

This article assumes that any saving in carbon emissions is a justification for research and reporting. Baseline data and reporting, as *Datum* projects, are integral for the development and pursuit of higher tiers in research projects (Stocker, Qin, Plattner, Tignor, Allen, Boschung, Nauels, Xia, Bex & Midgley, 2013: 129), from which fundamental arguments and methods could be derived. To this end, this article builds on previous research by the same authors' attempts to address serious shortcomings in available CF and EE data in both South Africa and Africa (Abanda, Nkeng, Tah, Ohandja & Manjia, 2014: 20-21). It also provides a basis for further research and comment by fellow researchers, as witnessed by the previous article by Hugo *et al.* (2012) that was constructively integrated in a study by Abanda *et al.* (2014).

This current study is based on a previous comparative LCA study (Hugo *et al*., 2012), which tested one proposed and two existing South African BRT trunk-route stations regarding the CF and EE intensity of their construction material use. The study set out to establish an objective conclusion by generating a single comparable figure for all the different designs. Although it may have disregarded qualitative aspects, by setting delimitations and assumptions beforehand, it objectively collates different subjects enabling their comparison (Fay, Treloar & Lyer-Raniga, 2000: 32, 36; Rai *et al.,* 2011: 2271-2273).

Using the BRT trunk-route stations as modular units provided a unique opportunity for a comparative LCA study of different designs (Hugo *et al.,* 2012). From the previous study undertaken by Hugo *et al.* (2012) an existing BRT station, *MyCiti* station, was benchmarked as the most CF- and EE-efficient solution. In addition, the preceding study also established a set of guidelines to improve the CF and EE efficiency of future design.

The guidelines were tested and utilised in the design of a prototypical BRT station, namely *Switch.* Using these guidelines at the conception of the project, as suggested by Basbagil *et al.* (2013), and iteratively analysing the design's CF and EE intensity, the *Switch* prototype proved to contain a lower CF and EE intensity than the *MyCiti* station. This comparative LCA study aims to prove that a CF and EE improvement can be made with the *Switch* prototype by using readily available and widely used South African construction materials.

2. Methodology

2.1 The study area

The BRT system of the City of Tshwane was used as the basis for the study. This BRT system is meant to address the growing problem of inefficient public transport and restricted mobility within the city (Olivier, 2009: 4). It will link the isolated suburbs on the outskirts of Tshwane with each other and with the city centre (Figure 1).

The phased implementation of the BRT system will commence with Route One that links Mabopane, a suburb to the north, with Pretoria Main Station (Advanced Logistics Group, 2008: 5-6) and Route Two which is planned to link the eastern suburb, Mamelodi, with Bel Ombre station in the city centre (Advanced Logistics Group, 2008: 69). The *Switch* station prototype was specifically designed for Route One, which predominantly runs in a north/south direction (Figure 1) (Advanced Logistics Group, 2008: 69) and responds to a context ranging from dense urban environments to lower scaled suburbs lacking basic infrastructure.

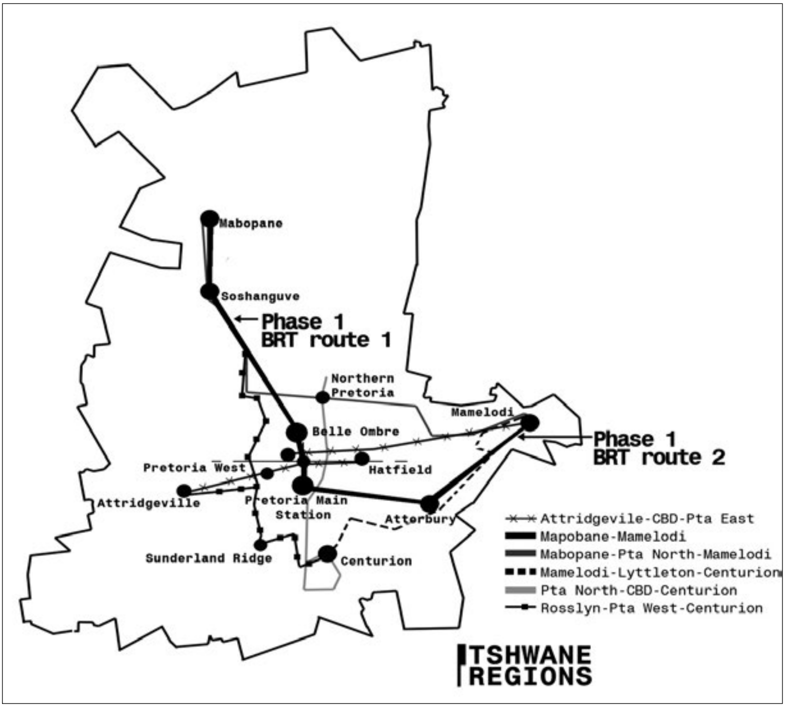

Figure 1: Planned route structure for Tshwane

Source: Hugo, 2010: adapted from a presentation by Olivier, K., BRT presentation: Salvokop Workshop 9 February 2009

2.2 Establishing station design parameters

The *Switch* station has been designed according to the South African National Road Agency Limited (SANRAL)[9] regulations[10] and international best practice, as set out by *The Tshwane Bus Rapid Transit Operational Plan* (Advanced Logistics Group, 2008) and *Bus Rapid Transit Guide* (Wright & Hook, 2007).

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[9] South African National Roads Agency Limited (SANRAL) is an independent statutory company authorised to finance, maintain, manage and improve the South African national road system.

[10] These design regulations specify the station's length, while station's width relates to the quantity of commuters using the station during its peak occupation hour.

The enclosed station requires that it be raised 940mm[11] above ground level and located on the road median (Advanced Logistics Group, 2008: 78). It should accommodate 6 400 commuters per hour (Advanced Logistics Group, 2008: 76), sized according to design parameters provided by Lloyd Wright and Walter Hook (*Bus Rapid Transit Guide* 2007). The prototype was sized to the minimum required length for a double-bay station (Advanced Logistics Group, 2008: 78) with the option of adding or removing a bay (Figure 5). The station (Figure 6) also accommodates busses running in opposite directions (Advanced Logistics Group, 2008: 78).

2.3 The design process

2.3.1 Design guidelines

The low-carbon design objective resulted in a specific station form, structural system and material use. In order to substantially improve a design's CF and EE efficiency, pertinent decisions must be made during the initial design phases, rather than implementing negligible changes on the final design resulting in small CF and EE improvements (Thormark, 2006: 1025; Cui *et al.*, 2010: 333, 335; Basbagil *et al.,* 2013: 81-82). Therefore, it is important to focus on verifiable and influential design principles to guide the design before it has been fully defined. In this study, initial design decisions were informed by a design framework developed in a previous study (Hugo *et al.,* 2012) and summarised in the following four strategies:

- Minimising the internal volume of the station to achieve spatial economy.
- Dematerialisation and scaling of building form and structure to improve resource efficiency (Van Der Ryn & Pena, 2002: 243-244).
- Dematerialising the station components by assigning multiple functions to these components (Van Der Ryn & Pena, 2002: 243-244; GBCSA, 2008: 261).
- Using low-carbon structural technologies and materials.

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[11] At the time of the study, the required height was 940mm above ground level; subsequently, the Tshwane BRT system lowered the required station base level to 340mm (Venter, 2012: 24). The preceding station base height was retained for comparison purposes.

2.3.2 Iterative CF and EE testing process

A series of design iterations was conducted to investigate and test the CF and EE intensity of various structural systems and materials for the design. "Embodied Carbon. The Inventory of Carbon and Energy (ICE)" database[12] (Jones, 2011b: 33-169) was used to compare the different design solutions. The identification and application of the CF and EE coefficient inventory is discussed in section 2.4. By assessing the structural attributes of the different structural systems, their CF and EE efficiency revealed a series of efficient solutions which improved the final design's performance in terms of its CF and EE.

Although the main objective of the study was to minimise the CF and EE of the structure, achieving energy autonomy[13] was an important secondary objective. Strategies of on-site energy resources harvesting and minimising energy consumption, using passive heating and cooling technologies and natural daylighting strategies were iteratively tested and analysed using Ecotect®[14].

2.4 Conducting the comparative life-cycle analysis

The final LCA compared the CF and EE of the *Switch* station design (Figure 4) with an existing precedent, the *MyCiti* station in Cape Town, designed by ARG Design (Figure 2).

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[12] The ICE Database, developed by G. Hammond and C. Jones at the University of Bath, is a comprehensive inventory defining the CF and EE of a wide range of building materials. It was specifically developed for the built environment to assist with embodied carbon and energy accountability and guide the industry in an effort to minimise their associated CF and EE (Jones, 2011b: 44-45).

[13] Autonomous can be defined as a building "operating independently of any inputs except those of its immediate environment" (Vale & Vale, 1975: 7).

[14] The study made use of an environmental analysis tool Ecotect®, distributed by Autodesk. It was used to simulate the thermal comfort and heat load within the kiosk by testing the thermal performance of different wall materials and the impact of various positions of the kiosk within the station.

Figure 2: *MyCiti* station, Granger Bay Station, Greenpoint, Cape Town
Source: Hugo, 2010: own picture

2.4.1 Choosing an appropriate carbon-footprint and embodied energy inventory

LCA studies use a wide range of CF and EE data[15] pertaining to a variety of materials and processes in order to quantify their respective environmental impacts (Fay *et al*, 2000: 32). It is often impossible to quantify all energy or carbon inputs which, to some extent, leads to uncertainty in derived coefficient[16] accuracy (Abanda *et al.,* 2014: 24). Yet, through a process of data identification and delimitation, LCA studies aim to develop CF or EE inventories[17] which convey, as accurately and precisely as possible, the primary data applied to these studies, thus limiting analysis discrepancies.

These studies usually employ one of the following two methods: the process and the input-output analysis. The process analysis collects all downstream energy inputs related to a certain project and quantifies its collective impact (Fay *et al.,* 2000: 33). This is very accurate, but can be a very difficult and time-consuming process for complex products such as buildings. The input-output process uses the national statistics of economic exchange between different sectors (Fay *et al.*, 2000: 33) in order to measure energy consumption. This is theoretically a more comprehensive method, but it is not site specific.

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[15] Data refers to the primary and secondary research and analyses used to quantify the CF and EE figures of specific materials (Jones, 2011b: 46).

[16] Coefficients represent the derived values equating the CF and EE of specific materials (Jones, 2011b: 46-47).

[17] An inventory is a collection of coefficients covering a variety of materials (Jones, 2011b: 46-47).

Both these methods proved to be unsuccessful for this project. During the process analysis, the primary data collected on CF and EE of materials from South African manufacturers proved to be either insufficient or did not follow similar analysis standards, thus distorting the inventory coefficient comparison as well as limiting the scope of materials analysed. Similarly, the input-output analysis was unsuccessful due to the results published by Statistics South Africa. The highly aggregated input-output tables do not differentiate between the different sectors in the construction industry, thus limiting any interpretation thereof.

Many studies overcome this quandary by collating different CF and EE coefficients or inventories from a variety of previous studies or analyses (Kofoworala & Gheewala, 2009; Cui *et al*., 2010; Ramesh *et al.*, 2012; Varun *et al.*, 2012). This proves to be problematic as the delimitation of data scope collected from primary and secondary data sources could differ, causing coefficient discrepancies.

As a result, a number of other studies (Verbeeck & Hens, 2010; Basbagil *et al.*, 2013; Abanda *et al.,* 2014) have opted to use existing inventories that cover a broad scope of materials analysed across identical life cycles. This current study applied a similar approach, but due to the lack of local South African primary data available (Abanda *et al.,* 2014: 20-21), it was decided to make use of a UK-based inventory, the "Embodied Carbon. The Inventory of Carbon and Energy (ICE)" (Jones, 2011b: 33-169).

The ICE inventory was developed using a three-stage process. First, secondary data was collected from peer-reviewed papers, technical reports and monographs. Secondly, all the data was rated according to criteria checking whether the research complied with international LCA standards, age of the data presented, whether clear analysis boundaries were defined, whether the studies were conducted and whether CF figures were included. Only current, well-defined and ISO 14040/44 compliant data were selected. Finally, a single median coefficient depicting the CF and EE of each material (Jones 2011b: 47-48) was derived from the collected data.

The comparative LCA study utilised the same CF and EE inventory used in the previous study (Hugo *et al.,* 2012) to ensure an impartial interpretation of the two case studies. The use of a single CF and EE inventory ensures the objectivity of the comparison study and allows one to replicate the analysis in new case studies. It covers a substantial range of materials, calculating both the CF and EE of each material. Yet the interpretation of the results is conducted in a comparative manner, ensuring that the conclusions drawn are only percentages and not actual CF and EE values. Therefore, any discrepancies in the primary data will reflect on both case studies, thus limiting the likelihood of misinterpretation. In addition, to ensure that the final interpretation of the LCA results is as accurate as possible, the CF and EE inventory covers the same cradle-to-gate life cycle as that used in the LCA study (Jones 2011b: 49).

The CF and EE of the *Switch* and *MyCiti* stations were calculated by assessing the material use of each design. The analysis calculated the CF[2] and EE[3], while carbon-footprint intensity (CFI)[21] and embodied energy intensity (EEI)[18] were used as comparable variables. This followed a process of measuring and analysing the total volume of materials used and applying the following calculation:

$M_{volume} \times M_{density} = M_{weight}$ M – Specific material type
$M_{weight} \times EE_{coefficient} = EE_{total}$ EE – Embodied energy
$M_{weight} \times CF_{coefficient} = CF_{total}$ CF – Carbon footprint
$EE_{total} \div \text{Floor area} = EEI$ EEI – Embodied energy intensity (per m^2)
$CF_{total} \div \text{Floor area} = CFI$ CFI – Carbon footprint intensity (per m^2)

2.4.2 Defining the life-cycle analysis period

Although numerous international LCAs focus on operational energy consumption of architecture, the recent increase in energy-efficient buildings has shifted the attention to embodied energy and material use in architecture (Thormark, 2006: 1025; Jones, 2011: 15; Rai *et al.,* 2011: 2272; Ambanda *et al.,* 2014: 20).

This study primarily assessed the CF and EE of construction materials[19] used within the BRT stations for the cradle-to-gate period[1]. Transportation and on-site construction energies have been excluded as negligible; respectively, less than 1% for material sourced within 400 km and less than 3% of the total embodied energy over a 20-year period (Mithraratne & Vale, 2003: 488, 489; Cole, 1999: 343, 347; Ramesh *et al*., 2012: 160).

Kofoworola & Gheewala (2009) identify the bulk of operational energy consumption to be attributed to artificial lighting and air conditioning. Only the ticket offices in BRT stations utilise air conditioning and artificial lighting; the ticket office of the *Switch* station has been designed to use alternative energy-efficient technologies, and the remaining stations use minimal artificial lighting. Therefore, the operational

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[18] The energy/carbon intensity quantifies the carbon or energy embodied per square meter and is used to compare the different station designs.

[19] Conduiting, wiring and electrical equipment were excluded from the analysis.

energy consumption is considerably less than conventional building types. This is confirmed by an analysis which revealed that, over a 20-year period, it embodies 28% (158 848 vs 543 110 kWh) of the total life-cycle energy consumption of the *Switch* station. As the *Switch* station uses renewable energy generated by photovoltaic panels, there are zero operational CO_2 emissions produced over a 20-year period (0.0 t CO_2 vs 128,3 t CO_2).[20]

The operation energy consumption only exceeds the embodied energy after 48.3 years, emphasising the importance of minimising the construction material used in these stations. Within this period, large portions of the station would be replaced due to maintenance and re-branding; therefore, one can conclude that the operational energy consumption will never exceed the embodied energy of the station.

The embodied energy of the *Switch* station is 1 491 115 MJ

3.6 MJ = 1kWh (Thompson & Taylor 2008: 59)

1 383 346 MJ ÷ 3.6 = 384 262.8 kWh

The daily energy consumption of the *Switch* station is 23.5 kWh

384 262.8 kWh ÷ 21.76 kWh/day = 17 659 days

17 625.5 ÷ 365 = 48.33 years

The embodied energy of the Switch translates into 48.33 years' energy consumption.

2.4.3 Elements of the comparative life-cycle analyses

The final LCA compared three aspects. The entire station was quantified to determine the overall CFI and EEI as well as each station's spatial economy.

Secondly, different station components were compared to quantify their respective CFI and EEI values and impacts on the entire built form:

1. Station base.
2. Wall.
3. Roof structure.
4. Signage and handrails (Figure 3).[21]

Finally, the overall material use was calculated to provide insight into efficient material choices and their impact on the structural systems used in the station designs.

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[20] The CF and EE of all electrical equipment, including photovoltaic panels, were excluded from the study.

[21] Note that *wall* includes the vertical wall structure and glazing, whereas *signage* and *handrails* include the signage towers positioned outside the stations.

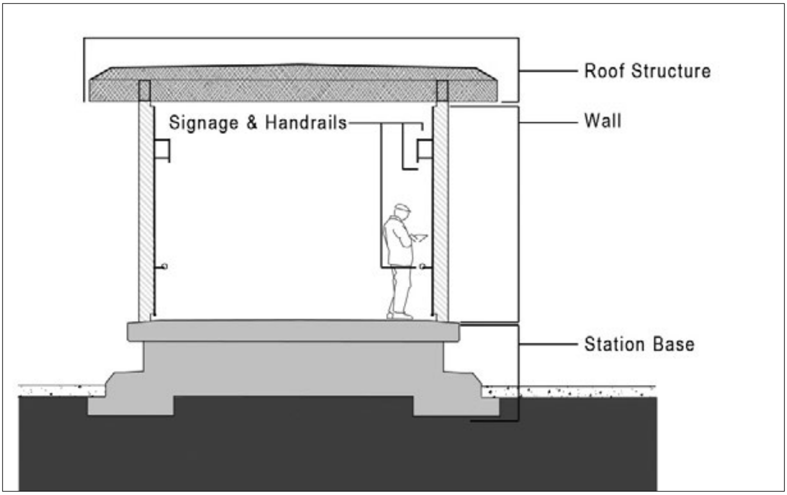


Figure 3: Structural components of BRT stations
Source: Hugo *et al.*, 2012: 28

3. Description of the final design

The *Switch* station is a linear, low-scaled building on a concrete base with slanted steel-framed walls, clad with steel mesh and Polymethyl Methacrylate (PMMA, Perspex) glazing. A steeply sloping roof with vertical slatted solar screens articulates the entrance (Figures 4, 5 and 7). A continuous lightweight steel roof on slanted steel portal frames is extended from the entrance roof and covers the remainder of the station (Figures 5 and 6).

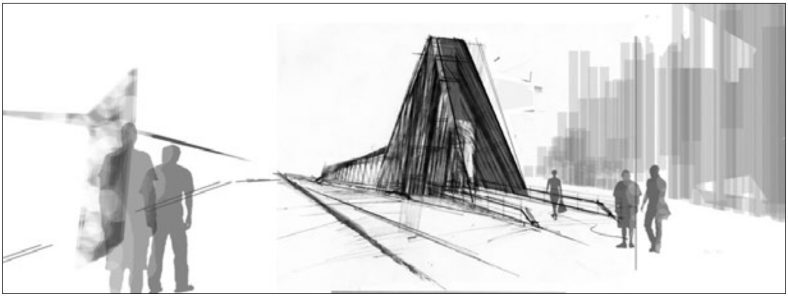


Figure 4: Conceptual sketch of *Switch* station, using entrance structure as landmark
Source: Hugo, 2011: own drawing

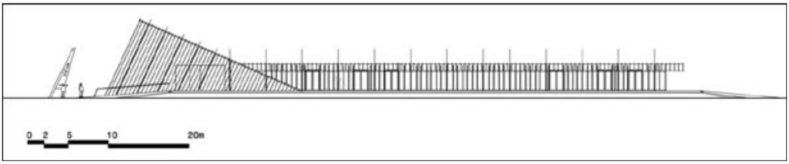


Figure 5: Elevation of *Switch* station
Source: Hugo, 2011: own elevation

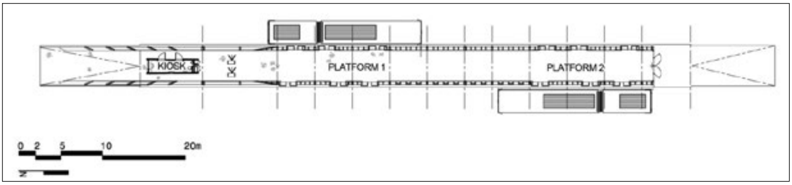


Figure 6: Plan of *Switch* station
Source: Hugo, 2011: own plan

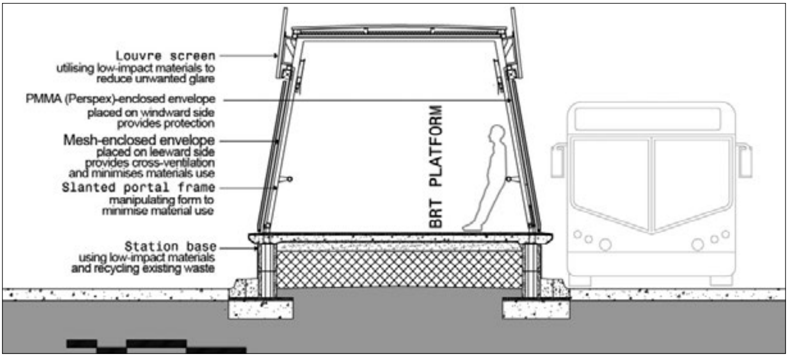
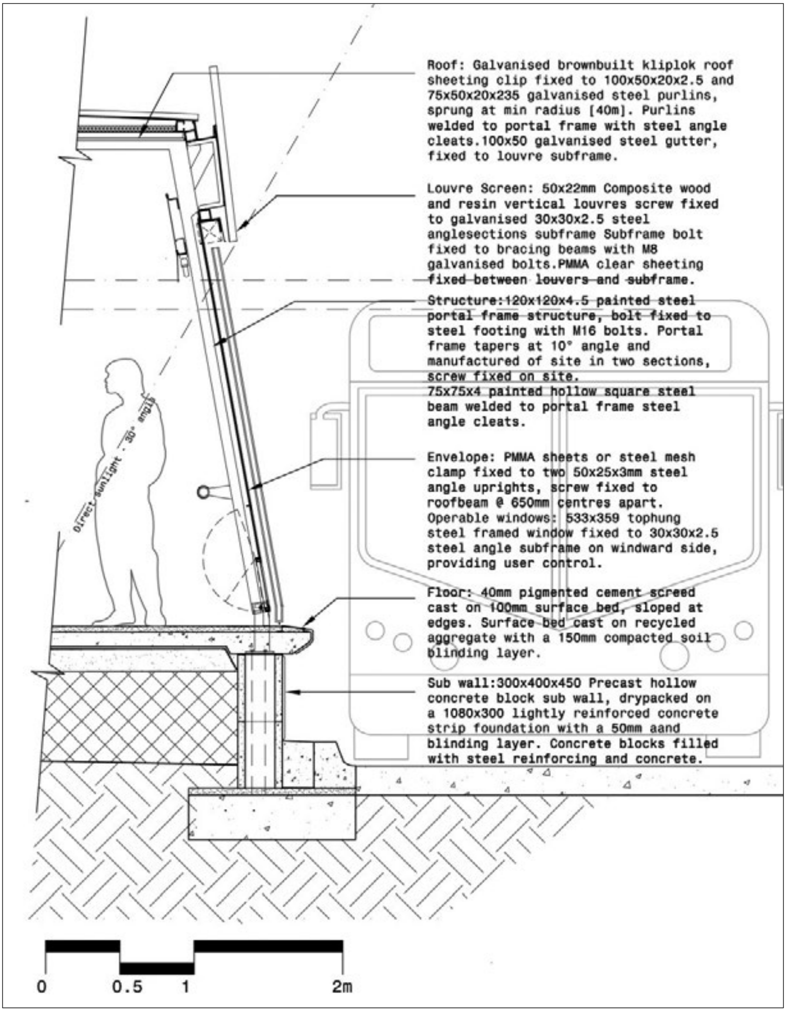


Figure 7: Typical section
Source: Hugo, 2011: own section



Roof: Galvanised brownbuilt kliplok roof sheeting clip fixed to 100x50x20x2.5 and 75x50x20x235 galvanised steel purlins, sprung at min radius [40m]. Purlins welded to portal frame with steel angle cleats.100x50 galvanised steel gutter, fixed to louvre subframe.

Louvre Screen: 50x22mm Composite wood and resin vertical louvres screw fixed to galvanised 30x30x2.5 steel anglesections subframe Subframe bolt fixed to bracing beams with M8 galvanised bolts.PMMA clear sheeting fixed between louvers and subframe.

Structure:120x120x4.5 painted steel portal frame structure, bolt fixed to steel footing with M16 bolts. Portal frame tapers at 10° angle and manufactured of site in two sections, screw fixed on site.
75x75x4 painted hollow square steel beam welded to portal frame steel angle cleats.

Envelope: PMMA sheets or steel mesh clamp fixed to two 50x25x3mm steel angle uprights, screw fixed to roofbeam @ 650mm centres apart.
Operable windows: 533x359 tophung steel framed window fixed to 30x30x2.5 steel angle subframe on windward side, providing user control.

Floor: 40mm pigmented cement screed cast on 100mm surface bed, sloped at edges. Surface bed cast on recycled aggregate with a 150mm compacted soil blinding layer.

Sub wall:300x400x450 Precast hollow concrete block sub wall, drypacked on a 1080x300 lightly reinforced concrete strip foundation with a 50mm aand blinding layer. Concrete blocks filled with steel reinforcing and concrete.

Figure 8: Detailed section through station
Source: Hugo, 2011: own detailed section

4. Results

4.1 Spatial economy by minimising internal volume

Spatial economy refers to minimising both volume and floor area. As the floor area of a BRT station has to prescribe to specific SANRAL regulations, little improvement can be made in this regard. Therefore, the study aims to reduce the internal volume in order to minimise material usage.

A 20.5m^2 reduction in floor area has been achieved by restricting the size of the enclosed waiting space while still providing adequate circulation space for the commuters. This led to a CF and EE saving of 9.5% (165.3 GJ & 12 t CO_2 vs 181 GJ & 13.1 t CO_2) of the wall and roof structure (Figures 5 and 6).

The floor-to-ceiling height of the station has been reduced to the lowest permissible height, while retaining a comfortable indoor environment to accommodate BRT bus clearances. The elevated entrance structure improves legibility, while the compact station form relates comfortably to the immediate environment (Figures 5 and 7).

4.2 Dematerialisation to optimise efficiency of station form and structure

The process of dematerialising the station form and structure entails minimising it, critically analysing and calculating the impact of minimisation on the station's structure, construction material use and spatial economy. It requires an understanding of the building type, function and footprint, its impact on the urban context, and its value in the urban hierarchy of building typologies. The structural system and station envelope were reduced to the simplest possible form to suit the functional and structural requirements. A simple robust portal frame structural system is used to reduce footprint and minimise the required structural spans. All secondary structural systems and station components are simplified to the bare essentials.

To address resource efficiency, the station walls are slanted to maximise floor area, while limiting enclosing material usage and minimising overhead space above the commuters (Figure 7). By slanting the portal frame at 10 degrees, the effective span is shortened (Figures 7 and 8), saving 17% of the primary steel structure and minimising the number of steel purlins required (Hugo, 2010: 279).

The envelope design collapses the robust main structure (portal frames) and secondary wall structure into a single entity, thus improving on existing precedents (Hugo *et al.*, 2012: 30-32). By fixing the steel-angled studs to the steel crossbeams and primary supports, the structure and enclosing envelopes are integrated into the same plane (Figure 8). The integrated structure and envelope saves 37% in terms of CFI (50.9 vs 80.0 $kgCO_2/m^2$) and 25% in terms of EEI (920.9

vs 1 232.9 MJ/m^2) compared to the typical South African BRT station designs analysed by Hugo *et al.*(2012).

A single continuous lightweight steel roof (which covers the entire station) is fixed to a steel portal frame system which is, in turn, fixed to the substructure at 4.5m intervals (Figures 5 and 7). Lateral steel square section beams are welded on site onto the pre-manufactured portal frames. The station building is stabilised by a diagonally formed entrance structure (Figure 5) which removed the need for additional bracing structures, saving 8% (513.9 kgCO_2 and 7 075 MJ) of the total CF and EE of the main structure.

4.3 Dematerialisation by developing multifunctional components

Three multifunctional components are utilised to improve the *Switch* station's resource efficiency. The station's steeply sloping entrance roof protects the user within, acts as a landmark and harvests photovoltaic (PV) energy (Figure 5). The slope of the entrance roof was informed by the specific angle for the optimum use of PV panels in Tshwane which eliminates the need for additional fixing structures for the panels (Figure 5).

The station base acts as an energy and water resource store, while securely containing sensitive electronic equipment. The front section of the station base houses batteries and an inverter for the photovoltaic systems as well as rainwater-harvesting tanks. A large portion (56%) of the waiting area is filled with recycled aggregate with an *in situ* cast concrete surface bed on top. A 22m^3 rock (thermal energy) store draws air through the substructure to control the indoor environment of the kiosk. The rock store will provide 1.5kW cooling and 2kW heating energy by means of night ventilation and solar energy strategies, respectively. Although the analysis excluded conduiting, electrical equipment and fittings, as well as building services, the CF and EE of the rock store are included as they have significant structural implications on the design. Because the rock store functions as both structure and indoor environmental control mechanism, its exclusion from the LCA study would compromise the final comparison between case studies.[22]

A single building envelope functions as enclosure, ventilation skin and access control. Two independent membranes enclose the station volume (Figure 7). The predominant windward side (usually east) is

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[22] All electrical equipment and ducting required to ventilate the rock store have been excluded.

enclosed with PMMA sheeting fixed to a steel subframe to provide shelter during poor weather. Small operable windows, which can be controlled by the commuters themselves, are fixed on the windward side to allow for ventilation if needed. The leeward side is enclosed with zinc-coated steel mesh to ensure good cross-ventilation, while still regulating access and providing safety.

4.4 Material choices

Low-carbon footprint and embodied energy-intensive materials have been identified and selected through an iterative simulation process. The design proposes minimal use of precast concrete and steel, while extensively using recycled materials such as aggregate and composite timber and resin slats.

In the previous study, precast concrete culverts in the station base were identified as energy-intensive components contributing, on average, 38% to the total CF and EE (Hugo *et al.,* 2012: 36-37). The *Switch* station base is constructed of precast (300x300x450mm) hollow soil/cement blocks, dry-packed and filled with reinforced concrete, functioning as both subwalls and permanent shuttering (Figures 7 and 8). Ensuring that the base can withstand extensive lateral forces, this new method uses less energy-intensive precast concrete (Jones, 2011a: 56-57) and saves 51% and 53%, respectively (130.3 $kgCO_2/m^2$ and 1 078.7 $MJ.m^2$ vs 268.2 $kgCO_2/m^2$ and 2 330.8 MJ/m^2).

Although the PMMA cladding to the windward envelope of the station (Figure 7) is used as a robust translucent material, it is more energy intensive than glass (2,73 $kgCO_2/kg$ and 80,5 MJ/kg vs 30 $kgCO_2/kg$ and 0,86 MJ/kg),[23] but 200 times stronger (Wegelen, 2006: 9.7; Jones, 2011b: 58, 61). To minimise potential damage to the PMMA, the sheets are recessed behind the handrail or steel balustrade. Although the use of zinc-coated steel mesh screen on the leeward edge of the station saves 13% (329 MJ/m^2 vs 377 MJ/m^2) embodied energy, it increases the carbon footprint by 48% (23.$kgCO_2/m^2$ vs 15.5 $kgCO_2/m^2$) when compared to using PMMA sheeting on both sides of the station (Figure 7).

As large portions of the translucent station envelope faces an east/west direction, external composite timber and resin solar screens protect the indoor environment from direct solar radiation and uncomfortable glare (Figure 8). This adds only 4% (58 987 MJ and 2 526,8 $kgCO_2$) to

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[23] The CF and EE coefficient for glass was adapted to accommodate two layers of glass laminated with an imported PMB layer, thus doubling the value reported in the Jones study (2011b).

the total embodied energy and reduces uncomfortable glare by 46% in winter and 49% in summer.[24] The slatted screens are made from solid composite sections which constitute 50% recycled wood fibres and 50% Polyethelyne binder that are UV resistant and do not require extensive maintenance (Envirodeck, 2010: 1).

Painted steel handrails and a soil/cement block wall[25] kiosk minimises the use of energy-intensive stainless steel (Hugo *et al.,* 2012: 41-42) seen in existing BRT stations .Taking a 20-year maintenance period into account, the painted steel handrails[26] save 70% on CF (1 003.6 vs 3 251.8 kgCO_2) and 45% on EE (16 474 vs 29 980 MJ).

Substituting the stainless steel envelope of the kiosk with soil/cement bricks achieves a further saving of 97% for CF (489 vs 15 316 kgCO_2) and EE (4 197 vs 145 172 MJ). The concrete blocks improve the kiosk's internal thermal comfort and its deep-set position within the station envelope minimizes excess solar heat gain in summer.

The station floor is finished with a 40mm pigmented cement screed. Using a pigmented screed as an alternative to ceramic tiles leads to an immediate EE saving of 76% (21 892 vs 89 543 MJ) and CF saving of 46% (3 503 vs 6 600 kgCO_2) for the same floor area. However, taking the service life period[27] of both floor finishes into account proves otherwise. Over a 20-year period, the CF of a pigmented screed is increased by 6%, but its EE is still lower, embodying only 49% compared to that of ceramic tiles. It is important to note that, over a much longer time period, the tiled floor finish becomes increasingly more efficient.

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[24] The percentage of glare control was calculated between the hours of 8:00 and 18:00 for both the summer and winter solstices. The study made use of an environmental analysis tool called Ecotect®, distributed by Autodesk, in order to simulate daylighting levels and distribution within the *Switch* station.

[25] Some cities insist on using bullet-proof kiosks – this was not researched in the current study and the kiosk's designs were excluded from all LCA analyses.

[26] Maintenance included three new layers of paint every 5 years.

[27] The service life period of a pigmented cement screed has been assumed to be 10 years (Infotile, 2013: 1). Due to the lack of information available on the durability of pigmented concrete screeds, the information supplied by Infotile (2013) was used, namely a life expectancy of 25 years for stained concrete and 10 years for epoxy resin floor finish. The service life of tiles was assumed to be 30 years as shown in the study by Mithraratne & Vale (2003).

5. Discussion

A cradle-to-gate LCA has been made of the *Switch* and the *MyCiti* stations and the findings are summarised in Table 1. In a previous LCA study (Hugo *et al.*, 2012), comparing two existing stations and one proposed South African BRT station, the *MyCiti* station has been benchmarked as the most efficient station in terms of its CFI and EEI. Therefore, the *MyCiti* station was used as comparable modular unit for this LCA, as both stations function similarly and followed congruent spatial regulations.[8] Both case studies differ in overall weight and floor area, as the *Switch* station accommodates four bus berths and the *MyCiti* only two (Figures 9 and 10); the overall analysis used their respective CFI and EEI figures as comparable units.

Table 1: Results of the life-cycle analysis of the two case studies

	Switch prototype				MyCiti station			
	Element total				Element total			
Station component	EE – MJ		CF – kgCO$_2$		EE – MJ		CF – kgCO$_2$	
Base								
Total	743 213	MJ	86 417	CO$_2$	565 207	MJ	63 773	CO$_2$
EI/CI	2 192	MJ/m^2	255	CO$_2$/m^2	2 869	MJ/m^2	324	CO$_2$/m^2
Wall								
Total	447 259	MJ	27 072	CO$_2$	405 195	MJ	28 332	CO$_2$
EI/CI	1 319	MJ/m^2	80	CO$_2$/m^2	2 057	MJ/m^2	135	CO$_2$/m^2
Roof structure								
Total	90 806	MJ	8 357	CO$_2$	189 321	MJ	13 225	CO$_2$
EI/CI	268	MJ/m^2	25	CO$_2$/m^2	961	MJ/m^2	62	CO$_2$/m^2
Handrail and signage								
Total	102 068	MJ	6 486	CO$_2$	77 971	MJ	7 882	CO$_2$
EI/CI	301	MJ/m^2	19	CO$_2$/m^2	396	MJ/m^2	40	CO$_2$/m^2
Total weight	772 457	kg			351 976	kg		
Total	1 383 345	MJ	128 332	CO$_2$	1 237 693	MJ	113 212	CO$_2$
	1 383.35	GJ	128.33	tCO$_2$	1 237.70	GJ	113.20	tCO$_2$
Floor area	339	m^2	339	m^2	197	m^2	197	m^2
EEI / CFI	4 080.66	MJ/m^2	378.60	CO$_2$/m^2	6 282.71	MJ/m^2	574.68	CO$_2$/m^2

Abbreviations: EE – Embodied energy; CF – Carbon footprint; EEI – Embodied energy intensity; CFI – Carbon footprint intensity
Energy intensity: Megajoules per square meter (MJ/m^2).
Carbon footprint intensity: Kilogram carbon per square meter (kgCO$_2$/m^2).
Excluded elements: Conduiting, wiring, kiosk, including all hardware, electrical equipment, door frames and door.

Source: Hugo, 2012: own table

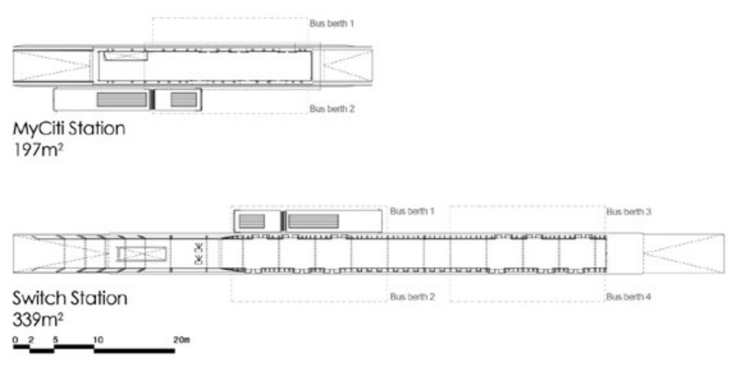

Figure 9: Comparative schematic plans of case studies

Source: Hugo, 2013. Sections redrawn from information supplied by architects; Rendall, 2011: Personal communication

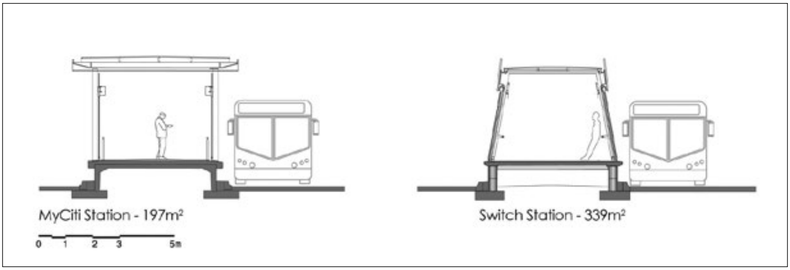

Figure 10: Comparative schematic sections of case studies

Source: Hugo, 2013. Sections redrawn from information supplied by architects; Rendall, 2011: Personal communication

5.1 Overall structure

The total EE of the *MyCiti* station is 1 237.7 GJ and CF is 113.2 t CO_2 with an EEI of 6.28 GJ/m². Comparatively, the *Switch* prototype embodies an overall EE of 1 383.3 GJ and CF of 128.3 t CO_2. However, its CFI and EEI is 35% lower than that of the *MyCiti* station at 4.08 GJ/m². Table 1 summarises the full comparison. Figures 11 and 12 indicate the difference in carbon and energy intensity (also refer to Appendices A and B).

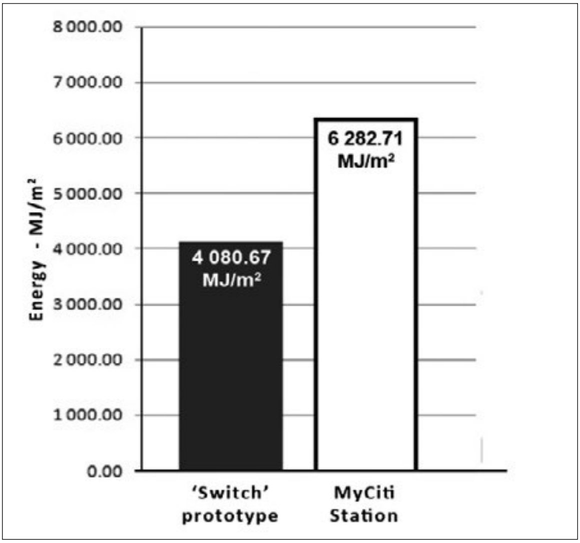

Figure 11: Embodied energy intensity of the two stations

Source: Hugo, 2011: own table

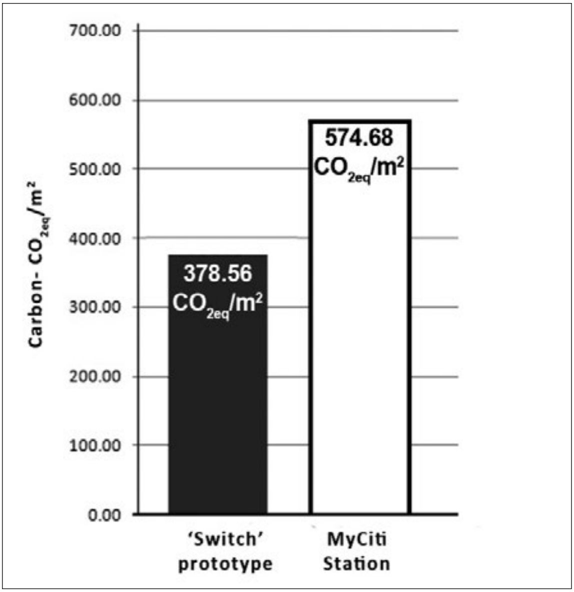

Figure 12: Carbon footprint intensity of the two stations

Source: Hugo, 2011: own table

5.2 Comparison of the separate station components

Tapering the steel structure of the *Switch* station saves 17% embodied energy (Hugo, 2010: 279). By dematerialising the *wall* and *roof structure* and utilising a smaller scaled and simple structural system, with a single continuous roof enclosing the space, 50% (105 vs 211 $kgCO_2/m^2$) and 47% (1 587 MJ/m^2 vs 3 018 MJ/m^2) savings were made in terms of the CFI and EEI of the *Switch* structural system compared to the structural system of the *MyCiti station* (Table 1 and Figures 5, 7, 13 and 14).

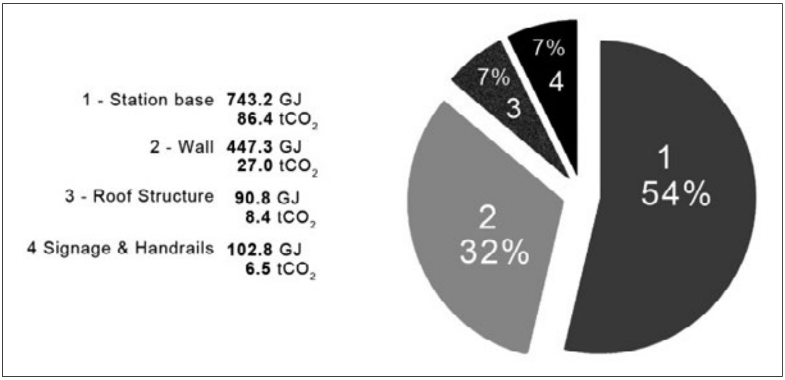

Figure 13: Proportionate energy consumption and carbon produced per component of the *Switch* Station

Source: Hugo, 2011: own figure

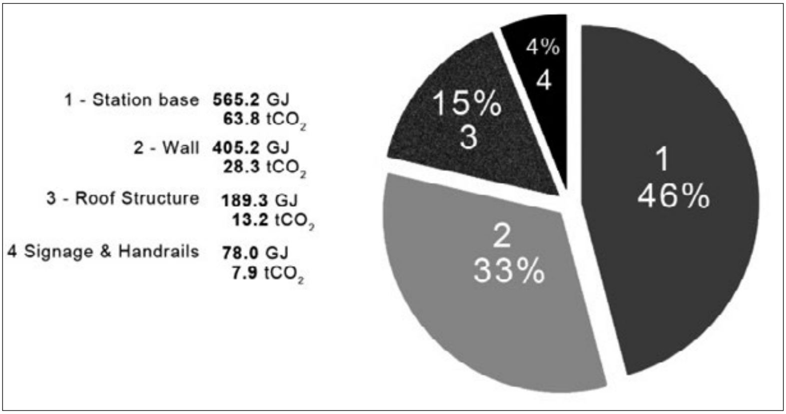

Figure 14: Proportionate energy consumption and carbon produced per component of the *MyCiti* station

Source: Hugo, 2011: own figure

The *MyCiti* station roof structure contributes 15% to the CF and EE; in the *Switch* prototype, this is limited to 7% (Figures 13 and 14). This equates to 62 $kgCO_2/m^2$ (CFI) and 961 MJ/m^2 (EEI) for the *MyCiti* roof structure and only 25 $kgCO_2/m^2$ (CFI) and 268 MJ/m^2 (EE) for the roof structure of *Switch*, an improvement of 68% and 70%, respectively. The savings have been effected by a roof of lighter steel members and tapered walls requiring less roof cover and the removal of a roof overhang by utilising slatted solar screens constructed from recycled materials (Figure 7).

As a ceiling material for the *Switch* station, fibre cement proved to be inefficient. Although the CF and EE coefficient of aluminium is, respectively, 90% and 97% higher than that of fibre cement, the final impact of fibre cement ceiling panels in the *Switch* station increased the CFI of the ceiling by 46% (17.3 vs 10.9 $kgCO_2/m^2$) and the EEI by 10% (206.4 vs 185.2 MJ/m^2) compared to that of the *MyCiti* station (Tables A2 and A3).

Although the entrance is lifted to function as both brace and energy-generation component, it has not made a significant difference (Figure 5). In both case studies, the *wall* constitutes a third (32% and 33%) of the total CF and EE, respectively (Figures 13 and 14). Yet, in terms of CFI and EEI, the *Switch* performs significantly better, saving 40% (80 vs 135 $kgCO_2/m^2$) and 36% (1 319 vs 2 057 MJ/m^2), respectively due to the dematerialisation of the envelope and structure. Merging the *Switch* station envelope design into a single entity or plane, unlike the *MyCiti* station, resulted in a 73% and 60% saving on the secondary enclosing structure's CFI and EEI (Figures 8 and 10).

The alternative base design of the *Switch* station performs remarkably better than that of the *MyCiti* station. It is 21% more efficient in terms of CFI (255 vs 324 $kgCO_2/m^2$) and 23% of EEI (2 192 vs 2 869 MJ/m^2) (Table 1, Figures 13 and 14). As the station base is the largest portion of the total CF and EE of the *Switch* station (54%, 743.2GJ and 86.4 t CO_2) (Table 1, Figure 13), the functional capacity of this component has been maximised. This improves the component's efficiency in terms of its material consumption.

The signage and balustrade of the *Switch* and *MyCiti* stations constitute 7% and 4% of the stations' total CF and EE (Figures 13 and 14), but the *Switch* station performs significantly better, with a 24% lower EEI (301 vs 396 MJ/m^2) for this station component. In addition, the CFI of signage and balustrade of the *MyCiti* station performs significantly worse, being 209% higher than the CFI of the *Switch* station (40 vs 19.1 CO_2kg/m^2) (Table 1). This indicates the considerably higher carbon footprint of stainless steel compared to steel (1.46 vs 6.1kgCO$_2$/kg) (Jones, 2011b: 21).

5.3 Comparison of material use

The *Switch* station uses a significantly smaller amount of steel, with a limited increase in concrete (Figures 15 and 16). Stainless steel is not used, whereas recycled products are specified wherever possible. In the *MyCiti* station, steel contributes 32% and 41% (37.4 t CO$_2$ and 506.7GJ) to the total CF and EE, respectively; in the *Switch* station, it only contributes 19% and 21% (23.8 t CO$_2$ and 255.5 GJ). The reduction can be attributed to identifying material-efficient structural systems and choosing lighter cold-formed steel sections (120x120x4.5mm) over hot-rolled steel sections (152x152mm x 23kg/m).

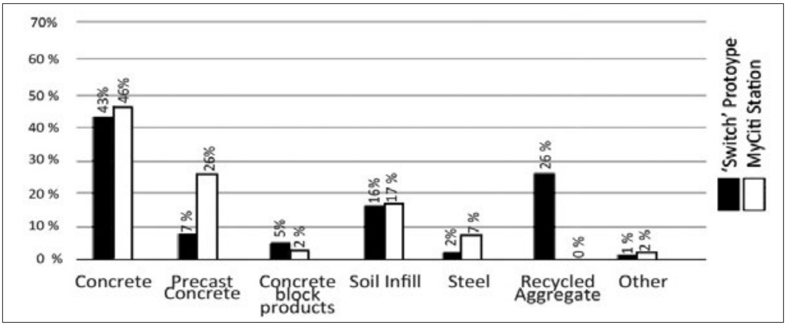

Figure15: Proportions of selected materials used in stations

Source: Hugo, 2011: own table

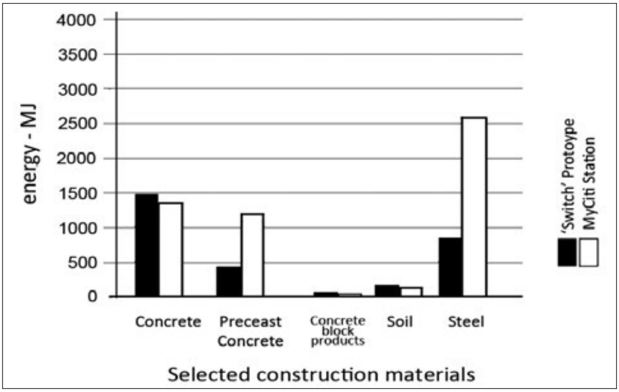

Figure 16: Comparison of the embodied energy of selected materials used in the stations

Source: Hugo, 2011: own table

Using the precast hollow soil/cement blocks as subwalls and permanent shuttering minimises the use of precast concrete (2.07 MJ/kg and 0,24 $kgCO_2/kg$), while maximising the use of *in situ* cast concrete (0.74 MJ/kg and 0,11 $kgCO_2/kg$) (concrete in its most efficient form) (Jones, 2011b: 54-55) (Figures 15 and 16). Incorporating the steel-reinforced *in situ* cast concrete with recycled aggregate as infill for the station base gives the additional weight to provide adequate lateral strength for the station base (Figures 7 and 8).

Although a low impacting structural system was utilised for the *Switch* station's base, saving 53% (1 078.7 $MJ.m^2$ vs 2 330.8 MJ/m^2) (Figure 8, Tables 1, A2 and A3) on the primary structure, minor elements such as screed depths and floor finishes contribute substantially. After analysing the entire base of the *Switch* Station, only a saving of 21% and 23%, respectively (255 $kgCO_2/m^2$ and 2 192 MJ/m^2 vs 324 $kgCO_2$ m^2 and 2 869 MJ/m^2) (Table 1) was made, due to the energy-intensive nature of the secondary elements. This emphasises the importance of focusing not only on the primary structure, but also on the secondary elements.

The floor finish, as secondary element, plays an important role in minimising CF and EE. Substituting the tiled floor finish of the *MyCiti* station with a pigmented cement screed used in *Switch* station lowered the CFI by 27% (10,4 vs 14,2 $kgCO_2/m^2$) and the EEI by 62% (64.8 vs 172 MJ/m^2) (Tables 1, A2 and A3).

A comparison of the material use of the envelope designs reveals that the large saving is primarily due to the minimal use of steel in the primary and secondary structure. Using PMMA and zinc-coated steel mesh to enclose the *Switch* station proved to increase its CFI by 35%, compared to the laminated glass and aluminium louvre design used in the *MyCiti* station (35.8 vs 26.5 $kgCO_2/m^2$). It also increased the envelope design's EEI by 45% (641,4 vs 441.6 MJ/m^2) (Tables 1, A2 and A3).

6. Conclusion

This article focused on the use of construction material in the built environment by assessing the architects' initial design decisions which contribute to mitigating climate change. Previous research (Hugo *et al.,* 2012) identified a set of guidelines to lower CF and EE of new BRT stations and this study has tested these guideline approaches in *Switch*, a prototypical BRT station.

To calculate overall CF and EE intensity, a cradle-to-gate 'comparative' LCA was conducted of the existing *MyCiti* station, established as the most CF- and EE-efficient South African BRT station (Hugo *et al.,* 2012) and the *Switch* prototypical station. An efficient CF and EE station prototype has been developed by iteratively testing the CF and EE of construction systems and their material use.

In the final comparative LCA study, it was proved that the CFI and EEI of the *Switch* station is 35% more efficient than the investigated *MyCiti* station. The value of this improvement in terms of construction material use becomes clear when applying these savings to existing BRT systems that are to be extended. The Cape Town BRT system will be implemented in four phases (City of Cape Town, 2010: 9, 36), of which the first phase aims to construct 43 trunk-route stations. It can be expected that, by extending this first phase over the entire BRT system, a total of 172 trunk-route stations will be constructed. If this 35% energy saving is theoretically implemented throughout the *MyCiti* BRT system, a total CF and EE saving of 56 stations will be possible. This translates into saving the CF and EE of more than one phase of the stations constructed for the entire *MyCiti* BRT system.

In order to achieve these savings, the focus must be on spatial economy and minimising the overall footprint of the station. During iterative assessment, the built form and structure can be dematerialised to optimise material use efficiency. Material choices should be informed by understanding the impacts of CF and EE of construction materials.

This article has shown that, through critically assessing current designs, a low carbon intervention can be developed. Following iterative design processes, which focus on continuous environmental improvement, can result in effective architectural design strategies that lower atmospheric carbon dioxide emissions and mitigate climate change.

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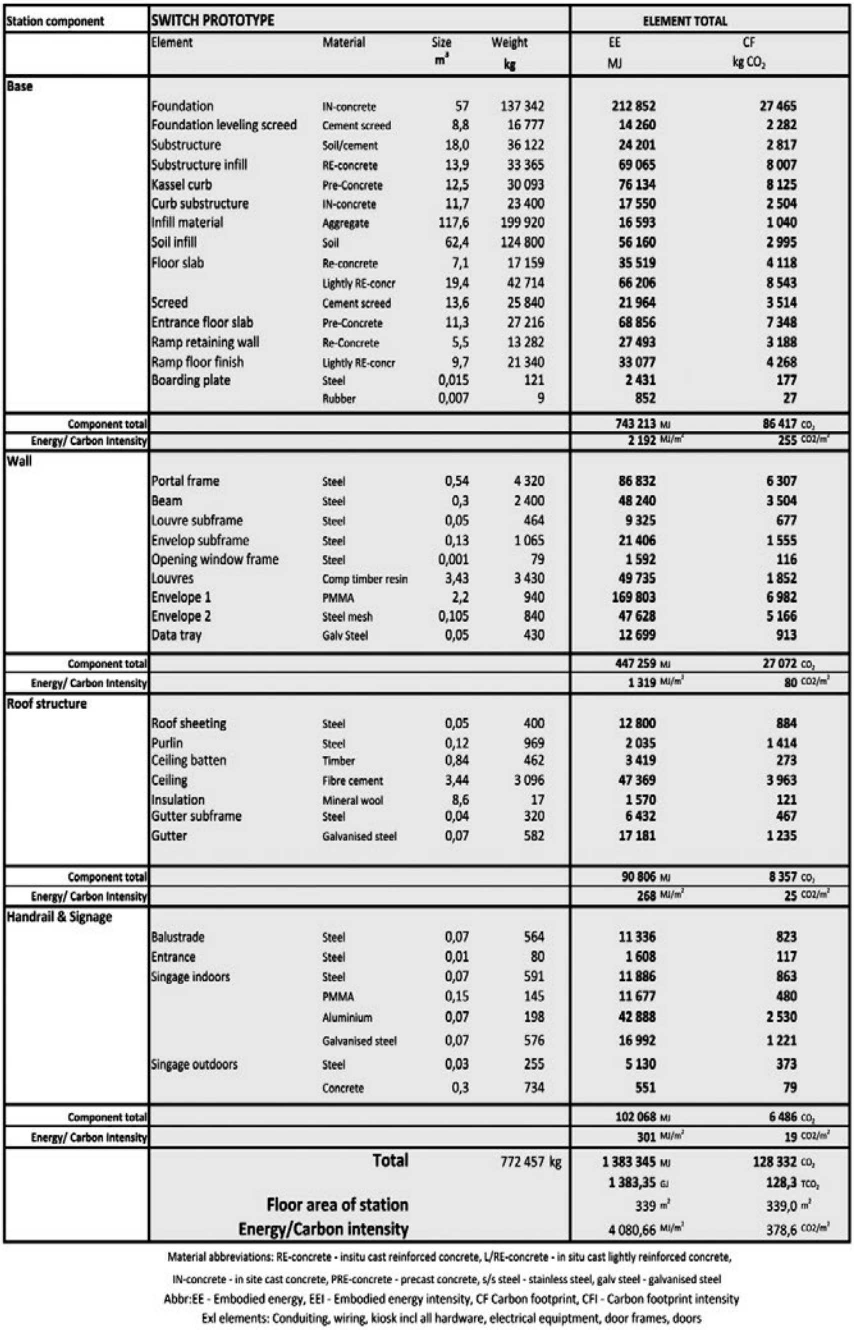
Appendix A: Supplementary table with full results of the *Switch* station's life cycle analysis



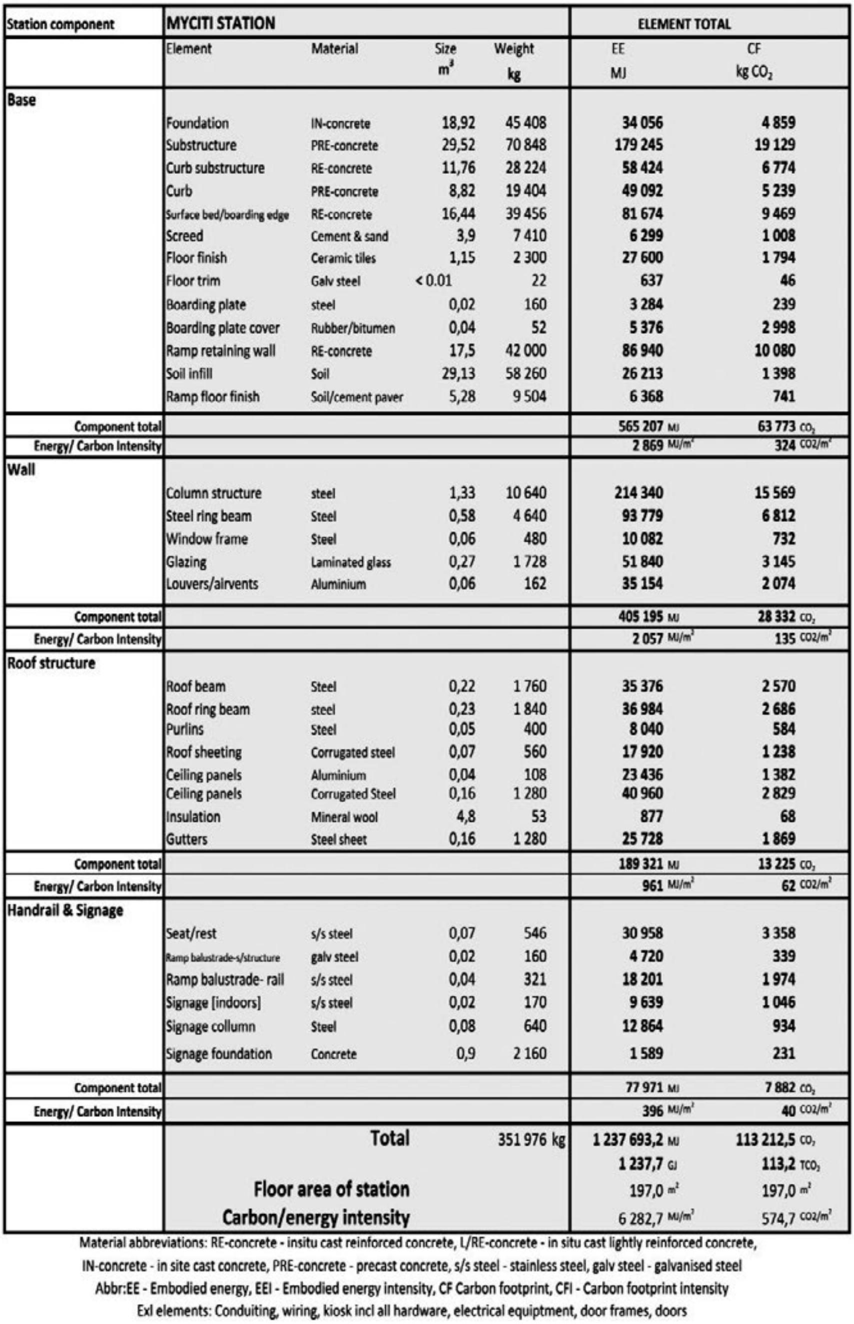
Station component	SWITCH PROTOTYPE				ELEMENT TOTAL	
	Element	Material	Size m^3	Weight kg	EE MJ	CF kg CO_2
Base						
	Foundation	IN-concrete	57	137 342	212 852	27 465
	Foundation leveling screed	Cement screed	8,8	16 777	14 260	2 282
	Substructure	Soil/cement	18,0	36 122	24 201	2 817
	Substructure infill	RE-concrete	13,9	33 365	69 065	8 007
	Kassel curb	Pre-Concrete	12,5	30 093	76 134	8 125
	Curb substructure	IN-concrete	11,7	23 400	17 550	2 504
	Infill material	Aggregate	117,6	199 920	16 593	1 040
	Soil infill	Soil	62,4	124 800	56 160	2 995
	Floor slab	Re-concrete	7,1	17 159	35 519	4 118
		Lightly RE-concr	19,4	42 714	66 206	8 543
	Screed	Cement screed	13,6	25 840	21 964	3 514
	Entrance floor slab	Pre-Concrete	11,3	27 216	68 856	7 348
	Ramp retaining wall	Re-Concrete	5,5	13 282	27 493	3 188
	Ramp floor finish	Lightly RE-concr	9,7	21 340	33 077	4 268
	Boarding plate	Steel	0,015	121	2 431	177
		Rubber	0,007	9	852	27
Component total					743 213 MJ	86 417 CO_2
Energy/ Carbon Intensity					2 192 MJ/m^2	255 CO2/m^2
Wall						
	Portal frame	Steel	0,54	4 320	86 832	6 307
	Beam	Steel	0,3	2 400	48 240	3 504
	Louvre subframe	Steel	0,05	464	9 325	677
	Envelop subframe	Steel	0,13	1 065	21 406	1 555
	Opening window frame	Steel	0,001	79	1 592	116
	Louvres	Comp timber resin	3,43	3 430	49 735	1 852
	Envelope 1	PMMA	2,2	940	169 803	6 982
	Envelope 2	Steel mesh	0,105	840	47 628	5 166
	Data tray	Galv Steel	0,05	430	12 699	913
Component total					447 259 MJ	27 072 CO_2
Energy/ Carbon Intensity					1 319 MJ/m^2	80 CO2/m^2
Roof structure						
	Roof sheeting	Steel	0,05	400	12 800	884
	Purlin	Steel	0,12	969	2 035	1 414
	Ceiling batten	Timber	0,84	462	3 419	273
	Ceiling	Fibre cement	3,44	3 096	47 369	3 963
	Insulation	Mineral wool	8,6	17	1 570	121
	Gutter subframe	Steel	0,04	320	6 432	467
	Gutter	Galvanised steel	0,07	582	17 181	1 235
Component total					90 806 MJ	8 357 CO_2
Energy/ Carbon Intensity					268 MJ/m^2	25 CO2/m^2
Handrail & Signage						
	Balustrade	Steel	0,07	564	11 336	823
	Entrance	Steel	0,01	80	1 608	117
	Singage indoors	Steel	0,07	591	11 886	863
		PMMA	0,15	145	11 677	480
		Aluminium	0,07	198	42 888	2 530
		Galvanised steel	0,07	576	16 992	1 221
	Singage outdoors	Steel	0,03	255	5 130	373
		Concrete	0,3	734	551	79
Component total					102 068 MJ	6 486 CO_2
Energy/ Carbon Intensity					301 MJ/m^2	19 CO2/m^2
			Total	772 457 kg	1 383 345 MJ	128 332 CO_2
					1 383,35 GJ	128,3 TCO_2
			Floor area of station		339 m^2	339,0 m^2
			Energy/Carbon intensity		4 080,66 MJ/m^2	378,6 CO2/m^2

Material abbreviations: RE-concrete - insitu cast reinforced concrete, L/RE-concrete - in situ cast lightly reinforced concrete, IN-concrete - in site cast concrete, PRE-concrete - precast concrete, s/s steel - stainless steel, galv steel - galvanised steel

Abbr:EE - Embodied energy, EEI - Embodied energy intensity, CF Carbon footprint, CFI - Carbon footprint intensity

Exl elements: Conduiting, wiring, kiosk incl all hardware, electrical equiptment, door frames, doors

Appendix B: Supplementary table with full results of the *MyCiti* station's life cycle analysis



Station component	MYCITI STATION				ELEMENT TOTAL	
	Element	Material	Size m^3	Weight kg	EE MJ	CF kg CO_2
Base						
	Foundation	IN-concrete	18,92	45 408	**34 056**	**4 859**
	Substructure	PRE-concrete	29,52	70 848	**179 245**	**19 129**
	Curb substructure	RE-concrete	11,76	28 224	**58 424**	**6 774**
	Curb	PRE-concrete	8,82	19 404	**49 092**	**5 239**
	Surface bed/boarding edge	RE-concrete	16,44	39 456	**81 674**	**9 469**
	Screed	Cement & sand	3,9	7 410	**6 299**	**1 008**
	Floor finish	Ceramic tiles	1,15	2 300	**27 600**	**1 794**
	Floor trim	Galv steel	< 0.01	22	**637**	**46**
	Boarding plate	steel	0,02	160	**3 284**	**239**
	Boarding plate cover	Rubber/bitumen	0,04	52	**5 376**	**2 998**
	Ramp retaining wall	RE-concrete	17,5	42 000	**86 940**	**10 080**
	Soil infill	Soil	29,13	58 260	**26 213**	**1 398**
	Ramp floor finish	Soil/cement paver	5,28	9 504	**6 368**	**741**
Component total					**565 207** MJ	**63 773** CO_2
Energy/ Carbon Intensity					**2 869** MJ/m^2	**324** $CO2/m^2$
Wall						
	Column structure	steel	1,33	10 640	**214 340**	**15 569**
	Steel ring beam	Steel	0,58	4 640	**93 779**	**6 812**
	Window frame	Steel	0,06	480	**10 082**	**732**
	Glazing	Laminated glass	0,27	1 728	**51 840**	**3 145**
	Louvers/airvents	Aluminium	0,06	162	**35 154**	**2 074**
Component total					**405 195** MJ	**28 332** CO_2
Energy/ Carbon Intensity					**2 057** MJ/m^2	**135** $CO2/m^2$
Roof structure						
	Roof beam	Steel	0,22	1 760	**35 376**	**2 570**
	Roof ring beam	steel	0,23	1 840	**36 984**	**2 686**
	Purlins	Steel	0,05	400	**8 040**	**584**
	Roof sheeting	Corrugated steel	0,07	560	**17 920**	**1 238**
	Ceiling panels	Aluminium	0,04	108	**23 436**	**1 382**
	Ceiling panels	Corrugated Steel	0,16	1 280	**40 960**	**2 829**
	Insulation	Mineral wool	4,8	53	**877**	**68**
	Gutters	Steel sheet	0,16	1 280	**25 728**	**1 869**
Component total					**189 321** MJ	**13 225** CO_2
Energy/ Carbon Intensity					**961** MJ/m^2	**62** $CO2/m^2$
Handrail & Signage						
	Seat/rest	s/s steel	0,07	546	**30 958**	**3 358**
	Ramp balustrade-s/structure	galv steel	0,02	160	**4 720**	**339**
	Ramp balustrade- rail	s/s steel	0,04	321	**18 201**	**1 974**
	Signage [indoors]	s/s steel	0,02	170	**9 639**	**1 046**
	Signage collumn	Steel	0,08	640	**12 864**	**934**
	Signage foundation	Concrete	0,9	2 160	**1 589**	**231**
Component total					**77 971** MJ	**7 882** CO_2
Energy/ Carbon Intensity					**396** MJ/m^2	**40** $CO2/m^2$
		Total		351 976 kg	**1 237 693,2** MJ	**113 212,5** CO_2
					1 237,7 GJ	**113,2** TCO_2
		Floor area of station			197,0 m^2	197,0 m^2
		Carbon/energy intensity			6 282,7 MJ/m^2	574,7 $CO2/m^2$

Material abbreviations: RE-concrete - insitu cast reinforced concrete, L/RE-concrete - in situ cast lightly reinforced concrete, IN-concrete - in site cast concrete, PRE-concrete - precast concrete, s/s steel - stainless steel, galv steel - galvanised steel

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