Comparative analysis and case study to evaluate conventional designs and environmentally sensitive infrastructure design solutions

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INTRODUCTION

Globally the construction industry is one of the main contributors to the depletion of natural resources and a major cause of unwanted side effects such as air and water pollution, solid waste, deforestation, health hazards, global warming and other negative consequences.

In the area of sustainability there is an urgent need to apply technologies and methods which deliver more sustainable performance in a way that is cost-effective. Sustainable, adaptive and mitigating approaches to climate change in the design of infrastructure are therefore important steering elements (FIDIC 2009).

Matar *et al* (2015) highlight the fact that more than 600 sustainability assessment tools currently exist. Most of these are primarily oriented towards buildings and do not direct sufficient attention to infrastructure projects. Civil engineering projects can have significant site-specific and cumulative impacts on our ecological and social systems if not correctly planned, designed and implemented. Engineers have to be at the forefront of developments finding, for example, innovative solutions to maximise water capture, and ensuring conservation of the resource from supply through to distribution, so that environmental impacts are avoided or mitigated. Understanding the context of the environment in which they work is thus essential for engineers (Kilian & Gibson 2007).

There exists a need to create eco-sensitive infrastructure design which encourages and promotes the use of 'softer' design solutions. Incorporating the eco-efficiency concept into various stages of infrastructure development has not been considered as much as it should have been.

By utilising improved environmentally friendly design solutions, this study aims to introduce environmentally friendly design decisions prior to the infrastructure design approval process. This increases overall competitiveness by bringing a whole new class of productive solutions to problems, while at the same time adding a fresh perspective to the traditional infrastructure design process.

OBJECTIVES

In view of the inadequacy of tools to assess the environmental impacts of infrastructure design decisions, the objectives of this study were as follows:

- To introduce environmentally conscious design decisions at inception stage, where they have the most influence.
- To identify existing green design technologies used in practice and extend these to township infrastructure.
- To define sustainability criteria for township infrastructure design.
- To develop an interactive decision-making toolkit which could assist consultants and clients by showing the greener options for infrastructure projects.
- To promote sustainable design for infrastructure township services by introducing various sustainable design solutions which are applicable at the various stages of a project.
- To raise awareness of green engineering benefits and the environmental impact of consultants' design decisions, in order to reduce the environmental impact of development.

METHODOLOGY

To illustrate environmental sensitivity when using conventional infrastructure solutions compared to the eco-friendly solutions that are available on infrastructure projects, a detailed analysis of the various green interventions that could be implemented in different types of infrastructure projects was undertaken, using the green township infrastructure rating system during the various stages of the project – from feasibility to detailed design and construction.

A variety of projects were chosen for the study, such as high-income and low-income developments, industrial parks, mixed-use developments and a project with no green interventions to determine its scoring. The rating system scoring method was evaluated and fine-tuned to determine its applicability and suitability for all types of projects.

THE PROPOSED GREEN TOWNSHIP INFRASTRUCTURE RATING SYSTEM

This article proposes a rating system that enforces environmentally sustainable design for township infrastructure services by integrating resources, the environment, ecologically sensitive innovative design, maintenance and recyclable materials from the early design stages of a project. The Green Township Infrastructure Design Toolkit, as illustrated in Figure 1, uses the concept of eco-efficiency and would allow the designer to evaluate design options, enabling him/her to choose the one likely to yield the best performance with the least environmental impact. This toolkit is intended to encourage developers to consider green methods and practices in the earliest stages of project planning, by assessing a number of recommended green practices and its environmental impacts on infrastructure services design, placing fewer burdens on the environment.

THE USE OF SUSTAINABILITY CRITERIA ON INFRASTRUCTURE DESIGN

The infrastructure sustainability criteria used in the proposed Green Township Infrastructure Design Toolkit are listed in Table 1 and were developed to:

- determine the means by which eco-environmental efficiency can be assessed, monitored, quantified and verified at any stage of the project, to ensure a value-added, quality-driven, green approach to infrastructure design;
- provide a basis for the consultants and clients to work together on creating and evaluating sustainable infrastructure solutions, thereby ensuring comprehensive infrastructure planning with maximum stakeholder involvement; and
- achieve the required balance of sustainability, expenditure, value for money and quality, between the various elements of the project.

Sustainability indicators are useful for monitoring and measuring the state of the environment and reflect the performance of the elements (Carden *et al* 2009).

GREEN DESIGN ELEMENTS THAT WILL IMPROVE THE ENVIRONMENTAL QUALITY OF INFRASTRUCTURE PROJECTS

Innovative approaches to planning and design can greatly mitigate the negative impacts of infrastructure services on the environment. In this study various green technology concepts were researched and modified to suit township infrastructure projects, with the aim of reducing the impacts of civil engineering infrastructure on residential developments.

Green technology that can be used on infrastructure projects may include the utilisation of natural or engineered systems which mimic natural landscapes in order to capture, cleanse and reduce stormwater runoff. Greener stormwater infrastructure solutions can include rain gardens, rain barrels, green roofs, wetlands, permeable pavements, and other methods intended to significantly reduce the amount of stormwater runoff entering the sewer system and our waterways.

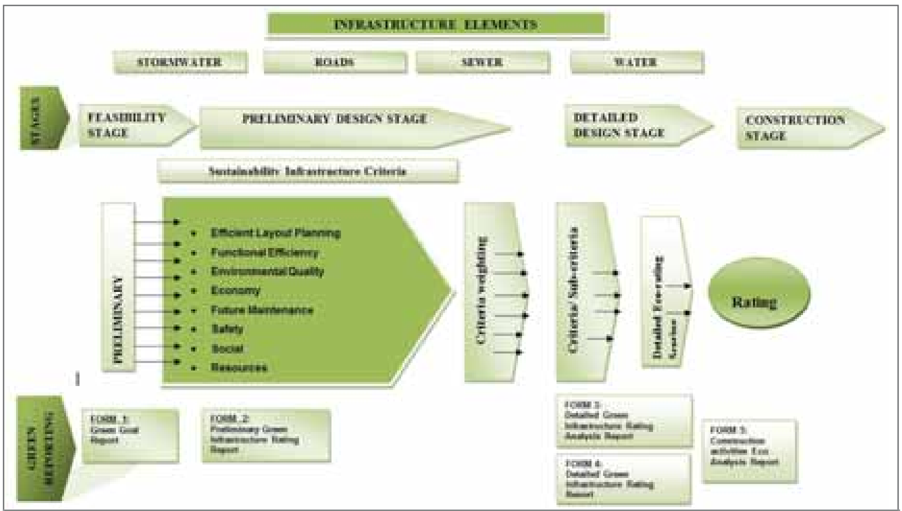

Figure 1: The Green Township Infrastructure Design Toolkit

Table 1: The sustainability performance criteria

Sustainable infrastructure criteria	Measure
1. Efficient layout planning	Placement of infrastructure in environmentally responsible, efficient ways, conserve land
2. Resources	Encourages the efficient utilisation of materials/resources, selection of environmentally friendly materials
3. Environmental quality	Design features that mitigate environmental impacts of infrastructure by reducing the effects of pollutants
4. Functional efficiency	Design of infrastructure that maximises the functional efficiency of infrastructure
5. Future maintenance	Maximises the opportunities for integrating capital and operation of infrastructure, ensuring reliability of level of service
6. Economy	Maximises the opportunities for integrated cost-effective adoption of green infrastructure options
7. Safety	Minimises the environmental impact of infrastructure by incorporating safety into the design
8. Social	Ensuring social sustainability of infrastructure, promoting convenience, social resources and public participation

Roads present many opportunities for green infrastructure application by incorporating a wide variety of design elements, including street trees, permeable pavements, bio-retention and swales. The various design solutions of a township were broken down into various elements in order to identify alternative ways in which greener solutions can be achieved.

With this eco-efficient design, various sustainable infrastructure solutions are categorised into a number of sustainability criteria, under different elements, as shown in Figure 2.

Green infrastructure for sustainable township development entails the establishment of green networks and green ways, the enhancement of pollution prevention, and stormwater management. It applies technologies and practices that use natural systems, or engineered systems that mimic natural processes, and includes low impact development, smart conservation strategies and Urban Green Best Management Practices (M'Ikiugu *et al* 2012).

Various design manuals were reviewed in search of alternative approaches to conventional design practices. These included manuals such as the National Guidelines for Evaluating Water Sensitive Urban Design, Water Sensitive Urban Design by the City of Knox, Urban Stormwater Retrofit Practices by the US Environmental Protection Agency, etc.

CASE STUDIES UNDERTAKEN TO SHOW THE CONTRAST BETWEEN CONVENTIONAL DESIGNS AND ENVIRONMENTALLY SENSITIVE DESIGN USING THE PROPOSED GREEN INFRASTRUCTURE TOOLKIT

Two residential development case studies were compared to show the usefulness of the rating in searching for green solutions. Each element was categorised, prioritised and rated into the various sustainability criteria.

A detailed green infrastructure rating analysis was done using the standard reports of the Green Township Infrastructure Design Toolkit. Due to the complexity and size of the detailed analysis reporting, Figure 3 only shows a snapshot of a Green Infrastructure Rating Analysis that evaluates the layout functional efficiency of stormwater infrastructure in townships. This analysis guides decision-makers in identifying alternative ways in which greener solutions can be achieved, and to rate their environmental performance in the project.

All performance criteria and sub-criteria are set within a performance scoring range from -2 to +5 assessment scale, or yes/no answers which are scored in accordance with their functionality and influence on the environment and the number of sub-criteria.

The results are then assessed as illustrated in Table 2. It assists the client and engineer to set and monitor eco-efficient goals for the development. In this way, innovative, sustainable and efficient designs are progressively developed.

Case Study 1

The first case study was a low-income development called Sunnyside Park which used conventional infrastructure and was chosen to assess how the model rates conventional infrastructure design solutions.

Conventional grid pattern roads and piped stormwater networks were adopted, with no major emphasis on midblock line sewer or water conservation measures. Conventional designs were undertaken and a simple set of sustainability targets were set. These targets indicated that "minimal interventions were to be undertaken" on its environment.

In this case study no consideration was given to the environmental impact, social impact, safety or maintenance needs. Even though a higher rating could have been achieved by using more environmentally sensitive solutions for the various infrastructure items, its primary objective was to achieve functional requirements by the most economic means.

Case Study 1 – results

Due to the complexity and size of the detailed analysis reporting, only the results are displayed in this article. Table 3 and Figure 4 show breakdowns of the scores for each infrastructure element, achieving an overall green rating of 18, and receiving low scores for almost all components, due to minimal environmental interventions having been undertaken. Scores between 0% and 25% Environment were not taken into account.

This indicated that the project had merely "Achieved compliance based on regulations". A higher rating could have been achieved by using more environmentally sensitive solutions for the various infrastructure items.

Case Study 2

The second case study was undertaken using a similar low-income development, but aiming to achieve limited damage to the environment by using a combination of green solutions and conventional infrastructure. Project features included alignment of the road with the natural topography and low-impact development (LID) which is an engineering design approach to managing stormwater runoff. LID emphasises conservation and uses on-site natural features to protect water quality. This approach implemented engineered bioswales with hydrologic controls to replicate the pre-development flow through infiltrating, filtering, storing, evaporating and detaining runoff close to its source. The project also involved the minimisation of conventional piped stormwater reticulation by maximising the use of the storage capacity of the roads. Water-efficient layouts and pressure reduction measures were undertaken.

Case Study 2 – results

The results shown in Table 3 and Figure 4 indicate that Case Study 2

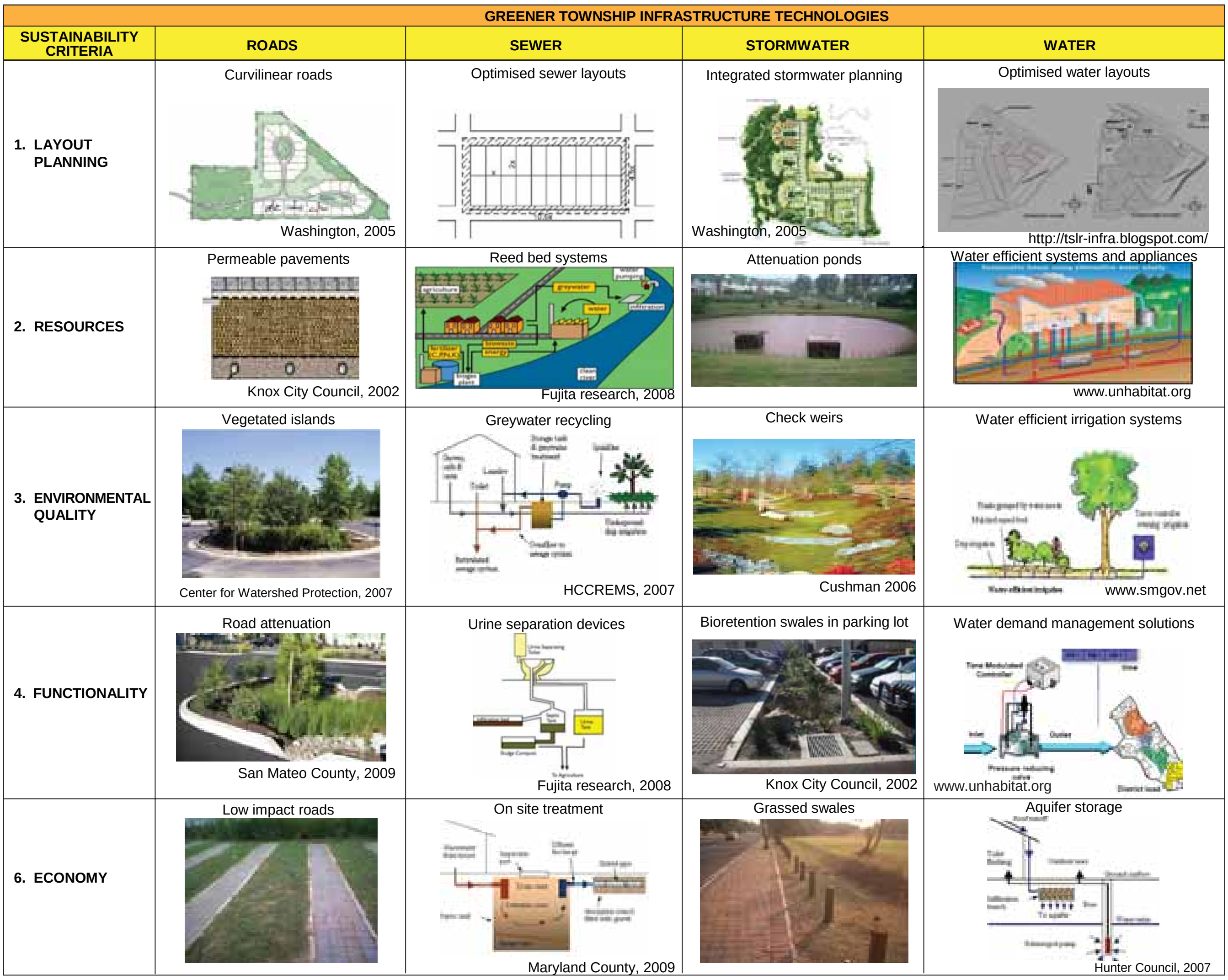

Figure 2: Green infrastructure technologies that can be used on infrastructure projects

demonstrated a significantly different performance, achieved a green rating of 66 and performed satisfactorily to moderate scores across all dimensions of sustainability, being able to maintain a balance between the needs of society and the preservation of the environment. This case study shows that green interventions can be achieved on low-income housing projects by using simple engineering interventions that do not have a significant economic impact on the project.

THE USE OF GREEN INFRASTRUCTURE ON LOW-INCOME DEVELOPMENTS

The Green Agenda concentrates on reducing the environmental impact of urban-based production, consumption and waste generation, focusing on the problems of over-consumption – issues which are more pressing in affluent countries. The Brown Agenda focuses on the problems of poverty and underdevelopment, and emphasises the need to reduce the environmental threats to health that arise from poor sanitary conditions, crowding, inadequate water provision, hazardous air and water pollution, and local accumulation of solid waste (Boswell 2010).

There is a need for more appropriate technologies for low-income developments which can:

2.0 FUNCTIONAL EFFICIENCY			**20.0**	**20.0**
1	Conventional systems that achieve minimum compliance	no	0.00	
		yes	0.74	0.74
2	Provision of surface water management system to ensure that the ultimate flow from the development does not result in any negative impacts on downstream properties or watercourse and is managed within the overall site	no	0.00	
		yes	0.74	0.74
3	Have the master drainage plans been prepared, in collaboration with adjoining communities and authorities, for the existing and future development of the entire catchments?	no	0.00	
		yes	0.74	0.74
4	Is > 70% of the road designed for sheetflow?	no	0.00	
		yes	0.74	0.74
5	Is the maximum velocity < 3 m/s?	no	0.00	
		yes	0.74	0.74
6	< 10% of roads have a maximum road gradient > 12%?	no	0.00	
		yes	0.74	0.74
7	What is the minimum road crown slope – < 2% – sediment?	no	0.00	
		yes	0.74	0.74
8	Is the maximum road crown slope – < 3% – operation problem driving, aware of vehicles?	no	0.00	
		yes	0.74	0.74
9	Are the potential drainage and storage functions of roads, roadside channels used?	no	0.00	
		yes	0.74	0.74
10	Are > 50% of the road gradients – < 2% – used for retarding stormwater runoff?	no	0.00	
		yes	0.74	0.74
11	Is the post development limited to pre-development?	no	0.00	
		yes	0.74	0.74
12	Are the roadside channels designed to prevent erosion?	no	0.00	
		yes	0.74	0.74
13	Are the stormwater flow depths < 0.5 m?	no	0.00	
		yes	0.74	0.74
14	Inlet – are the backwater effects designed for?	no	0.00	
		yes	0.74	0.74
15	Do the inlets/ponds have swing-type grids or are they self-cleansing to prevent blockages?	no	0.00	
		yes	0.74	0.74
16	Is stormwater quality controlled at the source by the use of rain barrels, soakaway, disconnecting downpipe from residential rooftop, etc, in order to prevent pollutant dumping?	no	0.00	
		yes	0.74	0.74
17	Does the reticulation limit runoff volumes with the use of bioswales filtering pollution?	no	0.00	
		yes	0.74	0.74
18	Does the reticulation limit volumes with the use of retention basin?	no	0.00	
		yes	0.74	0.74
19	Are velocities reduced with the use of check dams?	no	0.00	
		yes	0.74	0.74
20	Does the reticulation limit runoff volumes with the use of porous parking surfaces?	no	0.00	
		yes	0.74	0.74
21	In areas where the subsoil and water table are suitable, does the design of storage area surfaces allow for the re-charging of the underground water?	no	0.00	
		yes	0.74	0.74
22	Are flood plains and watercourses protected from erosion with gabions, dissipaters, Reno mattress, stilling basins, check weir, riprap protection, energy reduction, drop structures, riprap basins?	no	0.00	
		yes	0.74	0.74
23	Are there measures to prevent underground conduits from silting up?	no	0.00	
		yes	0.74	0.74
24	Are channels lined – earth, grass, concrete?	no	0.00	
		yes	0.74	0.74
25	Are the average channel slopes < 5%?	no	0.00	
		yes	0.74	0.74
26	Are the stormwater outlet structures designed to decrease flow velocity by the use of velocity dissipaters?	no	0.00	
		yes	0.74	0.74
27	Sediment control – silt fences/stilling basin	no	0.00	
		yes	0.74	0.74
3.0 ENVIRONMENTAL QUALITY			**20.0**	**20.0**
1	Some consideration for reducing environmental impact in the design	no	0.00	
		yes	1.54	1.54
2	Protection of environmentally sensitive areas	no	0.00	
		yes	1.54	1.54
3	Pre-development groundwater recharge rates are maintained	no	0.00	
		yes	1.54	1.54
4	SW pipes steeper than 1:3 < 10% of the total length	no	0.00	
		yes	1.54	1.54
5	Consolidate waterways and open space requirements	no	0.00	
		yes	1.54	1.54

Figure 3: Snapshot of a Green Infrastructure Rating Analysis

- enhance social sustainability through the use of labour-intensive construction activities that also present opportunities for poverty alleviation;
- promote local economic development by encouraging the use of small companies that are responsible for a large proportion of building material and plant manufacture;
- reduce material wastage by innovative methods of waste disposal and re-use;
- conserve water through improved water metering systems, rainwater harvesting systems, re-using water, waterless and low-flow technologies, and the use of water on construction sites and in the production of materials;
- provide innovative building materials and methods; and
- include food gardens to produce nutritious, home-grown food.

Low-income developments should strive to meet the sustainability criteria of resource efficiency, use of renewable resources, minimisation of pollution and waste, economic empowerment, health and safety, and human development (CSIR 2002).

ADVANTAGES OF USING THE ECO-APPROACH FOR INFRASTRUCTURE DESIGN

The eco-approach to infrastructure design takes a "design with nature" approach, to mitigate the potential impacts of a development. The benefits of this approach are as follows:

- Uses natural resources efficiently, maximises the use of local materials, and eliminates waste.
- Reduces the ecological footprints of roads, sewer, stormwater and water, allowing ecosystems to function more naturally.
- Uses energy-efficient systems and materials.
- Plans for future maintenance.
- Reduces, reuses, and recycles materials.
- Conserves and reuses water and treats stormwater runoff on site.
- Recharges ground water flow for streams, conserving water supplies.

Table 2: Assessment of the project

Environment not taken into account	0–25%	▲
Some considerations for the environment	25–50%	▲▲
Restricted damage to the environment	50–75%	▲▲▲
Best solution for the environment	75–100%	▲▲▲▲

CONCLUSIONS

There is an urgent need to apply eco-efficiency concepts into township infrastructure development.

Green techniques provide adaptation benefits for a wide array of circumstances, by conserving and reusing water, promoting groundwater recharge, and reducing surface water discharge, thereby reducing potential flooding. In addition to this, greener engineering improves urban aesthetics and community liveability by providing recreational and wildlife areas. Green infrastructure may save capital costs associated with paving, creating curbs and gutters, building large stormwater conveyance systems, other hard infrastructure and energy costs.

Though eco-friendly design is a major component of the green value assessment, several other basic sustainability requirements are also assessed. Taking a greener approach to infrastructure development not only mitigates the potential environmental impacts of development, but makes economic sense as well.

As can be seen in this article, there are numerous opportunities for improving eco-efficiency in infrastructure design. A new paradigm for infrastructure design is required in order to maintain environmental sustainability infrastructure.

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Table 3: Comparative assessment between Case Study 1 and Case Study 2

		Case Study 1					Case Study 2				
	Performance categories	**Overall project**	**Roads**	**Stormwater**	**Sewer**	**Water**	**Overall project**	**Roads**	**Stormwater**	**Sewer**	**Water**
1	Layout efficiency	**16**	13	10	33	10	**77**	88	60	89	60
2	Functional efficiency	**10**	15	7	6	7	**67**	75	63	53	67
3	Environmental quality	**14**	21	8	10	11	**50**	57	62	40	33
4	Economy	**35**	55	11	27	30	**83**	82	89	82	80
5	Future maintenance	**14**	10	13	13	25	**62**	50	73	63	75
6	Safety	**17**	13	10	17	33	**81**	80	60	83	100
7	Social	**46**	50	17	75	40	**60**	75	17	75	60
8	Resources	**21**	22	22	36	0	**52**	44	56	64	50
9	Construction	**6**	14	0	0	0	**34**	43	33	50	0
	Scoring	**18**	**24**	**10**	**18**	**16**	**66**	**69**	**66**	**62**	**66**

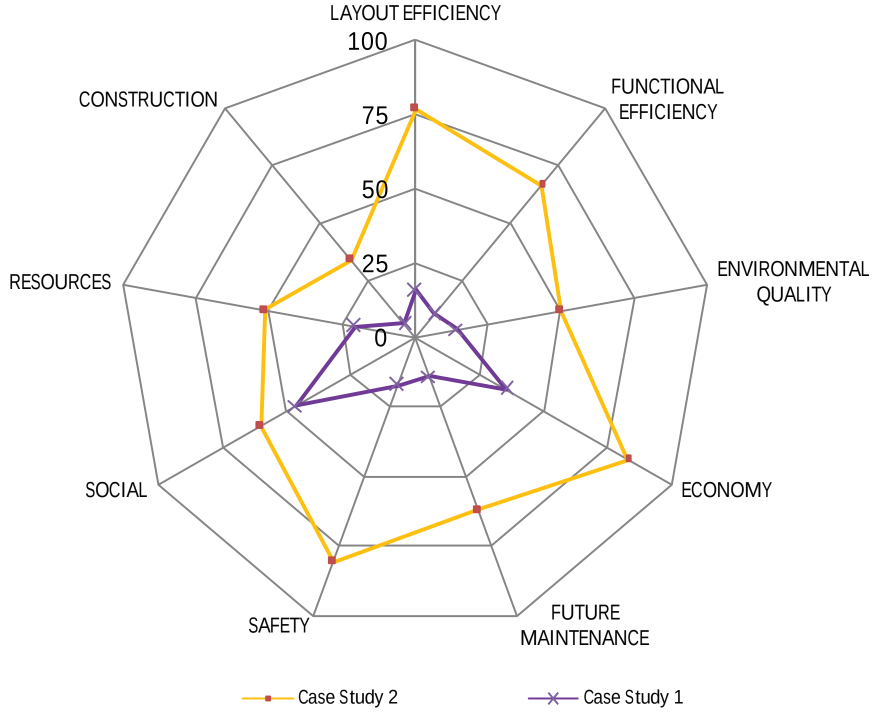

Figure 4: Comparative assessment between Case Study 1 and Case Study 2