DEVELOPING OBJECTIVE NORMALISED METRICS FOR COMPARING THE ENERGY USE OF HOSPITALS

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ABSTRACT

Key words: Hospitals, Energy benchmarking

INTRODUCTION

Buildings are one of the largest consumers of energy, especially in developing countries. Buildings account for 50% and 42% of the national energy used in Brazil and Botswana respectively (Abu Bakar et al. 2015). Hospitals are complex resource intensive buildings, with strict hygiene and air quality requirements, that provide round the clock healthcare services. Ensuring patient comfort and a hygienic environment requires the continuous operation of hospitals buildings' services. This has led to the high energy consumption associated with hospitals. Research has shown that hospitals are twice as energy intensive as commercial offices (Rajagopalan & Elkadi 2014).

Energy related expenses are a major cost point for hospitals, and are the third highest expense for a hospital after medicine and staff wages (Hu et al. 2004). Energy is used in both medical operations and by support services to ensure the effective and efficient operations of healthcare service provision and support activities in a hospital, and to maintain the health and comfort of both its patients and staff. The resource intensive nature of hospitals and rising global energy demand (which is projected to be 45% higher by 2025 than it was in 2002 (Abu Bakar et al. 2015)) created a need for sustainable and efficient energy practices within the health sector (Castro et al. 2015).

This study aims to aid in the reduction of hospital life cycle costs by improving macro level decision-making pertaining to the the operation and management of hospitals. This is done by reducing the subjectivity involved in benchmarking and comparing hospitals, by identifying the factors that influence, and normalising for the effects of context centred factors from the benchmarking parameters. The study aims to identify and calculate parameters to capture the effect of an array of predefined and selected characteristics on the energy consumption of a spectrum of hospitals within a specific region.

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This approach will ultimately aim to determine the true performance potential of a hospital by investigating how the characteristics and context of a hospital affect its energy consumption. This paper, however, details a literature review conducted to determine common benchmarking methodologies used for hospitals and other non-domestic buildings, and it details the factors that need to be considered to account for the both the building related aspects of a hospitals and the service provision related aspects of hospitals; and how each of these aspects influences a buildings energy consumption. The key objectives of this paper are thus to perform a structured literature analysis to obtain the factors affecting energy consumption in hospitals and to analyse methodologies for developing metrics and quantify the energy performance of hospitals.

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ENERGY USE IN HOSPITALS

A typical hospital building consists of patient wards, operating theatres, an X-ray department, administration offices, a boiler house and an array of support services such as workshops, laundry rooms, a kitchen and a dining hall (Gupta et al. 2007). Heating Ventilation and Air Conditioning (HVAC) and water heating account for 50% of the energy consumption in hospitals (WCDEADP 2008). Lighting and medical equipment (general and specialised) are also significant consumers of energy as shown in Figure 1.

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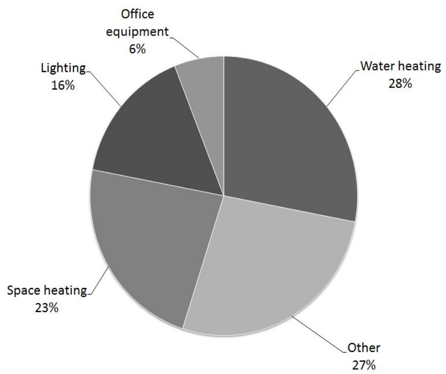

Figure 1: Breakdown of the energy load of a typical hospital (adapted from Western Cape Department of Environmental Affairs and Development Planning 2008)

Hospitals have two main types of energy sources: electrical energy which is used to power most hospital systems and thermal energy used for heating. Electrical energy is supplied via the grid and thermal energy is provided by combusting fossil fuels (i.e. oil, gas, coal). The thermal and electrical energy are consumed at different rates and in different quantities. Various research enquiries have studied the utilisation of energy by non-domestic buildings (i.e. office buildings, factories and hospitals) and how it relates to benchmarking. Table 1 shows the summary of the results of the literature analysis that focused on factors affecting the energy consumption in hospitals as well as other non-domestic buildings.

A literature analysis was conducted to identify and understand the factors that affect energy consumption in hospitals. The relationship between the factor and the energy consumption of the hospital was identified and tabulated. The relationship between respective factors and the normalisation methods used in each study were also identified and tabulated give the reference table / figure?. The terminology used by the different authors varied due to the differences in the objectives of their respective studies. Some authors mentioned factors that they used in their analysis, however they did not substantiate their choice of factors, making it challenging to identify the relationship between these factors and energy consumption.

Table 1 shows the respective referenced authors, year of publication and the factors identified in each publication. The full reference for each factor can be found in the list of references at the end of this paper. From the above analysis, the identified factors that influence....are categorised into six major groupings, namely:

1. Building characteristics
2. Context and environment
3. Service mix
4. Building systems
5. Equipment use
6. Management and operational practices

Each category represents a sub-set of factors that affect the energy performance of a building and should be accounted for when analysing a building's energy usage performance. In the subsequent sub-sections, each of these categories will be unpacked and described.

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Table 1: Factors affecting energy consumption as identified in literature

	Year of Publication	2008	2015	2015	2006	2014	2009	2005	2012	2008	2012	2012	2005	2012	2012	2015
	Referenced Author	Murray	Bagnasco	Castro	Szklo	Buonomano	Fumo	Zhu	Catalina	Caldera	Korolija	Korolija	Martini	Pacheco	Zhao	Rodhe
	Factor															
Building characteristics	Size	E		E	E		E	E				E				
	Building morphology						E			E	E	E				
	Building envelope construction materials						E	E	E		E	E		E	E	
	Age	E		E						E						
	Building zones/ thermal zoning					E	E		E	E				E		
Context and environment	Climate	E	E				E		E			E			E	
Building services	system type	E					E	E			E					
	Installed capacity of each end-use				E											
	system characteristics						E								E	
	system equipment and operation														E	
	operation schedules						E	E			E					
	internal heat gains from building systems											E				E
Service mix	Type service				E	E					E	E				E
	Complexity of services				E											
	Number of clinical specialty			E												
	catchment area			E												

	Year of Publication	2008	2015	2015	2006	2014	2009	2005	2012	2008	2012	2012	2005	2012	2012	2015	2009
	Referenced Author	Murray	Bagnasco	Castro	Szklo	Buonomano	Fumo	Zhu	Catalina	Caldera	Korolija	Korolija	Martini	Pacheco	Zhao	Rodhe	Singer
	Factor																
Equipment use	device prevalence												E			E	E
	equipment usage patterns							E					E			E	E
	Type of devices												E			E	
	power rating												E			E	
	Standby energy consumption															E	E
	Equipment efficiency				E						E				E		E

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Building characteristics

The size of a building is one of the most important determinants of its energy consumption (Singer 2009). Size is the parameter that most studies normalise for when analysing energy consumption of a building consumption. The size of a hospital has two aspects: the building size and the capacity of the hospital. Building size refers to the physical size of the building it is captured using parameters such as total roofed area, total floor area and heated volume. The capacity of a hospital is represented by the number of licensed beds available in a hospital. This provides a means of estimating the amount of people present in the building: patients, medical staff and support staff. Total floor area and number of licensed beds are some of the metrics used to represent the size and capacity of a hospital respectively. The size and capacity of a hospital affects the internal load due to occupancy, operating schedule and equipment use (Zhu 2006). Thus the parameters discussed above capture the demand placed on the buildings sub-level system by the size of the building.

The buildings morphology and the characteristic of the building envelope components (walls windows and roof) govern the amount heat gains/losses through the façade and the available area for heat loss through the façade. The type of construction material used to manufacture the building is essential to its heating and cooling loads. Different materials process heat loads differently and the energy that accumulates in the material differs due the material properties. The aspect ratio, orientation, Number of floors, the building relative compactness and windows to wall ratio are used to account for the buildings morphology (Fumo et al. 2010). The thermal transmittance of the envelope components affects the amount of heat transferred through the envelope (Catalina et al. 2013).

This parameter accounts for the effect of the characteristics respective climate zones that one are needed in a building. The number, size and set points of the respective thermal zone serviced by the buildings sub-level system (i.e. the heating and cooling system) determines the properties and sizing of the respective components that make up these system (i.e. air handling units in a cooling system) (Fumo et al. 2010). These building systems are sized according to the maximum demand value and the thermal zoning parameter is one of the controlling factors of the maximum demand value (Szklo et al. 2004).

The age of a building determines the material used in the its construction and the way it was constructed I.e. its wall thickness (Caldera et al. 2008). Thus the envelope of buildings from different eras designed using different design configurations and materials may vary in terms heat transmittance and thermal capacity. This can cause variation in the cooling and heating loads of different hospital. Caldera et al. (2008) did not account for building refurbishments and retrofits in his analysis. Retrofits and refurbishments offset the effect of the age of the building as they update the building’s design and technology.

Also, newer hospitals are generally more equipped than older hospitals and thus the whole building energy consumption is increased due to the presence of energy intensive medical equipment (Rohde & Martinez 2015). Part of the reasons for the high consumption of electricity by hospitals is the increase in the energy intensity of hospital specific equipment (Rohde & Martinez 2015).

Context and environment

The local climate of the region in which a hospital is situated affects the absorbed solar energy, which increases the heating load in winter and increases the cooling load in summer. Humidity of the area also influences the humidification or dehumidification required to maintain thermal comfort in the hospitals respective climate zones. Thus the local climate has an effect on the cooling and heating load of the hospital, which directly affects the energy intensity of the HVAC system.

The geographical area has an effect on parameters such as the climate and by extension the outdoor temperature and the humidity of the area in which the hospital is located. (Catalina et al. 2013)used outside air temperature and solar radiation intensity to represent the influence of local climate in the area in which the building is situated on its heat or cooling load. Buildings in three distinct geographical regions where studied namely: very cold climates (i.e. Moscow), warm-Mediterranean climates (i.e. Nice) and an intermediate point (Bucharest). This provided a temperature spectrum that includes all the expected temperatures in the area of their study

Korolija et al. (2013) discusses the benefits of overhangs on buildings and how they can result in significant reduction in a buildings cooling load by reducing the effect of solar heat gains. The effect of building overhangs on buildings energy consumption is dependent on three site specific parameters: the geographical position of the building, the climate conditions and properties of glazing (Korolija et al. 2013).

Service mix

Building use is an important determinate of energy use in commercial buildings: airports, office buildings and hospitals all have different energy load profiles due to the differences in their intended use. This is evident in the impact of a buildings use on the end uses i.e. airports and hospitals have different lighting load profiles office buildings are generally inhabited between 06:00 and 22:00 while hospitals have continuous operation and run 24 hours a day.

The building use criteria can be expanded to accommodate and account for the different types of hospitals i.e. when studying hospitals, hours of operation is an important criterion, hospitals that operate 24/7 and day hospitals will have different energy load profiles. The electrical end use that highlights the importance of distinguishing between types of hospitals are the process loads and plug loads. Rohde & Martinez (2015) studied the energy usage of medical equipment in large teaching hospitals in Norway. The study measured the electrical power consumption and found that it is responsible for a significant portion of both the electrical and heating loads of a hospital.

The clinical specialties of the hospital are a major determinant of its energy. The presence of different specialties has varying effects on the hospitals load profile i.e. the high power per unit consumption of large medical technical equipment associated with a medical imaging department. The respective clinical specialties have different energy requirements and this varying energy intensity affects the load profile to different degrees. Clinical specialty affects the internal load of a hospital in three ways: it governs the type of services provided by a hospital, also the type of equipment in use at the hospital and the capacity of a hospital. Thus clinical specialties have an effect on the internal loading and internal heat gain of a hospital due to occupancy, equipment and lighting.

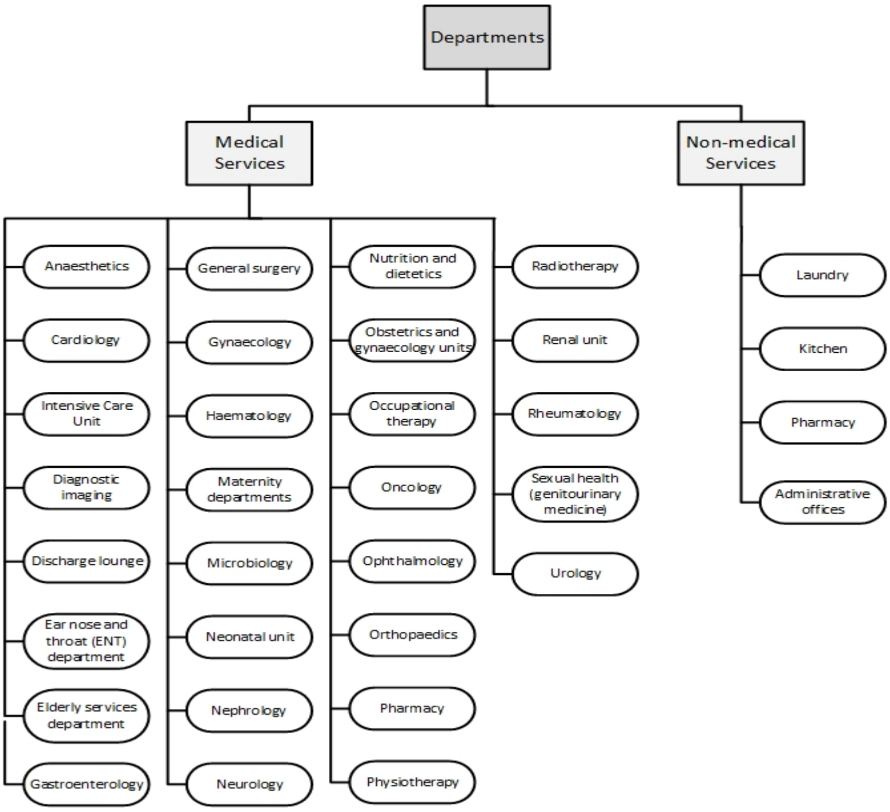

Figure 2: Typical service that make up the service mix of a hospital

Figure 3

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Furthermore, the medical equipment associated with each clinical specialty have different power ratings i.e. medical imaging equipment have higher power ratings then small technical medical equipment such as point of care devices (Rohde & Martinez 2015). However, although SMTE have a low per unit energy consumption rating, these devices are present in large enough numbers in hospitals and/or are operated continuously for extensive periods of time, thus making their collective energy consumption significant. This further emphasises the important role of the size and capacity of the hospital in its energy consumption.

Building system

The energy consumption of a building is captured by the energy demand of six sub-level building systems: the cooling system, space heating system, water heating system, lighting system, mechanical ventilation system; and plug and process loads (Leipziger 2013). It is important to account for the effect that the characteristics of these building systems has on the energy performance of building when determining the actual performance potential of a hospital.

The system type and system characteristics parameters encompass both the micro and macro inter-building system differences. Macro differences refer to the large scale difference between system configurations i.e. using a centralized variable air volume (VAV) HVAC system vs. using a constant air volume (CAV) HVAC system. The collective energy consumption varies depending on the system, the energy consumption of fans, pumps, motors and other significant electricity consuming devices varies depending on the type of system used (Korolija et al. 2011). Micro differences refer to the differences between components that make up the system, their electric loading and efficiency characteristics.

The varying configurations and combinations that are used to aggregated the respective system components in order to provide the service have different efficiencies. These efficiencies can be divided into two categories: macro-level efficiency, overall efficiency of the system and micro-level efficiency, efficiency of components that make up the system. Macro-level efficiency is the most important because efficient components can be combined in an inefficient manor resulting in wasteful energy consumption (Singer 2009). Both the design and part load condition macro and micro- level efficiencies are of interest because the building operated in these two modes most of the time (Zhu 2006).

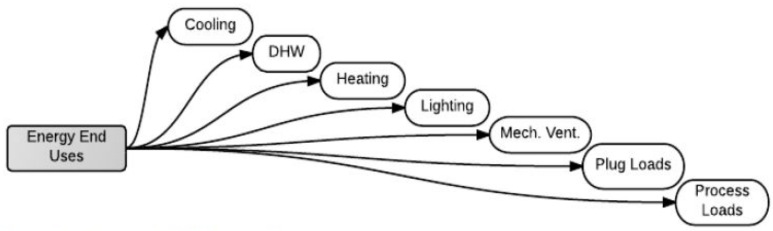

Figure 4: Energy end uses in hospitals (Leipziger 2013)

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Equipment use

One of the major drivers of energy consumption in hospitals is its equipment use or plug loads. Three types of equipment used in a hospital: Medical Technical equipment (MTE's) large and small; Building Equipment (BE); and ICT equipment. These equipment can be classified into two categories Energy consumption due to equipment has two components, namely: the direct equipment use induced electric load component from the operation of the various equipment and the thermal load component from the waste heat generated by the equipment. The contribution of these components are governed by three factors: the power rating or energy intensity of each device type, the variations in the usage level and activity patterns of respective medical device, and the prevalence of each device type in the hospital (Rohde & Martinez 2015).

Equipment generates waste heat that needs to be removing from the building this results in an extra cooling load component. The Location of this equipment in the hospital determines how this additional cooling load component is dissipated, if the device is situated close to the parameter. The heat can be dissipated through the building envelope. However if the device is situated in the centre of the building a combination of mechanical ventilation and cooling system operation is required to remove the heat from the building (Rohde & Martinez 2015).

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MODELLING ENERGY PERFORMANCE OF HOSPITALS: PERFORMANCE ASSESSMENT APPROACH

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Determining the actual performance potential of hospitals with different portfolios that do similar work is challenging due to the complex processes and systems that constitute hospitals. There is no "go to" method for determining the actual performance potential of hospitals. An array of methods have been used in literature to develop normalised benchmarks for buildings energy consumption in literature, namely: building physics, aggregated end-use analysis, multivariate regression analysis, energy utilisation index, descriptive statistics, and artificial neural networks (Burman et al. 2014,Hong et al. 2014). These methods provide a structured and systematic approach to objectively evaluating the energy performance of a building. Each approach has a different level of abstraction and differs in its application and use. The method chosen depends on Hong et al. (2014):

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- The objective of the analysis
- The availability of data needed to develop and normalise benchmarks
- The granularity of the data involved in developing benchmarks
- The accuracy and robustness of the desired model

The majority of these methods are regression based and study the annualised energy consumption in terms of a building or one of its systems as the dependent variable of interest in their models. Monts & Blissett (1982) energy utilisation index (EUI) approach is based on multivariate linear regression. The approach develops a reference EUI for a set of buildings and then assesses the performance of each building in that set relative to the reference EUI.

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A multivariate adjustment to the EUI approach introduces the required sophistication to give the benchmarks derived with this method the necessary sophistication and reliability appropriate for assessing the energy performance of hospitals and similar non-domestic buildings by capturing the diversity and importance of factors that significantly influence the energy consumption (Monts & Blissett 1982). A multivariate equation is generated with the EUI as the dependent variable and the building characteristics and other variables that need to be accounted for as the independent variables.

The model generates benchmarks by analysing a dataset that consists of the buildings energy consumption measurements and building characteristics data of the set of hospitals; and accounting for the various characteristics in the multivariate equation. This provides normalisation for the effect of these factors in the benchmarks, thus generating normalised benchmarks. Normalisation of the actual performance of the measured data occurs when it is applied into the multivariate equation to generate a EUI for the case of the hospital being studied to compare it to the benchmark. This provides an accurate way of quantifying the performance of a facility by determining the current performance of a hospital relative to its peers or relative to historic data of the same hospital.

The regression based approach described by Monts & Blissett (1982) has the same theoretical basis as various benchmarking approaches for non-domestic buildings found in literature. The US Environmental Protection Agency's Energy Star scheme is based on this method (Hong et al. 2014) Benchmarks for commercial buildings in Hong Kong were developed based on this method (Chung et al. 2006).

Different statistical approaches have been used in literature to develop a multivariate approach two benchmarking. (Hong et al. 2014) used an artificial neural network (ANN) to explore and learn the relationships between the independent variables (input variables) and the dependent variables (output) in the databases. The energy performance estimated by the ANN is representative of the crop of buildings used in the study and serves as the benchmark for those buildings. This method is limited by its use of simple indicators to generate the ANN used to assess building performance, thus it is more suitable for assessing how a building is performing relative to other buildings in its sector than assessing if a building is operating efficiently (Hong et al. 2014). Hygh et al. (2012) used a Monte Carlo simulation to test combinations of dependent variable parameters. The simulation yields a data set that can be used to develop and validate the multivariate regression model.

The regression model yields an equation that can be used to predict the energy consumption of the building as function of its key parameters. The regression equation is of the following form:

$$y(x_1, x_2, x_3, \dots, x_n) = \beta_0 + \sum_{i=1}^{n} \beta_i x_i$$

Where the y is the dependent variable, the variable of focus, characteristic being studied (i.e. the energy use intensity of the hospital). Hygh et al. (2012) suggest that you can study energy using separate equations for heating, cooling, electricity and total energy use. The independent/exploratory variables (x), the determinants for energy use at the hospital. The coefficients of the regression equation (β_i) are proportional to each exploratory variable's/parameter's sensitivity towards energy use (Hygh et al. 2012). The residual error variable (β_0) captures uncertainty in the data due to measurement error, modelling error or underlying stochastic processes that are driving the error.

Stapenhurst (2009) discusses benchmarking in general and the diversity of its areas of application. The concepts, uses, benchmarking process and learning potential of seven benchmarking methodologies are outlined. However, since benchmarking is used in a large number of vastly

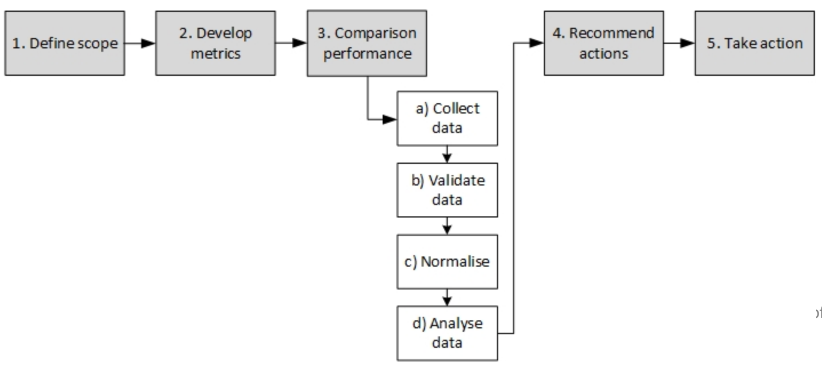

Figure 5: The benchmarking process (adapted from Stapenhurst 2009)

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different sectors these methods vary significantly in their application and their use. Of the methodologies discussed review benchmarking is most applicable to the study of energy consumption in hospitals and in line with the goal of this study.

In review benchmarking, there is a group of participants being studied and data pertaining to certain areas of interest is collected at each participating facility in order to identify areas of improvement (Stapenhurst 2009). The benchmarking process is outlined Figure 4 and consists of the following six steps:

1. Define and limit the scope of the benchmarking study
2. Define and develop performance metrics
    a. To standardise the way different facilities report their performance we need clear definitions
3. Perform performance comparison
    a. Collect data
    b. Validate data
    c. Normalise
    d. Analyse data
4. Recommend actions
5. Take action

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The relevance of the recommendations based on the findings of this benchmarking study is dependent on:

- The accuracy of the data used
- The appropriateness of the collected data for analysis
- The appropriateness of the analysis method
- The appropriateness of the metrics used

Normalisation allows us to perform useful comparisons of metrics that are not directly comparable by accounting for the underlying context driven differences between the metrics. Thus it is important to understand the context and characteristics of the facility in the time period which we are studying the facility. The weighting factor (WF) normalisation method identifies distinct packages based on the importance a specific factor or set factors have to the achievement of our current objective (Stapenhurst 2009). The WF of each set of factors or characteristics are added together to give the total weighting factor (TWF) of the work scope. For each facility in the comparison a TWF parameter needs to be calculated, the TWF is used to normalise the performance of that facility. Stapenhurst (2009) emphasises the importance of identifying key factors that influence the performance of that facility and deciding which of the identified factors should be used as weighting factors and which should not.

CONCLUSION

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