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Hospital Energy Demand Forecasting for Prioritisation During Periods of Constrained Supply

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Abstract:

Purpose: Sustaining healthcare operations without adequate energy capacity creates significant challenges, especially during periods of constrained energy supply. This research develops a clinical and non-clinical activity-based hospital energy model for electrical load prioritization during periods of constrained energy supply.

Design/methodology/approach: Discrete event modelling is adopted for development of the hospital energy model (HEM). The building block of the HEM is business process mapping of a hospitals clinical and non-clinical activities. The model prioritizes the electrical load demand as Priority 1, 2 and 3; Priority 1 activities are essential to the survival of patients, Priority 2 activities are critical activities that are required after one to four hours, and Priority 3 activities can run for several hours without electricity.

Findings: The model was applied to small, medium, and large hospitals. The results demonstrate that Priority 2 activities have the highest energy demand, followed by Priority 1 and Priority 3 activities, respectively for all hospital sizes. For the medium and large hospitals, the top three contributors to energy demand are lighting, HVAC, and patient services. For the small hospital, it is patient services, lighting, and HVAC.

Research limitations/implications: The model is specific to hospitals but can be modified for other healthcare facilities.

Practical implications: The resolution of the electrical energy demand down to the business activity level enables hospitals to evaluate current practices for optimization. It facilitates multiple energy supply scenarios, enabling hospital management to conduct feasibility studies based on available power supply options

Social implications: Improved planning of capital expenditure and operational budgets. Improved operations during periods of constrained energy supply, which reduces the risk to hospitals and ensures consistent quality of service.

Originality/value: Current hospital energy models are limited, especially for operations management under constrained energy supply. A simple to use model is proposed to assist in planning of activities based on available supply.

Keywords: energy, healthcare, hospital, business

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1. Introduction

Access to healthcare and energy are fundamental human rights, as identified by the United Nations Sustainable Development Goals 3 (focusing on good health and well-being) and Goal 7 (access to affordable and clean energy). Energy is a critical requirement for health care delivery (Suhlrie, Bartram, Burns, Joca, Tomaro & Rehfuess, 2018), with healthcare and energy demands increasing in proportion to city growth. This increased demand is apparent in developing countries, especially on the African continent, with South Africa a prominent example. Further to this, healthcare facilities are characterized as energy-intensive buildings (Franco, Shaker, Kalubi & Hostettler, 2017), with hospitals, the largest of the healthcare facilities, having significant energy requirements (de Oliveira, dos Santos, Neto, de Mello-Santos & de Oliveira, 2021; Vaziri, Rezaee & Monirian, 2020).

In South Africa the increased energy demand is driven by two key factors, urban migration and technological advancements including those associated with the fourth industrial revolution (4IR). The demand for energy in growing cities results in a significant load on the electricity grid. This has manifested in South Africa, where for the past two decades, energy demand exceeded grid capacity, resulting in rolling, planned local power service interruptions known as load shedding.

Such intermittent outages are highly disruptive and significantly impact healthcare services. According to (Laher, van Aardt, Craythorne, van Welie, Malinga & Madi, 2019; Porcaro, Mehta, Shupler, Kissel, Pfeiffer, Dora et al., 2017; Practical Action, 2010), the impacts of load shedding on South African and global hospitals include:

- Reduced reliability and effectiveness of sewage and running water systems.
- Lack of sterilization of surgical instruments can result in delays to surgeries, whilst poor sterilization can result in infections.
- Lack of use of ultraviolet light sources for eliminating viruses.
- Loss of refrigeration and temperature control leading to inefficiency of cold storage devices.
- Lack of lighting, which impedes the ability of the health care facility to operate 24 hours and impacts the quality of the service delivered.
- The inability to use medical equipment, including diagnostic and surgical equipment. This results in delays in diagnosis, and in some cases these delays can be fatal.
- Delays in dispensing of medication as most hospital pharmacies use electronic systems.
- Loss of proper waste management, as some medical waste disposal equipment such as waste autoclaves and grinders, require electricity to operate.
- Increase in the number of patients due to the use of alternative energy sources such as paraffin, wood, and coal, potentially leading to carbon monoxide and cyanide poisoning and burns, and
- Loss of healthcare workers, as the poor working environment discourages professional healthcare workers from taking up positions in these facilities.

Thus, the ability of hospitals to manage electrical load demand during periods of constrained supply is critical. There are various health and hospital energy management systems (Hijjo, Bauer, Felgner & Frey, 2015; Teke & Timur, 2014). These energy management systems focus on managing onsite supply, demand, and equipment, improving reliability, energy efficiency and general daily energy management, and utilizing renewable technologies Notably, there is limited work on how to manage hospital electrical load demand during periods of limited or no supply. With limited supply, time sensitive decisions need to be made with regards to critical/non-critical services to be provided. During these periods, it is essential to prioritize the equipment/services that are critical to human life requiring constant electricity, equipment/services that can operate for a short period without electricity and equipment/services that can operate for an extended period without electricity. The hospital facilities' demand for heating, ventilation, air conditioning (HVAC) and lighting must also be considered in this prioritization, as ventilation and lighting requirements vary based on the space activity such as intensive care units (ICU), theatres, and general wards. Together with the prioritization, the actual energy required must be determined. This requires the ability to predict energy demand based on all activities (clinical and non-clinical) performed at a hospital, hospital capacity and occupation rate.

This study proposes the use of discrete event modelling, based on the activities executed at the hospital, in the development of a hospital energy model (HEM). The HEM includes a prioritization function, to serve both as an electrical load predictive tool and to navigate energy usage based on the level of priority of services. The model output would enable informed decision making on hospital operations during periods of limited supply; based on the energy demand of essential activities, determination of minimum back-up power requirements and resource reallocation including staff to provide additional support for activities that would have typically been monitored by equipment.

2. Literature Review

In developing and low-income countries, access to reliable electricity is a challenge (Adair-Rohani, Zukor, Bonjour, Wilburn, Kuesel, Hebert et al., 2013; Franco et al., 2017). Globally, approximately, one billion people utilize health facilities that operate without electricity (Practical Action, 2010). In India, 46% of health service facilities (utilized by approximately 580 million people) operate without electricity. In sub-Saharan Africa, approximately 30% of health facilities (utilized by approximately 255 million people) operate without electricity (Practical Action, 2010). (Adair-Rohani et al., 2013) demonstrated two key findings related to electricity access at healthcare facilities in sub-Saharan Africa. The key findings include only 34% of the hospitals in the surveyed countries had access to reliable electricity supply and 26% of healthcare facilities had no access to electricity.

The lack of electricity supply or unreliable electricity supply is detrimental to healthcare service delivery. In Ghana, 16% of child immunization facilities have limited capacities due to unstable electricity supply disrupting the cold chain required for vaccine storage (Franco et al., 2017). A voltage surge at a hospital in Cameroon in 2011, resulted in the damage of 50% of its equipment including generators and medical devices (Franco et al., 2017). Frequent power outages have resulted in approximately 50% of vaccines losing their efficacy in developing countries (Practical Action, 2010), whilst poor power quality is identified as a key contributor to 70% of medical equipment failure (Porcaro et al., 2017).

There are various uses of electricity in a hospital, with researchers classifying the usage based on specific study objectives. (Unger, Campion, Bilec & Landis, 2016) defines the energy associated with various healthcare equipment and consumables based on usage and maintenance impacts. (Franco et al., 2017) categorizes health care facilities' energy demand into:

- Basic services, should be including amongst others, lighting, HVAC, communication, and water supply.
- Medical equipment
- Laboratory equipment

The wide application results in hospital energy demand management being focused on specific systems such as HVAC, lighting, and medical devices (Barrick & Holdaway, 2014; Franco et al., 2017; Shajahan, Culp & Williamson, 2019). In hospitals in India, the high electricity consumers are HVAC accounting for 30-65%, lighting accounting for 30-40% and water pumps accounting for 10-12% of total demand (Franco et al., 2017). According to (Barrick & Holdaway, 2014), based on the energy utilization index (EUI) or $kBtu/ft^2/yr$, the average energy consumption in US hospitals for HVAC ranges from 240 to 270 $kBtu/ft^2/yr$ with the largest portion (42.3%) used for reheating air. This is largely due to the high air change requirements needed in healthcare facilities.

2.1. Healthcare and Energy in South Africa

In South Africa, 13.5% of government spending is focused on healthcare (UNICEF, 2018), whilst internationally, healthcare expenditure averaged 6% in middle-income countries (Xu, Soucat, Kutzin, Brindley, Maele, Touré et al., 2018). Research indicates that higher spending levels do not always produce more value and better patient health outcomes. (Burger & Christian, 2018) state that health outcomes remain disparate in South Africa. Vulnerability of subgroups and persistent inequities exist, particularly when comparing healthcare in private and public facilities. However, this is not unique to South Africa with (Guerrini, Romano, Campedelli, Moggi & Leardini, 2018) discussing similar gaps between public and private healthcare in other countries. (Burger & Christian, 2018) indicate that these differences can be partly traced to interoperability problems; continued use of obsolete medical devices, energy and resources inefficiency and network interface problems. These problems result in longer waiting times, theft of resources, and a greater than 76% overall patient dissatisfaction rate in the public healthcare sector (Unger, Campion, Bilec & Landis, 2016). South African public healthcare ranks 8th lowest amongst the developing countries. This is in the lower cadre, after Turkey, whilst South African private healthcare is ranked 6th in the higher cadre, after Sweden and Switzerland (Unger et al., 2016).

In 2007, South African power provider, Eskom, experienced challenges in meeting the electricity demand; the available supply capacity far exceeded the demand. Eskom implemented load shedding to prevent electricity grid failure. Load shedding is the periodic disruption of electricity supply when supply exceeds demand capacity. Load shedding can range from two hours a day to several hours per day, depending on the severity of the supply shortfall. This disruption of power supply impacts the operations of hospitals. It is further exacerbated by the short notification periods prior to the start of load shedding. In SA, private health care facilities and secondary and tertiary level public hospitals are better equipped with generators to handle periods of load shedding. However, the cost of operating the generators is expensive; a private hospital group encountered an additional monthly expenditure of R800 000 ($60 000) due to generator usage (Laher et al., 2019).

A study conducted on the effect of load shedding on admissions at a South African paediatric hospital found a 10% increase in admissions on days of load shedding and no more than two days prior and a 14% increase in respiratory system diagnoses is observed during these periods (Gehringer, Rode & Schomaker, 2018).

2.2. Energy Evaluation of Healthcare Facilities

Healthcare has been the specific focus of many modelling studies (Gunal & Pidd, 2010), with various techniques adopted to simulate healthcare. (Morgenstern, Li, Raslan, Ruyssevelt & Wright, 2016) conducted an energy consumption benchmarking study across 28 departments, categorized into six areas of wards, theatres, imaging and radiotherapy, laboratories, day clinics and others, in eight hospitals in the UK. The study used actual electrical measurements for quantifying the energy consumption of the six areas. A limitation of the study is the exclusion of the electricity usage of HVAC, pumping and medical services. The study found that theatres, laboratories and imaging and radiotherapy had high energy intensities that exceeded the benchmark targets. (García-Sanz-Calcedo, Gómez-Chaparro & Sanchez-Barroso, 2019) conducted a study on the electrical and thermal energy consumption of 13 private hospitals in Spain. The energy data for the study period was obtained from the respective electrical and natural gas suppliers. The study determined that the number of discharges, emergencies, hospital stays, useful square area and staff contingent are highly correlated to the annual energy consumption of a hospital.

Christiansen, Kaltschmitt and Dzukowski (2016) evaluated the electrical energy consumption of specific hospital areas and large medical equipment at a hospital in Germany, by recording and analysing electrical measurements. Findings included; electrical energy consumption of medical equipment varies in the same discipline and among different departments, operating theatres are the largest consumers among the various departments, lighting accounts for almost 50% of the demand, and examination and treatment rooms are low electrical energy consumers.

Bhatia and Singh (2021) conducted an energy audit on a +1250-bed specialty hospital in India to determine the energy performance index (EPI), evaluated as kWh/m^2, for the period April 2019 to March 2020. The EPI is calculated by analysing the consumption of electricity, diesel and natural gas and the electricity bills of the selected period. The EPI calculated of 290.98 kWh/m^2/year was determined as "fairly good" by the authors, as it was near the benchmarked EPI of 264 kWh/m^2/year and was attributed to good performance practices such as energy metering, variable frequency drive and LED lighting. (Gonzalez, Garcia-Sanz-Calcedo & Salgado, 2018) conducted an energy study across 20 Spanish hospitals, with 80% of the hospitals categorized as small hospitals. The calculated average annual energy demand of Spanish hospitals was 0.27 MWh/(m^2.year), with a standard deviation of 0.07 MWh/(m^2.year).

Bagnasco, Fresi, Saviozzi, Silvestro and Vinci (2015) utilized artificial neural network (ANN) to predict the electrical consumption of the Cellini medical clinic of Turin. The data for the ANN model was electrical energy consumption data, in 15-minute intervals, from the local distribution operator. (Bertolini, Massucco, Silvestro, Grillo & Giacomini,, 2013) applied ANN to predict load demand at an eye clinic and the Department of Internal Medicine and Medical Specialties in GENOA, Italy. The model had a 77.57% accuracy for the eye clinic and 78.64% for the Department of Internal Medicine and Medical Specialties.

Cao, Li, Zhang, Jiang, Han and Wei (2020) evaluated eight machine learning algorithms of single and ensemble learning, for the prediction of a hospital electrical load in two time resolutions of daily and weekly. The 10 input variables for the models were classified into four categories: day type, weather, occupancy and operational and maintenance. The prediction accuracy of the ensemble models, XGBoost and Random Forest was better than the single models, and prediction was better at the daily resolution than the weekly resolution. The key variables influencing energy consumption at the daily and weekly levels were outdoor temperature, air pressure and status of the HVAC system. (Cao et al., 2020) further stated that there is limited research on healthcare buildings due to the complexity of their energy demand. Ventilation and support systems are crucial in healthcare facilities. (Shajahan et al., 2019) provides details on environmental factors to consider for HVAC of healthcare facilities and the impact of HVAC on patient and medical outcomes. Some HEM models focus on energy conservation and green supply (Isa, Das, Tan, Yatim & Lau, 2016; Teke & Timur, 2014).

Key observations in the aforementioned energy evaluation methodologies are listed below.

- The use of recorded electrical energy consumption, either from direct measurement or use of billing data.
- The energy evaluation is limited to specific areas or systems of the hospital.
- None of the researchers conducted a comprehensive energy demand analysis of the hospital, inclusive of clinical activities, non-clinical activities and building facilities' energy demand.
- The energy data gathered was not applied in energy load management during periods of constrained supply.

These models cannot assist decision makers on what services to run and how to prioritize the services of the hospital. These observations clearly indicate the need for an accurate hospital energy management tool that guides decision making with respect to critical activities and the associated energy demand requiring prioritization during periods of constrained supply.

Franco et al. (2017) prioritized the various hospital equipment based on the impact to patients' lives:

- Secured: Equipment that is critical to a patient's survival and requires protection against voltage variations and power disruptions.
- Non-secured: Equipment that is critical to a patient but has the capacity to operate during moderate voltage variations and short power disruptions.
- Non-critical: This equipment is not essential to a patient's survival.

Hence this research considers this hierarchy in hospital activity and service prioritization.

2.3. Healthcare 4.0

Healthcare 4.0 is defined as the application of real-time patient data to facilitate shifting towards individualization of care while simultaneously managing, integrating, and aggregating stakeholders' preferences and requirements through an improved clinical model (Karupan, Dunlap & Waldrum, 2016). The simultaneous management of stakeholder preferences consists of integrating energy efficiency, energy network flexibility, overall healthcare system capacities, security and privacy, scalability, cost, and coverage (Karupan et al., 2016). Examples of application of advanced 4IR technologies to healthcare systems are briefly reviewed.

- Zhou, Wang and Goh (2018) propositioned the Internet of Health Things (IoHT) as an approach to healthcare that includes automated robotics within pharmacies.
- Sun, Hu, Zhou and Chen (2018) adopted an advanced artificial intelligence (fuzzy) recognition system for patient diagnostics in healthcare facilities.
- Ortiz-Barrios, Herrera-Fontalvo, Rúa-Muñoz, Ojeda-Gutierrez, de Felice and Petrillo (2018) demonstrated the application of three widely used 4IR methods to evaluate the risk associated with adverse events on facilities, although this work does not address real-time analysis or energy usage.
- An, Meng and Xiong (2018) adopted analytical hierarchical processes (AHP) and other decision techniques advancing unit optimization at facilities. This is limited to the ranking of systems at the unit level only.
- Dovjak, Shukuya and Krainer (2018) provided for a technologically enabled view on the treatment of burn patients.

These authors determined that the enablement and delivery of patient care depend critically on facility energy management. A careful equilibrium of energy demand and available supply is needed to ensure that the advanced technological systems needed for the treatment of burn patients are not compromised, ensuring patient safety.

Raue, Lermer and Streicher (2018) provided a detailed analysis on the need for effective communications at a healthcare facility and reinforces the need for digital information infrastructure. (Crain, Brossoit & Fisher, 2018) provided a long-range, idealistic view of the potential uses of 4IR in healthcare. It is noted that the adoption of such 4IR technologies could significantly increase energy requirements. Localized energy networks being down are likely to result in a loss of network connectivity. (Maktoubian & Ansari, 2019) stated that for healthcare facilities without adequate 4IR technologies, maintenance is a key driver of higher energy consumption. Sophisticated maintenance techniques deliver a more energy-efficient facility allowing for improved healthcare services.

Industry 4.0 adopts business process models as a key navigator towards digitalization. Combined with its technical specificity, business process models are an ideal basis for electrical load evaluation at hospitals. Further to this, changes in business process models due to changes in activities driven by new technologies, new processes, or energy efficiency improvements, can be easily incorporated into the model. This enables continuous determination of the facility status, providing insights for optimization. This is especially relevant for hospitals, where the high electrical load demand necessitates continuous energy optimization and forecasting.

2.4. Business Processes and Discrete Event Modelling

Business processes (BP) detail the sequence of steps in the execution of business activities, including interlinks with other business activities (Bradford & Gregory, 2015). In the context of a hospital, a business activity is any activity executed to meet the hospital's mandate of healthcare delivery. The activities can vary from admitting a patient to conducting surgeries to payment of staff salaries. Each step of the business process is detailed and explicit, to ensure proper execution of the task. The level of detail of each business process step enables determination of the resources required in the execution of the task, including the medical devices. Thus, the prioritization of the hospital services (activities) inherently prioritizes the equipment. The collation of all hospital activities is a representation of the hospital, with the simulation of the business processes creating a digital representation of the hospital.

Discrete event simulation (DES) models a sequence of events (Agalianos, Ponis, Aretoulaki, Plakas & Efthymiou, 2020). Thus, the modelling of business processes, a sequence of events (activities), is discrete event modelling. (Williams, Szakmany, Spernaes, Muthuswamy & Holborn, 2020) applied DES in analyzing the impact of various scenarios on critical care bed occupancy. (Hajrizi & Berisha, 2019) applied DES and multi-objective optimization simulation to reduce the length of stay and waiting times at an emergency department. (de Almeida, Ramos, Rutten-van Molken & Al, 2021) applied DES in evaluating the impact of early warning systems (with and without diagnostics algorithms) on patients with heart failure. (Zhang, 2018) conducted a systematic literature review on the application of DES in healthcare. (Zhang, 2018) categorized the application of DES into four areas, with the healthcare system having the highest application, but more than 68% of the application focused on individual units.

The literature defines the current energy challenges, and future healthcare energy demand based on the evolution of healthcare technology. The literature also identifies the current inability to prioritize healthcare services based on accurate models. The challenges of energy supply constraints are a reality and can be managed by a 4IR based predictive model; healthcare managers can optimize service management if the correct hospital activities can be prioritized in real time. This study applies DES in creating a digital representation of a hospital, with every hospital activity prioritized towards determining the minimum energy demand required during periods of constrained energy supply.

3. Methodology

The proposed approach facilitates decision making for energy allocation, with full consideration of a healthcare facility's energy priorities (Franco et al., 2017). This research presents a computational back-end model that facilitates these decisions based on a prioritization model developed from clinical and non-clinical hospital activities. The essence of the modelling approach is capturing every activity performed by every function at a hospital. This includes clinical (surgery, X-rays, blood analysis, pharmacy) and non-clinical (administration, maintenance, finance, human resourcing, planning) activities. Business processes, which detail the sequence of steps in the execution of business activities, are adopted to capture every activity performed in each functional area of the hospital. Modelling of a hospital's clinical and non-clinical business processes are considered representations of a hospital's activities. The inclusion of the facility's demand for HVAC and lighting provides a comprehensive representation of a hospital energy demand. Figure 1 illustrates the high-level approach to the study.

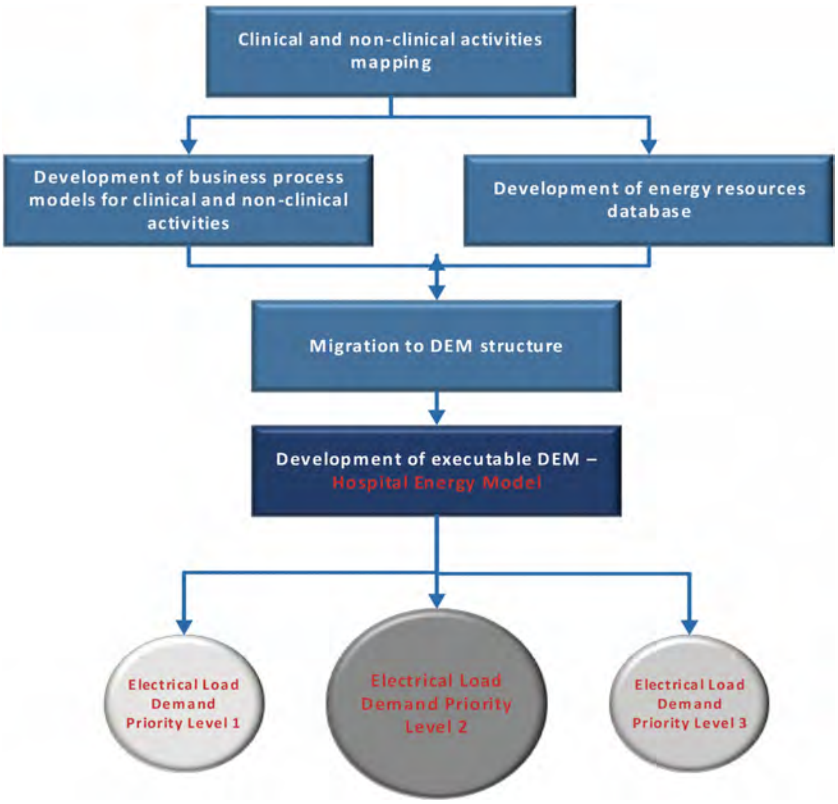

Figure 1. Hospital energy model development approach

The development of the hospital energy model (HEM) commences with the acquisition and mapping of the clinical and non-clinical activities, as business processes. As the business processes can be large and complex, it requires the development of a multi-level business process hierarchy. A 4-level hierarchy was developed for this model: Level 0 represents the functional areas within a hospital; Level 1 is the process areas within each functional area; Level 2 is business processes (clinical and non-clinical), and Level 3 are specific execution activities for each business process, referred to as the business process step. Level 0 (P_0) functions are financial management (FM), human resources (HR), health care delivery (HCD), analysis and imaging (AI), specialized treatment (ST), marketing (M), customer service management (CSM), information and communication technologies (ICT), risk and compliance management (RCM), heating, ventilation, and air conditioning (HVAC), lighting (L), network (N), healthcare planning systems (HPS) and standby (S).

Figure 2 illustrates a surgical business process (Level 2), demonstrating the detail and specificity of business processes, interlinks with other processes, and decision blocks ("can the patient undergo the surgical procedure") which guide the process execution path. The mapped business processes are modelled in Microsoft Visio to create an integrated business process model.

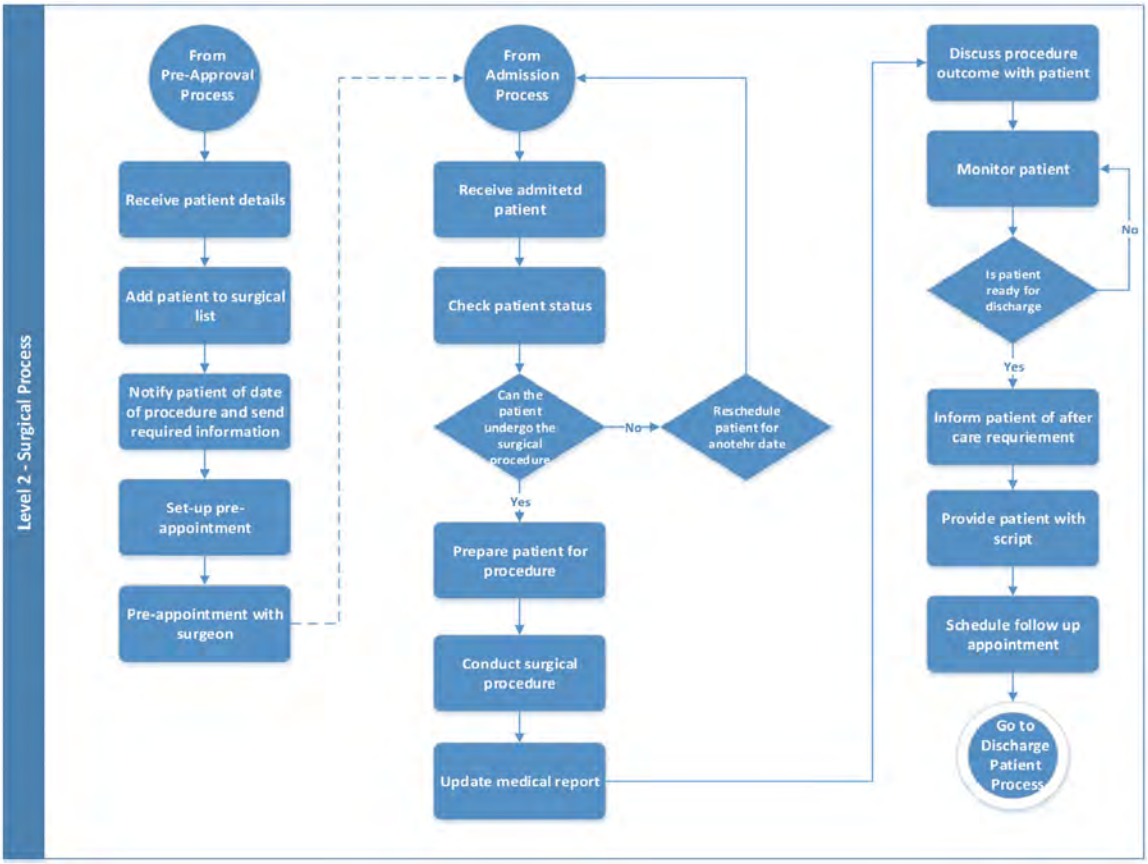

Figure 2. Surgical business process model extract

Whilst the business processes detail the steps in the execution of hospital activities, the resources required in the execution of the business processes are needed to quantify the energy demand. Thus, the next key component is the hospital energy resources databases (ERD). The ERD comprises all electricity consuming resources (ECR) required for the execution of the clinical and non-clinical business processes. The database is defined as a set: (ERD) = $\{ECR_1 \dots ECR_n\}$. The ECRs are varied, and categorized as per (Franco et al., 2017; Practical Action, 2010):

- Clinical - equipment required for clinical activities such as X-ray machines, blood group analysers, microscopes, and dialysis machines.
- Office - equipment typically found in offices such as laptops, printers, telephones, screens, and tablets.
- Network - infrastructure equipment to support ICT such as routers, switches, servers, and firewalls.
- HVAC - equipment for maintaining a sterile environment at the required temperatures, such as air handling units and cold and hot generators.
- Lighting - differing lighting options are required by the various areas of the hospital.

- Other - includes resources required for laundry and catering/kitchen services.

The next step is the prioritization of the hospital's electrical energy load. (Franco et al., 2017) adopted a three-point priority scale in prioritizing the equipment of a hospital. The equipment prioritisation assists in identifying critical activities and the resources requiring energy supply during periods of constrained power supply. Thus, this model adopts a three-point priority scale for prioritizing hospital activities (both clinical and non-clinical):

- Priority 1: Essential activities that require completion in one hour or less, where there is a danger to life, eyesight or limb. These are lifesaving activities and include specific surgeries, dialysis, specific blood analyses, maintaining of a negative pressure space for immune comprised patients and maintaining of cold storage temperature for vaccines and other medications.
- Priority 2: This constitutes critical and/or emergency care that would be needed within one to four hours and includes activities such as specific surgeries, transplants, ensuring availability of oxygen and blood, and x-rays. If these activities are not executed within the one to four hour time frame, they become essential activities.
- Priority 3: Activities and resources that can run for an extended period without power. These activities are not critical for a patient's survival and includes elective surgeries, HR activities such as training and conducting interviews and financial activities such as invoicing and procurement.

This is followed by the migration of the business process models to a Discrete Event Modelling (DEM) structure. For the DEM structure, each functional area (Level 0) is expanded to the applicable process areas (Level 1), with each process area delineated to the required business processes (Level 2) and each business process is delineated to the business process steps (Level 3). Figure 3 illustrates the DEM structure for one process area of Patient Admission, for the HCD functional area. The process area of patient admission comprises five business processes, as illustrated in the third level in light blue, with the first business process having eight business process steps (green circles at the fourth and fifth levels). The resources required are defined at the business process step (level 3), as illustrated by the resource key alongside each business process step. The description of the resource keys is displayed in the top right-hand corner of Figure 3. Only the applicable resources are illustrated for each business process step. The model is executed for each process step (event) with the required resources determined.

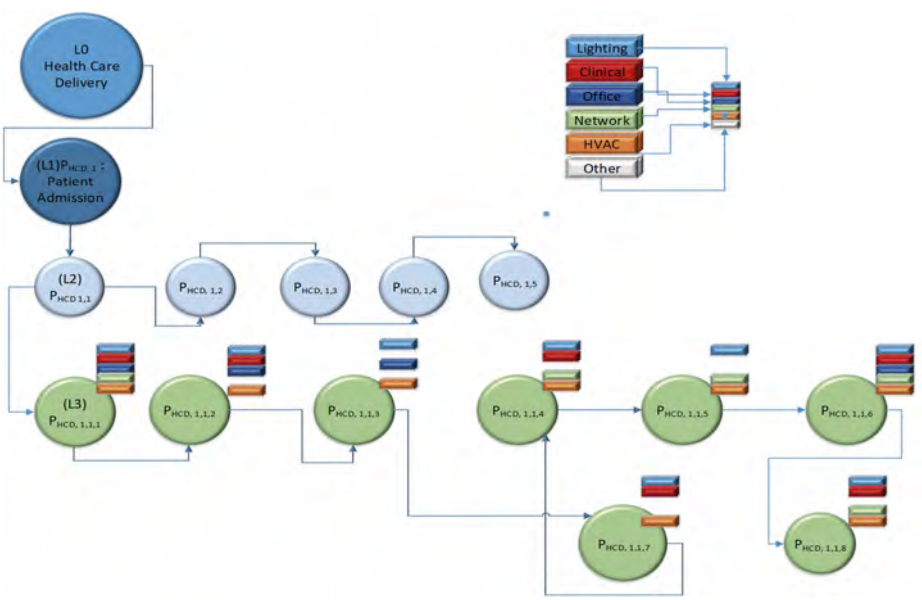

Figure 3. Sequencing of business processes to discrete event modelling

Utilizing the DEM structure, the executable hospital energy model is developed in Microsoft Excel VBA. The model determines the energy utilization of a hospital and categorizes the utilization requirement per priority level, as per Equations 1 and 2.

$$Total\ Energy\ Priority, P_x = \sum_{1}^{i}\sum_{1}^{j}\sum_{1}^{k}\sum_{1}^{l} RR_{i,j,k,l}\, RED_{i,j,k,l} RUT_{i,j,k,l} \quad (1)$$

Where

P_x = Priority level 1, 2, 3
i = Number of functional areas (Level 0)
j = Number of process areas (Level 1)
k = Number of business processes (Level 2)
l = Number of business process steps (Level 3)
RR = Resource required
RED = Resource energy demand
RUT = Resource utilization time

* Activity execution time ranges from seconds to days to weeks, thus all calculations are rolled up into a year basis.

$$Total\ \text{Hospital Energy (all priorities)} = \sum_{x=1}^{3} \text{Total Energy } (P_x) \quad (2)$$

Where total hospital energy is the energy required to sustain the facility with all systems operational.

Table 1 illustrates the calculation methods as expressed in Equation 1 in greater detail. The hierarchy is expanded from Level 0 to Level 3 for the functional area HCD. The inputs for all Level 3 activities are illustrated specific to the Level 2 activities associated with Schedule the patient ($P_{HCD,\ 1,1}$) and Perform initial intake ($P_{HCD,\ 2,1}$). This approach is replicated for all the business activities and summed (based on the number of times the activity is performed over the period), as per Equation 1.

The calculation conducted at each process step of the DEM or Level 3 activity is rendered by Equation 3. Each business process has a specific number of business process steps (l), as represented by the upper limit on top of the summation sign.

$$P_{HCD,1,1}(Energy) = \sum_{1}^{l} RR * RED * RUT \quad (3)$$

With $l = 5$ (as per Table 1)

The calculation for the energy demand of the functional area Heath Care Delivery (HCD) is illustrated by Equation 4. HCD has four process areas of patient admission (HCD,1) patient attendance (HCD,2), discharge patient (HCD, 3) and surgical (HCD, 4), as illustrated in Equation 4. The number of business process vary per process area, with patient admission having four business processes (HCD,1,1; HCD,1,2; HCD,1,3 and HCD,1,4), and patient attendance three business process (HCD,2,1; HCD,2,2 and HCD,2,3).

$$P_{HCD}(Energy) = \sum_{1}^{k} P_{HCD,1,k}(Energy) + \sum_{1}^{k} P_{HCD,2,k}(Energy) + \sum_{1}^{k} P_{HCD,3,k}(Energy) + \sum_{1}^{k} P_{HCD,4,k}(Energy) \quad (4)$$

Level 0: P_{HCD}	Level 1: $P_{HCD, n}$	Level 2: $P_{HCD, n, m}$	Level 3: $P_{HCD, n ,m, o}$	Priority Level	Resource Required (RR)	Resource Energy Demand (RED) (kW)	Resource Utilization Time (RUT) (hr)
Healthcare Delivery	$P_{HCD, 1}$: Patient Admission	$P_{HCD, 1,1}$: Schedule the patient	Create or update the medical record($P_{HCD,1,1,1}$)	3	Laptop	0.03	0.083
			Create or update the medical record ($P_{HCD,1,1,1}$)	3	Telephone	0.002	0.083
			Solicit the referral source from the patient ($P_{HCD,1,1,2}$)	3	Laptop	0.03	0.050
			Solicit the referral source from the patient ($P_{HCD,1,1,2}$)	3	Telephone	0.002	0.050
			Schedule the patients requested care ($P_{HCD,1,1,3}$)	3	Laptop	0.03	0.083
			Remind patient of scheduled appointment ($P_{HCD,1,1,4}$)	3	Laptop	0.03	0.05
			Pre-register the patient in the system ($P_{HCD,1,1,5}$)	3	Laptop	0.03	0.133
	$P_{HCD, 2}$: Patient Attendance	$P_{HCD, 2,1}$: Perform initial intake	Confirm identification of patient ($P_{HCD,2,1,1}$)	3	Tablet	0.005	0.08
			Triage patient ($P_{HCD,2,1,2}$)	1	Tablet	0.005	0.05
			Determine medical history ($P_{HCD,2,1,3}$)	3	Tablet	0.005	0.13
			Identify current medication ($P_{HCD,2,1,4}$)	3	Tablet	0.005	0.08
			Perform physical assessment ($P_{HCD,2,1,5}$)	3	Tablet	0.005	0.05
			Assess patients' vitals ($P_{HCD,2,1,6}$)	2	Tablet	0.005	0.05

Table 1. Business process hierarchy with details the resource required, resource energy demand and resource utilization time for the following set of activities: Health Care Delivery (Level 0), Patient Admission (Level 1), Patient Attendance (Level 1), Schedule the patient (Level 2), and Perform initial intake (Level 2)

Modelling for integration is the ability to interlink the different functions, such as the integration of HCD function with the Healthcare Planning System (HPS) function. The energy model for points of integration is calculated with the process flow.

$$P_{HCD/HPS}\,(E) = \{P_{HCD,\,1,1}\,(E) + P_{HPS,\,5,3}\,(E)\}*\text{Number of integration activities} \tag{5}$$

Where

$P_{HCD/HPS}$: Notation for point of integration between HCD and HPS

The model executes as per the process activities of the hospital and the total energy is the sum of the energy of all processes, together with all integration energies for all priority levels. The cumulative energy model is;

$$P_{Total}\,(Energy) = \sum_{1}^{3}\{PFM\,(E) + PHR\,(E) + PHCD\,(E) + PAI\,(E) + PS\,(E) + \cdots + PHCD/HPS\,(E) + PHCD/AI\,(E) + \cdots\} \tag{6}$$

The model is designed to execute based on the number of times the individual activity is performed over the period being quantified, this includes the potential looping with other Level 3 processes that are in the same event sequence. For the period of a week or a month, the DEM is run with the relevant sequencing and the energy calculated. The event sequencing may change, dependent on the event. The model is constituted with each activity having unique identifiers on the levels of priority (Priority 1, Priority 2, Priority 3). The model execution can be separated, and energy determination conducted at each priority level, refer to Equation 2. The simulation records the sum of the energy for all activities, as the simulation executes.

3.1. Data

This research requires various data to develop the business process model and the energy databases. The business process model data is sourced from the American Productivity and Quality Centre (APQC) (APQC, 2018), and is validated by experts in the different functional areas. Data for the energy resources database is sourced from the research teams existing database, and include (APQC, 2018; CISCO South Africa, 2018; Knight, Konidari, Knight, Blatch, Alexandre, Freire et al., 2014; Menezes, Cripps, Buswell, Wright & Bouchlaghem, 2014; Morgenstern, 2016).

4. Results and Discussion

Hospital operations are complex due to their dynamic nature; 24 hours of operations; and daily variation in the number of patients treated; number of surgical procedures performed and hospitalized patients. Further, hospital operations are influenced by external factors such as seasonal changes, natural disasters, and emerging infectious diseases such as COVID-19.

The research team developed the clinical and non-clinical business processes as per the identified functional areas. From the developed business processes, 45 internal and external variables influencing hospital operations were identified, ranging from the number of patients treated to the number of blood tests to the number of invoices processed. The 45 variables are applicable to all hospitals, with only the operational range different given the specific constraints of the hospital(s) being evaluated. Table 2 provides a sample of the variables, which further illustrates its commonality across all hospitals.

Number of inquiries handled successfully	**(E_{WS})**	Number of recruitment requisitions approved	**(R_{RA})**	Number of training requisitions approved	**(T_{RA})**
The number of walk-in patients that have medical insurance	**(P_{WMI})**	Number of recruitment requisitions have suitable candidates	**(R_{SC})**	Number of suppliers meeting contractual terms	**(S_{CT})**
Number of walk-in and in-hospital patients requiring diagnostic testing	**(P_{WD})**	Number of candidates selected for interview require travel arrangements	**(R_{TA})**	The number of patients whose medical insurance covers the required procedure/treatment	**(P_{MIC})**
Number of walk-in and in-hospital patients requiring blood tests	**(P_{WDB})**	Number of selected candidates pass background check	**(R_{BC})**	Is the hospital SHEQR compliant	(SHE_{C})
Number of walk-in and in-hospital patients requiring MRI scans	**(P_{WDBT})**	Did the selected candidates accept the offer	**(R_{AO})**	Is the improvement plan to address the non-conformances acceptable	**(IP_{NCA})**
Number of walk-in and in-hospital patients requiring CT scans	**(P_{WDCT})**	Number of payments received via third party collectors	**(PY_{RR})**	Number of customer queries for invoices issued	**(P_{II})**
Number of walk-in and in-hospital patients requiring X-rays	**(P_{WDXR})**	Number of procurement requisitions approved	**(P_{RA})**	Number of the valid early retirement applications approved?	**(PE_{ERA})**
Number of walk-in and in-hospital patients requiring amino acids tests	**(P_{WDAT})**	Number of acceptable tenders received for the approved procurement requisitions	**(TE_{RA})**	Number of walk-in and in-hospital patients requiring blood group tests	**(P_{WDBG})**

Table 2. Sample of variables influencing hospital operations

Hospitals vary in size, with a small hospital having less than 500 beds, a medium hospital having between 500 to 1 000 beds and a large hospital having greater than 1 000 beds. The HEM is applied in calculating the energy demand of three different hospital sizes.

- Small hospital having a bed count of 350, and a total area of 23,875 m^2.
- Medium hospital having a bed count of 501 and a total area of 68,527 m^2.
- Large hospital having a bed count of 1065 and a total area of 80,676 m^2.

In simulation of the hospital energy demand, the bed occupancy of the small, medium, and large hospital are set at 90% each. For analysis purposes, the hospital energy demand is categorized as; patient services inclusive of clinical and non-clinical activities, HVAC, lighting, network and standby medical devices and other equipment which stay on when not in use. Figure 4 illustrates the energy demand at each priority level for the small, medium, and large hospitals.

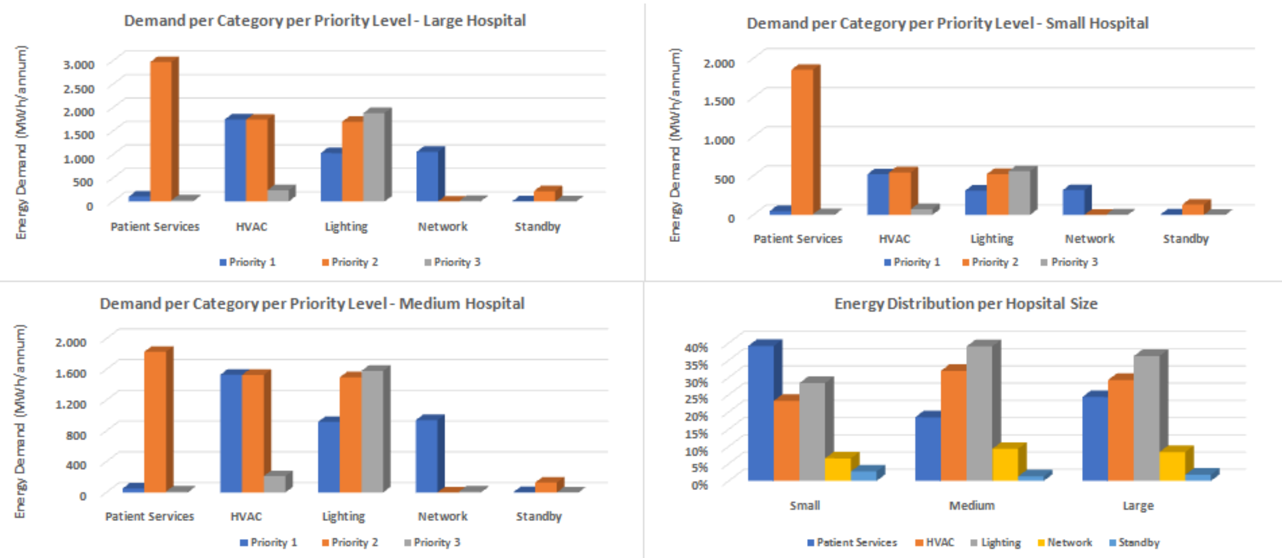

Figure 4. Energy demand distributions for Priority 1, 2 and 3 activities for small, medium, and large hospitals

Priority 2 activities have the highest electrical energy demand (as seen in the top row, and left frame of bottom row), followed by Priority 1 and Priority 3 activities. The major contributors to energy demand at each priority level are HVAC and lighting, with patient services a major contributor to Priority 2 energy requirements. At the hospital level for the medium and large hospitals, the top three contributors are lighting (39% for medium hospitals and 36% for large hospitals), HVAC (32% for medium and 30% for large hospital) and patient service (18% for medium and 24% for large). The (ECO-III Project, 2009) conducted in India to develop a best practice guide for improving hospital energy efficiency identifies the HVAC system as having the highest energy demand (30 - 65% of total hospital energy demand), followed by lighting (30 - 40% of total hospital energy demand). (Barrick & Holdaway, 2014) reported HVAC hospital systems utilize around 42% of total hospital energy demand. The lighting energy demand calculated by the HEM for the medium and large hospitals aligns to the higher range of the ECO-III project, while the HVAC energy demand aligns to the lower range of the ECO-III project. SA experiences a temperate climate, thus requiring a lower HVAC demand.

For the small hospital, the top three contributors are patient services (39%), lighting (28%) and HVAC (23%). In the small hospital, the lighting and HVAC demands are lower than the patient services given the smaller hospital area in comparison to the medium and large hospitals. Furthermore, South African hospitals generally have a large facility square meterage, thus the lighting energy demand is greater than the HVAC energy demand, given the temperate climate.

4.1. Model Application for Energy Management

The application of the model illustrates the decision-making opportunities the model provides. South Africa experiences periodic load shedding, due to the demand exceeding supply, severely hindering the operation of hospitals. The proposed HEM can be applied by hospitals to assist in how to best plan for such disruptions and to potentially develop onsite sustainable energy sources. The model prioritizes the energy demand of all operational activities in a hospital, enabling management to identify the minimum energy requirement (summation of Priority 1 activities) during periods of load shedding. The energy demand for a medium-sized hospital with 351 beds (90% bed occupancy) and facility area of 68 527 m^2, is illustrated in Table 3.

Clinical and Non-Clinical Functions	Clinical and Non-Clinical Process	Priority 1	Priority 2	Priority 3
Health Care Delivery	Patient admission			350
	Patient attendance	1	5,940	7
	Discharge patient		690	360
	Surgical	48,011	209	29
	Energy (kWh/annum)	48,012	6,839	746
Analysis and Imaging	Chemical analysis		559,022	
	Medical imaging		1,262,707	
	Energy (kWh/annum)		1,821,729	
Specialized Treatment	Dialysis and other	3,024		
	Energy (kWh/annum)	3,024		
Marketing	Develop marketing strategy			18
	Develop and manage business development plans			8
	Develop and manage marketing plans			9
	Energy (kWh/annum)			35
Customer Service Management	Develop customer service strategy			8
	Manage customer service workforce			398
	Evaluate customer services operation			8
	Energy (kWh/annum)			414
Financial Management	Accounts payable and reimbursement			688
	General accounting			49
	Manage taxes			5
	Payroll management			587
	Procurement			748
	Revenue accounting			5,834
	Energy (kWh/annum)			7,911
Human Resources	HR strategy			10
	Employee development			273
	Recruitment			22
	Redeploy and retire employees			73
	Reward and retain employees			329

Clinical and Non-Clinical Functions	Clinical and Non-Clinical Process	Priority 1	Priority 2	Priority 3
	Energy (kWh/annum)			707
ICT	Deploy ICT solutions			1,013
	Develop and manage ICT customer relationships			5
	Manage enterprise information	7		7
	Manage ICT	4		5
	Manage ICT technology solutions			7
	Energy (kWh/annum)	11		1,037
Risk and compliance management	Risk and compliance strategy			4
	Risk and compliance planning			3
	Execute risk management			11
	Energy (kWh/annum)			18
HVAC	HVAC for all buildings	1,530,223	1,527,339	210,943
	Energy (kWh/annum)	1,530,223	1,527,339	210,943
Lighting	Lighting for all internal and external, priority lighting for emergency facilities.	916,665	1,497,087	1,580,308
	Energy (kWh/annum)	916,665	1,497,087	1,580,308
Network	IT networks, all computers, all systems	939,400	0.00	11,177
	Energy (kWh/annum)	939,400	0.00	11,177
Standby	Medical devices	3,573	128,000	762
	Energy (kWh/annum)	3,573	128,000	762
Grand total	**Total Energy (kWh/annum)**	3,440,908	4,980,994	1,814,058
	Total Energy (MWh/annum)	3441	4981	1814

Table 3. Energy demand of clinical and non-clinical operations in a medium-sized hospital, with a 351-bed count

The model details the energy demand per priority level, together with the respective activities. For the hospital to ensure the functioning of Priority 1 services (essential services) during periods of load shedding an energy supply of 3,440,908 kWh/annum is required, equivalent to 393 kWh. For Priority 2 activities the demand is 4,980,994 kWh/annum, equivalent to 569 kWh, while for Priority 3 activities the demand is 1,814,058 kWh/annum equal to 207 kWh. The results illustrate that Priority 2 activities have the highest demand, as these activities ensure continued operations of the hospital, not focusing only on lifesaving activities as per Priority 1. The prediction of the energy demand down to the process and activity level enables the hospital to determine which activities should continue during periods of constrained supply and based on the hospital needs may be a mix of Priority 1, 2 and 3 activities. The resolution of the electrical energy demand down to the business activity level (L3), enables the hospital to revaluate current practice for optimization. It also facilitates multiple energy supply scenarios, including various small-scale options. A key feature of the model is the various results resolution available; per hospital (Figure 4), per energy category (Figure 4), per hospital function (Table 3) and hospital activity (Table 3).

5. Conclusion

The key objective is to develop a cross-functional and comprehensive hospital energy model to facilitate energy utilization decision making under constrained energy supply. The research team adopted clinical and non-clinical business processes to constitute a cross-functional hospital energy model. The model was executed and the results validated against published hospital energy data, with the proposed HEM results comparable to that of the

(ECO-III Project, 2009); the calculated HVAC demand of the medium (32%) and large (30%) hospitals align to the lower end of the projections (30 - 65%), while the lighting demand of the medium (39%) and large (36%) hospitals align to the higher end of the projections (30 - 40%).

The model was successfully applied to small, medium, and large hospitals. The results demonstrate that Priority 2 activities have the highest energy demand, followed by Priority 1 and Priority 3 activities, for all hospital sizes. For the medium and large hospitals, the top three contributors to energy demand are lighting, HVAC, and patient services. For the small hospital, the top three contributors are patient services, lighting, and HVAC, respectively.

The model developed in this study has the dynamic capacity to determine demand based on hospital capacity and size. The model provides for activity-based energy operations of a hospital, specifically based on clinical and non-clinical activity prioritization. Assuming limited energy supply, the energy model enables a hospital to reduce demand logically from 100% usage to only critical services. The model enables hospital management to conduct feasibility studies on the options available for the total power supply or a portion thereof during periods of load shedding and improved planning for capital expenditure and operational budgets. It also reduces risk to the hospital and ensures consistent quality of service to patients. The model can be adapted to include/exclude any clinical or non-clinical activity, with the capacity to calculate the energy demand.

Planned future work, based on this research approach, is for the application of the hospital energy model towards developing a city-based model, for the prediction of city demands of sanitation services, water, electricity, and healthcare.

Declaration of Conflicting Interests

The authors declare no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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