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Evaluation of Energy-Efficiency in Lighting Systems using Sensor Networks

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Abstract

In modern energy aware buildings, lighting control systems are put in place so to maximise the energy-efficiency of the lighting system without effecting the comfort of the occupant. In many cases this involves utilising a set of presence sensors, with actuators, to determine when to turn on/off or dim lighting, when it is deemed necessary. Such systems are installed using standard tuning values statically fixed by the system installer. This can cause inefficiencies and energy wastage as the control system is never optimised to its surrounding environment. In this paper, we investigate a Wireless Sensor Network (WSN) as a viable tool that can help in analysing and evaluating the energy-efficiency of an existing lighting control system in a low-cost and portable solution. We introduce LightWiSe (LIGHTting evaluation through WIreless SEnsors), a wireless tool which aims to evaluate lighting control systems in existing office buildings. LightWiSe determines points in the control system that exhibit energy wastage and to highlight areas that can be optimised to gain a greater efficiency in the system. It will also evaluate the effective energy saving to be obtained by replacing the control system with a more judicious energy saving solution. During a test performed in an office space, with a number of different lighting control systems we could highlight a number of areas to reduce waste and save energy. Our findings show that each system tested can be optimised to achieve greater efficiency. LightWiSe can highlight savings in the region of 50% to 70% that are achievable through optimising the current control system or installing an alternative.

Categories and Subject Descriptors

H.4 [**wireless, sensor, networks, embedded, energy-efficiency, buildings, lighting Applications**]: Miscellaneous; D.2.8 [**sensor networking**]: Metrics—*complexity measures, performance measures*

Keywords

sensor, network, energy, efficiency, building, decision, support, lighting

1 Introduction

Buildings are responsible for up to 40% of energy use as official US statistics report [6]. It is evaluated that 39% of all office building electricity costs in the US are due to lighting [5]. An estimated 30% of this can be classified as wasted energy. providing more efficient lighting control systems that reduce the amount of wasted energy in office buildings can provide a major contribution to lowering overall energy consumption.

Many new structures incorporate building management systems such as intelligent lighting or heating controls to improve occupants comfort and to save energy. However, a large number of existing buildings still have traditional lighting and heating installations. This market is more responsive to quantifiable benefits and building owners (individuals or companies) are prone to invest in a modern lighting control system if the system promises them significant energy saving in the monthly bill. Currently, energy consultants an installer can provide only a rough estimation of the energy saving through simulation and experience from previous installations. The estimation error is large as consumption is tightly coupled to occupants activity, building utilisation and its structural characteristics. Control system installers are usually faced with the problem, how can energy usage be reduced without impacting negatively on human experience? One solution is to look at the way we use energy and determine where energy is wasted. We can then save energy by reducing this waste. Previous tests performed in an office building over a seven month period [7] show a need to evaluate the performance of existing control systems and advise on an energy saving solution. The findings prove that a significant amount of energy saving (46%) can be gained by correctly installing a system into its environment or installing an alternative system.

Wireless Sensor Network (WSN) technologies have introduced a cheap and portable method of measuring our surrounding environment. By using a WSN, we can better represent the nature of a changing environment and use this to better control factors within the environment. This is particularity relevant in buildings where certain factors, light level, temperature, humidity, are constantly controlled in a closed environment. In this paper we will investigate how a WSN can be used to evaluate a lighting control system in terms of energy-efficiency. In stark contrast to existing approaches, WSN is an infrastructure-less and portable system that can be used to *observe, gather and interpret* real sensor data in situ while the building is in everyday use, taking into account the building occupancy, work styles, preferences, etc. The aim is to use LightWiSe to evaluate lighting control systems in existing office buildings. The rest of this paper is organised as follows: Section 2 describes traditional lighting control systems and where energy waste occurs with these systems. It also introduces energy saving concepts used in lighting systems to reduce energy waste. Based on this, section 3 introduces a WSN approach to evaluating a control system and describes what LightWiSe aims to achieve. Section 4 describes the the design of the system and presents a set of design considerations when using the LightWiSe system. This section will also discuss how the data is modelled and used. Section 5 describes the experiments, what environmental variables are considered, hardware used, how the data was gathered and presents the results set after data modelling. Section 6 concludes this paper and introduces further work.

2 Lighting Control Systems

This section describes the most common lighting control techniques and concepts used in buildings. In order to understand how a sensor network approach can be appropriate in evaluating light control systems, it is important to understand how existing light control systems operate. In general energy loss for a lighting control system can be determined when the lighting system is illuminating a space that is not being used at that given time or is illuminating a space that has sufficient ambient lighting for the needed tasks to be performed. The Chartered Institution of Building Services Engineers (CIBSE) code for lighting recommends lighting level to be maintained at *500lux* for an office environment [4]. A brief description the most common lighting control systems is as follows.

Manual Switch: This lighting control system is composed of a user switch to turn on/off one or more lights. The user decides to turn on or off a light or set of lights as to there preference.

Occupancy detecting: The occupancy detecting lighting control systems with Passive Infra-Red (PIR) sensors are popular within large buildings and offices. When the PIR sensor detects movement in a space the control system activates the lighting system. Occupancy sensors use timers and timing models when activating lighting. Savings can be made by optimising the timers to suit the environment.

Ambient light compensated: The ambient light compensated control system uses a concept know as *'daylight harvesting'* through the use of light sensors. The control system uses the data from the light sensors and the PIR sensors to make decisions with the lighting system. We now describe two main energy saving concepts used for optimising the operations of lighting control systems.

2.1 Energy Saving Concepts

Controlled spaces: A controlled space is an area where a light or set of lights that can independently be turned on or off under a certain condition. This condition may be evaluated over a single sensor or set of sensors. By partitioning a large office space into controlled spaces the control system can activate the lighting system in independent areas, pinpointing certain areas where illumination is needed. Sensors can have a one to one or a many to one mapping with a controlled space.

Daylight harvesting: the daylight harvesting system [3] monitors the amount of natural light present in a space. The objective is to identify portions of the building where there is sufficient natural light. The control system can then adjust the lighting to illuminate only the spaces receiving inadequate natural light.

3 Sensor Network Approach

Evaluating existing lighting control systems is key to identifying and address sources of energy wastage. In stark contrast to existing approaches based on simulations or expensive infrastructures the solution proposed uses a WSN approach. The use of a WSN will give a high level of flexibility and portability. Using a WSN it is possible to achieve quick, low-cost and non-invasive deployment of the testing system. The WSN approach is scalable and adaptable to fit a wide range of spaces and office topologies. As nodes are added to the network in an ad-hoc fashion and can be placed almost anywhere in a building they provide a flexible framework to produce a complete model of the system and environment. The WSN is used to collect key environmental data from the structure under evaluation from which our recommendations are drawn. The LightWiSe system is used to determine points in the control system that exhibit energy wastage and to highlight areas that can be optimised to gain a greater efficiency in the system while considering the effects on the human experience. We use a comprehensive approach that takes into account **(1)** human activity **(2)** Ambient lighting and **(3)** Artificial lighting when evaluating the control system. By analysing this data we can determine when and where in the building energy wastage occurs. Recorded data is sent wirelessly to a central gateway for storage and analysis.

The LightWiSe system aims to evaluate the energy-efficiency of a lighting control system while highlighting areas that can optimised for greater energy-efficiency and to quantify the amount of energy saving that is possible by replacing the control system with an alternative solution. To achieve this the LightWiSe system must measure exactly how much energy is wasted in the lighting system. It should determine in what way the office space is used from the data. Optimising the control system to its environment and saving on wasted energy can be achieved by using this information. From the data the LightWiSe system should also discover how and why energy inefficiencies occur in the control system.

4 System Design

Many factors should be taken into consideration when designing an evaluation tool. The tool must be able to adapt to varying environments so that it can evaluate a variety of systems in varying situations. An effective tool must be easy to deploy and provide a simple yet comprehensive results set to allow full and quick analysis. A model of the evaluated system must be constructed from its fundamental properties and evaluated on its ability to perform its task.

4.1 Deployment Considerations

There are a number of factors that must be taken into consideration during deployment which can effect the results derived from the WSN.

Network layout: The sensor positioning and orientation is crucial for deriving useful data from the sensor network. Careful consideration needs to be given to to an appropriate position for each type of sensor. The network layout should is to mirror the perception of the environment by the *people* using it. We use this as the central paradigm for our model to deduce where each sensor type is placed. We can determine two types of used spaces, *workstations* and *walkways*, in an office environment. Light sensors are placed on used surfaces (desk, wall) to determine a comprehensive model of the perceived light level in the office. Occupancy sensors are placed to monitor any movement within a controlled space.

Data gathering: There are some trade-off's to be considered for data collection when deploying the WSN. Each node samples its sensors periodically to return environmental data. Sampling the sensors has an energy cost overhead on the node. On the other hand the accuracy of the model of the environment is increased with a higher sampling rate. We also need the node to remain active for the duration of the testing period. This results in a trade-off between model accuracy and node lifetime. A similar trade-off occurs between data throughput in the network and node lifetime as propagating messages through the network has an energy cost overhead on the sending and receiving nodes. Consideration must be taken to avoid congestion caused by heavy throughput in the network. Although energy and congestion issues are not the focus of this paper, the system installer should take this into account when deploying the LightWiSe system. The resulting data set from the network must be easy to analysis. A large data set can be computationally challenging to analyse while a smaller set can provide less accurate results. The sampling rate and the throughput will affect the accuracy of the model of the environment, so then a trade-off exists between obtaining an acceptable model of the environment against node lifetime, network congestion, and ease of analysis.

Based on the described considerations, the following section describes how data are gathered from the sensor network and then modelled to obtain meaningful information of energy wastage of the lighting control system in place. Ultimately such information is used to provide recommendations for enhancing a light control system installation.

4.2 Data Modelling

In order to capture environmental parameters of the building, LightWiSe uses two common sensing devices: (1) A light detector used for detecting ambient light and luminaries state; (2) A PIR sensor to detect people presence. The resulting dataset allows the creation of a model of the environment, and shows how efficiently the system runs within the environment. The model will describe the light level throughout the office, the occupancy within office and the state of the lights in the office over a period of time. Acquiring of the result set from the data follows the model shown in Figure 1. The algorithm defines two independent counters, namely Ambient light Waste (ALW) counter and Timing Model Waste (TMW) Counter. The ALW counter will increment when both the ambient light exceeds the predefined threshold and the luminary state is active. This records the energy wasted due to ambient light. The TWC counter is used to record wasted energy when the timing model is not calibrated for its environment.

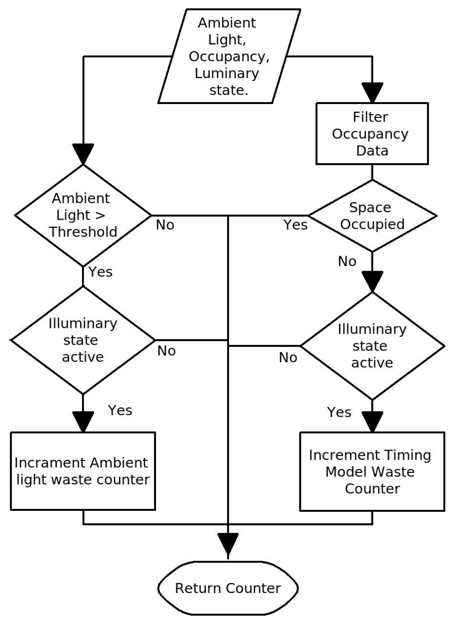

Figure 1. Process flow for modelling data

Data collected by the WSN defines three environment variables, ambient light, occupancy and luminary state. Ambient light and the luminary state data are used to evaluate the ambient light waste in the system. For each data point the Ambient light is checked against the threshold of *500lux*. When the ambient light level is under the threshold no waste due to ambient light occurs at this point. When the ambient light level is over the threshold the luminary state for that data point is checked. Active Luminary state at this point will correspond to energy waste. Measuring the energy waste due to the lighting control system timing model also requires occupancy data. The occupancy data is passed through a low pass filter to stabilize the data received from the occupancy detector. The resultant is an envelope over the occupancy data that can be tuned for varying activity and user comfort levels. The occupancy filter process is shown in Figure 2. The Occupancy filter algorithm describes a low pass filter with two counters, namely No Motion Counter (NMC) and Occupancy Counter (OC). The NMC increments every data point that shows no movement and is reset when movement is detected. The OC increments when movement is detected. The key threshold in the filter varies over time of day and the controlled space according to the amount of activity expected in the space. Expected activity for a space is obtained through empirical measurement. Each point in the data set then contains the luminary state and filtered occupancy state. Waste due to timing model is then recorded when luminary state is active and filtered occupancy is zero. The energy waste can then be expressed as a type of loss over a period of time. The energy loss is calculated by multiplying lighting power in a controlled space by the calculated wasted time the lights were active in the controlled space. The energy loss within the system can then be approximated for a monthly or yearly basis.

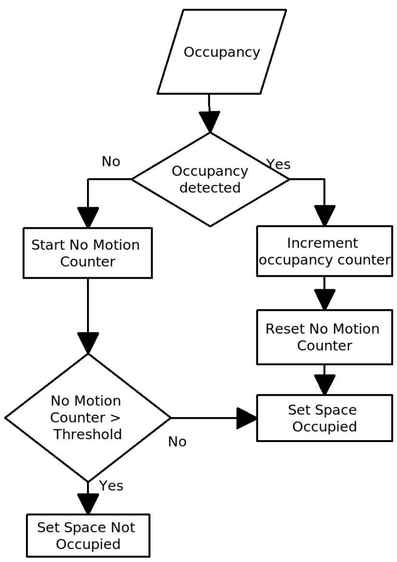

Figure 2. Process flow of data in filter

5 Experimentations

A test environment was established in a real world office scenario to validate findings of the LightWiSe system. We chose a site that is representative of many office environments. The test site is shown in Figure 3. Testing took place in three separate spaces, a large open plan office, a small individual office and a corridor and present two types of control systems, presence detecting control system and manual switch control system. The layout of occupancy sensors are shown in Figure 3. The building is situated on latitude 53 degrees 20 minutes north with windows facing north-Northwest, this provides an even distribution of light throughout the office. In the open plan office we used four occupancy detecting sensors with two light sensors to detect ambient light and as the open plan office contains a single control area a single light sensor is used to detect the state of the lighting system. We used a single light detector and occupancy detector for the private office and the corridor.

The experiment used a set of telosb motes produced by crossbow technology [1] shown in Figure 4. The telosb motes are low powered devices with IEEE 802.15.4 compliant radio module, array of on-board sensors and battery pack. The on-board light sensor was used to detect ambient light and luminary state. EasySen [2] produce a sensor board, that is compatible with telosb motes, that contains a long range PIR sensor. This board was used to detect occupancy. The motes have been programmed in nesC and run on the TinyOS platform [8], a lightweight, low-power platform for wireless embedded systems.

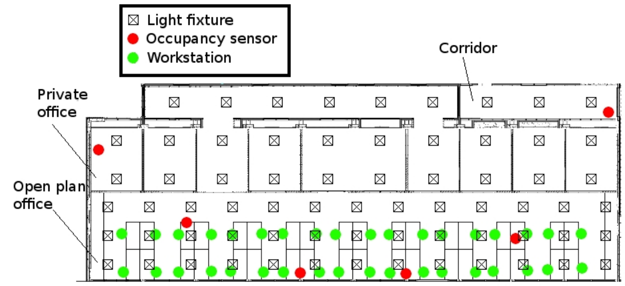

Figure 3. Office plan including occupancy sensor and workstation placement

Figure 4. Crossbow telosb mote and EasySen sensor board

5.1 Evaluation Criteria

The evaluation criteria for a system are based on how well it performs its task. The task of a lighting control system is to provide illumination to a space when it is necessary. When minimising energy overhead is added as a goal for the lighting control system the task becomes providing illumination to a space when necessary and only when necessary. In an office environment it is necessary to provide illumination to a space when this space is occupied by a person and the space does not have sufficient light for this person to perform office tasks. We regard the main environmental variables to take into consideration when evaluating a lighting control system to be occupancy of a space and level of ambient light in a space. The lighting control systems use of the lighting system is evaluated by monitoring the state (on/off) of the lighting system in the controlled space. To provide a simple yet comprehensive dataset for the evaluation we consider these variables for a given space: **(1)** occupancy **(2)** light-level **(3)** state of lighting system.

5.2 Network Setup

Sensor data is polled every second and packets are sent through the network every 10 seconds. The sensor nodes send packets with a single value. The light sensor sends an average of the sensor readings over 10 samples. The Occupancy sensor sends true if it detects occupancy over 10 samples. The light state sensor sends lighting state at time of sending message. This gives highly granular results. By using four occupancy detectors in the open plan office space we can achieve 4 distinct control spaces. Each control space is monitored by a single occupancy detector. A single control space is considered for the office and corridor areas. Data is collected over a 24 hour period in the open plan office and the corridor, and over a 09:00 - 17:00 period for the private office. This reflects the manner in which the spaces are used. To quantify the waste occurring due to ambient light the light level taken in the open plan office is compared to the time during the day the lighting system is active. According to standard conditions for office specifications [4] LightWiSe has been tuned to capture lighting levels less than 500lux, as this is considered the lower threshold of comfort for the occupant. Waste in the system is then measured when the lighting system is active when the ambient lighting is greater than 500lux. *'Light harvesting'* is not considered for either the private office nor the corridor as neither have a window towards a natural light source.

5.3 Experimental Setup

To quantify the energy waste existing in the timing model of the system the data received from the occupancy sensors is analysed. We first needed to perform a few tests before we could analyse the data. We perform an experiment to determine the light output from the lighting system. We take this measurement for each ambient light sensor. A measurement is taken from each ambient light sensor with lighting system on while impeding light from external sources. As light intensity at a point is the sum of the effective light intensity from each source we can compensate for the lighting systems effect on the ambient light sensors. We perform another experiment to measure office activity level. Occupancy readings are taken and workspace is occupied during the test. This provides normal activity characteristics for a single user for the space in an office environment. The characteristics are used to tune the filter applied over the data received from the occupancy sensors. The key filter threshold for a single user is taken as the longest time measured between activity "spikes" during testing. Using a probabilistic method we could deduce the movement characteristics for single use, light use, and heavy use of a space. A filter using a threshold for single use is applied to the occupancy data received from the private office. The filter for the open plan office data is applied for:

- users $>$ 10 from 09:00-18:00 (heavy use)
- 5 $<$ users $<$ 10 from 07:00-09:00 and 18:00-20:00 (light use)
- users $<$ 5 from 20:00-07:00 (single use)

The corridor is a unique space in the building. This is because the corridor is only used for transit so constant movement can be measured when the space is occupied. We can apply a filter to the data, using this assumption, to represent the movement in the space and so quantify the energy saving possible by using a more relevant timing model.

5.4 Performance Evaluation

This section discusses the results derived from the experiment and provides recommendations for reducing energy waste. Figure 5 shows the ambient light in the open plan office over a 12 hour period. The figure shows the ambient light level with the period of time the lights were active. Significant energy wastage can be seen in the presence detecting system during the day when ambient light levels are consistently over the ambient light threshold.

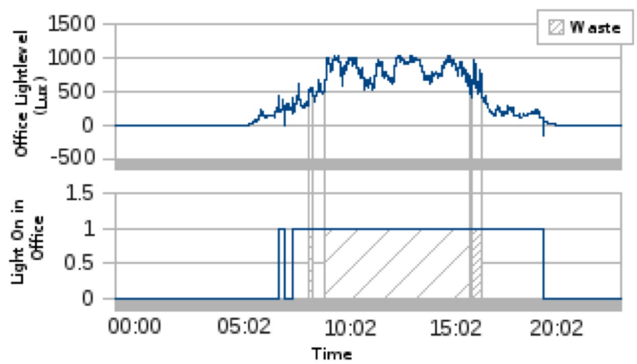

Figure 5. Open plan office ambient lighting levels compared to time lighting is activated over a 24hr. period

Figure 6 shows a section of data received from the occupancy sensors in the open plan office with filter. from the figure we can see waste occurring at approx. 8:00 and 9:00. The occupancy signal is the combination of all four sensors in the open plan office area. The figure shows the waste due to the timing model in the open plan office.

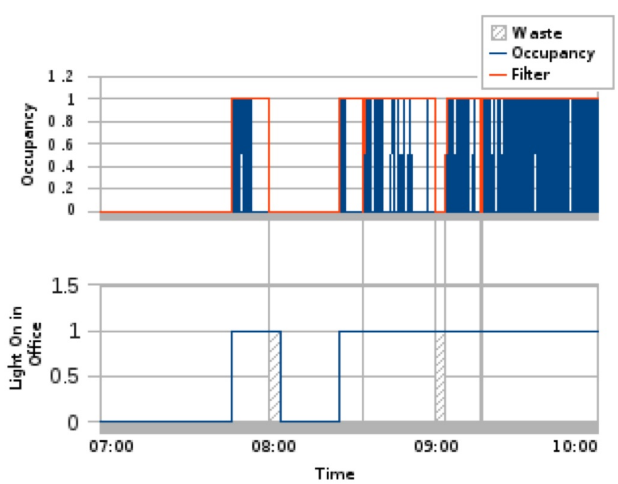

Figure 6. Open plan office presence detection with filter

Figure 7 shows the occupancy data taken from the private office with the filter applied. We can determine waste as any time the office is empty as the lighting in the private office is active throughout the testing period .

By analysing the data from the four occupancy sensors individually we can determine the level of waste that occurs in

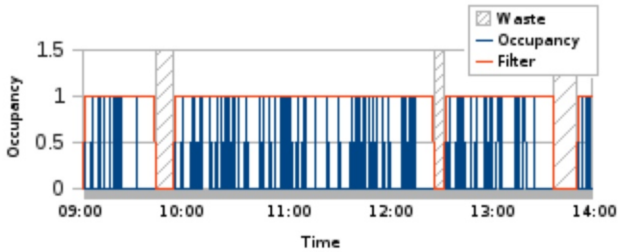

Figure 7. Private office presence detection with filter

each area of the open plan office. This highlights the amount of energy that can be saved by using four lighting control areas in the open plan office instead of one large are as it is currently. Table 1 shows the energy waste for each type of wastage for each area. The waste is described as active time in the lighting system, effective energy wasted and waste as a percentage of overall use in the area.

Table 1. Measured energy wastage

	Open Plan Office	Private Office	Corridor
Light Active per Day	12.1 hours	8 hours	16.5 hours
Timer Module			
Waste	21 min	38 min	6.2 hours
% of used	2.9	7.9	70.9
Energy Waste - kWh	0.44	0.7	1.4
Ambient Light			
Waste	7.1 hours		
% of used	58.6		
Energy Waste - kWh	8.9		
Controlled Space			
Waste	2 hours		
% of used	16.5		
Energy Waste - kWh	2.52		

The private office is currently using a manual switch lighting control system. For this office we can see that a saving of 7.9% of daily use can be expected with the installation of an occupancy sensing lighting control system.

The open plan office currently uses a presence detecting system with lighting activated for over 12 hours of the day. The introduction of Ambient light compensated system can achieve a saving of 58.6%. As this large office space can be separated into multiple control areas we can achieve a saving by introducing separate controlled areas in the system. By monitoring the open plan office over four control areas we can achieve a saving of 16.5% of lighting energy use. In this experiment we applied a simple controlled space implementation, using a single controlled space for each occupancy detector. Each occupancy detectors range will overlap with its neighbours, we can use this overlap as a separate controlled space. This controlled space will then be dependant on the state of both occupancy detectors. By introducing more controlled spaces to the room we can gain a greater saving.

The corridor currently uses a presence detecting system. As expected the corridor shows significant wastage due to the timing model used. A saving of 70.9% of operational usage can be achieved by optimising the timing model for a corridor environment.

6 Conclusions and Future Work

This paper demonstrated how a low-cost and portable sensor network is a viable and powerful tool to assess existing lighting control systems in office space scenarios. The LightWiSe system showed that a standard installation of lighting control systems can exhibit energy wastage when not optimised to the surrounding environment. By deploying a WSN we can easily and effectively evaluate the energy loss in a lighting control system and pinpointing where the loss occurs the LightWiSe system makes recommendations where/when savings can be made. In an evaluation of a typical lighting control system in an office building we demonstrated that a better installation can reduce energy use and make up to 58% saving on lighting energy by highlighting areas of loss and recommending an existing solution to reduce this loss.

This is part of a longer process to develop a comprehensive tool that help reduce overall energy use in buildings. We believe that by monitoring and evaluating the energy waste in a building we can make informed recommendations on how to reduce overall energy usage without effecting human comforts. Interesting future directions may include **(1)** developing an application framework to allow a rapid configuration of the system and mapping with node location and functionalities, **(2)** Extending LightWiSe to provide the most appropriate recommendations for a better installation compiled from existing systems on the market.

7 Acknowledgements

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