# A COMPARATIVE STUDY TO BENCHMARK ENERGY PERFORMANCE USING BUILDING SIMULATION TOOLS

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**Abstract.** Building performance assessment is a process of using a numerical model "simulation tool" to predict performance of both the building and system metrics. The decision to choose a suitable simulation tool is a continuous challenge. Issues such as model data availability, integrity and applicability add additional constraints to the modeling process. This paper discusses the process of using different building simulation tools to identify a credible building energy performance indicator. A typical building is modeled using different tools utilizing similar input data and weather conditions. A series of building performance experiments are conducted and the resulting trends are compared to real-time metered data. The paper presents a pilot project to create an energy benchmarking tool for facility managers and the challenges facing the development team.

## 1. Introduction

As CAAD technology evolves, much work is in process to bring the real and virtual environments closer. The use of energy simulation as a building performance assessment method is one aspect of this work that has developed over the past decade. To achieve efficiency goals, building designers require effective design tools for analyzing and understanding the complex behavior of building energy use. In the past decades, computer simulation was utilized to provide a reliable proof of concept and detailed evaluation of the building energy performance. The benefits of employing such tools during the design process are immense, providing the designer with early feedback during the documentation phase, and similar level of information for end-users to optimize their existing environments to be more energy efficient. The drawback on the other hand, is that the building simulation process can consume a considerable amount of time before getting reliable results. Modeling the building and accurately defining its

properties, materials, internal loads, and desired mechanical systems is a daunting and time consuming process, requires an expert level user and a sense of functioning between different applications to overcome many interoperability issues.

A considerable amount of work has been published in this field documenting the history, evolution, range of applications, newer generations, current challenges, testing and validations (Nall 1983; Clarke 1985; Newton, James and Bartholomew 1988; Seth 1989; Papamichael 1991; Hensen, et al. 1993; Augenbroe 2002; Malkawi and Augenbroe 2003; Hensen and Augenbroe 2004; Malkawi 2004; Crawley, et al. 2005). A large number of simulation tools are also available for the designers and are used as applicable to each project. Some are intended to be used at the early design stages; others need the building to be well-defined before the simulation can be performed. The feedback on reliability, interface design, ease of use, data requirements, and output vary from one user to the other.

As part of Penn's commitment to improve its environmental performance, reduce its energy cost, provide incentive to individual school to conserve energy, and better manage its energy demands, the T C Chan Center was commissioned to carry on this effort to audit the energy performance for campus buildings. An open-source normative computational model was adopted and customized in form of a web-based toolkit is currently under development. The tool provides normative measures of building energy consumption and is easy to use but requires many data points. The algorithms on which the tool is based were originally developed in Europe (NEN2916) and were extensively calibrated on a set of existing buildings for which dynamic simulations were also done. Recently, the algorithms are expanded to produce a European norm (ISO TC163) on which progressive new building energy codes are based. In addition, the U.S. General Service Administration (GSA) is currently in the process of utilizing it to help manage its own portfolio of buildings and to perform total building quality assessments.

This paper is inspired by the previous work and discusses the process of using different building simulation tools to identify a credible building energy performance indicator. A comparative approach is applied on a typical building using EnergyPlus, NEN2916 and ECOTECT. The output results are compared against actual utility metered data, and against the university current allocated cost models. The results indicate that dynamic simulation methods can accurately predict energy performance with higher precision than normative calculation algorithms. This research is work in progress and the outcome is expected to advance the development of the tool.

## 2. Case Study

The Robert Schattner Centre at the University of Pennsylvania.

### 2.1. DESCRIPTION

The University of Pennsylvania's campus consists of 269 acres in West Philadelphia, with 151 buildings housing all 12 of the University's schools as well as a variety of residential halls, libraries, offices, performance centers, athletic facilities, and retail spaces. Penn's buildings total 12.1 million gross square feet, 24% of which is office space, 21% residence, 19% labs, and the remaining 36% divided between instructional and study spaces, athletics, assembly, food services, healthcare and support, Figure 1. (Penn Sustain Phase I, P.10)
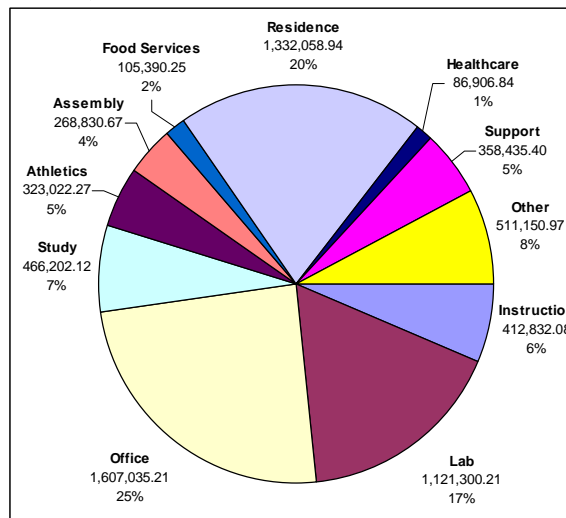


*Figure 1.* Distribution of campus buildings by type

Campus buildings range in size from 875 SF in area to 384,000 SF. The smallest buildings, those with an area less than 10,000 SF, make up 11% of Penn's campus. Those with areas from 50,000 SF to 100,000 SF comprise the largest percentage of total buildings, constituting one quarter of the campus. Only 5% of campus buildings are over 250,000 SF in area.

The age of campus buildings range from the newly constructed to those with significant historical status, including several buildings over 150 years old. 19% of the campus was constructed prior to the 20th century, and many parts of it have been included on the National Register of Historic Places or designated as historic by the Philadelphia Historical Commission. Of the remaining buildings, 55% were completed after the end of World War II,

including a large amount of construction that occurred during the 1960's and 1970's. A distribution of all buildings by size, age, and use can often reveal meaningful differences in patterns and intensities of energy usage, leading to general strategies of improvement. At this time, the University does not yet have sufficiently fine grained data to make such an analysis possible, Figure 2. (Penn Sustain Phase I, P.11)
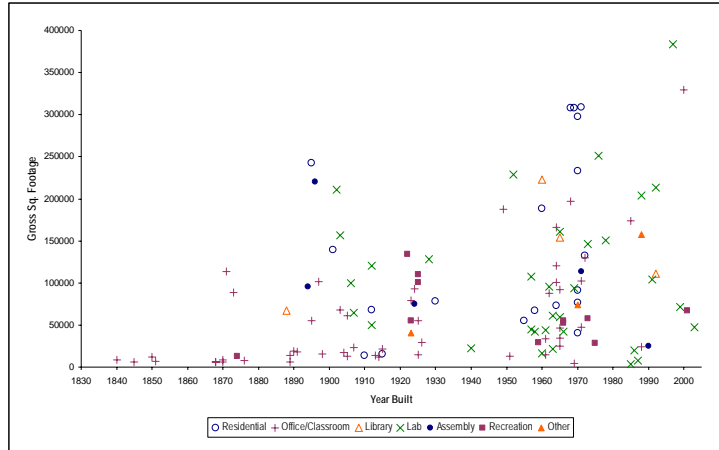


*Figure 2.* Distribution of campus buildings by age

## 2.2. ENERGY TRENDS

During the past ten years, total campus energy consumption has increased 24%. On average, the amount of energy consumed for heating is six times greater than that consumed for cooling. In Philadelphia, the number of heating degree days is on average 3.5 times greater than the number of cooling degree days, Figure 3. (Penn Sustain Phase I, P.15)
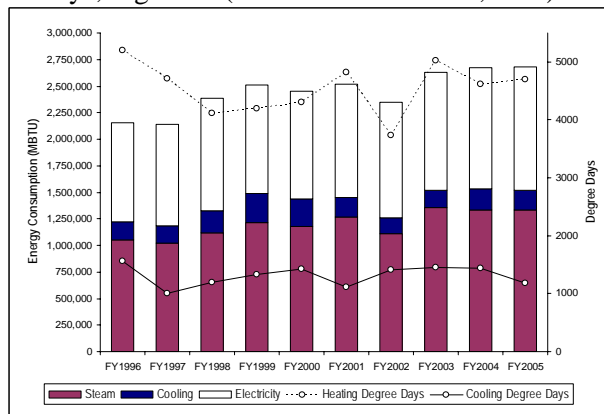


*Figure 3.* Distribution of total campus energy consumption and heating and cooling degree days for Philadelphia, PA (FY1996-FY2005)

From FY1996 to FY2005, the total campus area has increased by 9% while the energy consumption per square foot has increased 14%, Figure 4.
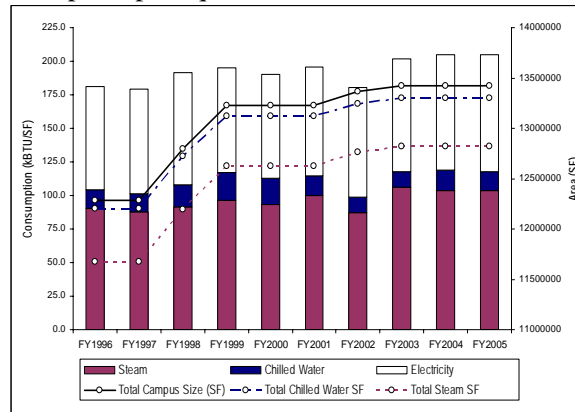


*Figure 4. Distribution of total campus energy consumption and heating and cooling degree days for Philadelphia, PA (FY1996-FY2005)*

### 2.3. BUILDING SELECTION

Robert Schattner Center, a 70,000-square-foot facility which opened in 2002 during the school's 125th Anniversary celebration, is the new gateway to Penn's School of Dental Medicine, tying together the school's historic Thomas W. Evans Building and its Leon Levy Center for Oral Health Research. Figure 5



*Figure 5.* The Robert Schattner Center

The Schattner Center offers dental care to the campus and West Philadelphia communities in its state-of-the-art clinics, which have also greatly enhanced the school's research and educational resources. The adjacent Evans Building, dedicated in 1915, contains administrative offices, classrooms, dental clinics, and the school library, and the adjoining Leon

Levy Center, dedicated in 1969 and home to the basic science faculty, is the hub of the school's research activities (see Figure 6).
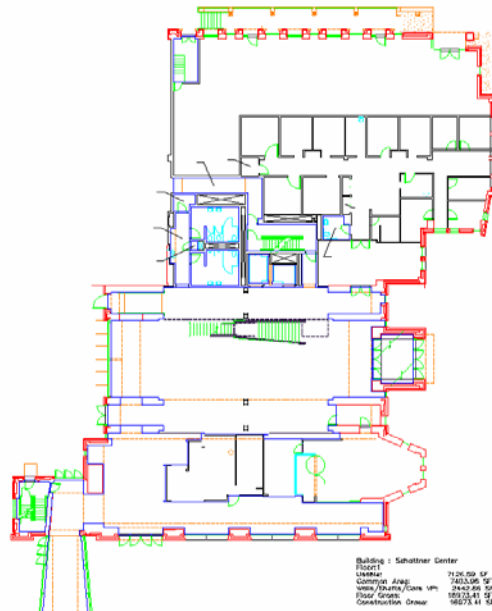


*Figure 6.* Schattner ground floor plan

## 3. Data

### 3.1. WEATHER TRENDS

Historic weather data, including temperature, precipitation, wind, and heating and cooling degree days were obtained from the NOAA (National Oceanic and Atmospheric Administration). However, this data is recorded at the Philadelphia International Airport, located over 8 miles away from the center of Penn's campus. In addition to its distance from campus, the airport also does not share many of Penn's climate-influencing characteristics such as its urban location and proximity to the Schuylkill River. NOAA's data is available as daily or monthly average, minimum, or maximum values, Figure 7.
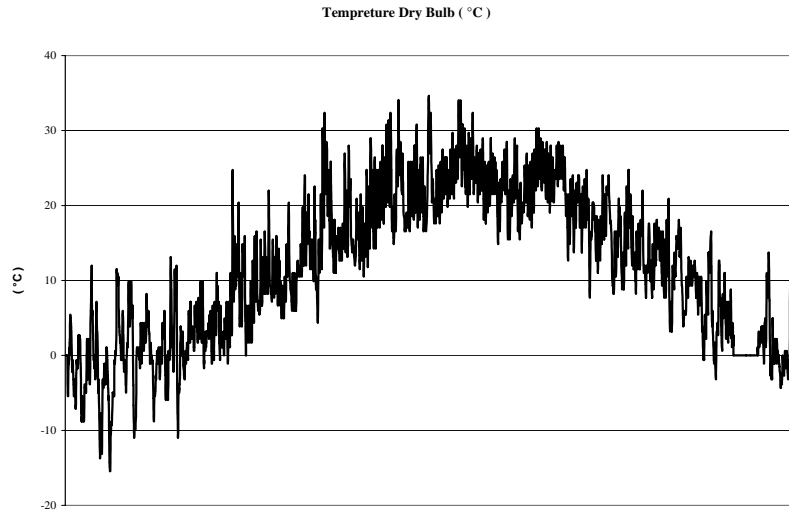
**Tempreture Dry Bulb ( °C )**



*Figure 7.* Annual TMY2 Mean Temperature (hourly)

A comparison between the actual real-time data taken on site from a local weather station and the TMY2 weather file is shown in Figure 8 which indicates similarities between the two weather patterns.
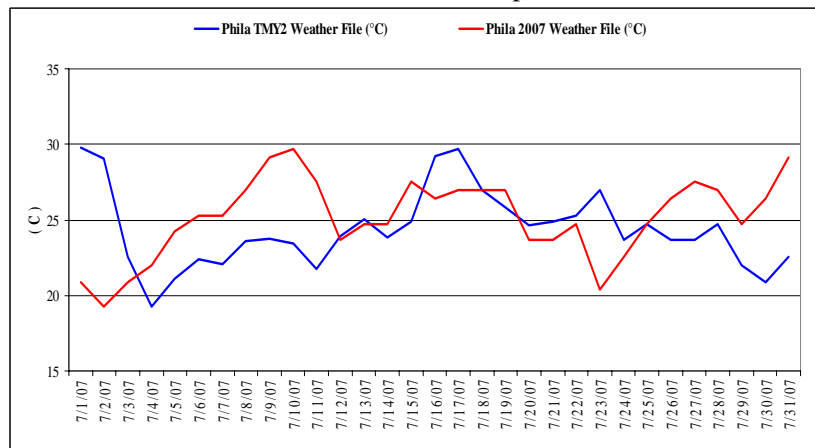


*Figure 8.* Comparison between two weather files (July'07 only)

### 3.2. UTILITY METERING

A digital vortex steam meter is recently installed and calibrated. The output RS-485, 4~20mA, cumulative pulse and provides instant flow rate, cumulative flow rate, temperature, cumulative validated operating time. The chilled water meter is insertion type meter with RS-485, 4~20mA,

cumulative pulse output and provides Instant cooling power, cumulative cooling power, supply temperature, exhaust temperature, temperature difference, instant flow rate, cumulative flow rate, cumulative validated operating time. The following illustrate the actual building behavior for the month of July 2007. Figure 9.
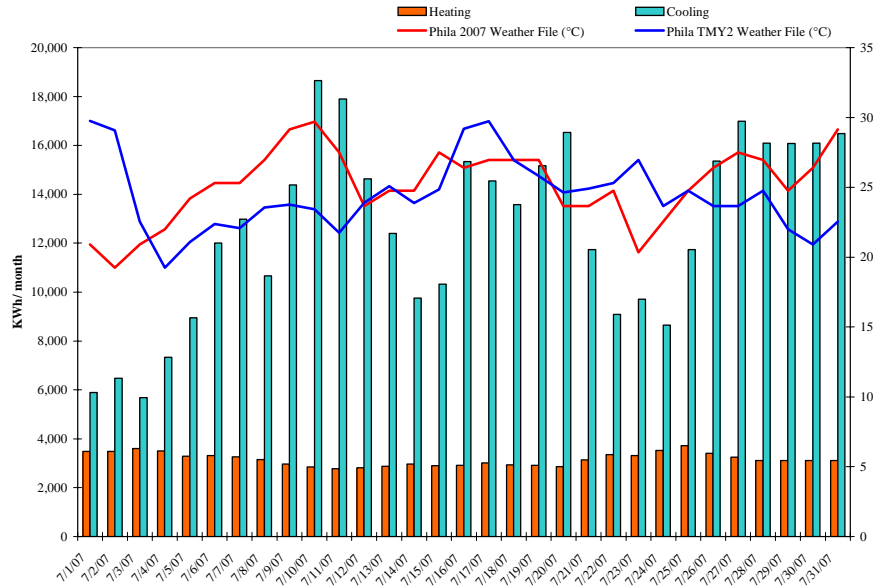


*Figure 9.* Steam and Chilled water real-time metered data

## 3.3. BUILDING SYSTEMS AND EQUIPMENT AUDIT

Electricity power consumption of the entire Schattner building has been tracked for 48 hours on May 25th~26th, 2007 (including one weekday and one weekend day). The results show that during the weekend and night (from 20:00pm to 7:00am next morning) the electrical power consumption of the whole building is almost constant around 220KW to 230KW (the outside temperature varying from 20 deg C to 40 degree C). The peak power during the weekday is around 31KW which occurs approximately at 3:00 pm in the afternoon. Schattner building consumed 2,009,915KWh of electricity power in FY-2006 and 1,833,218KWh in FY-2007. The following is the breakdown of the systems, plug loads and equipments. Figure 10.
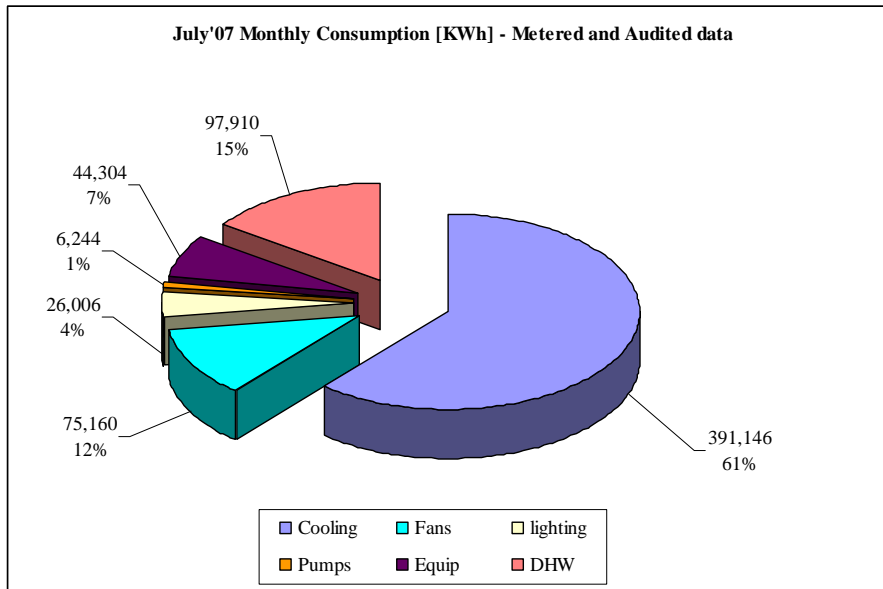
*Figure10.* Breakdown of Metered data

## 4. Input Data

The following are the key inputs by tool.

TABLE 1. Schattner Center – Input data for NEN2916, ECOTECT and EnergyPlus

| | **NEN2916** | **ECOTECT** | **EnergyPlus** |
|---|---|---|---|
| Floor Area (m²) | 5567 m² | | |
| Number of Occupants | 250  ( 0.037 people/m²) | | |
| HVAC System | Central cooling of ventilation air and heating by radiators or additional heaters (VAV system) | Full Air Conditioning with exception to the basement (Heating Only) | VAV |
| Heating - Coefficient of Performance | 0.5 | N/A | 0.5 |
| Cooling - Coefficient of Performance | 1.0 | N/A | 1.0 |

| | | | |
|---|---|---|---|
| Windows - Heat transfer coefficient U-Value W/m² K | Low-E Insulating double glazing u-value = 1.703 | | |
| Windows - Light transmission g-value (%) | 55 | 62.4 | 62.4 |
| Wall - Heat transfer coefficient U-Value W/m² K | Brick veneer, cavity, 1" insulation and CMU U-value = 0.049 | | |
| Solar Coefficient (SC) | 0.66 | | |
| Wall Thickness (mm) | 160 | 152.4 | 152.4 |
| Lighting | Room switch + individual switch in façade zone | 12 W/m² | Gain: 15 W/m² Lighting control Off |
| Ventilation | Mechanical (40% of exhaust air is re-circulated) | N/A | Mechanical (40% of exhaust air is re-circulated) |
| Heat recovery system | Heat exchange plates/pipes | N/A | Heat exchange |

## 5. Simulation

### 5.1. USING ENERGYPLUS

EnergyPlus (E+) is a dynamic building simulation engine which calculates energy consumption and thermal loads of a building using algorithms from two parent programs, DOE-2 and BLAST (Building Loads Analysis and System Thermodynamics). The simulation is based on the first law of thermodynamics and requires user input of a building's physical characteristics, including size, form, materials, location, and orientation, as well as its occupational schedule and usage type, its primary mechanical systems, and specific operational patterns such as thermal control set points, secondary HVAC systems, equipment efficiencies, and day lighting controls. EnergyPlus can be used as a predictive tool to estimate energy consumption

of a proposed building during its design phase or as an audit tool to evaluate energy consumption of an existing building. Figure 11.
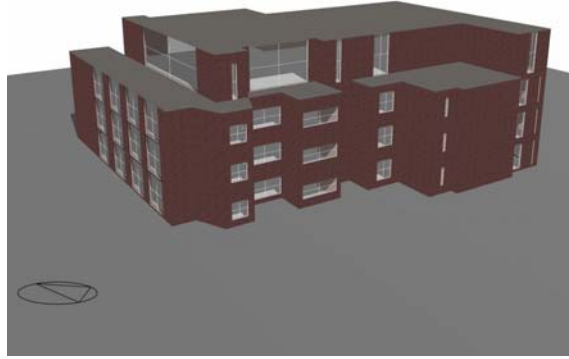


*Figure 11.* Schattner model in EnergyPlus using the Design Builder user interface

5.2. USING ECOTECT

ECOTECT is a highly visual and interactive building design and analysis tool that links a comprehensive 3D modeler with a wide range of performance analysis functions covering solar, thermal, energy, lighting, acoustics, resource usage, and cost aspects. While its modeling and analysis capabilities can handle geometry of any size and complexity, its main advantage is a focus on feedback at the earliest stages of the building design process. In addition to the extensive selection of internal calculations that ECOTECT can perform, it also exports to a range of more technical and focused analysis engines such as Radiance, EnergyPlus, ESP-r, among others. The downside of using this approach is the limited detail in the HVAC systems breakdown. Figure 12.
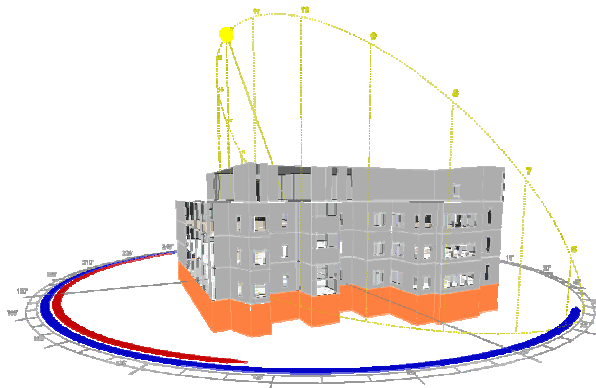


*Figure 12.* Schattner model in ECOTECT

SECTION IV: Simulation and Virtual Prototyping

5.3. USING NEN2916

The NEN2916 is a method for determining the performance and energy consumption of a building without the need to install meters or develop complex simulation models. It uses a series of equations which take user input about the physical nature of the building, the specific systems and equipment used to condition the building's interior, the building's type, and number of occupants.

The algorithm is based on the European Standard NEN 2916: "Energy Performance of Non-Residential Buildings – Determination Method." This standard was developed in large part by modifying previous standards calculated for residential buildings, NEN-EN 832: "Thermal performance of buildings – Calculation of the energy use for heating – Residential Buildings" and NEN-EN 5128: "Energy Performance of dwellings and residential buildings – Determination Method."

For use in this work, the European standards were also modified to reflect construction in the United States. Modifications include changing building type specifications and internal set point temperatures. Localization is also necessary in order to take into account the monthly average outdoor dry bulb temperatures and quantity of solar radiation that a specific location experiences throughout a typical year.

The NEN2916 calculates the total energy consumption of a building as the sum of the consumption of individual functions: heating, cooling, humidifying, lighting, domestic hot water, fans, and pumps. For heating and cooling consumptions, these equations are linked. In addition to calculating energy consumption, the NEN2916 also determines the Energy Performance Coefficient (EPC) of a building, a performance standard developed by the Netherlands Standardization Institute and required by the Dutch Building Decree.

To calculate the EPC, the algorithm uses a ratio of the calculated total energy consumption of the building to the admissible characteristic energy consumption of the building. The admissible characteristic energy consumption is derived by an equation which takes into account the building type, the EPC requirements for that specific building type, and its size. The EPC is a useful tool for quick and objective normative comparisons. Figure 13.
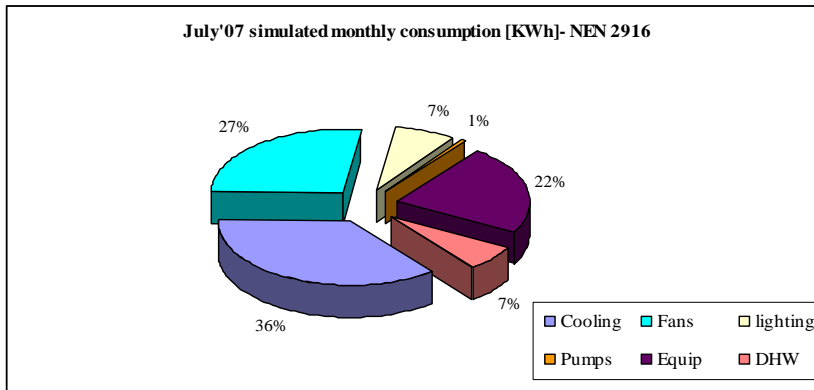
**July'07 simulated monthly consumption [KWh]- NEN 2916**



*Figure13.* Breakdown of NEN 2916 output

## 5. Simulation results

The energy consumption of the Schattner building during the month of July was calculated by ECOTECT, NEN2916, and EnergyPlus. ECOTECT is the closest to the metered data, being 21% below the metered data. Both NEN2916 and Energy Plus are lower than the metered data by 55% and 31% respectively in following table, and Figures 14,15,16, and 17.

TABLE 2.Output comparison by tool or method

|  | Metered Data | ECOTECT | NEN2916 | EnergyPlus | Penn |
|---|---|---|---|---|---|
| Total Energy Consumption (KWh) | 640,711 | 506,415 | 287,943 | 437,173 | 326,902 |
| Energy Use Intensity (KWh/m²) | 97 | 77 | 44 | 66 | 50 |
| Difference | 0.0% | -21.0% | -54.6% | -31.0% | -49.0% |
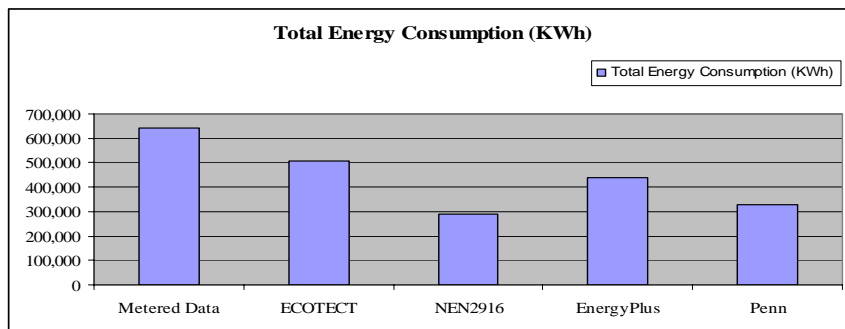


*Figure 14.* Total Energy Consumptions predicted or calculated

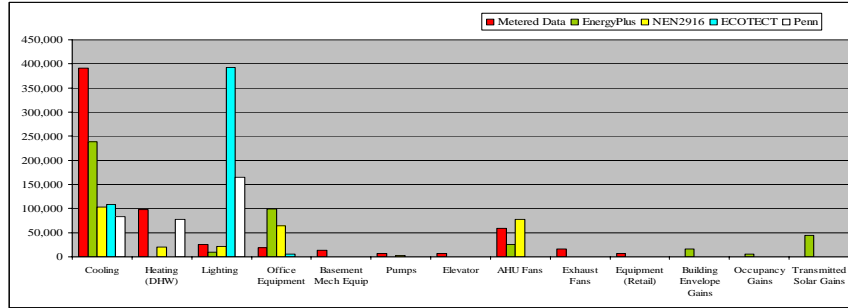SECTION IV: Simulation and Virtual Prototyping

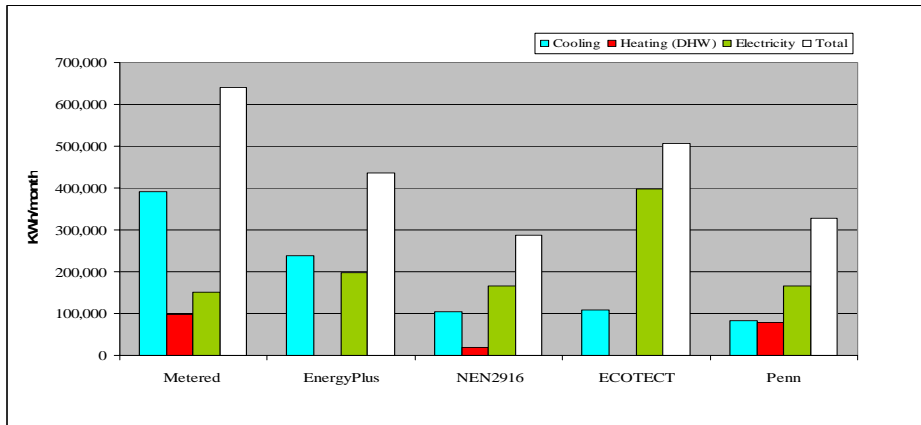*Figure 15.*   Total Energy Consumption breakdown by output



*Figure 16.*   Normalized breakdown of Energy Consumption
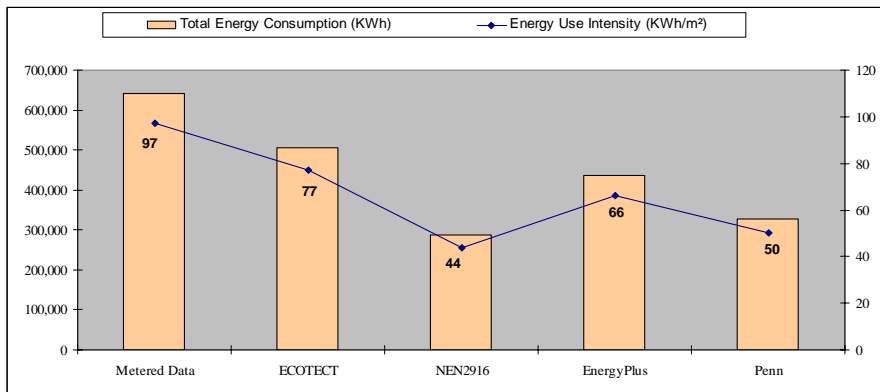


*Figure 17.*   Building Energy Performance Indicator by tool or method

## 6. Conclusion

ECOTECT, NEN2916, and EnergyPlus were used to explore the best approach to benchmark energy performance for a university campus. The comparative approach presented in this paper coupled with real-time weather and utility data allowed us to test the validity of a popular normative tool against widely used energy performance assessment methods. As in any simulation process, the data integrity, expert level, and extent of assumptions play an important role in conducting a successful process. Based on the previous pilot study, we conclude the applicability of the NEN2916 method in cases that require low precision. EnergyPlus is recommended for use if higher level of precision is required. As for ECOTECT, its applicability will depend on the level of analysis required beyond energy performance on the building level. Careful attention must be given to the data integrity and the time needed to conduct such simulations.

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