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3D Reality Energy Modeling Software

Brett Bass, PhD
Joshua New, PhD
Drury Crawley, PhD

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Electrification and Energy Infrastructure Division

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Prepared by
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, TN 37831
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ABSTRACT

As part of a Collaborative Research and Development Agreement (CRADA), Oak Ridge National Laboratory's (ORNL) and Bentley Systems partnered to convert geometry information to physics-based digital twins of a city's buildings. This team extended ORNL's building energy modeling capabilities and combined them with Bentley Systems' ContextCapture to create digital twins of buildings, which allow designers to make simulation-informed improvements to the energy efficiency and demand response of the built environment. ORNL serves the US Department of Energy as one of three core laboratories developing building energy modeling tools EnergyPlus and OpenStudio. ORNL's Automatic Building Energy Modeling (AutoBEM) software can create full EnergyPlus and OpenStudio models using building properties extracted from a variety of data sources (e.g., aerial imagery, lidar). Bentley Systems' ContextCapture software processes data from 3D laser scanning and photographs through photogrammetry to create photorealistic 3D meshes of individual objects for geographic areas as large as a city, providing visualization models and platforms that can be used to evaluate sustainable design alternatives.

This report details how the team used ContextCapture models and other available building-specific information as inputs to create digital twins of buildings in a sharable format (i.e., cityGML) for any vendor to use. With regard to commercial application, designers using Bentley Systems' tools can use the simulation-informed energy use data provided by this methodology to better consider the energy impacts of a new building during the design phase with longer-term consideration given to derivative business products or services.

1. STATEMENT OF OBJECTIVES

Oak Ridge National Laboratory (ORNL) serves the US Department of Energy (DOE) as one of three core laboratories for building energy modeling. This work includes active development for EnergyPlus [1], DOE's flagship whole-building simulation tool, and OpenStudio [2], a middleware software development kit (SDK) that allows for the creation of building energy models and subsequent energy analysis of buildings. Both products are open source and actively supported; improvements are released every 6 months and downloaded approximately 40,000 times with each release. ORNL also leads several urban-scale energy modeling efforts to extend building-specific simulation to geographical areas the size of a city or larger [3]–[12].

ORNL established this CRADA with Bentley Systems, a company that provides software and services for the design, construction, and operation of buildings. By extending ORNL's building energy modeling capabilities and combining them with Bentley Systems' ContextCapture, the team created an approach to building modeling that is replicable on an urban scale. The team used ContextCapture mesh models and other building-specific information retrievable in areas that Bentley Systems scans as inputs to create building energy models. The team leveraged ORNL expertise to create both an OpenStudio and EnergyPlus model of each building and packaged the data into a CityGML file, a sharable format that any software vendor can use. (Many cities in Europe have standardized, publicly available city data in CityGML format; consequently, many software vendors support input and analysis of that data with their tools and simulation engines.) These building models allow simulation-informed energy efficiency to be incorporated into the design and operation of buildings in a way that properly accounts for each building's unique surroundings.

2. TECHNOLOGY DESCRIPTION

2.1 BENTLEY SYSTEMS

Bentley Systems' ContextCapture software[1] (Technology Readiness Level 9) processes flyover and ground-based information from laser scanning and aerial photography to create photorealistic, 3D, tessellated mesh of individual buildings and city-sized areas. It is often used—as it was recently for the 26 km^2 central core of Helsinki, Finland—to aid in the visualization of sustainable design alternatives for buildings. (https://www.bentley.com/en/project-profiles/city-of-helsinki_helsinki-3d and https://kartta.hel.fi/3d/mesh/Kalasatama/).

ContextCapture supports products used to analyze high-resolution flyover LIDAR and photogrammetry, shown in Figure 1 with Acute3D Viewer, for individual buildings. University campuses, such as Brown University (Figure 1) have coupled ContextCapture with internal work order systems to show work on different floors. However, ContextCapture alone cannot assess opportunities to improve energy efficiency.

Figure 1. Bentley Systems' 3D, texture-mapped mesh from flyover data collection.

2.2 ORNL'S BUILDING TECHNOLOGIES RESEARCH AND INTEGRATION CENTER

The building energy modeling team at ORNL's Building Technologies Research and Integration Center has developed capabilities for the detection of building properties, building energy model creation, EnergyPlus simulation engine deployment on high performance computers, scalable simulation, big data analysis with machine learning agents, and calibration, as well as accompanying websites and web services for sharing results. These capabilities were developed with investments from the Building Technologies Office (BTO), National Nuclear Security Administration's Defense Nuclear Nonproliferation R&D (NA-22), and the Office of Electricity Delivery and Energy Reliability as part of the Grid Modernization Laboratory Consortium.

[1] https://www.bentley.com/en/products/brands/contextcapture

AutoBEM was developed to create building-specific energy models for large geographical areas [13]–[17]. It comprises approximately 17 software packages that can process satellite, aerial, and street-level imagery; lidar; cartographic layers; tax assessor data; and other data sources to extract building footprints, heights, window-to-wall ratios, building types, vintages, and other building properties. It can then combine these properties into a full OpenStudio or EnergyPlus model. AutoBEM can also perform quality control and assurance, simulate at scale, store results, analyze buildings' various use cases, and deploy results in a scalable visual analytics platform. It has created 178,368 building energy models, empirically validated with 15 min whole-building electrical use data, from partner utility Electric Power Board of Chattanooga, to inform technology-specific program decisions (see Figure 2). The AutoBEM software packages used in this project include the following:

- AutoBEM-Gen (TRL 7): the world's fastest building energy model creator. It fuses all data sources listed previously into a model that can be simulated. It currently generates more than 500 EnergyPlus models in 1 s on a laptop. (The OpenStudio version creates 1 building energy model every 40 core-seconds.)

- AutoSIM (TRL 7): the world's fastest building simulator. It can simulate 15 min building performance data for 100 metrics over the course of a year for more than 500,000 buildings (45 TB to disk) in 1 h using the nation's fastest supercomputer (i.e., Titan at ORNL).

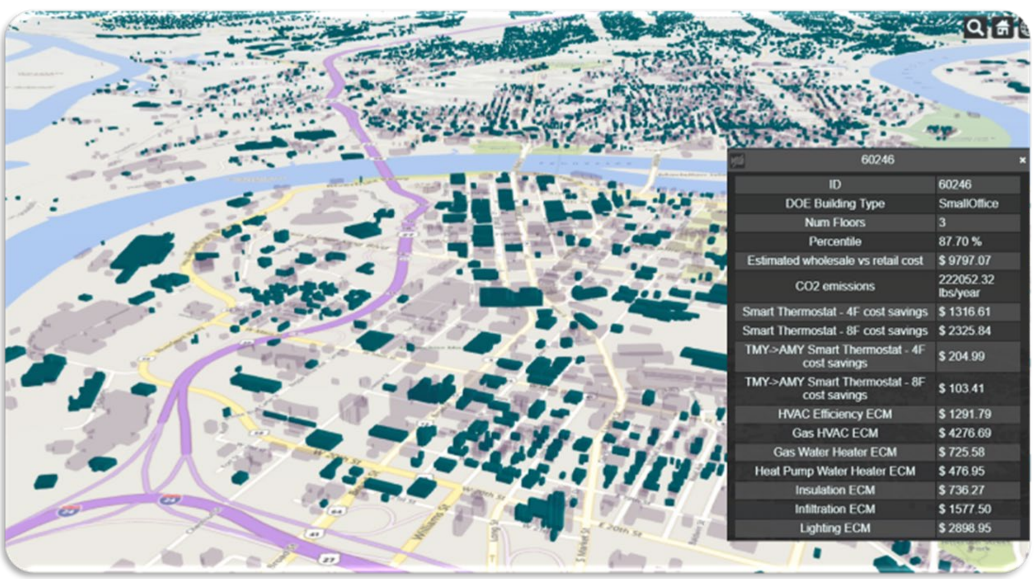

Figure 2. AutoBEM building energy models of Chattanooga, TN validated against 15 min data and integrated with the utility to inform energy efficiency, demand response, and infrastructure planning programs.[2]

3. BENEFITS TO THE FUNDING DOE OFFICE'S MISSION

DOE's and BTO's respective missions are both focuses in this work. DOE's mission is to ensure the United States' security and prosperity by addressing its energy, environmental, and nuclear challenges through transformative science and technology solutions. BTO's mission is to develop, demonstrate, and accelerate the adoption of cost-effective technologies, techniques, tools, and services that enable high-performing, energy-efficient, and demand-flexible residential and commercial buildings in new and existing buildings markets, in support of an equitable transition to a decarbonized power sector by 2035

[2] https://evenstar.ornl.gov/autobem/virtual_epb/

and a decarbonized energy system by 2050. Furthermore, BTO aims to reduce energy use intensity of US buildings by 30% by 2030 compared with a 2010 baseline.

ORNL partnered with Bentley Systems and used their ContextCapture software to create digital twins of buildings at the design phase to promote energy-aware building designs and help translate simulation-informed analysis into actualized energy and cost savings that directly further BTO's overarching mission. Modeling building energy usage is crucial to understanding nationwide energy patterns and promotes the development and adoption of building technologies. While modeling individual buildings is useful, modeling large numbers of buildings further scales potential benefits. Aggregating building metadata at scale is the primary challenge to upscaling building energy modeling analyses. This project explored the use of different types of aerial imagery in combination with niche software to develop 3D meshes of urban landscapes that allow for expanded building energy modeling efforts.

4. TECHNICAL DISCUSSION OF WORK PERFORMED BY ALL PARTIES

The process of translating aerial imagery from drones into building energy models can be separated into the steps shown in Figure 3. These steps are further explained in the following subsections.

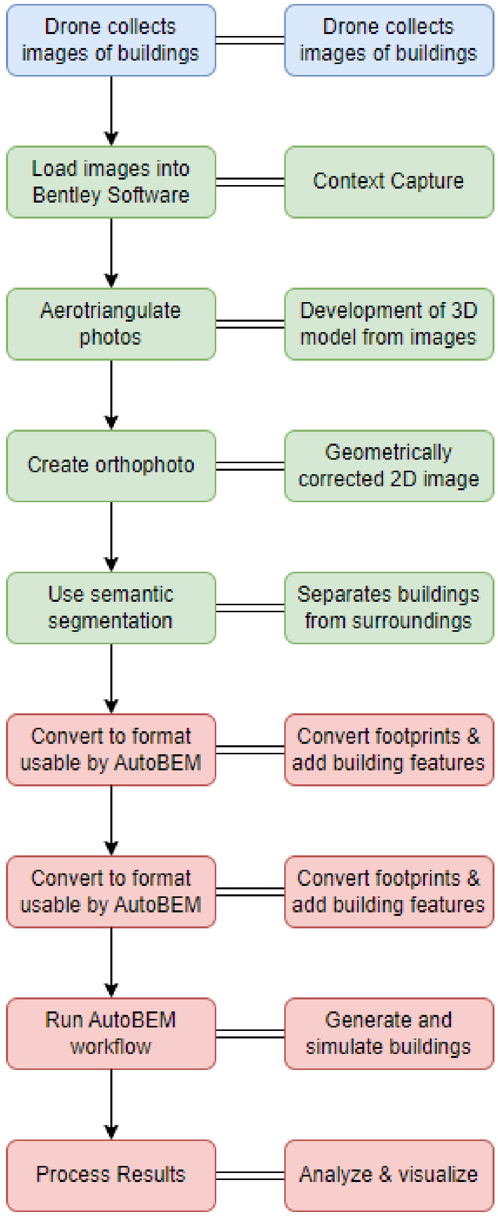

Figure 3. Three-stage workflow for this project. The first stage (blue) was collection of aerial images by flying an aerial platform (drone or helicopter) over target locations. The second stage (green) used Bentley Systems technology, and the last stage (red) was accomplished using ORNL/AutoBEM software.

4.1 AERIAL IMAGERY

Drones or helicopters collected aerial imagery of the following locations of interest:

- Glasnevin Campus of Dublin City University in Dublin, Ireland
- Helsinki, Finland
- Ahmedabad, India

A combination of imagery, reality mesh files, and geospatial data was made available for each of these cities.

4.2 BENTLEY SYSTEMS SOFTWARE

Using Bentley Systems' software, the aerial images were transformed into 3D reconstructions of the locations of interest using aerotriangulation, which accounts for camera position and set of images to develop the 3D reconstruction. These 3D reconstructions can be used directly or further analyzed. An example of the 3D reconstruction of the Glasnevin Campus is shown in Figure 4.

Figure 4. 3D reconstruction from images of Glasnevin Campus.

Bentley Systems software was used to convert the 3D reconstructions into 2D representations called *orthophotos* so that building footprints could be extracted. This was necessary because segmentation detectors are trained on 2D orthophotos to create trained building classifiers. To segment the building footprints from the surrounding area, a Bentley Systems segmentation detector was downloaded and used to classify building footprints. The result was a segmented orthophoto that could be extracted to typical geospatial file formats.

The heights of the buildings were determined using the 3D reality mesh of the surrounding area. An example of the measured height of a building on the Glasnevin Campus is shown in Figure 5.

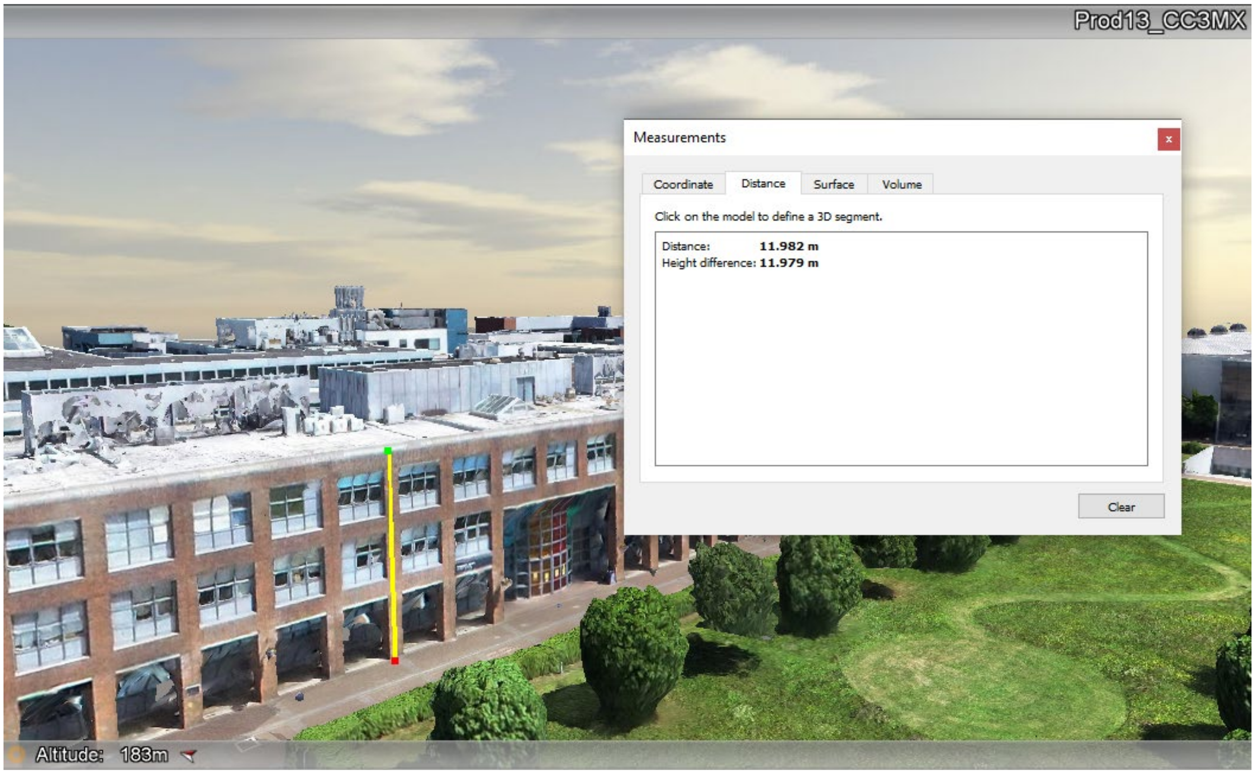

Figure 5. 3D reconstruction for the Glasnevin Campus showing dynamic measurement of building height.

4.3 ORNL/AUTOBEM SOFTWARE

AutoBEM requires four primary building properties to infer the remaining building characteristics: the building footprint, height, type, and standard. The geospatial output from the Bentley Systems software provides building footprints and building heights. This output may be appended to the building type and standard, which can be gathered from local data sources such as city parcel data, be estimated based on aerial imagery, or be assigned based on a heuristic or machine learning model.

After being converted into a compatible format, the geospatial output from the Bentley Systems software was used as input to AutoBEM. Several steps were taken to improve the building energy models and provide context to the analysis:

- The geometry was simplified to reduce the number of vertices from an average of 22 per building to four per building.
- 2D building area was calculated based on the simplified geometry.
- Climate zone was assigned using the latitude and longitude of each building.
- Buildings without assigned building types were classified using a heuristic based on the 2D areas and heights of the buildings.
- Buildings without assigned building standards were assigned based on the distribution of average building ages in the United States.
  - Although these assumptions likely do not apply to the buildings in India, they can be used as placeholders to ensure proper model creation.
- Buildings with heights less than 8 ft and 2D areas less than 250 ft^2 were omitted from the data set.

A 0.3 km^2 sample of 280 buildings in Ahmedabad was used to demonstrate the conversion and building energy model generation and simulation. The results from the simulation were aggregated and appended to the geospatial building data, which were converted to a CityGML file that Bentley Systems or other stakeholders could use to inform the energy use of the buildings in the data set.

5. PROJECT TASKS COMPLETED BY ALL PARTIES

5.1 TASK 1: DATA AND SOFTWARE SHARING

Task description: Bentley Systems renewed its agreement with ORNL to share all relevant software necessary for this project. Bentley Systems also selected and shared non-disclosure agreement–protected, Freedom of Information Act–exempt ContextCapture data.

ORNL and Bentley Systems delivered the following:

- Data sharing
  - Site tentatively selected for demonstration: Helsinki, Finland
    - Description and some files were made publicly available[3]
    - Other sites considered: Glasnevin Campus of Dublin City University, Germany (1.2 GB *.3mx file also received); Ahmedabad, India; Kaunas University campus; Austin, Texas; West Cambridge campus
    - Meetings were held discussing data resolution, building segmentation, simulation, occupancy modifications, and other details with data holders across these cities/campuses.
  - Initial data
    - Context Capture data (*.3mx) for Helsinki (70.4 GB) and Helsinki's city center (5.8 GB) includes building geometry (10cm resolution) and Red-Green-Blue information across 86 tilesets
- Software
  - Bentley Systems' enterprise software via ORNL's LEARN subscription was replaced with a user-controlled subscription.[4] ORNL was approved by Bentley Systems' admin staff to access the additional software required, and team members successfully downloaded and installed ContextCapture and related software necessary for the project.
  - Converted *.3mx data into shapefile or *.csv that AutoBEM's traditional workflow could use to extrude 2D footprints to typical height for block building generation via OpenStudio and simulation in EnergyPlus.

5.2 TASK 2: GEOMETRY AND DATA IMPORT

Task description: AutoBEM's building energy model generator (i.e., AutoBEM-Gen) currently uses an arbitrary building geometry of the conditioned footprint and height to extrude the geometric shell of a building before populating it with floors, HVAC system types and efficiency, lighting density, and other necessary details (directly measured or assumptions from DOE prototype building characteristics) for a fully articulated building energy model. ORNL extended AutoBEM-Gen's geometry import to enable creation of building energy models for the buildings in the area provided.

ORNL and Bentley Systems delivered the following:

- Processing of output from Bentley Systems' ContextCapture software into a building metadata format usable by AutoBEM for a 0.3 km^2 region in Ahmedabad.
  - This region contains 280 buildings.

[3] https://www.hel.fi/helsinki/en/administration/information/general/3d/utilise/
[4] https://education.bentley.com

- o Aerial photos were processed and output as a shapefile containing building footprints with associated heights above sea level.
- o The shapefile was converted into building metadata that could be used as input to AutoBEM.
  - – Building height was calculated by subtracting the elevation at that location from the building height above sea level.
  - – Geometry was simplified to reduce the number of vertices from an average of 22 per building to 4 per building.
  - – Geometry was converted to a format usable by AutoBEM.
  - – 2D building area was calculated based on the simplified geometry.
  - – Climate zone was assigned by associating the latitudes of the buildings to the closest latitudes in the United States (1A).
  - – Building type was assigned using the same heuristic as applied to the Model America data set.
  - – Building vintage was assigned based on the distribution of average building age in the United States.
    - ▪ Although these assumptions likely do not apply to India, they can be used as placeholders to ensure proper model creation.
  - – Buildings with heights less than 8 ft and 2D areas less than 250 ft^2 were omitted from the data set.
- o The AutoBEM input CSV was then used to generate and simulate 265 building energy models.

5.3 TASK 3: INTEROPERABILITY EXPORT

Task description: ORNL simulated building energy models on Argonne National Laboratory's Theta supercomputer and provided both building descriptors and simulation outputs in data formats (e.g., CityGML) for use by the Bentley Systems software and potentially sharable with other software vendors.

ORNL and Bentley Systems delivered the following:

- Source code for converting building descriptors to file format (i.e., CityGML) for Bentley Systems' software.
- Files and simulation results for 280 buildings in Ahmedabad, India.
  - o CityGML file with building shapes and metadata.
  - o AutoBEM created:
    - o EnergyPlus models (Input Data File, *.idf) models
    - o OpenStudio Models (*.osm)
    - o Comma-separated value files (*.csv) containing Excel spreadsheet of end-use output, and tabular output for each building

5.4 TASK 4: ASSESSMENT

Task description: ORNL and Bentley Systems iteratively assessed and revised supporting data structures and software to enable streamlined conversion of ContextCapture data to building energy models. The final software functionality was documented, and Bentley Systems assessed whether the demonstrated prototype warrants additional efforts for a full product offering.

Bentley Systems determined that the prototype may be of long-term interest but does not warrant further effort at this time given current priorities.

6. SUBJECT INVENTIONS

The primary subject invention from this work was a methodology for transforming aerial imagery taken by drone flyovers into a set of building energy models. These building energy models may be used for countless types of urban-scale analyses, including evaluation of building technologies, electric grid resilience, renewable energy generation and distribution, and climate change impacts. No patents or software copyrights were filed as part of this CRADA, though three registered copyrights were extended as part of this work:

1. AutoBEM:AutoBEMGen (US Copyright TXu 2-141-227) for quickly creating OpenStudio and/or EnergyPlus building energy models from building-specific descriptors (effective May 28, 2019)
2. AutoBEM:AutoSim (US Copyright TXu 2-141-960) for running EnergyPlus simulations quickly using high-performance computing resources (effective May 29, 2019)
3. AutoBEM:AutoGen (US Copyright TXu 2-159-000) for quickly editing and creating OpenStudio and/or EnergyPlus building energy models from a list of input parameters and range of input parameter values

7. COMMERCIALIZATION POSSIBILITIES

Since 2015, Bentley Systems has been actively developing, deploying, and supporting ContextCapture results in many areas, including buildings, transportation, urban planning, city-scale models, telecommunications inspection, defense, and utilities operations with demonstrations in dozens of cities around the world. Bentley Systems also develops and supports tools for building simulation and energy analysis (e.g., OpenBuildings Designer) and city-scale modeling (OpenCities using CityGML and other formats) for promoting high-performance buildings and communities. However, software was needed to fill the gap between ContextCapture's 3D digital twin and software for building energy analysis based on simulation of possible policy or building modifications. ORNL closed that gap via software that can take custom geometries and modify building simulation properties in a way that can create an OpenStudio and/or EnergyPlus model of the building.

Bentley Systems can now utilize the methodology developed in this work to provide estimates of building energy to its customers. Customers who have previously conducted flyovers for a particular area may wish to expand their digital twin capability to include energy estimates for a group of buildings. While internal discussions at Bentley Systems indicate that this may be of long-term interest and worth revisiting at some point, it does not warrant further effort at this time given current company priorities. Given this status, there are currently no actionable plans for future collaboration.

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