RAPID ENERGY MODELING FOR EXISTING BUILDINGS:

Testing the Business and Environmental Potential through an Experiment at Autodesk

NOVEMBER 2009

Autodesk®

ICF INTERNATIONAL

Table of Contents

About ICF International

ICF International (NASDAQ: ICFI) is a global professional services firm that addresses today's most complex management, technology, and policy challenges in four key markets: energy and climate change; environment and infrastructure; health, human services, and social programs; and homeland security and defense. Over 3,500 employees on four continents combine passion for their work with industry and technical expertise to protect and improve the quality of life.

For 30 years, ICF has provided a portfolio of strategy, analysis, advisory services, and implementation tools to clients in the building energy and climate space. Our clients include Fortune 500 companies, utilities, municipal power authorities, U.S. federal government agencies, international and multinational organizations, energy enterprises, power developers, regulated transmission and distribution companies, energy traders and marketers, oil and gas companies, industry associations, investors, financial institutions, and regulators. ICF regularly performs detailed analytic studies to help its clients understand leading building industry trends and the value of a wide range of building modeling and analysis tools.

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About Autodesk®

Autodesk, Inc. (NASDAQ: ADSK) is a world leader in 2D and 3D design, engineering and entertainment software. Autodesk delivers a broad portfolio of solutions that enable architects, designers and engineers to digitally design, visualize and simulate real-world project performance. More than nine million customers around the world use Autodesk software, including 100 percent of the Fortune 100 companies and spanning industries including architecture, manufacturing, transportation, utilities, telecommunications, video games and film, and more.

By enhancing collaboration and communication and digitally improving the real-world performance of projects before they are built, Autodesk customers are improving efficiency, productivity and innovation; solving business challenges; avoiding costly rework; accelerating project cycles and time to market; and ultimately gaining competitive advantage. By bringing the right information and analysis tools to the forefront of decision making throughout the design process, Autodesk tools can enable customers to make smarter, more sustainable design decisions.

More information about Autodesk and its sustainability efforts can be found at www.autodesk.com/green.

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1. Executive Summary

Retrofits of existing buildings represent a huge, growing market and an opportunity to achieve some of the most sizable and cost-effective carbon reductions in any sector of the economy. More and more "zero energy" and "carbon neutral" buildings are being conceived every day by combining energy efficiency measures with renewable energy technologies. However, for all the progress, the building industry continues to face major technical and cost challenges in identifying the highest potential candidates for retrofit. This report investigates one potential solution, a technology-driven workflow called "rapid energy modeling," to accelerate and bring to scale the process of energy modeling for existing buildings.

ICF estimates that using software solutions like those tested by Autodesk and profiled in this report could lead to 90 Mt or more of additional annual CO_2 reductions globally.[1]

1.1. The Environmental Imperative

Implementation of efficiency measures and renewable energy generation in existing buildings is poised to become the global approach to carbon reduction with the largest impact and lowest costs to address climate change.

The magnitude of the climate challenge facing the world today requires scale and speed to address the largest greenhouse gas emitters:

- The International Energy Agency has targeted a reduction of 77 percent in the global carbon footprint by 2050[2] in order to achieve climate stabilization. At roughly 40 percent of global energy consumption[3] and global energy carbon emissions, buildings are the linchpin to achieve that 2050 climate stabilization goal.
- In some places, such as the United States, buildings alone account for 40 percent of national carbon emissions[4] due to the heavy electrical loads from lighting, heating, cooling, computers and appliances.
- In recognition of this, the major economies of the world are producing a drumbeat of national and regional building directives, promoting an aggressive push toward zero energy or carbon neutral buildings.

And yet, our current toolbox will fail us. Even if, for example, 1,000 dedicated energy auditors worked full-time, 365 days a year throughout the United States, it would take them over 13 years to do one-day audits of the entire U.S. commercial building portfolio.[5] **To respond to the climatic challenge at the scale, speed and efficiency required, we will have to be able to quickly and cost effectively prioritize, mobilize and focus our retrofitting efforts. Achieving these goals requires leapfrogging traditional energy modeling methods and building audit techniques.**

> *"Rapid energy modeling techniques, like the one I've seen at Autodesk, help users evaluate numerous design alternatives with less time and cost. Such tools are important for enabling better designs that save energy and money and can create competitive advantage for both designers and clients."*
>
> AMORY B. LOVINS, CHAIRMAN
> AND CHIEF SCIENTIST,
> ROCKY MOUNTAIN INSTITUTE

1.2. The Business Imperative

We face an unprecedented market opportunity to implement building energy upgrades that serve as an engine for new jobs and capital investment.

- Approximately 75 percent of buildings globally will be either new or have undergone significant renovation by 2035.[6]
- About 150 billion square feet of existing buildings (roughly half of the entire building stock in the United States) will need to be renovated over the next 30 years.[7]
- A recent analysis estimates that green building retrofits in the United States

1. Buildings account for 9Gt of annual CO_2 emissions globally and ICF assumed that uptake of Rapid Energy Modeling could increase by 10 percent the number of buildings retrofitted for energy performance, with an average improvement of 10 percent.
2. International Energy Agency (2008), Energy Technology Perspectives.
3. World Business Council for Sustainable Development (2009), Energy Efficiency in Buildings: Transforming the Market.
4. Energy Information Administration (2008), EIA Annual Energy Outlook.
5. According to the most recent information available to the Energy Information Administration, in 2003, there were nearly 4.9 million commercial buildings accounting for more than 70 billion square feet of floor space in the U.S. alone.
6. http://www.architecture2030.org/ (2009)
7. American Institute of Architects (AIA) COTE (2009), Ecology and Design: Ecological Literacy in Architecture Education.

represent a $400B market[8] in the next 20 years.

- In fact, six of the world's largest economic regions (Brazil, China, European Union (EU), India, Japan and USA) could reduce their energy and carbon footprints by 40 percent by investing US$150 billion, with a payback period of only five years.[9]

National economic stimulus programs throughout the world are investing billions of dollars combined in energy efficiency programs over the next few years. In the United States, approximately 86 percent of building construction expenditures is now being directed to renovation of existing buildings, as opposed to new construction.[10] But these massive resources must be channeled into the most cost-effective and scalable of approaches to building upgrades.

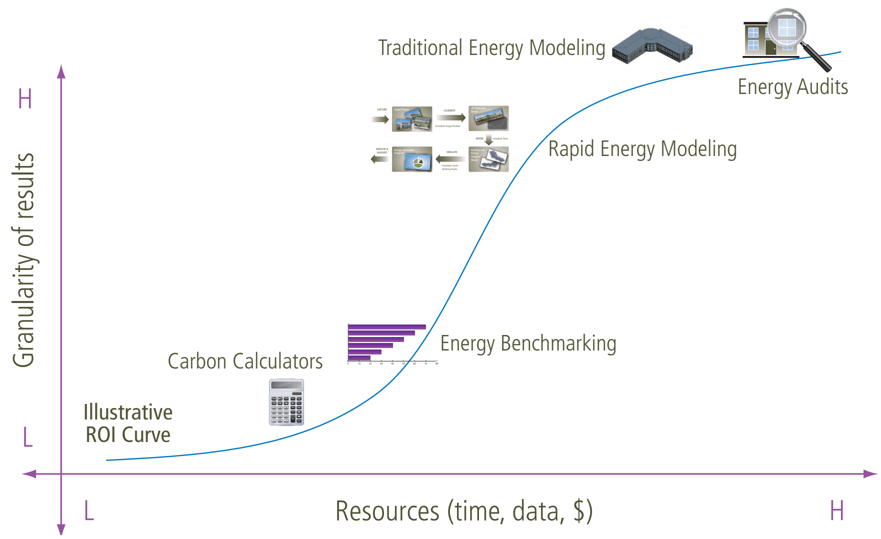
Each of the above solutions provides a unique value by addressing a specific market demand. **However, cost, time, effort, lack of expertise and lack of scale in existing energy modeling will thwart the widespread application of building energy analysis, which is so clearly demanded by the environmental and business imperatives described earlier.**

1.3. The Challenge: Time, Tools and Techniques

Through our discussions with leading green architecture and engineering firms, we have found that:

- *Energy benchmarking* is useful but needs to be supplemented with the ability to model, choose and test the energy and cost savings of different design measures and alternatives.

THE SPECTRUM OF ENERGY REDUCTION TOOLS AND APPROACHES



- *Traditional energy modeling* capabilities often require weeks to months to construct before they can provide the information necessary to guide the design and retrofit process, and are therefore often restricted to only high-budget projects. Their results too often do not accurately represent the measured energy use once buildings are operating. For these reasons, traditional energy models have not penetrated the market sufficiently to meet carbon reduction goals for buildings.

- *Building audits* can provide crucial perspectives on the unique operational details of a building, but they are time consuming, expensive, and require travel and significant investment of time on the part of auditors and their clients. So they only provide optimal value if targeted at buildings with known high potential for improved energy performance.

1.4. The Solution: Rapid Energy Modeling

To address this challenge, this report explores rapid energy modeling as a way to help commercial and residential property owners identify buildings with the greatest potential for energy and carbon emissions savings at the lowest cost and in the shortest time. **Rapid energy modeling is a streamlined process that involves moving rapidly, and with minimal data, from image capture of building exteriors through simplified simulation to building energy analysis.** It offers the capability to:

- Supplement energy benchmarking by providing numerous design alternatives to users.
- Democratize the energy and carbon footprinting process by making it accessible to a wider audience of practitioners.
- Make modeling faster, cheaper, and more likely to be used.

8. Pike Research (2009), "Energy Efficiency Retrofits for Commercial and Public Buildings," Executive Summary.
9. World Business Council for Sustainable Development (2009), Energy Efficiency in Buildings: Transforming the Market.
10. American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) Journal (2008), http://findarticles.com/p/articles/mi_m5PRB/is_1_50/ai_n25376330/

- Augment, refine, and focus traditional on-site building energy audits.

This type of workflow will benefit a number of constituencies as illustrated by the picture below.

1.5. Autodesk's Rapid Energy Modeling Workflow

This report summarizes the results of an in-house experiment at Autodesk, where three Autodesk products (Autodesk® ImageModeler™, the Autodesk® Revit® platform and Autodesk® Green Building Studio web service) were applied to Autodesk's own facilities.

ICF and Autodesk worked together over the span of three months to test solutions for rapid energy modeling on six Autodesk facilities and investigate the application of Autodesk tools in the wider architecture community. While the rapid energy modeling workflow can be applied to both new and existing building projects, we chose to focus this study on existing buildings, both to address a much needed demand described in Section 1.2 and to validate the models using actual energy consumption data. Autodesk's software products provide the ability to deliver a detailed energy and carbon report, beginning with pictures of building exteriors taken with a digital camera.

We took a two-pronged approach to help validate our hypotheses:

- Interview leading architecture firms to help understand their experience with, and perspective on, the potential value of such a workflow.
- Apply this workflow to a selection of Autodesk's own facilities and compare the modeling results with data from existing carbon footprint and energy audit reports.

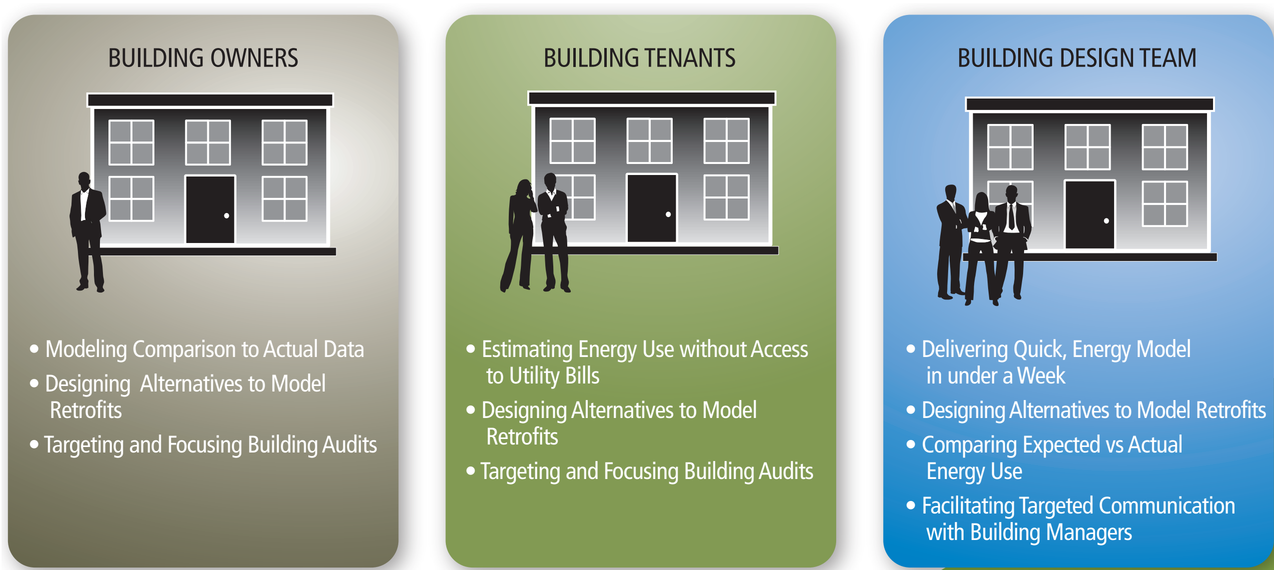
1.6. Key Conclusions

Adoption of rapid energy modeling techniques can significantly increase the number of existing buildings that undergo energy assessments and subsequent upgrades within a smaller budget and shorter time frame.

There is considerable interest in the building community to streamline the modeling process. Property managers, tenants, home buyers, design teams, public policy advocates and energy consultants are expected to benefit from such a workflow in the following ways:

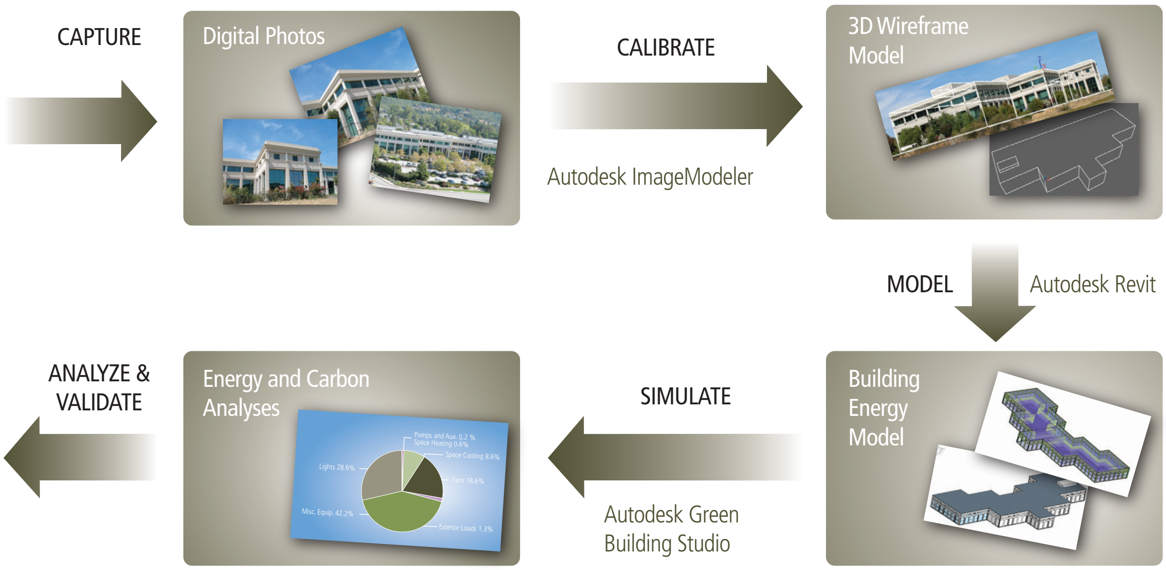
A. **Shortcut to estimating actual energy use:** Applying a set of standard parameters to all facilities,[11] we found that for three of the six Autodesk buildings, the energy intensity (kWh/square foot) predicted by the model fell within 6 percent of actual energy data, one facility was 12 percent off, and two others showed higher deviations. Given that we constructed the initial models without knowing anything about the facilities' operations, and applied the same set of modeling assumptions to facilities that were diverse in geographies, weather zones, operational schedules and power efficiencies, we were pleased by the results' proximity to actual consumption data.

RAPID ENERGY MODELING BENEFITS



11. A 12-hour/7-day (12/7) operation schedule, a lighting power density of 1.5 W/sf, equipment power density of 1.65 W/sf.

RAPID ENERGY MODELING WITH AUTODESK TOOLS



B. Stepping stone between quick benchmarking and detailed audits: Rapid energy modeling alone is not yet sufficient in capturing unique operational details that can only be captured through discussions with on-site personnel or through in-person building audits. However, rapid energy modeling does provide a quick, sophisticated way of going beyond carbon footprinting and energy benchmarking to look at tangible energy reduction opportunities. It provides useful data points to prompt tangible dialogue with the facility manager, a useful outcome in and of itself.

For example, the two outliers mentioned above prompted U.S. to have conversations with facilities managers, which led to further insights by identifying:

- Gaps in the model's assumptions that could be subsequently addressed to improve accuracy of the model.
- Operational inefficiencies that were previously unknown and could be addressed through efficiency investments.

C. Screen for high potential buildings: Rapid energy modeling represents a prioritization screen to determine how to focus on-site building audits and renewables assessments, which can be very time- and resource-intensive. Through rapid energy modeling, we were able to determine the following:

- Autodesk's six facilities had relatively similar energy intensities, with the exception of Shanghai, which had a lower intensity. As a result, it was also important to look at the buildings' carbon intensities to prioritize targets for energy reductions.
- Autodesk's Novi facility had the highest carbon intensity of all modeled facilities, due in part to more carbon-intensive electricity sources, potentially making this facility the highest priority for carbon reduction activities.
- Autodesk's Farnborough and Toronto facilities had the highest wind energy potential.
- Autodesk's San Rafael office had the highest natural ventilation and photovoltaic potential.

These findings will help Autodesk prioritize its energy and carbon reduction efforts, focusing on facilities that have the most potential in each relevant area.

D. Communicate Return on Investments for priority buildings: Rapid energy modeling can increase the ability to evaluate the potential financial and environmental values of an energy efficiency project, as well as those of specific green building measures including day-lighting, natural ventilation, and solar photovoltaic and solar thermal applications.

- Assuming a rough electricity reduction estimate of 10 percent,[12] the reduction potential

12. 10% reduction is a conservative estimate based on ICF's extensive experience with building retrofit projects. We find that most buildings have a significantly higher cost-effective energy reduction potential.

across the six modeled Autodesk facilities is equal to approximately $122,000 in annual cost savings.[13]

E. **Achieve economies of scale across a portfolio:** The rapidity of the process and its ability to point to a subset of high potential buildings allows property owners to achieve economies of scale when investing in efficiency measures or renewable energy technologies.

Autodesk and ICF personnel, with no previous experience with Autodesk tools, completed the rapid energy modeling process for the six Autodesk facilities on three continents in a matter of days for each one, and in some cases, hours, without any travel to the building sites. We estimate that with two dedicated modelers with little or no training and with access to basic facility information and photographs, Autodesk could have completed rapid energy modeling of all 72 of its corporate facilities in under two months,[14] and immediately have a workflow to test the value of a variety of energy and carbon reduction measures, as well as a prioritized list of facilities with high photovoltaic, wind, and natural ventilation potential.

F. **Stimulate creation of skilled green jobs:** The growth of rapid energy modeling could lead to an increased number of green jobs, as entry-level professionals could quickly learn the skills necessary to seamlessly create energy models. Implementing a rapid energy modeling process for the 4.9 million commercial buildings in the United States alone could employ 20,000 new entry-level energy modelers in a year.[15]

13. Based on energy spend data taken from Autodesk® Green Building Studio® model results.

14. Assumed 2 modelers working 21 days a month, averaging eight hours per model.

15. Assuming modelers working 21 days a month, 12 months a year, averaging eight hours per model.

2. Methodology

We adopted a two-pronged approach to help test our hypotheses, as described below.

2.1. Needs Assessment via Customer Interviews

Autodesk and ICF interviewed users of Autodesk software for rapid energy modeling from four firms, Glumac, Atelier Ten, BNIM and Clayco/ARBA Studios. These firms represent a diverse set of leading-edge green design firms in the country. Each of the interviews began with a few key questions:

- What do you see as the strengths and weaknesses of a rapid energy modeling workflow?
- How do you feel Autodesk's solutions compare to other energy modeling tools, particularly in terms of ease of use and accuracy of the results?
- How do you feel the energy savings component of this workflow compare to that of traditional energy building audits?
- Are there specific applications where you think the rapid energy modeling workflow, including the one from Autodesk, would be particularly useful or not useful?
- Can you give any specific examples and/or quantitative results regarding your use of the rapid energy modeling workflow?

Excerpts of these interviews and cross-cutting themes across all interviews are contained in text boxes throughout this report.

2.2. Autodesk Facility Selection, Modeling and Comparison

Autodesk and ICF reviewed reports from an internal fiscal year (FY) 2009[16] carbon footprint and a building energy audit of Autodesk facilities performed by Jones Lang LaSalle (JLL) in order to:

a. Prioritize the most carbon-intensive facilities.

b. Validate the accuracy of the energy model relative to actual consumption data.

c. Compare the process to JLL audit in terms labor hours and quality of results.

Based on our initial analysis, Autodesk and ICF chose a set of six facilities (Toronto, Canada; San Rafael, CA, Novi, MI, Manchester, NH, United States; Farnborough, UK; and Shanghai, China) that represented a diversity of geography, size, age and building type, with a focus on high energy-use facilities. Autodesk and ICF then used a rapid energy modeling process for these prioritized facilities and validated the modeling results against past energy audits (by JLL) and actual energy consumption data.

The Autodesk Green Building Studio web service provides the capability of exporting DOE-2 files to other popular building energy simulation engines such as eQuest and EnergyPlus. Autodesk and ICF cross-validated Green Building Studio outputs and confirmed that the models were being exported correctly to both engines. **ICF considers this a strength of Green Building Studio, as eQuest and EnergyPlus can allow users to model more complicated energy modeling and thereby potentially supplement the value of the rapid energy modeling process.**

We also briefly analyzed the Green Building Studio web service reports on carbon neutral, water and photovoltaic potentials of these buildings.

16. The Autodesk's fiscal year runs from February 1 to January 31.

3. Autodesk Rapid Energy Modeling Workflow

3.1. Selection of Software Tools

The Autodesk tools that we investigated included Autodesk ImageModeler software, the Autodesk Revit platform and Autodesk Green Building Studio web service, which can be used in that order to build a comprehensive energy model from simple digital pictures of a building's exterior. This section gives a brief overview of these software tools, as well as tips for future users of these tools. For more detailed descriptions, please go to www.autodesk.com.

3.2. Workflow

The picture below describes the high-level flow and interaction between the tools:

1. **Capture:** The workflow begins with scoping and prioritizing facilities (described in Section 4.1) and taking digital pictures of a building's exterior.[17]
2. **Calibrate:** The 2D images are calibrated in Autodesk ImageModeler software and placed in a 3D user-defined coordinate system to produce a simple wireframe model that can be exported to Autodesk Revit software.
3. **Model:** The user can then add basic design elements, such as walls, floors, windows and roof from within Revit, to get a very rough 3D model that can be exported to Autodesk Green Building Studio.
4. **Simulate:** The building and energy analysis model can be simulated in Green Building Studio web service using a number of user-defined parameters to obtain a comprehensive energy and carbon report.
5. **Analyze and Validate:** The report can be used for further analysis and benchmarking.

This study was focused on validating the workflow described above, and thus we did not test all the available tool capabilities.

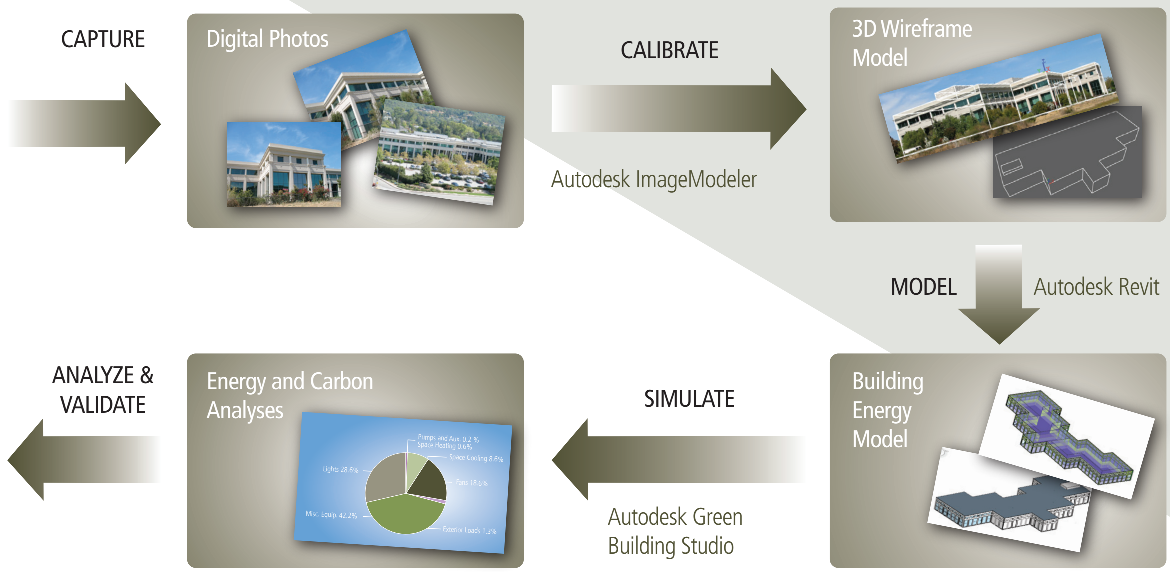
CUSTOMER INTERVIEW INSIGHT

Rapid energy modeling tools are particularly useful to quickly get building geometry into energy models.

3.3. Autodesk ImageModeler

Autodesk ImageModeler image-based modeling and photogrammetry software

RAPID ENERGY MODELING WITH AUTODESK TOOLS



17. See Appendix C for tips on taking pictures that lend themselves well to calibration.

generates 3D models from 2D digital images. The goal of ImageModeler is to enable its users to capture real-world images of buildings and easily create 3D models. ImageModeler software provides editing, modeling, and texturing tools that allow the user to further refine the rendered objects. The 3D objects can then be exported into various formats, including Autodesk Revit software.

A common ImageModeler project work-flow is described below:

- Take photographs of the subject to reconstruct or measure.
- Calibrate of the photographs.
- Set the coordinate system and scale.
- Model over the images and take measurements.
- Add Texture.
- Export.

Texturing was not used in our study. Please see Appendix B for further details.

3.4. Autodesk Revit

The Autodesk Revit platform is Autodesk's purpose-built solution for building information modeling. Applications such as Autodesk Revit Architecture and Autodesk Revit MEP built on the Revit platform are complete, discipline-specific building design and documentation systems supporting all phases of design and construction.

As part of Autodesk's rapid energy modeling solutions, Autodesk Revit converts 3D CAD files to a building information model, which is required as an input to the Green Building Studio web service.

For the purposes of rapid energy modeling, it is not necessary or desirable to construct a very detailed Revit model. In fact, an internal test at Autodesk found very little difference in the conclusions that can be drawn between models with low, medium or high level of detail and granularity.[18]

3.5. Autodesk Green Building Studio

The Autodesk Green Building Studio web service is designed to allow users to perform whole building energy, water and carbon emission analyses of a new or existing building. These analyses are performed by users over the Internet from within their own design environment. This streamlines the entire analysis process and allows the user to get immediate feedback on his or her design alternatives — making green design and green policy creation more efficient and cost effective.

The web service simulates a building's whole-building energy consumption, water use, carbon emissions, and the user is able to view the output in a web browser, including the estimated energy and cost summaries, as well as the building's carbon neutral potential. In addition, the Green Building Studio web service also calculates an ENERGY STAR® score, estimates photovoltaic and wind energy potential, calculates points toward LEED day-lighting credit, and estimates natural ventilation potential.

CUSTOMER INTERVIEW INSIGHT

One firm we interviewed plans to model a number of buildings (previously modeled using eQuest), using Autodesk Green Building Studio web service to test whether Green Building Studio is faster and easier to use and to confirm where in the energy modeling timeline it can be used.

Finally, Green Building Studio includes a Design Alternatives functionality that allows the user to test different building measures in the model in order to determine potential energy savings and green benefit.

Please see Appendix A for further details on the product, as well as a sample of a Green Building Studio report.

18. "Creating Models for Performance Analysis on Existing Buildings," Autodesk Whitepaper, 2008.

4. Rapid Energy Modeling in Action

Autodesk and ICF worked together to select and model six Autodesk facilities in order to gauge the ease of using Autodesk's rapid energy modeling solutions, compare the modeling results with actual consumption data, contrast the workflow with traditional energy modeling and energy audit approaches and point to other potential benefits of such a workflow.

4.1. Prioritization and Selection of Autodesk Facilities

ICF reviewed Autodesk's FY09 carbon footprint and an energy audit of Autodesk facilities performed by Jones Lang LaSalle (JLL) to prioritize the most carbon-intensive facilities for sampling.

CUSTOMER INTERVIEW INSIGHT

Rapid energy modeling tools are easier to work with than more complex tools, but users should ensure that some of the common human errors in inputs and assumptions (e.g., orienting building elements, assigning proper reflectivity, accounting for thermal mass) are addressed earlier in the project.

ICF analyzed Autodesk's carbon footprint and energy data for 72 buildings including 3 datacenters, 2 warehouses and 67 offices. ICF then constructed a scatter plot of Autodesk facilities in order to identify clusters of particularly energy-intensive facilities for further review.

In particular, we looked for buildings that were unusually energy intensive: those that had a high-energy usage per square foot compared to other buildings of similar function. This indicator can often be an initial guide in building portfolios to those facilities that represent unusual opportunities for improvement. In general, the ICF team focused on buildings that present the most likely targets for reducing energy and greenhouse gas (GHG) emissions. ICF then eliminated facilities with significant datacenters on-site in order to target more typical office facilities and prioritized a dozen facilities. The Autodesk team members then discussed the list with their regional facilities managers and further narrowed it down to a geographically diverse set of six facilities (Toronto, Canada; San Rafael, CA, Novi, MI, Manchester, NH, USA; Farnborough, UK; and Shanghai, China) that could be modeled in the project's timeframe. The selected facilities include historic and contemporary buildings representing a variety of sizes and structures in four countries spanning three continents.

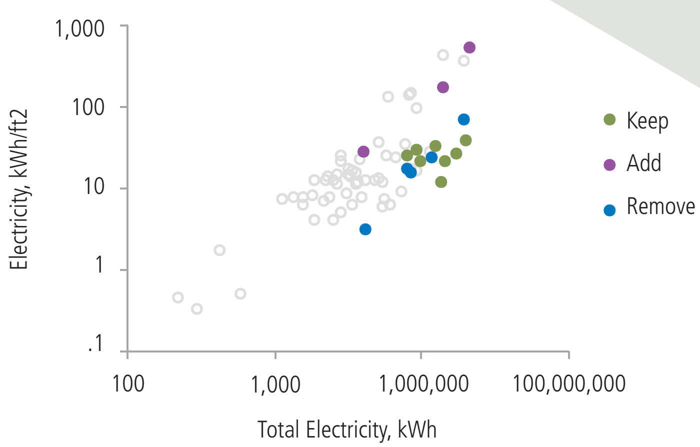
Autodesk applied its rapid energy modeling workflow on five facilities and ICF corroborated the workflow on one of the facilities. The modeling results were then compared against actual consumption data from building energy audits.

Appendix D has further details on each of the facilities, such as modeling challenges, solutions and tips. The following sections detail the results and benchmarking of the modeling efforts.

CUSTOMER INTERVIEW INSIGHT

Rapid energy modeling tools are particularly useful for performing quick analyses to get project team and client buy-in for green measures when there isn't enough time for more complex energy models. In some cases, rapid energy modeling tools helped show that measures would be cost-prohibitive; in some cases, they helped justify additional investment.

SCATTERPLOT OF ENERGY USE IN ALL AUTODESK FACILITIES



AUTODESK FACILITIES MODELED FOR THIS PROJECT

4.2. Autodesk Facility Cross-Cutting Modeling Results

After completing the models and testing and analyzing the results for each of the six facilities, we attempted to uncover common themes and trends. We provide our initial conclusions below.

4.2.1. Predicted vs. Actual Energy Intensity

One primary goal of this project was to test how effectively rapid energy modeling could estimate the energy usage of existing buildings. Thus, from our perspective, one of the most important metrics of success was the comparison of electric intensity (kWh/square foot) predicted by the model against the actual energy usage of the building as measured from actual utility bills. Another reason for choosing electric intensity over raw energy consumption (kWh) for comparison was the fact that a rough model generated from digital pictures alone was bound to be inexact in terms of geometry, dimensions, square footage and room volumes. We worked under the assumption that as long as the errors were small, a model that over- or underestimated the area and volume of a building was likely to also over- or under estimate the energy consumption by a similar percentage, resulting in an intensity ratio that was less affected by these errors.

CUSTOMER INTERVIEW INSIGHT

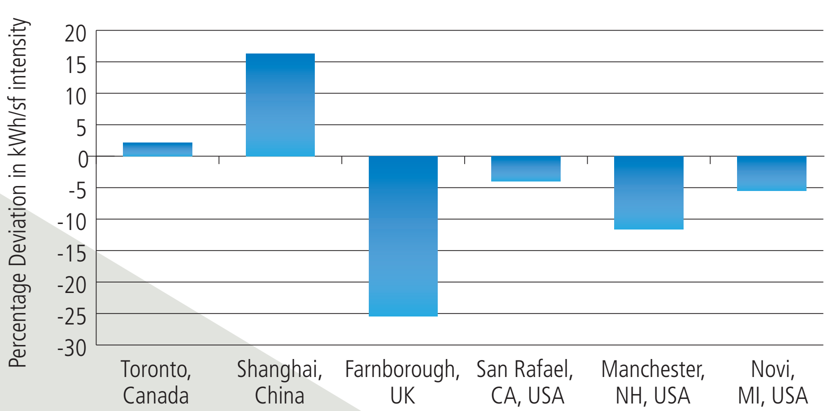
Most new building projects do not end up comparing actual building energy usage data to the energy models used in the design process. Incorporating actual data is a crucial part of improving the value and performance of modeling tools and ensuring that buildings operate the way they are designed. All modeling tools need to work harder to make it easy to incorporate actual performance data into the model. This issue has gained traction throughout the green building community, as many LEED certified buildings are not actually performing as well as expected, and as claimed in LEED documentation.

We applied a set of standard parameters to all facilities (i.e., 12-hour, 7-day operation schedule, a lighting power

CUSTOMER INTERVIEW INSIGHT

BNIM's use of rapid energy modeling tools for its work on the National Building Museum (an existing building retrofit project) gave energy intensity results that came within 10 percent of actual measured energy use at the building, the best results of three different energy models BNIM tested for the project.

COMPARISON OF ENERGY USE IN MODEL VS. REALITY



density of 1.5 W/SF, an equipment power density of 1.65 W/SF and an open office plan). We found that for three of the six building models, the expected energy intensity (kWh/square foot) as modeled fell within 6 percent of actual energy data, one facility was 12 percent off, and two others showed higher deviations.[19]

Given that we constructed these initial models without knowing anything about the facilities' operations, and applied the same set of modeling assumptions to facilities that were diverse in geographies, weather zones, operational schedules and power efficiencies, we found these results to be surprisingly close to the real data. **For the two facilities that showed higher deviation, our interviews with the facilities' managers provided insight into the possible root causes for the deviations.** We do recognize that the sample size included in this study is small. We also recognize that each building has a different operational schedule and power loads, but our intention was to test the tools for rapid energy modeling by keeping the parameters constant, and then subsequently dive into operational details on facilities with outlier results. Future users of the rapid energy modeling workflow should test the validity of the results for an existing building, compare modeling results against actual utility data and take into consideration actual operational details, whenever possible.

THE OUTLIERS

The clear outliers in this study were the Autodesk Shanghai facility, in which the modeled energy use *overestimated* the measured energy by 16 percent, and the Autodesk Farnborough facility in which the modeled energy use *underestimated* energy use by 25 percent.

Our follow-up interviews with the facility managers in Shanghai and Farnborough uncovered some potential reasons for such discrepancies (detailed below). Users may benefit by conducting interviews like these, and then adjusting the energy model assumptions to closely match operational details prior to a simulation run in order to achieve results that match actual energy use.

SHANGHAI

Through our interview with the facilities manager, we learned a number of relevant facts that pointed to plausible explanations for the model's overestimation:

- The air conditioning, airflow and ventilation for the building have been found to be insufficient, particularly during summer. The current air conditioning system is not designed to cope with a fully occupied office space. The manager estimated that the current air conditioning capacity is 30 to 40 percent below ideal.
- An energy audit conducted last year found the lighting to be very low (160–200 lux).
- Occupancy of facility is at 60 to 70 percent of capacity. Some sections of the office were shutdown during various times of the year, due to low occupancy and/or construction.
- The building is on a 10 hours per day, 5 days per week operating schedule, which is around 30 percent shorter than the 12 hour per day, 7 days per week schedule we input into all models.

FARNBOROUGH

We learned the following facts that may point to the root cause of the model's underestimation:

- While a portion of the first floor was vacant, its heating and cooling was not decoupled from the rest of the facility, causing energy to be consumed in a vacant space.
- The heating and cooling systems ran 24 hours a day, 7 days a week (the period that was benchmarked).
- There is an on-site restaurant and kitchen that could lead to higher energy use.

CUSTOMER INTERVIEW INSIGHT

Use the building geometry analysis and weather data to test out the value of particular measures, including:

- Solar load analysis
- Daylighting—shading and window configuration
- Natural ventilation and wind characteristics
- Solar thermal and solar PV potential
- HVAC equipment sizing

Based on our own experience with building modeling, and through our discussions with users of Autodesk modeling tools, we knew that there would be challenges associated with modeling buildings using a set of standard parameters and without knowing key details about occupants' behavior and operational details. These are challenges that face building modelers no matter what tool they use. Discussions with the facility managers provided information that was crucial to fine tuning the model in order to

19. Electricity consumption data in Autodesk's FY09 footprint database was used for benchmarking for all facilities, except Farnborough, UK, where consumption data from the JLL audit report was used, due to missing information in the footprint database.

increase the chance that the model results reflected the real energy consumption of the facility. This underlines the conclusion echoed by all of the architects interviewed for this study that no modeling software can account for all the unique operational characteristics of a building.

Going forward, we would recommend that users conduct similar interviews with managers responsible for each facility to uncover operational details that will shed light on the deviation of the model predictions of energy and CO_2 consumption from the billing information. Given that we achieved the above results through a rough building model, standard assumptions for operations, and power densities, using just 2D digital images of building exteriors, there is significant potential for further fine tuning assumptions with a small amount of extra investigation. In addition, initial energy modeling results that differ greatly from measured energy use can provide an important data point to prompt tangible dialogue with the facility manager, a useful outcome in and of itself.

CUSTOMER INTERVIEW INSIGHT

One interviewee stated: "Even the perfect building model cannot know that the maintenance person likes to step outside every hour in winter to smoke and leaves the door open until he comes back in."

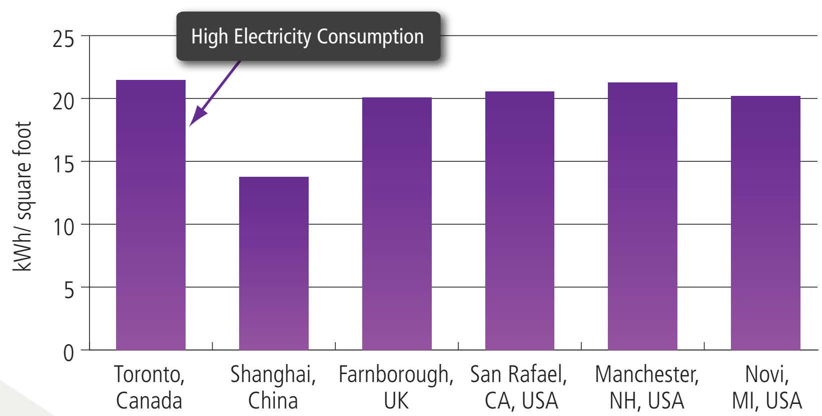
4.2.2. Analyzing the Carbon Intensity

The model also predicted the facilities' carbon footprint. The Autodesk Green Building Studio web service calculates CO_2/kWh intensity from Environmental Protection Agency (EPA) data for U.S. buildings and Carbon Monitoring for Action (CARMA) for International buildings.[20] The charts below show the energy intensity (kWh per square foot) and the CO_2 intensity (CO_2 tons per square foot) for each facility, as modeled by Green Building Studio.

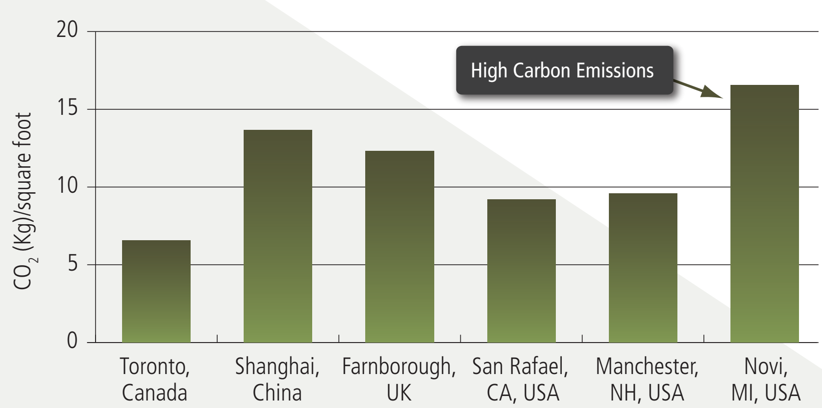
This analysis led to some interesting results. While Shanghai had the lowest energy intensity ratio, its CO_2 intensity was one of the highest of all facilities, implying it was using electricity generated from sources, such as coal, with particularly high carbon emissions. Conversely, the Toronto facility had a high electricity intensity, but the lowest CO_2 intensity, implying "cleaner" electricity sources. Finally, Novi, MI, stood out as a high CO_2/sf emitter despite having electricity intensity in line with those of most North American facilities.

While it is not surprising that different locations would have different electricity sources and emission factors, this analysis does underline the fact that if carbon reduction is our ultimate goal, CO_2/sf will often be a more useful metric than kWh/sf in prioritizing buildings for energy efficiency retrofits. In this case, Shanghai and Novi would be higher priorities for retrofits with a CO_2/sf analysis than they would have been based solely on a kWh/sf analysis.

ELECTRIC CONSUMPTION



CARBON EMISSION INTENSITY



20. U.S. Environmental Protection Agency, Egrid 2006 Data (2004 plant-level data) and Carbon Monitoring for Action at www.CARMA.org.

ESTIMATED ELECTRICITY SPEND REDUCTION POTENTIAL

Facility Name	Annual Electricity Spend (Local Currency)	Annual Electricity Spend ($US)	Building SF	$/SF	10% Reduction in Annual Spend
Toronto, Canada	198,559	$198,559	102,760	1.93	$19,856
Shanghai, China	2,712,082	$383,527	125,593	3.05	$38,353
Farnborough, UK	67,416	$107,866	33,620	3.21	$10,787
San Rafael, CA, USA	295,863	$295,863	130,987	2.26	$29,586
Manchester, NH, USA	151,080	$151,080	56,013	2.70	$15,108
Novi, MI, USA	84,217	$84,217	37,944	2.22	$8,422
Total		**$1,221,111**	**486,917**	$ Savings Potential	**$122,111**

4.2.3. Annual Electricity Spend Savings

One of our goals was to analyze the expected annual electricity spend for the facility. A user is able to enter the electricity rate ($/SF) for each facility as an input to the simulation. To determine a rough order-of-magnitude estimate for the annual cost savings available to Autodesk, we compiled the expected spend from the Green Building Studio outputs, assumed a fairly conservative 10 percent reduction in annual electricity spend,[21] and compiled the totals, as captured in the table above.

As shown in the table, there appears to be a range of annual energy spend/SF in the modeled facilities of $2.05 to $3.22. Total annual electricity spend in the six Autodesk facilities is approximately $1.3 million, making a 10-percent reduction equal to approximately $122,000 in annual cost savings.

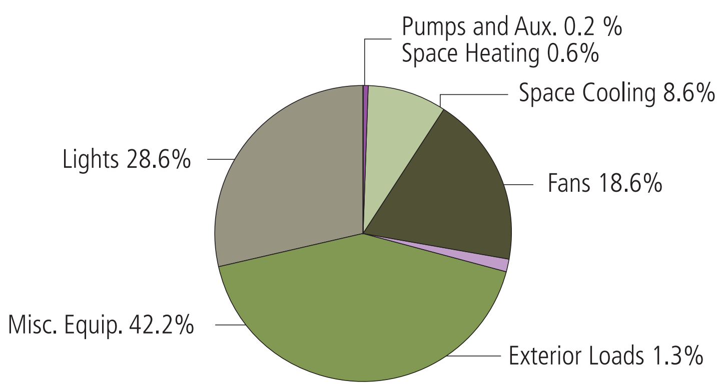
Certainly, it is difficult to measure the precise value of these savings without first knowing the cost of the energy retrofits required to achieve a 10-percent reduction in electricity use annually. With this information, we would be able to calculate an expected internal rate of return for these investments and gauge the overall economic value to Autodesk. This is an area where a detailed building audit could build upon the above findings.

4.2.4. Electric End Use

The Autodesk Green Building Studio web service also estimates where the energy spend is going. The chart below shows an example.

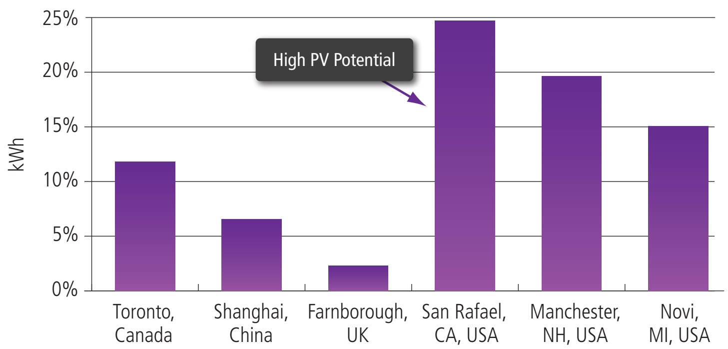
Because this study focused on Autodesk's workflow for rapid energy modeling to get to these results, we did not investigate in detail the allocation of energy spend. In addition, since all modeling exercises started with the same set of standard parameters (such as operational schedule and power densities), further refining of these

ANNUAL ELECTRICITY END USE



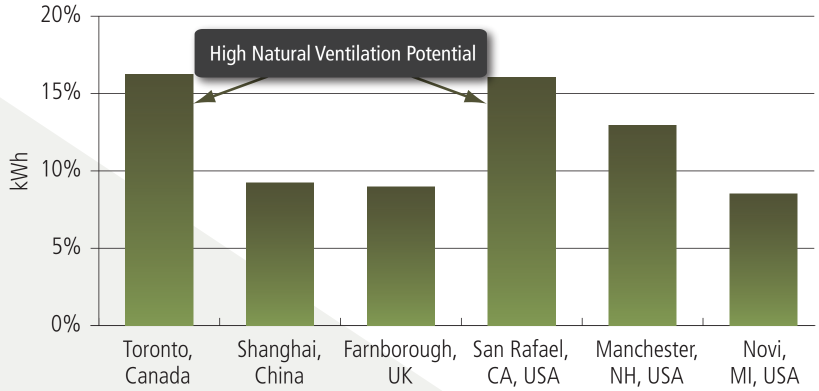
21. In ICF's extensive experience with building energy assessments, virtually all existing buildings that have not been significantly retro-commissioned have a cost-effective energy reduction potential of at least 10 percent.

PV POTENTIAL AS % OF ANNUAL ENERGY CONSUMPTION

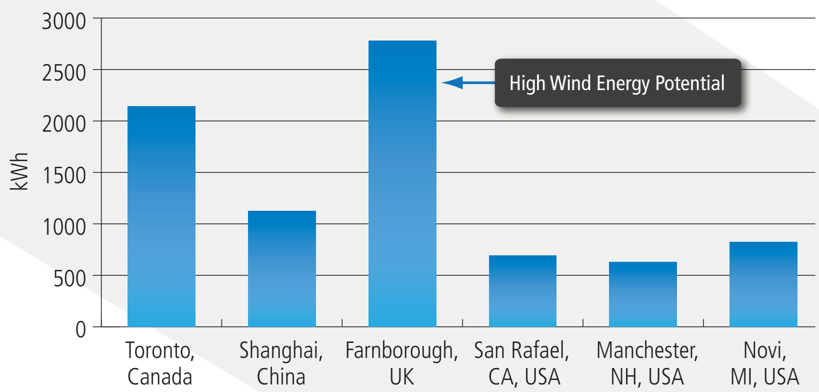


*Autodesk suspects an error in Farnborough data that needs further investigation.

NATURAL VENTILATION POTENTIAL AS % OF ANNUAL ENERGY CONSUMPTION



WIND ENERGY POTENTIAL



parameters so that they closely match the reality on the ground, is needed before conducting further analysis.

4.2.5. Photovoltaic Potential

The reports also provided an estimate for photovoltaic potential, based on the orientation, roof area, location and weather associated with each facility modeled. While ICF did not investigate these results, we believe these results could be useful as a prioritization or filtering tool.

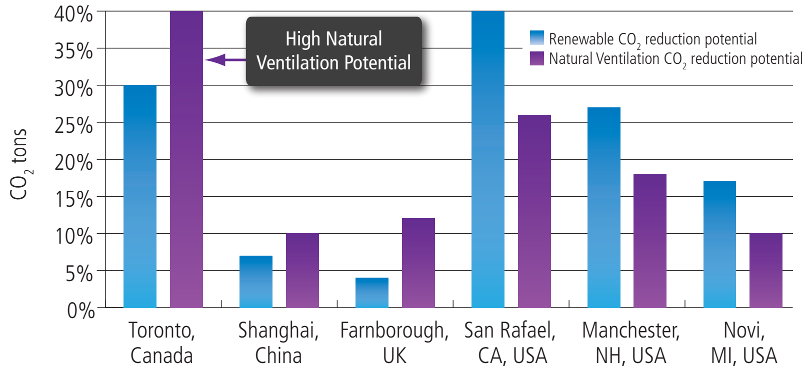
4.2.6. Wind and Natural Ventilation Potential

Similarly, if Autodesk were considering pursuing wind generation or natural ventilation at its facilities, it could use rapid energy modeling to prioritize the facilities that merited a deeper investigation into these options. ICF also did not validate these results, but used them as a prioritization tool, as shown in the charts on this page. The San Rafael headquarters would be the facility most likely to show cost savings through natural ventilation and Farnborough, UK, and Toronto, Canada, would be the facilities most likely to have significant wind energy potential.

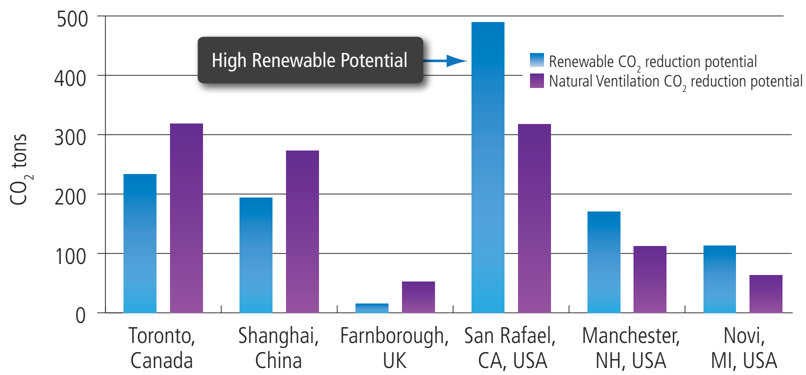
4.2.7. Carbon Neutrality Potential

Carbon neutrality potential analysis of a building (based on carbon reductions through renewable energy, natural ventilation or biofuels) could further help guide energy efficiency discussions from an environmental perspective. The charts on the following page show a cross-facility comparison of CO_2 reduction potential, both in absolute terms as well as in terms of their proportion of the facilities' respective total carbon footprint.

CO_2 REDUCTION AS % OF TOTAL CO_2 EMISSIONS



ABSOLUTE CO_2 REDUCTION POTENTIAL



These are certainly not definitive approaches to prioritizing a facility for energy efficiency or renewable energy measures. In all cases, significant additional due diligence and investigation would be required before any installation or design decision could be made. **However, results such as those highlighted in this section have the ability to help decision-makers filter through their options, narrow their choices, and ensure that when they make a choice to devote time and resources to exploring an option at a particular facility, they are doing so in an efficient and constructive manner.**

5. Key Conclusions

Adoption of rapid energy modeling techniques can significantly increase the number of existing buildings that undergo energy assessments and subsequent upgrades within a smaller budget and shorter time frame.

We see considerable interest in the building community to streamline the modeling process. We expect property managers, tenants, home buyers, design teams, public policy advocates and energy consultants to benefit from such a workflow in the following ways:

A. **Shortcut to estimating actual energy use:** Applying a set of standard parameters to all facilities,[22] we found that for three of the six Autodesk buildings, the energy intensity (kWh/square foot) predicted by the model fell within 6 percent of actual energy data, one facility was 12 percent off, and two others showed higher deviations. Given that we constructed the initial models without knowing anything about the facilities' operations, and applied the same set of modeling assumptions to facilities that were diverse in geographies, weather zones, operational schedules and power efficiencies, we were pleased by the results' proximity to actual consumption data.

B. **Stepping stone between quick benchmarking and detailed audits:** Rapid energy modeling alone is not yet sufficient in capturing unique operational details that can only be captured through discussions with on-site personnel or through in-person building audits. However, rapid energy modeling does provide a quick, sophisticated way of going beyond carbon footprinting and energy benchmarking to look at tangible energy reduction opportunities. It provides useful data points to prompt tangible dialogue with the facility manager, a useful outcome in and of itself.

   For example, the two outliers mentioned above prompted us to have conversations with facilities managers, which led to further insights by identifying:

   - Gaps in the model's assumptions that were subsequently addressed and led to improved accuracy.
   - Operational inefficiencies that were previously unknown and easily addressed through efficiency investments.

C. **Screen for high potential buildings:** Rapid energy modeling represents a prioritization screen to determine how to focus on-site building audits and renewables assessments, which can be very time and resource-intensive. Through rapid energy modeling, we were able to determine the following:

   - Autodesk's six facilities had relatively similar energy intensities, with the exception of Shanghai, which had a lower intensity. As a result, it was important to look at the buildings' carbon intensities to prioritize targets for energy reductions.
   - Autodesk's Novi facility had the highest carbon intensity of all modeled facilities, due in part to more carbon-intensive electricity sources, potentially making this facility the highest priority for energy reduction activities.
   - Autodesk's Farnborough and Toronto facilities had the highest wind energy potential.
   - Autodesk's San Rafael office had the highest natural ventilation potential.

   These findings will help Autodesk prioritize its energy and carbon reduction efforts, focusing on facilities that have the most potential in each relevant area.

D. **Communicate return on investments for priority buildings:** Rapid energy modeling can increase the ability to evaluate the potential financial and environmental values of an energy efficiency project, as well as those of specific green building measures including day-lighting, natural ventilation, and solar photovoltaic and solar thermal applications.

   - Assuming a rough electricity reduction estimate of 10 percent,[23] the reduction potential across the six modeled Autodesk facilities is equal to approximately $122,000 in annual cost savings.[24]

E. **Achieve economies of scale across a portfolio:** The rapidity of the process and its ability to point to a subset of high potential buildings allows property owners to achieve economies of scale when investing

22 For example, a 12/7 operation schedule, a lighting power density of 1.5 W/sf, equipment power density of 1.65 W/sf.

23 Ten-percent reduction is a conservative estimate based on ICF's extensive experience with building retrofit projects. We find that most buildings have a significantly higher cost-effective energy reduction potential.

24 Based on energy spend data taken from Green Building Studio model results.

in efficiency measures or renewable energy technologies.

Autodesk and ICF personnel, with no previous experience with Autodesk tools, completed the rapid energy modeling process for the six Autodesk facilities on three continents in a matter of days for each one, and in some cases, hours, without any travel to the building sites. We estimate that with two dedicated modelers with little or no training and with access to basic facility information and photographs, Autodesk could have completed rapid energy modeling of all 72 of its corporate facilities in under two months,[25] and immediately have a tool to test the value of a variety of energy reduction measures, along with a prioritized list of facilities with energy and carbon reduction potential, photovoltaic, wind, and natural ventilation potential.

F. **Stimulate creation of skilled green jobs:** The growth of rapid energy modeling could lead to an increased number of green jobs, as entry-level professionals could quickly learn the skills necessary to seamlessly create energy models. Implementing a rapid energy modeling process for the 4.9 million commercial buildings in the United States alone could employ 20,000 new entry-level energy modelers in a year.[26]

25. Assumed 2 modelers working 21 days per month, averaging eight hours per model.

26. Assuming modelers working 21 days per month, 12 months per year, averaging eight hours per model.

6. Future Research Steps

In this first proof-of-concept phase, we kept the sample size for the study intentionally small in order to be able to move quickly to publish our initial results. We are fully aware of the need to expand on these efforts. We hope that you, the reader, and others in the architecture, engineering and construction industry will work with us to:

- **Expand the sample size and diversity of existing buildings modeled:** Over time, we hope to continue to track the performance of energy modeling results versus actual energy data for buildings and to test the validity of the reduction opportunities.
- **Test new types of data inputs such as satellite images:** As we attempt to make rapid energy modeling even more rapid and seamless, these techniques could eliminate the need over time to physically take digital photos of any building.
- **Explore design alternatives:** Make use of this and other features of Green Building Studio in order to test the value of modeling different energy reduction measures and design techniques.
- **Offer feedback** to improve Autodesk's tool guidance and to improve upon the software's functionality itself. Only through this communication will the tools improve to achieve the pressing needs of the building and energy modeling community.
- **Share the outputs** with property owners, insurers, law firms, and other members of the building industry to identify where the tool adds value and where it may need improvement.

To learn more about Autodesk's sustainability initiatives and read examples of how customers have used Autodesk software for sustainable design, visit www.autodesk.com/green.

Appendix A: Autodesk Green Building Studio

The Autodesk Green Building Studio Web Service is designed to allow users to perform whole building energy, water, and carbon emission analyses of new or existing buildings over the Internet from within their own design environment. This streamlines the energy analysis process and gives users immediate feedback on their design alternatives, making green design and green policy creation more efficient and cost effective.

Based on the building's size, type, and location (which drives energy and water usage costs, as well as the carbon emissions from electricity), this web-based service determines the default material, construction, system and lighting and equipment power densities by using regional building standards and codes to make appropriate assumptions. Using drop-down menus or templates, architects and engineers can quickly change any of these assumptions to define aspects that are specific to their design, for example, a different building orientation, a lower U-value window glazing, internal loads, or a 4-pipe fan coil HVAC system.

Autodesk Green Building Studio provides a complete year of weather data for design and building energy analysis. With 55,000+ locations, a virtual weather station is no farther than 14 km (8.8 mi) from any given project within the contiguous 48 states of the United States. Outside of the United States, the weather data has a higher resolution of 12 km in most significantly populated areas of every continent. This means that if you are within boundaries of domains such as Europe or Asia, you are never more than 6 km (3.7 mi) from a virtual weather station.

Green Building Studio uses emission data for electric power plants across the United States and includes a broad range of variables needed to assess the carbon-neutral potential for a given building form and set of design criteria. The current version of the software uses carbon emission factors (CO_2 tons/kWh) data from Carbon Monitoring for Action (www.carma.org) for international buildings and from the U.S. Environmental Protection Agency (EPA) EGRID 2006 (2004 plant level date) for U.S. buildings to calculate the carbon emissions.

The web service simulates a building's whole-building energy consumption, water use and carbon emissions, and the user is able to view the output in a web browser, including the estimated energy and cost summaries and the building's carbon-neutral potential. In addition, the web service also calculates an ENERGY STAR score, estimates photovoltaic and wind energy potential, calculates points towards LEED day-lighting credit, and estimates natural ventilation potential.

Finally, Green Building Studio includes a design alternatives functionality, which allows the users to test different model parameters in order to determine potential energy and carbon savings. As part of this study, we did not extensively test design alternatives and instead left that exercise as a potential next step.

On the following pages, we provide a sample of the Energy/Carbon tab of a Green Building Studio report summarizing the modeling outputs in these areas.

SAMPLE REPORT

General Information

Project Title: SR 12/7

Template Title: SR 12/7 (Last updated on: 10/6/2009 6:29:00 PM)

Run Title: SR v6 ground floor exterior epd 1.65

Building Type: Office

Floor Area: 130,987 sq ft

Location Information

Building: San Rafael, CA 94903

Electric Cost: $0.13 / kWh

Fuel Cost: $1.17 / Therm

Weather: GBS_04R20_044114

Estimated Energy & Cost Summary

Annual Energy Cost	$353,224
Lifecycle* Cost	$4,810,906
Annual CO_2 Emissions	
Electric†	1,196.4 tons
On-site Fuel	31.9 tons
Large SUV Equivalent	111.7 Large SUV's
Annual Energy	
Electric	2,667,578 kWh
Fuel	5,494 Therms
Annual Peak Electric Demand	764.0 kW
Lifecycle* Energy	
Electric	80,027,340 kWh
Fuel	164,809 Therms

* 30-year life and 6.1 percent discount rate for costs.

† Does not include electric transmission losses or the renewable and natural ventilation potential.

Carbon-Neutral Potential[1] (CO_2 Emissions)

Base Run:	1,228.3 tons
On-site Renewable Potential:	-191.3 tons
Natural Ventilation Potential:	-310.0 tons
On-site Fuel Offset/Biofuel Use:	-31.9 tons
Net CO_2 Emissions:	695.1 tons
Large SUV Equivalent:	63.2 Large SUVs

1. Carbon neutrality is defined here as eliminating or offsetting fossil-based electricity and fuel use. For example, if the electricity grid is 60 percent fossil fuel and 40 percent hydroelectric, reducing grid electricity use by 60 percent and eliminating/offsetting on-site fuel use will make the project carbon neutral. Use any combination of efficiency, natural ventilation, renewable energy, carbon credits and biofuels to reach this goal. Renewable potential is the sum of photovoltaic and wind potential shown below.

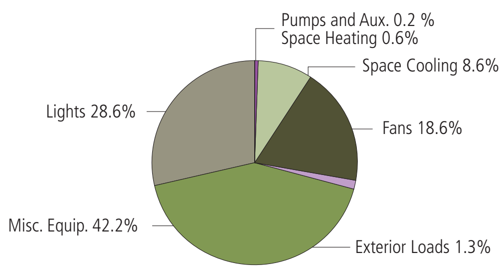
Electric Power Plant Sources[2]

Fossil:	61%
Nuclear:	14%
Hydroelectric:	15%
Renewable:	10%
Other:	0%

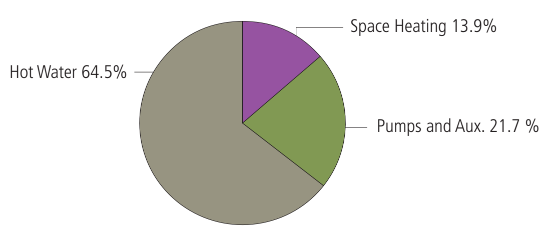
2. Based on U.S. Environmental Protection Agency EGRID 2006 Data (2004 plant-level data).

Energy End-Use Charts *Click on chart for more or less detail.*

Annual Electric End Use



Annual Fuel End Use



Water Usage and Cost[3]

Total:	2,529,824 Gal/yr	$15,291 / yr
Indoor:	2,503,724 Gal/yr	$15,223 / yr
Outdoor:	26,100 Gal/yr	$68 / yr

3. Based on American Water Works Association (AWWA) Research Foundation 2000 Residential / Commercial and Institutional End Uses of Water.

Photovoltaic Potential[4]

Annual Energy Savings:	259,158 kWh
Total Installed Panel Cost:	$2,354,502 / yr
Nominal Rated Power:	294 kW
Total Panel Area:	22,891 ft^2
Maximum Payback Period:	44 yrs @ $0.13 / kWh

4. Results based on all exterior surfaces being analyzed. Escalation rate of 2 percent applied to electric rate. Payback calculation does not include federal or state incentives, loan information, or tax breaks.

LEED Daylight[5]

Area w/Glazing Factor > 2%: 48.8% - No LEED Credit

5. Glazing factor is the ratio of exterior illumination to interior illumination and is calculated using floor area, window geometry (area and height) and visible transmittance of the glass. The project qualifies if glazing factor is > 2 percent in a minimum of 75 percent of all regularly occupied areas.

Building Summary

Quick Stats

If values are red or blue, they appear to be higher or lower than typical ranges, respectively.

Number of People	695 people
Average Lighting Power Density	1.50 W/ft²
Average Equipment Power Density	1.65 W/ft²
Specific Fan Flow	0.9 cfm/ft²
Specific Fan Power	0.676 W/cfm
Specific Cooling	449 ft²/ton
Specific Heating	17 ft²/kBtu
Total Fan Flow	121,133 cfm
Total Cooling Capacity	291 tons
Total Heating Capacity	7,817 kBtuh

Wind Energy Potential[6]

Annual Electric Generation: 693 kWh

6. A single 15-ft diameter turbine, with cut-in and cut-out winds of 6 mph and 45 mph respectively, and located at the coordinates of the weather data.

Natural Ventilation Potential[7]

Total Hours Mech. Cooling Required:	3,211 Hours
Possible Natural Ventilation Hours:	2,431 Hours
Possible Annual Electric Energy Savings:	420,996 kWh
Possible Annual Electric Cost Savings:	$54,730
Net Hours Mech. Cooling Required:	780 Hours

7. Assumes natural ventilation only during comfort zone periods and air changes per hour are less than 20 ACH. Building form & opening design must be able to allow stack effect or cross ventilation.

Appendix B: Autodesk ImageModeler Workflow

Autodesk ImageModeler image-based modeling and photogrammetry software generates 3D models from 2D digital images. The goal of ImageModeler is to enable users to capture real-world images of buildings and easily create photorealistic 3D models. Editing, modeling, and texturing tools allow further refining of rendered objects. The 3D objects can then be exported into different formats, such as for Autodesk Revit in order to conduct energy analysis.

A common ImageModeler project workflow is described below:

- Take photographs of the building.
- Calibrate photographs.
- Set the coordinate system and scale.
- Model over the images and take measurements.
- Texture.
- Export.

Texturing was not used in our study.

Taking Shots

The first stage consists of taking good quality shots. See **Appendix C** for more information and tips on taking pictures that lend themselves very well for calibration and modeling. In summary, the photographs have to be taken from different points of view, cover the subject that you want to reconstruct and have as many common points (locators) as possible between them. The following photographs illustrate images with locators and markers.



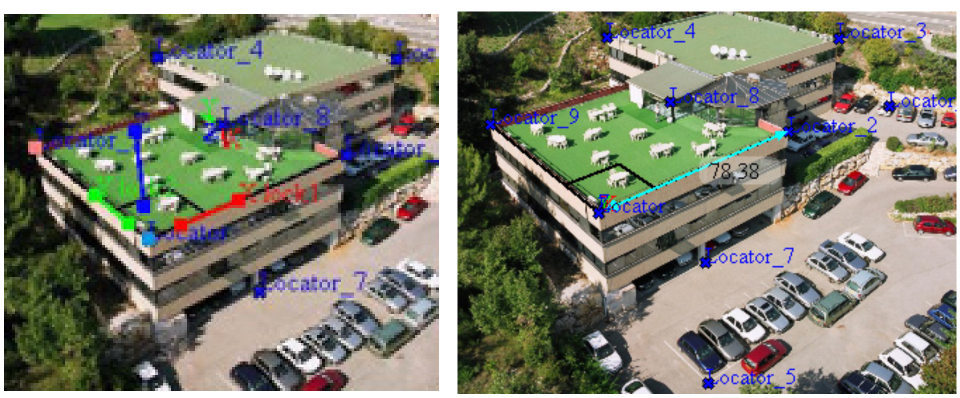
Calibration

The calibration tool of ImageModeler is the heart of the software and the most crucial part of the process. It estimates the camera parameters for all the shots that were taken (such as orientation and focal length). By identifying 2D points in the images ("markers") that correspond to the same point in space ("locators"), the user can "provide ImageModeler with sufficient information to derive the 3D position, orientation, focal length, and distortion of the camera(s) that were used to capture the photographs.

This computation is precise and the error is expressed in pixels (generally ±1 pixel). The error in metric units can be derived by calculating the average distance in the real scene as represented by a pixel in the 2D images.

Scale and User Coordinate System

Defining the coordinate system in ImageModeler consists of selecting the origin and the main X, Y and Z axes of the scene. All further points and objects will be expressed in this newly defined User coordinate system. The following photographs show locators and reference measurements.

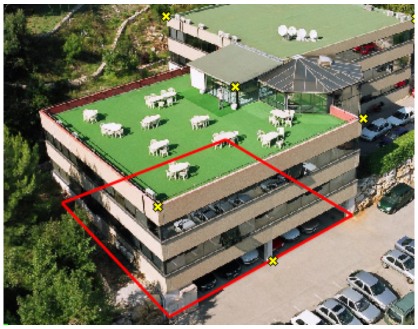


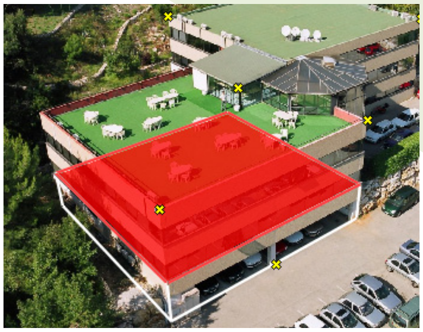
The scale will be computed from a known distance in the scene for example, width of the building or height of an archway. We call these reference measurements. Getting accurate measurements of an object that is large, long or wide enough is important.

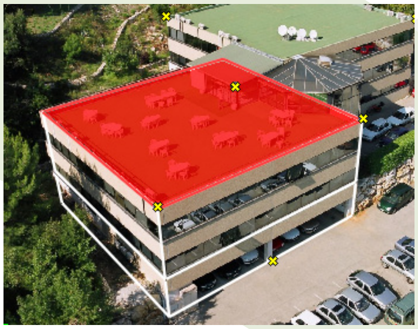
Modeling and Measuring

Once the pictures are calibrated and a coordinate system is set, one can start creating a 3D wireframe model over the images. A user can also measure any distance or angle in the scene using the measure functionality.

ImageModeler offers creation tools (e.g., create points, faces, cubes, spheres, cylinders) and edition tools (e.g., move, split/subdivide, push pull extrusion) to help with modeling 3D objects directly over existing pictures. For example, the elevation of a building can be easily measured on the image and a cubical model can be layered on top of the image, as illustrated below.







Texturing

In this optional step, Autodesk ImageModeler automatically maps the original photographic images onto the mode's surface as texture maps, resulting in a highly realistic model. The different points of view are used and blended together to get the best texture possible for those perspectives, as shown below.

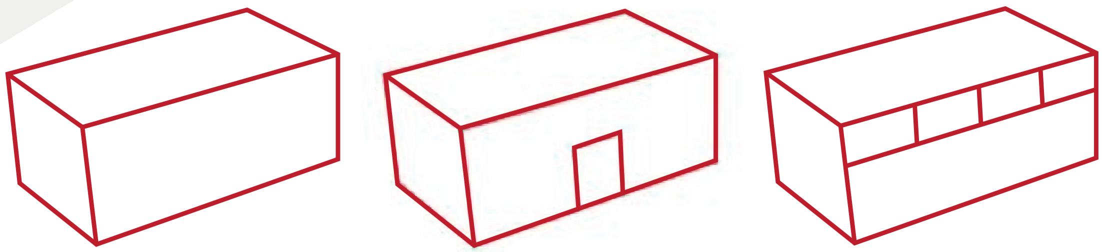
Export

The points, measurements and meshes can then be exported in **DWG** format. The cameras, points, meshes and textures can also be exported in **FBX** format. Finally, meshes and textures can be exported in **OBJ** format.

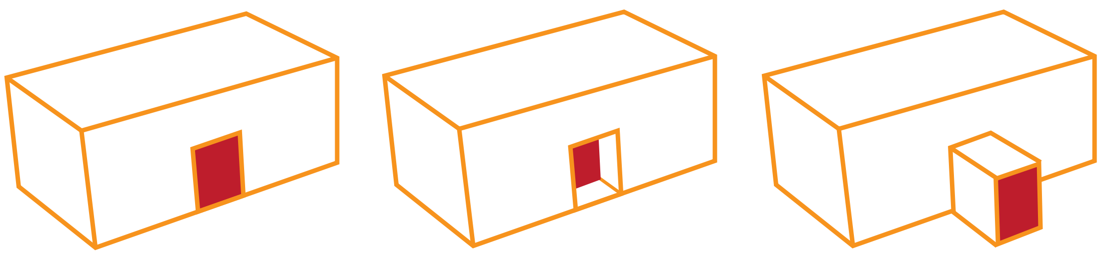
About Split and Extrusion Functions

During our study, we took advantage of these functions to speed up modeling in Autodesk ImageModeler.

The split tool is a modeling feature in ImageModeler that consists of subdividing a mesh (for example, a box) locally by adding new user-defined edges. This tool allows users to create new details such as a door or window on an existing wall.



The extrusion tool is a modeling feature in ImageModeler that consists of adding depth to an existing mesh. The user selects a face and pulls or pushes it to create an indentation (middle picture) or an extension (right picture).



The split and extrusion tools are often used to create more complex objects, like building extensions starting from simple primitives. Illustrated below is an example of how Autodesk used these functions while modeling one of its facilities.

About Calibration Constraints

Buildings that are well constructed have a lot of exterior features that facilitate calibration. Constraints, such as “right angle” corner or “same height as” can be created in Autodesk ImageModeler software to further help the process.

Illustrated below is an example of how Autodesk used such calibration constraints while modeling one of its facilities. Three constraints of the type “right angle” were created on the building corner (see locator 3).

All other locators (in red) on the top of the building were set as sharing the same height (Z coordinate).

It is important to note that constraints should be used when the user is sure of their validity. It is not necessary to have too many constraints in a scene. Few constraints that are valid and well defined are preferred to many that are guessed.

Appendix C: The art of taking *good* pictures

The goal of Autodesk ImageModeler software is to enable its users to capture real-world images of buildings and easily create photo-realistic 3D models. It all starts with taking good pictures that lend themselves well to calibration and modeling. Below are some tips that enable quick and accurate 3D modeling from 2D digital images.

Capturing a Scene Volume

Shooting a scene at an angle captures the 3D volume much more precisely than shooting a face-on view. Shooting at a slight angle just above or below the plane parallel to the horizon gives details of zones normally hidden by a flat photograph. The first image below shows a bad angle of view. The picture does not show enough depth information (all the points we can extract are on the same planar façade). The second image is preferable since it shows volume information.

An image like the one on the left can be calibrated if sufficient images with depth (like the one on the right) are present.

Avoid Frequent and Large Zoom Changes

Try to avoid large zoom changes between pictures. For example, in the first image below, the details are lost, and in the second image, there is too much detail.

If possible, try to maintain a constant zoom and focal length when shooting your subject. If geographical constraints (such as foliage, water bodies or highways) prevent one from keeping a constant zoom, try to remember groups of shots that were taken with the same focal length. ImageModeler can simultaneously calibrate groups of pictures with a common focal length.

Shoot Scenes with Lots of Detail and Texture

The visual texture in the photos is what ties them together. A blank wall won’t calibrate. One with lots of art or posters will work well.

Rule of 3

Each part of the scene you’re shooting should appear in at least three or more separate photos taken from different locations and/or angles. Having some points (e.g., a chimney, flag on a roof, antenna, a corner of a tower) present in all or in a maximum of pictures helps link them together.

Shots taken from an elevation

For the purpose of linking pictures, taking shots from a higher elevation could prove very useful. Such elevations generally provide good depth and coverage of a building.

However, shots taken from too far above (like satellite ortho photography) may not be good candidates.

Going Around Corners

Avoid large and frequent changes in viewing angles. The images below show the same building extension, but there are too few common points visible to get a good calibration.


Adding four to six intermediate shots taken 5 to 10 m (5.5 to 11 yd) apart, between the pictures above would allow better calibration,[26] as shown in the next four photos.






26. Pictures from Microsoft Photosynth guidelines: http://photosynth.net/howtosynth.aspx.

Appendix D: Modeling Autodesk facilities

Autodesk and ICF applied Autodesk's solutions for rapid energy modeling on a geographically diverse set of six facilities (Toronto, Canada; San Rafael, CA, Novi, MI, Manchester, NH, U.S.A.; Farnborough, UK; and Shanghai, China) that could be modeled in the project's timeframe. The selected facilities included historic and contemporary buildings, representing a variety of sizes and structures in four countries spanning three continents.

Autodesk applied its rapid energy modeling workflow on five facilities, and ICF corroborated the workflow on one of the facilities. The modeling results were compared against actual consumption data. We have summarized our modeling experiences for each building.

Toronto

This historic facility, situated in downtown Toronto, Canada, consists of four historic warehouses (three of them designated as heritage buildings), built between the 1930s and 1960s. Digital pictures for this facility already existed because of another BIM digital modeling project.[27]

The team faced a few challenges in calibrating these pictures: (a) Lack of enough reference points in the foreground (that were not on the building itself) that were common to the same points on two or three other pictures, (b) very close zoomed in shots of the rear façade of the buildings due to the narrow available space, and (c) lack of locators on the east side that completely adjoined another building. The pictures below show the narrow alleyway that limited the amount of depth possible in 2D images.

Picture taken from too close due to a narrow alley

27. Undertaken by Autodesk in partnership with Carleton University, Ottawa, and Faro Technologies, www.digital210king.org.

The team overcame these problems by using additional pictures from the library that helped stitch together the above images and provided additional calibration points. The modeling was achieved by creating simple box primitives first, which were then edited (split, subdivided, moved) to get a more complex primitive that fit the building. These Autodesk ImageModeler functions allowed us to place a rectangular cuboid on the west-most building and extrude the other buildings from this base model.

Completed 3D wireframe using split and extrude functions on the westmost (leftmost) cuboid

The last picture on the right shows a very rough Autodesk Revit model with just a few basic design elements, such as walls, floors, roof and windows, that predicted energy consumption that was very close to the actual consumption.

Shanghai

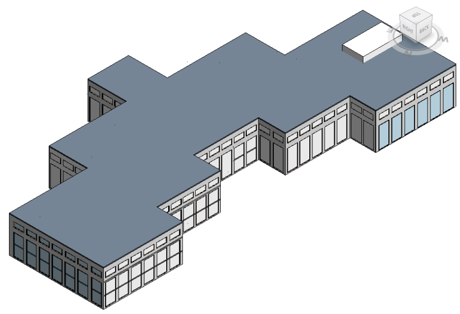
Unlike the historic buildings in Toronto, the Shanghai facility was a modern high-rise building with a complex multi-faceted contemporary structure. Autodesk leases the top 12 floors, of which only nine were occupied.

While creating a 3D wireframe model using Autodesk ImageModeler software did not pose any major challenges, there were some idiosyncrasies related to irregular structure that made modeling correct floor plans in Autodesk Revit for the 12 Autodesk leased floors from exterior images alone tricky. In addition, all pictures of the top floors were taken from a ground perspective. A typical picture distortion introduces higher errors in calibration and measurements at the edges of the picture than at the center. The picture on the right shows the rough Revit model that was used for energy analysis.

San Rafael

The San Rafael, CA, facility is the worldwide headquarters of Autodesk. The challenges in modeling this facility stemmed from its complicated, multi-faceted, architecture along with some geographic constraints, such as a creek and heavy foliage on one side. Calibrating the front and the rear of the building from a diverse set of images was difficult, as was building a panoramic perspective from a single view point.

We were able to overcome this problem by using pictures (see below) taken from an elevation and from a greater distance that showed portions of the roof.

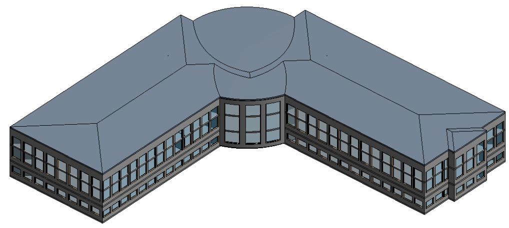


The final picture shows the irregular structure and a rough Revit model that consisted of 3 floors, a roof, walls and windows.

Novi

The Novi, MI, building is a 3-floor class-A multi-tenant office building by a lake. The building consists of two cuboid wings with a central cylindrical portion containing the atrium, as shown in the following two photos.

The challenge in modeling this facility was in reconciling opposite ends of the large two-winged structure for calibration. We overcame this problem by first calibrating one wing and then manually extrapolating the other wing (that was partially hidden) based on the geometry and dimensions of the already calibrated wing, as illustrated on the right below.

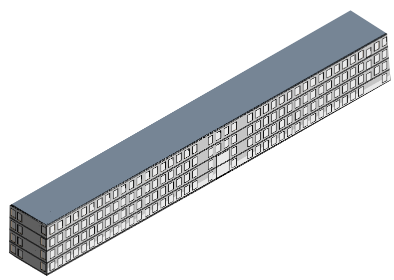


Other modeling intricacies included appropriately modeling the cylindrical portion and the unconditioned space around it.

Manchester

The Manchester, NH, facility was an interesting challenge since it consisted of a very long 122-m (400-ft) tannery building, shown below, that could not be accommodated into a single photo. In addition, the site had geographical constraints such as heavy foliage in the front and at the rear, a stream at the rear of the building, and a nearby highway that made taking good pictures very difficult. We could not calibrate the pictures using the traditional method described earlier in the project.

Since the building geometry was a regular rectangular cuboid, we adopted a new method in which we calibrated only one face of the building and extrapolated the cuboid based on the measurements we obtained from the facilities manager. Once we had a cube in place, the faces could be adjusted so that the ratio of height to length to breadth matched the real dimensions.

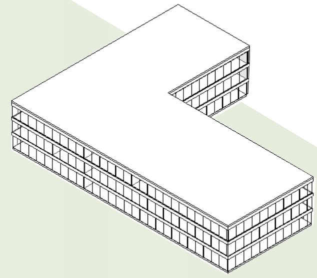


The photo on the left shows the single face that was used in the calibration and drawing that resulted in the rectangular cuboid image on the right.

The cuboid was then scaled in Autodesk Revit software and design elements added as usual.

Farnborough, UK

The facility at Farnborough, UK, is an “L“ shaped 3-story building, with glass covering most of the building façade.



Our initial attempt to develop a calibrated image set from pictures taken around the building, shown above, proved to be difficult due to a lack of an aerial perspective that could tie common points on 3 sides of the building. As a result, we took a new approach that we had not used on any of the other buildings. We used Microsoft’s publicly available Virtual Earth™ service to obtain aerial view pictures of the facility. These pictures provided an angle and depth perspective in all four cardinal directions and helped reconcile points common to other pictures, which otherwise could not be stitched together. With these aerial pictures, it ended up being surprisingly quick to calibrate the pictures. This could be an alternative way to complete calibration for large buildings, complex multi-faceted structures or for buildings obstructed by foliage or geographical.

The glass façade along with roof, floor, ceiling and occupied/unoccupied spaces were defined during Revit modeling, shown in the image on the right.

Appendix E: Customer Interview Acknowledgements

We'd like to thank the following organizations for participating in the interviews we conducted for this report.

Rocky Mountain Institute

The Rocky Mountain Institute (www.rmi.org) is a non-profit organization in the United States dedicated to research, publication, consulting, and lecturing in the general field of sustainability, with a special focus on profitable innovations for energy and resource efficiency. RMI was established in 1982 and has grown into a broad-based institution with more than 60 staff and an annual budget of some $8 million. RMI's work is independent and non-adversarial, with a strong emphasis on market-based solutions. The work of RMI has benefited more than 80 Fortune 500 companies in a diverse range of sectors. RMI is headquartered in Snowmass, CO, and also maintains offices in Boulder.

BNIM Architects

BNIM (www.bnim.com) is an architecture and design firm founded in 1970 in Kansas City, MO. With offices in Kansas City, Houston, TX, Des Moines, IA, and Los Angeles and San Diego, CA, the firm has nearly 100 design professionals and support staff. BNIM is known as a national leader in sustainable design, practice and technology through its work on buildings, such as the Lewis and Clark State Office Building in Jefferson City, MO (LEED Platinum), the School of Nursing and Student Community Center at The University of Texas Health Science Center at Houston (LEED Gold), and the Omega Center for Sustainable Living in Rhinebeck, NY (designed to achieve LEED Platinum; under construction). The Omega Center for Sustainable Living received recognition at the 2007 GreenBuild Convention as a winner of the Living Building Challenge from the U.S. Green Building Council (USGBC) and the Cascadia Green Building Council.

Glumac

Glumac (www.glumac.com) provides consulting engineering for four market segments, mechanical, electrical and plumbing (MEP) consulting engineering services, sustainable design, information technology and commissioning services. Glumac deploys LEED accredited professionals on every project and currently employees 78 LEED accredited professionals. All of the Glumac principals and associate principals are LEED® Accredited as well. Glumac has offices in Seattle, WA; Portland, OR; San Francisco, Irvine, Sacramento, Los Angeles and Silicon Valley, CA, and Las Vegas, NV.

Atelier Ten

Atelier Ten (www.atelierten.com) is an environmental design consulting engineering firm that has been working with the natural physical laws to produce buildings that consume less energy, and so function more economically. The firm has been committed to low energy principles since setting up in 1990, and the firm's portfolio contains numerous award-winning buildings that reflect its success in putting these principles into action. Atelier Ten has bases in the UK and the United States, and undertakes projects around the world, ranging in scale from primary schools to national art museums, and from individual buildings to entire neighborhoods.

Clayco

Clayco (www.clayco.com) is one of the nation's largest, privately owned real estate, architecture and engineering, design/build and construction firms. Clayco works, through key business groups and subsidiaries, to prove that by "doing what we say we will do" it can create partnerships with its clients, suppliers, subcontractors and the community, allowing it to deliver the lowest cost, highest quality solutions. The company operates out of St. Louis, MO, as its headquarters and has full service offices in Chicago and Detroit and provides turnkey services nationwide.

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