Revit2DALEC: A BIM-based building energy performance simulation tool used during the early design stage for design driven optimization

Josef Miller¹, Rainer Pfluger¹, Martin Hauer¹,²
¹University of Innsbruck, Unit of Energy Efficient Buildings, Innsbruck, Austria
²Bartenbach GmbH, Innsbruck, Austria

Abstract
The impact of early design decisions is decisive to achieve better building energy performance. By simulating the energy performance from the first sketch, simple adjustments such as shape, orientation, and window-to-wall ratio can be optimized, having a major impact on the building’s energy consumption. Research and industry are already well advanced in structural and cost analysis, but in energy analysis, they still face challenges to fully adapt BIM2BEM. With Revit2DALEC, a BIM-based approach has been developed to improve the BIM2BEM workflow and motivate an early design energy performance optimization. In this paper, the Revit2DALEC tool is described by means of a case study. The benefits and challenges of this early design BIM2BEM tool workflow will be validated.

Highlights
- Throughout IFC based BIM2BEM tool workflow
- Inside Revit application for fast model setup
- Annual simulation in a few seconds
- Using standardized parameters from the Austrian BIM property server (ASI)

Introduction
Buildings are responsible for over 40% of the global CO₂ emissions, of which more than two third emitted during the operation time (Senel Solmaz, Halicioglu, and Gunhan 2018). Although Building Information Modelling (BIM) and the benefits of the MacLeamy curve, are widely known nowadays, the overall acceptance and adaptation of BIM is still low (Charef et al. 2019). Besides that, BIM2Building Energy Modelling (BEM) is even less adapted. As shown by the MacLeamy curve, the cost-influence ratio shifts as the project progresses, costs increase and influence decreases. At some point of the project, design changes are no longer possible anymore. Energy and comfort problems such as overheating, high heating or cooling loads and insufficient daylighting must then be compensated by technical equipment. This leads to rising operating costs that could have been avoided by optimizing the design at an early stage. By optimizing the shape, location, window-wall-ratio and orientation from the very first draw, where design changes can be made easily and quickly, building energy demand can be already optimized (Oduyemi and Okoroh 2016). The software industry offers several applications, capable of performing such early-stage calculations. Sefaira (SketchUp 2023) for example, is a Revit API-based plugin performing fast and simplified energy and daylight simulations. But using an API integrated approach comes with the dependency of using a specific software. Also, since it is not open source, the correctness of the algorithm and the results cannot be clarified. Furthermore, since it is not manufacture-independent, the long-term usability has to be questioned. Also, it is not possible to compare result with different simulation tools, since there is no similar input/output structure. And lastly, even the simulation results are fast, there are only for a specific time setting, which do not represent a full year based on an hourly simulation. BEM tools like IDA ICE, OpenStudio or Design Builder are going another way. As a central approach, the tools enable the import of the 3D model, exported form a BIM authoring tool. Even these tools are capable of high-quality simulations, they come with several restrictions. None of these tools support import of element and material properties, only geometry import is supported (Porsani et al. 2021). Some of them are offering libraries, which then can be mapped to elements and materials, but there is no direct import. Although the geometry can be imported, there are still a number of errors in the geometry import. Both of these challenges are leading to a state-of-the-art process, where every new model is redesigned within the BEM tools (Porsani et al. 2021). This process is time-intensive and also requires a high qualification to perform the process. While architects are mostly lacking in simulation expertise for such workflows, early design stages are often do not have all necessary information for such detailed simulations. The above described struggles and software landscape are part of a state-of-the-art process in the AECO (Architecture, Engineering, Construction, Operation) industry, where design-driven optimization is not widely applied, especially during the early design phase (Khoeder and Nessim 2018). Simulations are mostly performed during the last design phase, the detailed design, probably when the first construction phase already begun.

With Revit2DALEC a central IFC-based approach was chosen. DALEC (Day- and Artificial Light Energy Calculation, www.dalec.org) runs an annual full year simulation within a seconds per simulated space (Werner et al. 2017). This allows for repetitive simulation within the design process for comparison of different variants and optimization. By using a default setting database, user knowledge and specification of the model needed in a first stage are reduced to a minimum. All necessary
information’s for the DALEC simulation kernel is imported from the IFC, geometrical as well as alphanumerical. Within this paper, a short tool overview is given and the functionality and usability are demonstrated within an optimization show case.

Revit2DALEC tool overview

DALEC is a web-based tool and was developed by a research cooperation of University of Innsbruck, Zumtobel GmbH and Bartenbach GmbH. Based on pre-calculated values, the tool is capable of simulating the annual energy demand considering day- and artificial lighting within seconds. The room dimensions have to be squared and can vary in width (2-10 m), depth (4-10 m) and height (2.5-4 m). For the façade shading/daylighting system, 9 options can be selected. The room can only have one façade which is divided into three horizontal parts (FA1: 0.0–1 m; FA2: 1–2m; FA3: 2 m – room height). Three control strategies per façade area can be set:

- Basic (unshaded)
- Glare protection
- Sun- and glare protection

Reaching such a short simulation time comes with some limitations as written above. By defining specific cases in terms of geometry dimensions and shape, pre-calculations for daylight- contributions could be performed. Each room width, depth and height combination has been pre-calculated in steps of 0.5 m, so that only the daylight contribution provided by the climate file of the chosen location has to be multiplied with the existing matrices. This method is based on the three-phase method, which divides the travelling light into three parts (Ward, Greg 1998). Light coming from the sun/sky striking the exterior façade (i), light travelling through the façade exterior to interior (BSDF) (ii), and light travelling from the interior façade through the room striking a measuring point (iii). Matrices from step (i) and (iii) are pre-calculated and then only need to be multiplied with the matrix describing the sky contributions by each individual patch. Room lengths, that differs from pre-calculated room dimensions, are then iterated with weight-factors. With Revit2DALEC, the DALEC tool has now been integrated within Revit and further developments have been done to support a complete building simulation. With a multizone model, a full building can now be simulated. The heating/cooling demand of each room is simulated individually, the demands of all rooms are summed up and divided by the total treated floor area (TFA) of the building to calculate the overall specific heat demand. Also, multiple façades are supported now and besides windows, curtain walls are also supported now. Furthermore, transparent elements can also be connected to a shading mask (azimuth 1-degree steps, altitude 1-degree steps) (Diagram 1).

Diagram 1 Long and short distance combined mask

A 180° azimuth range with 90° altitude is caused by the transparent surface itself, since it’s the backside. In addition, an exterior surface area algorithm has been developed. A combination of the IFC 4 and IFC 2x3 had to be used to implement this algorithm. Since the exported space boundaries by Revit are not complete and also faulty, the Space Boundary Tool (SBT) has been used to create correct space boundaries, but the SBT only supports IFC 2x3 (Rose and Bazjanac 2015). Because the SBT does not support IfcCurtainWall and also all element properties like window frame depth and sill height are erased during the algorithm, both, the IFC 4 from Revit export and the IFC 2x3 from the SBT tool have been used. By the combination of all information from both IFC formats the exterior surfaces can be detected:

- i. Exterior wall
- ii. Roof
- iii. Slab to air
- iv. Slab to ground
- v. Facade

By an automated exterior surface detection not only the accuracy of simulation is increased, but also the time expenditure for setting simulation inputs are decreased. To also reduce the necessary user input for simulation settings, like window thermal transmittance value, primary energy factor, occupation time, minimum illuminance value and so on (76 parameters for DALEC), Revit2DALEC contains a user interface to ease and reduce the user effort to a minimum.
For example, by only setting the room use and the reflectance class of the surfaces, 27 parameters are set automatically. But the user still has the possibility to set and change each of these parameters individually. In total, 13 drop down menus form the categories project, room, window, curtain wall, artificial light and shading system have to be set to define the model total settings, which then are connected to default values on an Excel database. The default values of this database can be changes or extended.

The Revit2DALEC tool workflow exists off several steps:

1. Parameter Mapping
2. Model Settings
3. Export IFC 2
4. Run SBT
5. Export IFC 3
6. Simulation
7. Result Viewer

Step 2, 3, 4 and 5 are already explained. Step 1 is an automated one-way mapping tool, which creates all necessary DALEC specific parameters within Revit and connects them to the Revit building and spatial elements. It is also possible to manually map already existing parameters within Revit to the DALEC parameters to avoid duplicate parameters.

Step 1-3 and 5 are Revit tools, connected to the Revit specific API. Step 4 is an execution of the SBT. Although executed from Revit, Step 6 is a standalone tool. The Revit2DALEC simulation kernel is programmed with C# and Matlab. To handle all IFC specific operations the xBIM toolkit SDK is used (Rose and Bazjanac 2015). First of all, the IFC is converted into a Matlab specific structure with the IFC2MatlabStruct kernel. The DALEC simulation kernel is programmed with Matlab. This kernel is built as a .NET assembly and can be run within C#, with the created struct from the IFC2MatlabStruct kernel. After the simulation, results are exported into a specific energy results IFC which only contains simulations results as building elements and spatial elements properties. This IFC can then be opened with the Result Viewer (step 7) to see results. A workflow overview is given within Figure 4.

The functionality and flexibility of the DALEC tool is clearly limited by the requirements of a shoebox model with minimum and maximum lengths. The Revit2DALEC tool is a first development step to make the tool more accessible for the early design phase, because now also whole buildings can be simulated and the input effort is reduced to a minimum and therefore the required know-how is low. Although the limitation of the spaces to shoe boxes is a limitation of the design flexibility, the majority of the designs from the area of commercial buildings can still be covered. These limitations are necessary to ensure an extremely fast calculation time -1 second per room-. Other tools such as Sefaira, IDA ICE, IES VE or Design Builder can simulate specific times (e.g. July 21st 12am) also fast, but need several minutes to hours for a full year calculation based in hourly steps. In addition, while the aforementioned tools take solar inputs into account for heating and cooling load calculations, not all tools support coupling effects with artificial lighting and the shading system. In addition, for this type of calculation, complicated settings must be made within the simulation tools, which require a high level of expertise and necessary setting information are often not available in the early planning phase. DALEC simulates already by a few assumptions in the early planning phase the correlations of solar irradiation, artificial light demand depending on the solar irradiation and the shading system and the resulting heating/cooling load by the artificial light in the time step hour over the whole year. This functionality with such a fast calculation time is not given by any other tool.

**Methodology**

Within this paper a design driven optimization process is executed as demo case, in order to show the capabilities as well as the benefits provided by the Revit2DALEC tool. Several boundary conditions have been defined to create a realistic scenario. The construction field is located in...
Innsbruck Austria in the Schöpfstraße (Figure 5). It is in the middle of the city, surrounded by a typical urban environment with buildings up to 4 story’s and 18 meters.

![Figure 5 Construction field](image)

The construction field measures 1160 m² and the allowed building density is defined as 60%. 4 stories are required. Within the construction field the positioning of the building is flexible (Figure 6). The optimization process is executed manually and by that the amount of reviewed and evaluated designs is restricted within this paper. It was also defined to evaluate the influence of a generalized shading mask for each story compared to a detailed specific shadow mask for each window. Also, the design optimization criterions are orientation and location (south and north) within the construction field.

![Figure 6 Construction filed with surrounding buildings](image)

The building shape is once designed, room distribution and usage and also windows are fix (Figure 6). The building is simulated as an office space, with a usage distribution shown in Table 1. With a building perimeter of 91m and height of 12.20m, the external wall surface area is 1110 m². The total window area is 310m², by that the building design has an 28% window-wall-ratio.

![Figure 7 building basic design](image)

Within Revit2DALEC the building settings are set by default. A Passive house standard is used which defines the envelope elements as shown in table 2.

<table>
<thead>
<tr>
<th>Building Element</th>
<th>Heat transfer coefficient [kWh/(m²*K)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Floor</td>
<td>0.35</td>
</tr>
<tr>
<td>Roof</td>
<td>0.35</td>
</tr>
<tr>
<td>Wall</td>
<td>0.15</td>
</tr>
<tr>
<td>Window</td>
<td>0.85</td>
</tr>
</tbody>
</table>

The facade shading system for the base design is defined with no shading system. Within DALEC there are 76 parameters form project information, room information, windows, daylight and artificial light usage that have to be set. This process is simplified by offering default settings based on an excel database, which can be changed, adjusted or extended based on personal criteria. With this simplification the user only has to set 13 drop-down menus (Figure 1, red square), within the 6 main settings (Figure 1, green square).

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With the Grasshopper Honeybee add-in and other modules from Grasshopper a template is created, which exports near-field shading masks for each window in a text file format (Figure 8). Also, the far-field (relevant mountains around Innsbruck in the Alps) shading mask is downloaded from the TirolSolar homepage (TirolSolar 2023). These two shading masks can be combined by a self-developed tool, to generate an absolute shading mask containing the highest altitude value of each azimuth (1-degree steps) (Diagram 2), which can be seen, is necessary since the azimuth of long-distance shading can be higher higher as short distance shading.

To compare and evaluate the results following simulations results from DALEC have been chosen as criteria’s:

- Primary total energy demand
- Primary energy demand - heating
- Primary energy demand - cooling
- Primary energy demand - artificial light
- Daylight autonomy
- Exceeding Luminance

Primary Energy Total (heating, cooling, artificial light) is compared on the building level.

$$ P_{ET_{\text{total}}} = \frac{\sum P_{E_{\text{room}}}}{\Sigma T_{F_{\text{room}}}} $$

Daylight and glare ratio are also compared on the building level.

$$ \text{Ratio}_{\text{total}} = \frac{\sum \text{Ratio}_{\text{room}}}{\Sigma \text{Ratio}_{\text{room}}} $$

Counting the daylight autonomy ratio (DA) undershoot and the glare ratio (lm) overshoot, are compared on the room level.

$$ DA_{\text{criteria}} > DA_{\text{room}} \rightarrow \text{Count} + 1 $$
$$ lm_{\text{criteria}} < lm_{\text{room}} \rightarrow \text{Count} + 1 $$

The building has 4 stories of which each story has 13 rooms and 19 windows. In total the building has 76 windows, 8 variants are defined, which end up in a total number of 608 calculated shading masks. Also, all 8 variants are simulated with only the long-distance shading and with a shading mask per story, by that the following 3 simulation scenarios are calculated and compared:

- Specific simulation with absolute altitude of long and short distance shading mask
- Simulation with only long-distance shading mask
- Simulation with absolute altitude of long and short distance shading mask of construction field middle point for each story

Since connecting more than 608 shading masks to each window manually is not really a practical workflow, a tool has been developed, which if the shading masks are same named as the windows in Revit, links all shading masks to the model automatically.

The design with an optimal location and orientation is further detailed in 2 steps. First a 1.2m protrusion is added on the southside for the 3rd and 4th floor, to have a passive overheating protection during summer. Second a complex shading system is set:

- No system for basic control
- Diffuse Screen for glare protection on façade area 0-2m
- Daylight redirection with horizontal blinds on the south side on façade area 2-3m for glare and sun protection
- Daylight redirection with cut off blinds on the west and east side on façade area 2-3m for glare and sun protection

To compare and evaluate the results following simulations results from DALEC have been chosen as criteria’s:
The maximum value for glare ratio is 5% and the minimum value for daylight autonomy is 50%.

Besides the simulation results, also the design optimization workflow will be evaluated. The workflow of the location and orientation optimization process consists of 15 (17, two extra steps for high resolution shading mask) steps (Table 3).

<table>
<thead>
<tr>
<th>n</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Create model</td>
</tr>
<tr>
<td>2</td>
<td>Name all windows</td>
</tr>
<tr>
<td>3</td>
<td>Revit model export as DWG and import into Rhino</td>
</tr>
<tr>
<td>4</td>
<td>Replace window meshes by Rhino surfaces</td>
</tr>
<tr>
<td>5</td>
<td>Align model (location and orientation)</td>
</tr>
<tr>
<td>6</td>
<td>Transer windows into Rhino GH Template</td>
</tr>
<tr>
<td>7</td>
<td>Assign all Rhino surface elements to the Grasshopper workflow</td>
</tr>
<tr>
<td>8.1</td>
<td>Shadow Mask Creator GH with Density 0</td>
</tr>
<tr>
<td>8.2</td>
<td>Shadow Mask Creator GH with Density 3</td>
</tr>
<tr>
<td>9.1</td>
<td>Create DALEC shadow masks from Rhino Shadow Masks with programmed tool Density 0</td>
</tr>
<tr>
<td>9.2</td>
<td>Create DALEC shadow masks from Rhino Shadow Masks with programmed tool Density 3</td>
</tr>
<tr>
<td>10</td>
<td>Combine DALEC shadow masks with Tirol Solar distance shading</td>
</tr>
<tr>
<td>11</td>
<td>Do settings with Revit2DALEC within Revit</td>
</tr>
<tr>
<td>12</td>
<td>Map shadow masks into model with programmed Tool</td>
</tr>
<tr>
<td>13</td>
<td>Export IFC_2x3</td>
</tr>
<tr>
<td>14</td>
<td>Run SBT</td>
</tr>
<tr>
<td>15</td>
<td>Export IFC_4</td>
</tr>
<tr>
<td>16</td>
<td>Run Matlab2Struct (programmed tool)</td>
</tr>
<tr>
<td>17</td>
<td>Run DALEC simulation within Matlab</td>
</tr>
</tbody>
</table>

| Table 3 Workflow steps |

Results

Sum up all workflow steps (Table 3), it takes 114 minutes (1.9h) for the low-resolution model and 141 minutes (2.4h) for the high-resolution model. Step 8 (8.1 10 minutes, 8.2 36 minutes) takes the most time to be executed. But not all steps have to be done each time a new model is simulated. In this case the model shape and usage were fixed and only orientation and location have been varied. By that step 1-4 and 6-7 only needed to be executed once. So that each new simulation only takes 23 minutes (8.1) or 50 minutes (8.2).

Figure 9 Variation orientation north location north
Comparing the 8 models from location and orientation combination, the variation orientation north and location north has the best performance with 26.26 kWh/(m²*a) primary energy total (Figure 9) and orientation south location south was the worst with 29.99 kWh/(m²*a) (Diagram 4). Comparing the primary energy heating demand of the best and worst variant ends up in a 22% difference.

Diagram 4 Detailed shadow mask

All variants also have been simulated with only a long-distance shading mask for all windows and a shading mask per story, which was calculated in Rhino Grasshopper in the centre of the construction field with an elevation of 1.5m, 4.3m, 7.1m and 9.9m. First 8 variations (Diagram 5) are with the detailed combined shadow mask, 9 to 12 are with only long-distance shading mask and 13 to 16 are with the story shading mask. The use of an only long-distance shading mask underestimates the artificial light energy demand by 26.9% (average). The use of a story shading mask underestimates the artificial light energy demand by 16.8% (average). Furthermore, the best and the worst case have also been simulated with the high-resolution mask.

Diagram 5 Primary energy artificial light
Comparing the low- and high-resolution shading mask against each other, the difference between both methods is 2.5%, with less energy demand using the high-resolution shading mask (Diagram 6).

Diagram 6 Low vs high resolution shading mask

Since it can be expected that a building with no shading system will have glare issues, two strategies have been simulated. The protrusion reduced the primary energy demand by 1.5%, compared to the variant with no shading system. The complex shading system raised the primary energy demand by 13.4% (Diagram 7). This seems to be a reasonable increase to argue against a complex shading system. Also, looking on the daylight autonomy undershoot number, the shading system variant has 19 (36.5%) rooms not matching the daylight autonomy criteria of 50% (Diagram 8, blue).

Diagram 7 Orientation north location north variants

Comparing both variants by daylight autonomy ratio and illuminance limit ratio the protrusion variant has an average near window (0 to 3m depth) daylight autonomy ratio of 90% and far from window (3 to doom depth) of 66% and the complex shading system has 81% and 49%, which is almost within the minimum 50% daylight autonomy ratio criteria (Diagram 9 - blue). The illuminance limit ratio for the protrusion variant near window is 30% and far from window 32% and for the complex shading system 9% (close) and 8% (far from) which is close to the hard criteria of maximum 5% and within the soft criteria of 10% (Diagram 9 - green).

Diagram 9 Daylight and luminance limit ratio

The protruson variant has 30.8% of the rooms not matching the hard criteria which is defined as 5% (hard) and 10% (soft) of the occupied hours per year should not be overseen. It shows that for the protrusion variant almost all rooms (94%) are not matching the criteria, while the complex shading system only 44% do not match the criteria of 44% (Diagram 8, green) and for soft criteria all rooms are fulfilling the criteria.

Diagram 8 DA undershoot and illuminance overshoot

Diagram 9 Daylight and luminance limit ratio
Conclusion

During the workflow of a location and orientation optimization, several steps had to be made (Table 3), which are clearly complicated and error prone and by that are not suitable for practical use. All steps have been reviewed and evaluated considering the possibility of further automations. It is truly believed that steps 2 to 10, by using Revit Dynamo instead of Rhino, could be simplified and automated mostly. Step 16 and 17 are already automated within the Revit2DALEC tool (older version), which right now does not support multiple facades. Besides the optimization potential, 23min per model after 1.9h preparation for an hourly based full year and building simulation (without the potential automations), is an acceptable time amount that should support the design process.

The results should be considered specific for this case study and should not be carelessly transferred:

- Simplified shadow mask are may faster and easy to create, but do not represent the actual exposure situation and lead to clearly wrong results
- The benefits of high-resolution shading mask do not justify the long calculation time
- Even all variants fullfill the PH Standard criteria of 15 kWh/(m²*a) heating demand, within such high efficient building, small changes can have high impacts, 23.5% difference between best and worst variant
- The choosen design has quite similar façade area on all orientations, but still has clear result differences. Location and orientation impact on building energy performance with other shapes can expected even more clear

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References


