

## An Automated Verification Workflow for Planned Lighting Setups using BIM

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### 1 ABSTRACT

The use of Building Information Modeling (BIM) methods is becoming more and more established in the planning stage, during the construction, and for the management of buildings. Tailored BIM software packages allow to handle a vast amount of relevant aspects, but have so far not been covering specialized tasks like the evaluation of light distributions in and around a 3D model of a building. To overcome this limitation, we demonstrate the use of the open-source IFC format for preparing and exchanging BIM data to be used in our interactive light simulation system. By exploiting the availability of 3D data and semantic descriptions, it is possible to automatically place measurement surfaces in the 3D scene, and evaluate the suitability and sustainability of a planned lighting design according to given constraints and industry norms. Interactive visualizations for fast analysis of the simulation results, created using state-of-the-art web technologies, are seamlessly integrated in the 3D work environment, helping the lighting designer to quickly improve the initial lighting solution with a few clicks.

Keywords: analysis, visualisation, lighting design, verification, BIM

### 2 INTRODUCTION

Building Information Modelling (BIM) is becoming more and more of a standard in terms of planning, supervising and managing the complete lifecycle of a building. The base of a BIM project is a single data set, consisting of 3D geometry together with all kinds of semantic information, reaching from material properties over electrical installations up to the designated purpose of rooms. The main advantage and idea (but at the same time one of the biggest challenges) of this holistic approach is the possibility that all involved users work on the same, single data basis, which reduces redundancy, miscommunication issues and exchange problems. For this to work, specific views onto this model have to be defined for the individual experts: The access to only relevant parts of the data avoids reduces the handling complexity, and improves the efficiency by providing domain-specific tools.

In praxis, not all relevant planning and management responsibilities can be performed in a single software environment: Even though available BIM tools (see Section 3) cover an enormous amount of workflows for complex planning tasks, specialized parts are still carried out using the established tools tailored towards the needs of the corresponding industry. Hence, the data exchange plays a crucial role in this environment: In order to exploit the availability of the BIM data source with all its meta information, to create specialized views onto it, and to synchronize the externally generated data with the source BIM model, the open-source data exchange format IFC has been proposed: Apart from geometric and material information, it also holds semantic annotations and information that can be used for verification purposes.

In this work, we propose a novel approach for an optimal BIM-based lighting design workflow using multiple components. Lighting design is one of the fields that relies on specialized design tools, but that can benefit immensely from both the 3D geometry as well as from the metadata immanent in the BIM model: For the first time, a digital system includes nearly every necessary information needed to automatically verify all formal requirements of a lighting solution. This would make it possible to find an optimal lighting design solution in a short time period, and apply necessary modifications in cost-effective phases. With the goal to make steps towards this automation, we strive to properly handle the following aspects:

- Data preparation: For an optimal export and use in a lighting design environment, we suggest a way to use the existing annotation possibilities the BIM standard offers. It is crucial that the overhead for this annotation stays low, both in terms of modeling time as well as in data size.
- Data exchange: Using the IFC data format for the exchange from the BIM tool to the lighting design software and vice versa, we are not tied to a certain feature set only a certain software manufacturer

has created. Nevertheless, the needed data conversion requires certain considerations and precautions.

- **Data enhancement:** A proper, physically accurate light transport relies not only on the exact 3D geometry, but also on a physical description of both the light sources as well as any surface property (i.e. material) in the 3D scene. BIM tools as well as the IFC standard do not take physical material measurements into account, and this has to be considered.
- **Verification of lighting-induced constraints and norms:** The lighting industry has established toolsets and methods for the verification of a planned lighting solution. In order to evaluate the suitability of the light in the scene, certain criteria and norms have to be fulfilled. In the real-world, these can be measured using special devices; in a simulation environment, these measurement tools have to be artificially simulated as well. The setup of this tools can be automatically derived by using the proper information prevalent in the BIM data.
- **Visualization of the lighting result:** Emerging light simulation data has so far been visualized in multiple ways, like the direct display of the incoming light on the geometry, false color visualizations, etc. - but together with the available semantic context, it is now feasible to automatically apply information visualization methods to gain more insight on the results.
- **Use of state-of-the-art technologies and tools:** We try to exploit the availability of various existing tools and libraries such as xBIM(eXtensible Building Information Modelling Toolkit[XBIM]) for parsing and editing the IFC files, or CEF (Chromium Embedded Framework [CEF]) for the creation of information visualization gadgets using web-based technologies. This has not only the benefit of rapid prototyping, but also guarantees a wide range of support.

By taking these aspects into account, we demonstrate our first version of a continuous workflow from the BIM software into a light planning setup, including fully automatic verification steps and visual guidance for further improvements. In this process, we have identified the following scientific contributions:

- Automatic and seamless creation of a light planning view onto a BIM data set (with little preprocessing effort), including a physically-based conversion of material and light data
- Automatic placement of light measurement surfaces based on semantic information prevalent in the BIM meta, including an assignment of light-relevant constraints from norms and industry standards
- A real-time visual guidance system, relying on web-based techniques for information visualization, giving fast insights on the achieved quality of the solution, and where improvements are necessary.
- An outlook on further possible extensions that could be seamlessly integrated in such a system, making it possible to verify time-dependent, perception-based or psychological aspects of a lighting design.

In the next sections, we will first give an overview on the current state of the art in the related fields of lighting design and BIM (Section 3), followed by an overview on our system components and the BIM data exchange in Section 4. In Section 5, we demonstrate the initial visualization results of the light distribution. The use of the additional semantic context is used in a visual guidance system that is explained in Section 6, followed by a results Section (7). We conclude this paper and give an outlook on future work in section 8.

### 3 RELATED WORK

#### 3.1 Lighting Design Tools

In the field of lighting design, various solutions are available [DAVOODI] to solve the challenges that occur during the creation of a lighting concept. Photometric measurements provided by luminaire manufacturers serve as one of the important input factors for a physically accurate light transport simulations. This photometric data represents lighting characteristics of luminaires in the form of IES [IES] or EULUMDAT [EULUMDAT] files. All relevant lighting design software tools feature a kind of measurement surfaces that measure illuminance values (see Section 4.1.4), which can be used to evaluate any lighting scenario.

The most common software products combining CAD modeling, measurement tools and possibilities to evaluate lighting scenarios are Relux[RELUX], DIALux[DIALUX] or AGi32 [AGI32]. Dialux and AGi32 perform calculations for the light simulation based on the concept of radiosity [GORAL]. Relux uses the Radiance renderer by Ward [WARD] for the light simulation. HILITE, a light planning-software currently developed in an academic environment, calculates and visualizes a physically based light simulation in real-time. It uses a many-light global-illumination solution [LUKSCH, 2013] to calculate light maps, and filtered environment maps to create glossy material effects [LUKSCH, 2014]. A unique feature of this tool is its interactivity, allowing users to change materials, positions of luminaires, or entire luminaire models, while the light simulation is updated at interactive framerates. This makes rapid iterations on a lighting concept possible and therefore provides a very fast workflow. In this work, we opted for HILITE as the used light simulation tool, since the physically-based interactive simulation together with HILITE's capabilities to evaluate lighting scenarios and an easy-to-extend programming interface form the ideal environment for our work.

### 3.2 BIM and Lighting

In recent years, Building Information Modeling (BIM) has gained more and more importance in architectural design and construction workflows, and first research effort has already been dedicated to using BIM data for energy or light simulations. Yan et al. [YAN] developed system interfaces to connect BIM with Building Energy Models (BEM) to provide the possibility of energy simulations using BIM data. The authors use Revit as BIM tool and Radiance, a high-quality ray-tracing software system, and DAYSIM [REINHART] for daylight simulations. Their prototype Revit2Radiance represents the first direct translator between Revit and Radiance. It generates input geometry for Radiance and DAYSIM by extracting and triangulating surfaces from Revit models. Similarly, Kota et al. [KOTA] focused their research on combining different tools to ease daylight simulations and analysis for BIM models. The authors investigated the benefits and challenges of integrating BIM into daylight simulation tools and developed a prototype that integrates Revit as BIM tool into Radiance and DAYSIM for daylight simulations.

Research on Building Energy Management Systems (BEMS), like conducted by Ock et al. [OCK], also investigates possibilities for using BIM data for daylight simulations. The goal is to generate control patterns for BEMS using weather data together with BIM models and Computational Fluid Dynamic (CFD) simulation. The control system Ock et al. propose does not use real-time light simulation of whole buildings, since the authors deemed it too expensive in terms of processing time to control the lighting embedded in their BEMS. Instead, pre-computed daylighting illuminance levels for each full hour are computed with Autodesk 3D Max Design, DAYSIM or Radiance from a BIM model. The system looks up the respective illuminance levels to evaluate a pre-defined lighting setup, resulting in control instructions for the BEMS to adjust the lighting.

Yan et al. [YAN] and Kota et al. [KOTA] already proved that it possible to convert BIM data into other models, that can be used by thermal or daylight simulation tools, in an accurate and efficient manner.

Building on their research, we also chose Revit as source for our BIM data and took their approach one step further by integrating BIM data in HILITE, a light planning software that is not only capable of daylight simulations, but also provides physically accurate simulations of very complex indoor lighting scenes, while allowing interactive changes and various possibilities to automatically evaluate the illumination in a scene based on physically correct values and norms.

### 3.3 BIM Data Exchange

In their recent case study of two industrial facilities, Gourlis[GOURLIS] investigated potentials and deficits of converting BIM to BEM data and possible uncertainties that arise in the process. From their literature review of state-of-the-art research on BIM to BEM, the authors conclude that most projects still require custom software or domain specific design guidelines that are formulated by domain experts and are therefore influenced by their personal views and skills. This supports our claim that there is a demand for automatic methods, which enable reliable workflows from BIM data to BEM or light simulation tools.

Davoodi[DAVOODI] compared multiple light simulation tools in her thesis and investigated the use of BIM models for light simulations. The author states that current workflows requires various manual steps to convert data back and forth between different BIM and simulation tools. Since most processes in this

toolchain are purpose-driven, the respective tools often do not provide all the necessary information for other tools. For example, material parameters (like the reflectiveness of a material), or physically-based specifications of light distributions of luminaires, are rarely provided by material /element vendors and therefore have to be added manually for the light simulation. Lu et al. [LU] recently published an in-depth review of numerous publications about applications of BIM in the context of green buildings and their development. After a critical reflection on currently used BIM software tools, the authors confirm the missing information as one major issue for the integration of green BIM with light simulations tools like Radiance and DAYSIM.

Without solution, missing light data is automatically inserted from a light database. Our tool also provides means to handle missing material properties similarly by connecting a material database or a lookup table.

#### 4 SYSTEM COMPONENTS FOR AN AUTOMATED VERIFICATION OF LIGHTING DESIGNS

To verify the suitability and sustainability of a planned lighting design for a given BIM model, three major components are necessary: A BIM modeling software to generate a 3D scene together with semantic information, a light simulation application, and the data exchange interface between them. We first describe the main considerations for the suitability of a light simulation system, followed by the aspects of a BIM tool relevant for the verification of lighting designs.

##### 4.1 Light Simulation

A light simulation application usable for this purpose has to at least fulfill the minimal photometric measure accuracy to allow lighting design verification, i.e. the light transport simulation must not deviate from real light transport by more than 10-15%. To create such highly accurate measurements, the light interaction between various complex materials as well as the luminaires themselves have to be described in detail. Moreover, the simulation quality strongly correlates with the complexity of the light transport algorithm. In our approach, we opted for the HILITE application, as its light transport algorithm has been optimized for architectural scenes and is extremely fast due to GPU acceleration.

###### 4.1.1 Luminaries

Every luminaire in the scene must be described by photometric data, which mainly consists of the light distribution information. The light distribution describes how a luminaire emits light into the scene, based on real-world measurements. The light simulation application relies on these measurements to decide in which direction which energy amount has to be distributed. Furthermore, the photometric data contains various manufacturer's details like color temperature (see Figure 1) and a color rendering index.



Fig. 1: Color temperature comparison. Left: warm white (3000K). Right: cool white (5000K)

###### 4.1.2 Daylighting

Lighting design is not only based on placing artificial luminaires, it also includes daylight to achieve a high light quality solution and reduce the overall energy consumption. As sunlight is our natural main light source, the human visual system is optimized for its light spectrum, and the presence of daylight within a building improves the quality of life. During the planning and management stages of a building, considering the influence of daylight can obviously help tremendously to reduce energy costs - but also more complex light-induced aspects, like glare, reflections, and hard shadows are often caused by sunlight. Therefore, the lighting design tool has to be capable of considering daylight within the architectural planning phase to avoid glare prone constellations of highly reflecting areas, like glass coverings or windows. A physically-based daylight model provides time and location-dependent photometric data for these aspects (Figure 2).



Fig. 2: Daylight simulation for a train station. Both direct sunlight as well as ambient light are simulated, and multiple light bounces are considered. The light transport computation in this scene took approximately 20 seconds

#### 4.1.3 Materials

Materials have to be described in a physically plausible way to correctly simulate the light interaction within a scene. Opaque materials reflect all incident light, while transparent materials refract portions the incoming light. To describe the reflection behavior of an opaque surface a Bidirectional Reflectance Distribution Function (BRDF) is used. Metallic reflections manifest as a highly specular reflection, while non-metallic materials tend to appear diffuse with low specular reflections. The material's microstructure or roughness strongly influences the glossiness of an object. In case of transparent materials, the light propagates through its medium. While light enters another medium, the light direction is bent according to the material's refractive index. By applying real-world observation and physical laws, a huge variation of materials can be simulated.

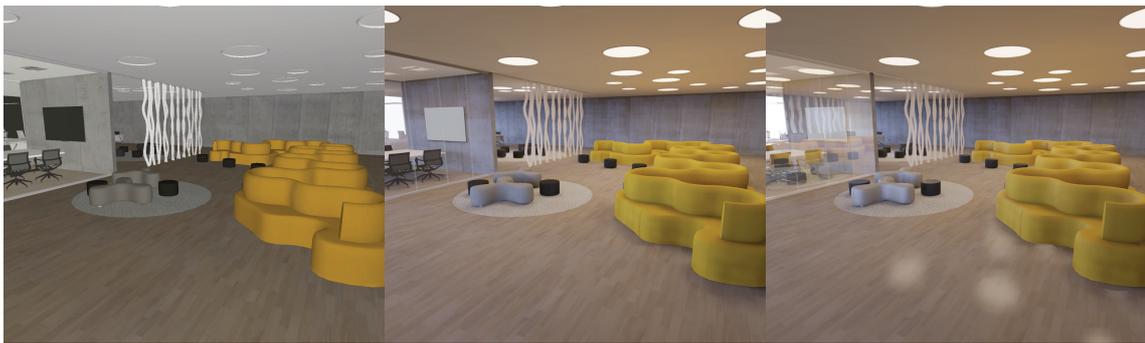


Fig. 3: Various renderings of the same scene. Left: Abstract material shading. Middle: Illumination values applied to material model. Right: Illuminated scene inclusive view dependent material effects.

#### 4.1.4 Measurement Surfaces

For architectural projects, especially in public space, the light intensity within a certain area is described by industry norms. The light simulation provides a light intensity value for each point in a scene. To form statistical terms for a certain area, the light measurements for all points within this space have to be evaluated. To define the area of interest on an object's surface, measurement surfaces can be described by the user. Measurement surfaces are linked to a certain industry norm to allow automatic evaluation. The most prominent lighting norms regarding a measure area are lighting level ( $\bar{E}_m$ ) and uniformity of illuminance ( $U_0$ ). The lighting level represents the average illuminance within a measurement surface and is used as a maintenance factor to ensure a minimum level of light quality. Uniformity of illuminance states how evenly light is spread over the measurement surface.

#### 4.1.5 View-dependent LightingEffects

Lighting design norms provide guidelines to handle view dependent lighting quality. Glare is the most prominent effect as it represents a safety issue. Heavy glare can lead to tiredness, errors and even to injuries. Proper lighting implies to avoid or reduce glare as much as possible. The unified glare index (UGR) states how much glare is present at an actor's position within the scene with a given field of view. By introducing a time component and moving actors, effects like the adaption of the human visual system can be simulated as well. HILITE currently supports this partly in the form of adaptive tone mapping during interactive walkthroughs, but not yet in statistical evaluation scenarios.

## 4.2 BIM Software

BIM-based modeling software allow to describe a complex life cycle of an object, and is capable of properly handling various aspects, starting with the object's planning and construction right through to its usage, maintenance and even deconstruction. For the usage of BIM data in lighting design, though, we (and others, see Section 3.3) have encountered the problem that several aspects in the data need special considerations:

### 4.2.1 Luminaire Dummies

To allow the simulation of light within a BIM project, photometric data needs to be linked to luminaire objects. To place the luminaire within the scene, each luminaire must be attached to a placeable geometry. A detailed luminaire geometry is not necessary for the calculation of a light simulation: First, the measured photometric data already describes how the light is affected by the luminaire's casing. Second, we intend to automatically switch luminaires in multiple simulation runs to find the best fit, i.e. in such a case, only position and orientation information is needed.

To simplify the lighting design process, only the luminaire's dimensions are necessary to check geometry intersections within the scene. Basic geometry shapes (box, pyramid, cone, and cylinder) are used as luminaire dummies instead of detailed casings. Real-world projects tend to contain a great number of luminaires, which have an impact on the rendering performance. The simplification of complex models to luminaire dummies reduce the rendering overhead, but also reduces realism of the rendered images displayed in the viewport. To counter rendering performance issues, either instancing or a level-of-detail approach can be used.

### 4.2.2 Annotations

Every 3D object within a BIM project can have various properties assigned. On the one hand, properties can hold simple numerical, nominal or Boolean values, like manufacturer's details, quantities or geographic information - but on the other hand, they can store more complex information like spatial relationships. The user can add, edit and remove properties of an object type, while each instance of an object holds its individual values. Additional information, like photometric data or semantic area descriptions (e.g. the purpose of a room or area, such as "office area" or "train platform"), need to be provided to the light simulation software. This required information for proper lighting evaluation can easily be attached to existing objects by defining new properties for a certain object type. By annotating existing objects, the manual creation of additional helper objects (e.g. measurement surfaces) can be avoided, as their location and purpose can be automatically derived. Luminaire annotations hold metadata, like photometric data or orientation. Walls, floors or other building parts can be annotated to later automatically represent measurement surfaces for given lighting design norms.

### 4.2.3 IFC and Property Sets

As every object may hold many properties of various fields, their organization is important to keep a well-structured view. Properties are grouped to generate a tidy overview, allowing the user to fast identify relevant information. IFC (Industry Foundation Classes), an open data model for BIM, is a useful file format to export 3D data and metadata from a BIM project. To simply export all properties of an object via IFC is possible, but leads to an unnecessary work overload as only a portion of the immense data is of importance. Depending on the used IFC-scheme, several properties are included by default. User defined properties, like the lighting design relevant properties, are grouped together to a property set. To efficiently export the BIM project property sets are filtered.

## 4.3 Data exchange interface and verification workflow

For our automated verification workflow (Figure 4), the lighting design tool (Section 4.1) is connected to a BIM modelling software (Section 4.2) using a data exchange interface. In our current BIM projects (see Section 7), the BIM models were generated using Revit Autodesk - but any other BIM software capable of exporting IFC can be used as well. The architectural model is enriched with photometric data or semantic area annotations, which are grouped together into property sets. To export a clean BIM model via IFC only the light simulation relevant property sets are additionally included.

Note that our workflow proposal is not restricted solely to the IFC file format. Any other semantically enhanced geometry format, such as CityGML, could be used as an exchange format. For example, the used light simulation system is based on libraries that support the handling of COLLADA and CityGML files as well. The handling and interpretation of the corresponding meta data would of course have to be adapted correspondingly to enable GIS applications like street lighting simulation for urban space planning.

To import the IFC file into our .NET-based lighting design application HILITE, we use the free open source toolkit xBIM[XBIM]. xBIM is a middle ware toolbox for IFC-based applications and provides a rich API to interact and modifying the IFC packed BIM model. Next to IFC-file parsing, xBIM provides a geometry engine, which turns IFC geometry data into an accessible mesh representation. We use this functionality to import geometry data as well as metadata into HILITE.

HILITE then accesses the xBIM representation and translates it to its own internal representation. In this translation process, the previously attached annotations are used to trigger creation rules:

- **Luminaires:** The dummy holds a lookup key to query the local HILITE luminaire database. The HILITE luminaire database contains an optimized geometric representation of the luminaire and its photometric data. The luminaire dummies, previously placed within the BIM model, provide orientations and positions, which are used to place the HILITE luminaires in the scene.
- **Measurement Surfaces / Lighting Norms:** While adding the geometries to the HILITE scene, every associated IFC-object is checked for annotations that lead to the need for a measurement surface. The annotations act as a key property to query the local lighting norm database. After generating and placing the measurement surface on top of the annotated object, the queried lighting norm is linked to it. For automatic lighting norm verification, each measurement surface is evaluated after the simulation has been calculated, and compared to the linked lighting norm. The result can be immediately displayed (Section 6) or saved (in near future, see Section 8) to an IFC file.
- **Materials:** The xBIM material description can only hold as many parameters as the IFC-materials offers. Hilite requires additional, non-default parameters due to its more sophisticated material model. The current workflow uses a local material database to complete the missing material parameters.

Lighting design norms, such as statistical terms like lighting level or uniformity of illuminance, can be directly validated by the measurement surfaces. View-dependent lighting effects have to be evaluated for each required position and field of view within the scene. To validate light specific norms, such as color temperature or a color rendering index, all luminaires contributing to the measurement surface have to be analyzed.

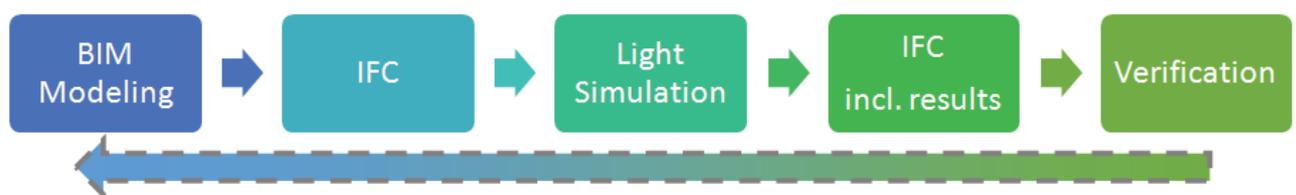


Fig. 4: The workflow concept and its components. Based on the BIM data, an IFC file is generated. The IFC file is analyzed, and the semantic data is used to enrich material properties, place measurement surfaces according to industry norms, and load photometric light profiles. After the physically correct light simulation, the results are stored, and the verification process is performed. In the future, these results will be made accessible to the original BIM again (via IFC).

## 5 VISUALIZATIONS

The light simulation application calculates the illuminance for all visible surface points within a scene as numerical values. By hovering with the mouse over the scene, the measured illuminance values can be inspected for each point. Nevertheless, distributed light in a scene is perfectly suited for a direct visualization by combining the illuminance values with the objects' underlying material models to produce a photorealistic view of the scene, including lighting and shadows. Such a rendering gives a good preview of how the lighting design affects the final building (Figure 3) visually, but does hardly give any information if the requirements defined by the industry norms are met! For the purpose of quickly visualizing the quality of a lighting solution, false color methods are applied.

## 5.1 FalseColorVisualization

The simplest false color visualization interprets illuminance values as grayscale values. The mapping of an illuminance value to a grayscale value is described by a so-called transfer function. A linear transfer function simply maps the illuminance values onto the range of renderable gray values. Most approaches rely on a logarithmic transfer function as it better correlates to our human perception.

More complex transfer functions map ranges on color schemes, where certain areas of interest can be better emphasized (Figure 5, left). By using the global minimal / maximal illuminance values, the range can be automatically set. This approach is a good starting point to explore the current lighting design, but comparisons with other scenes are hard to achieve. To reveal weak spots, a manual adjustment of the transfer function is necessary: To optimize the illuminance uniformity, the transfer function range is successively refined to expose even small illuminance differences. Furthermore, fixed ranges allow to compare different simulation runs.

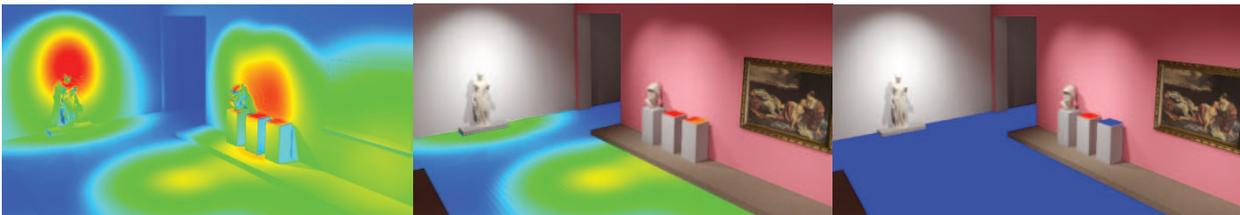


Fig. 5: Left: Global false color visualization. Middle: Measurement surface false color visualization with varying sample size. Right: Local false color view for measurement surfaces with visual verification.

## 5.2 Local False Color Visualization on Measurement Surfaces based on Norms and Constraints

The default false color visualization approach described above is based on one global transfer function. While evaluating multiple measurement surfaces, linked to individual lighting design norms, a global range is not sufficient to identify irregularities on the fly. Therefore, the range of the transfer function is set separately for each lighting design norm. By restricting false color visualizations only to measurement surfaces, the areas of interest are easy to detect within the scene (Figure 5, middle). A globally fixed color scheme allows to easily identify under- or overexposed measurement surfaces in respect to their linked lighting design norm (Figure 5, right). The automatic generation of this visualization is only possible due to the availability of semantic information from the BIM. It directly helps the user to add, move or remove luminaires in proximity to the measurement surface in order to find an optimal lighting design solution more efficiently.

## 6 INTERACTIVE VISUAL GUIDANCE

The semantic context for each measurement surface allows to verify the results of the current simulation run. Depending on the application area, the industry norms vary, which makes an individual, interactive treatment of the measurement areas necessary. The current validation state is visualized in various ways (Figure 6). We provide an interactive visualization within the 3D planning view to give immediate feedback for each measurement surface within the viewport. We opted for a traffic light symbol, as its concepts is generally well-known, and it is powerful enough to visualize the current verification status. Note that the yellow traffic light could be linked to the maintenance status of the light sources illuminating the measurement surface, which could be derived from the installation date in the BIM system.

To provide a global overview of the current verification status, all measurement surfaces are enlisted in a separate 2D view. The traffic light color scheme is re-used to easily detect unfulfilled lighting norms. By selecting a list element, the user can demand a more detailed visualization of the current verification status. For this purpose, we rely on various (scientific) visualization techniques that have been developed to present data in the most informative way. Especially the web-developing community provides an enormous amount of reusable content, mostly based on interactive JavaScript tools. HILITE provides the possibility to embed web-based content within its user interface, allowing fast prototyping and access to a wide range of visualizations. To demonstrate how easily various complex visualizations can be reused, we sketched the detail verification status view within the 2Dview using the well-known visualization tool Highcharts [HIGHCHARTS].

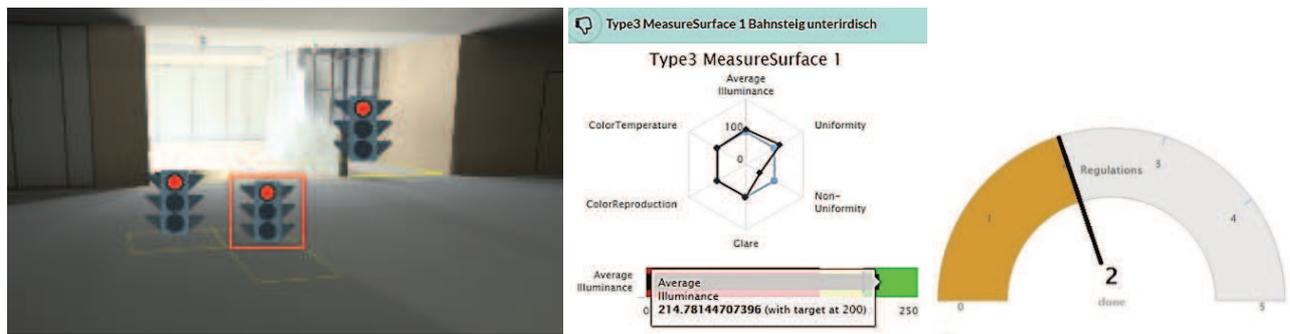


Fig. 6: Interactive visualizations using web-based technologies. Left: Traffic light symbol within 3D scene, quickly indicating whether all required norms are fulfilled for the selected measurement area. Middle and Right: Detail analysis view for the selected measurement area. The selection states of the areas are synced between 2D and 3D views. We integrated multiple plots for example purposes – note that they can be easily exchanged by other web-based visualizations. A polar plot (middle, top) provides a detailed overview on the fulfillment of all requirements. A bullet plot (middle, bottom) is used to visualize how well the current average illuminance requirement is met. The gauge (right) is best suited for a really quick overview on the number of valid constraints.

Our detail visualization uses a polar plot to visually compare the current values to the desired norm values. By normalizing all measured values to a range between 0 and 100, the polar plot contour can be directly compared to the desired norm values. A bullet plot is useful to depict ranges, which is suitable to compare the quality of the current measured value in relation to the accepted norm range. To quickly visualize the progress of all norms of a measurement surface, we use an angular gauge chart. The needle within the angular gauge chart indicates how many of the norms are currently satisfied.

As both views (2D / 3D) rely on the same dataset, their content as well as the user interactions on them are synchronized. While hovering over an element in the 2D view, the corresponding symbol in the 3D view is highlighted, and vice versa. This linkage helps the user to access additional information or to locate a specific measurement surface within the scene.

## 7 RESULTS

Autodesk Revit provides an example BIM project, where a building is modeled in detail. Figure 7 shows a side by side comparison of the default building in Revit (left) and the illuminated scene in HILITE (right). The annotated floors were automatically mapped to measurement surfaces (show in false color mode).

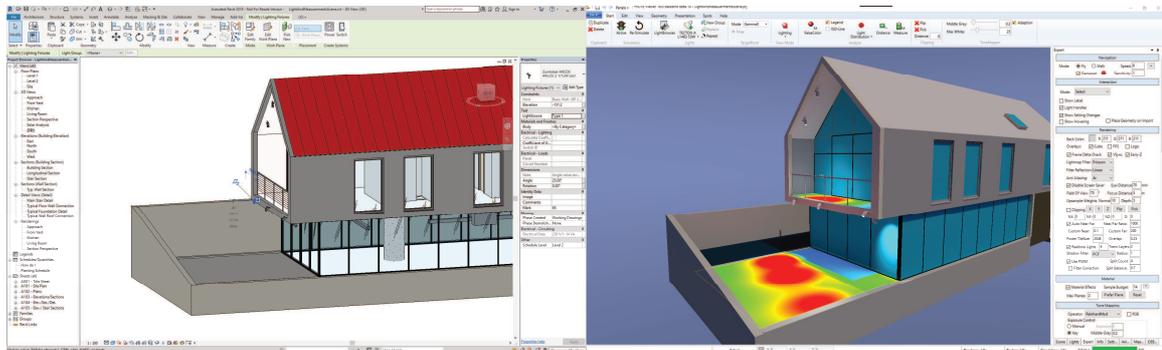


Fig. 7: Side by side comparison of Revit (left) and HILITE (right)

In cooperation with the Austrian Railway Association (ÖBB), we could apply our work flow to a BIM model of a rail station that is currently in the planning phase. Updates to the BIM model are planned on a regular basis, making an automatic, flexible approach a necessity. Figure 8 shows the scene with automatically placed measurement surfaces (left), and using a global false color visualization (right).

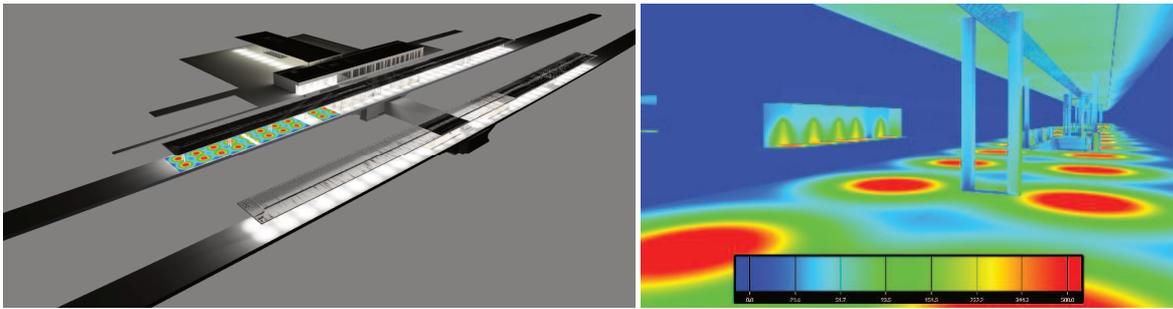


Fig. 8: An early planning stage of a train station: automatically placed measurement areas (left) and false colors (right).

### 7.1 Limitations

Currently the measurement surface is simply generated on top of an annotated object with a given offset. Intersections with other objects, like a pillar (Figure 9), are currently not excluded from the measurement surface evaluation. Therefore, the current measurement surface generation is limited to open areas.

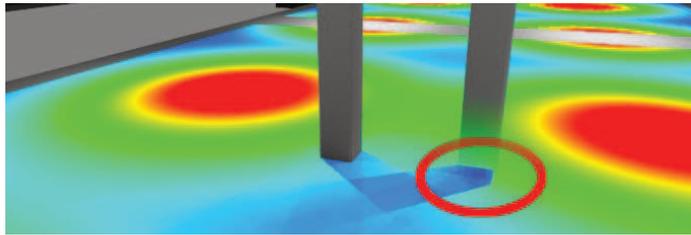


Fig. 9: Visualization of the measurement surface, where the red circle indicates the wrongly included intersection area (dark blue).

## 8 CONCLUSION AND FUTURE WORK

We have demonstrated a novel, reproducible and easily extendable approach for the automatic verification of lighting setups planned in BIM environments. We rely on BIM data in the form of IFC files, and enhance them in terms of material description and photometric information in order to generate physically accurate results. Using semantic data, measurement surfaces with constraint set to the corresponding industry norms are automatically created and evaluated. The approach has proven to be successfully applicable for demo scenes as well as in a large real-world scenario, and acts as a basis for further developments in the direction of a fast validation of light-related aspects in the planning and management phases of buildings.

Apart from properly handling the limitations described in Section 7.1, we plan to further enhance our system in various ways to solve problems that are relevant in this domain. For example, even though there has been some research regarding architecture for lighting-control systems [GUILLEMIN, PANDHARIPANDE], or comparisons of lighting setups [SORGER], the optimal placement of luminaires and sensors for such systems has hardly been addressed. We plan to investigate optimization methods for automatic luminaire placement and use BIM data for the verification as presented in this paper. The web-based visual information systems are predestined to develop guidance systems that help a designer with suggestions for further modeling steps. Another important aspect is the thorough verification of further lighting aspects, such as the color rendering index, color temperature, contrast, or to put more focus on view-dependent light effects. In order to find viewing positions and angles that cause problems, we plan to use an agent-based simulation system. This would also allow to investigate issues regarding eye adaptation, or other time-related effects.

This brings us closer to Virtual-Reality-based evaluations: Since a human’s perception of light is highly dependent on the surrounding lighting conditions, renderings of 3D scenes that are observed on a 2D computer monitor can only give an impression of the effects of a certain lighting setup. By combining our light simulation with a virtual or augmented reality application in future work, we want to provide more immersive possibilities to evaluate lighting conditions in a scene. In comparative studies with real-world situations, we plan collaborative research with psychologists and lighting designers. We also want to investigate the influence of vision impairments on the ability of people to navigate through a building. There, we want to especially focus on the influence of lighting conditions and how they can be adapted to aid people with reduced visual acuity, and will provide means to evaluate current norms, taking visual impairments into account.

In order to follow the BIM philosophy, the availability of the light verification results should not be limited to the lighting tool, but should be accessible via IFC for external verification. We plan to propose methods to integrate the verified aspects in the exported files, and will propose validation methods accordingly.

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## 10 REFERENCES

- XBIM: “eXtensible Building Information Modelling Toolkit”, <http://docs.xbim.net/>. [Accessed 13 01 2018].
- CEF: “Chromium Embedded Framework”, <https://bitbucket.org/chromiumembedded/cef/>. [Accessed 13 01 2018].
- DAVOODI, A.: Lighting simulation for a more value-driven building design process (PHD Thesis), Lund: Miljöpsykologiska enheten, Institutionen för arkitektur, Lunds tekniska högskola, 2016.
- IES: Illuminating Engineering Society, <http://www.ies.org/>. [Accessed 13 02 2017].
- EULUMDAT: Light Consult Inc., Berlin, <http://www.helios32.com/Eulumdat.htm>. [Accessed 13 02 2017].
- RELUX: Relux Infomatik AG, <http://www.relux.com/>. [Accessed 13 02 2017].
- DIALUX: DIALux GMBH, <http://www.dial.de/dialux/>. [Accessed 13 02 2017].
- AGI32: Lighting Analysts, Inc., <http://www.agi32.com/>. [Accessed 13 02 2017].
- GORAL, C. M. et al.: “Modeling the Interaction of Light Between Diffuse Surfaces,” SIGGRAPH Comput. Graph., vol. 18, pp. 213-222, 1984.
- WARD, G.: “Radiance Renderer”, <http://radsite.lbl.gov/radiance/>. [Accessed 13 01 2018].
- LUKSCH, C. et. al.: “Fast Light-Map Computation with Virtual Polygon Lights,” in I3D 2013, Orlando, Florida, 2013.
- LUKSCH, C. et. al.: “Real-Time Rendering of Glossy Materials with Regular Sampling,” The Visual Computer, vol. 30, pp. 717-727, 2014.
- YAN, W. et al.: “Interfacing BIM with building thermal and daylighting modeling,” in BS2013, Chambéry, 2013.
- REINHART, C.: “DAYSIM”, <http://daysim.ning.com/>. [Accessed 13 01 2018].
- KOTA, S. et al.: “Building Information Modeling (BIM)-based daylighting simulation and analysis,” Energy and Buildings, vol. 81, pp. 391-403, 2014.
- OCK, J. et al.: “Smart building energy management systems (BEMS) simulation conceptual framework,” in Winter Simulation Conference (WSC), Washington, DC, 2016.
- GOURLIS, G. et. al.: “Building Information Modelling for analysis of energy efficient industrial buildings—A case study,” Renewable and Sustainable Energy Reviews, vol. 68, pp. 953-963, 2017.
- LU, Y. et al.: “Building Information Modeling (BIM) for green buildings: A critical review and future directions,” Automation in Construction, vol. 83, pp. 134-148, 2017.
- HIGHCHARTS: Highsoft AS, <https://www.highcharts.com/>. [Accessed 13 01 2018].
- GUILLEMIN, A. et. al.: “Innovative lighting controller integrated in a self-adaptive building control system,” Energy and Buildings, vol. 33, no. 5, pp. 477-487, 2001.
- PANDHARIPANDE, A. et. al.: “Smart indoorlighting systems with luminaire-based sensing: A review of lighting control approaches,” Energy and Buildings, vol. 104, pp. 369-377, 2015.
- SORGER, J. et. al.: “Litevis: integrated visualization for simulation-based decision support in lighting design,” IEEE Vis, vol. 22, pp. 290-299, 2016.