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MATHEUS KÖRBES BRACHT

DEVELOPMENT OF A METHOD FOR INTEGRATING BIM WITH A THERMAL LOAD PREDICTION METAMODEL USING GBXML

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Matheus Körbes Bracht

Development of a method for integrating BIM with a thermal load prediction metamodel using gbXML

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Coorientador Profª. Ana Paula Melo, Drª

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O presente trabalho em nível de mestrado foi avaliado e aprovado por banca examinadora composta pelos seguintes membros:

Profª. Drª. Fernanda Marchiori
Universidade Federal de Santa Catarina (UFSC)

Prof. Dr. Sergio Scheer
Universidade Federal do Paraná (UFPR)

Sergio Pinheiro, PhD.
University College Dublin (UCD)

Certificamos que esta é a **versão original e final** do trabalho de conclusão que foi julgado adequado para obtenção do título de mestre em Engenharia Civil.

Documento assinado digitalmente
Poliana Dias de Moraes
Data: 21/12/2020 14:58:13-0300
CPF: 613.571.209-82

Profª. Poliana Dias de Moraes, PhD.
Coordenadora do Programa de Pós-Graduação

Documento assinado digitalmente
Roberto Lamberts
Data: 21/12/2020 14:41:17-0300
CPF: 294.003.840-68

Prof. Roberto Lambers, PhD.
Orientador

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RESUMO

A realização de simulações energéticas ainda não está completamente inserida no processo de projeto de edificações. Uma solução promissora para a integração de ferramentas de simulação energética no processo de projeto pode ser alcançada pelo uso de modelos de informação da construção (*Building Information Model* – BIM). A integração de BIMs com modelos de análise energética (*Building Energy Model* – BEM) durante o ciclo de vida pode reduzir o retrabalho e facilitar a avaliação de diferentes alternativas de projeto. Entretanto, uma interoperabilidade completa no processo de integração BIM-BEM ainda não foi alcançada. Metamodelos de predição de desempenho podem auxiliar na resolução desse desafio e permitir análises mais rápidas nas fases iniciais de projeto. Dessa forma, este trabalho apresenta o processo de desenvolvimento e validação de um método de integração entre *Building Information Models* e o metamodelo de predição de carga térmica desenvolvido para a Instrução Normativa do Inmetro para edificações residenciais (INI-R).

O método de integração baseia-se em uma ferramenta desenvolvida na linguagem *Python* com o objetivo de retirar os dados encontrados nos arquivos de formato aberto baseados no esquema *gbXML* exportados de ferramentas autorais BIM, proceder com transformações matemáticas e lógicas; e preencher corretamente os parâmetros do metamodelo desenvolvido para a INI-R. Uma edificação residencial unifamiliar foi modelada em três diferentes ferramentas autorais BIM para a validação da ferramenta de integração desenvolvida, observando a consistência do esquema gbXML.

Os resultados demonstram a viabilidade de desenvolvimento da ferramenta de integração, entretanto, apontam algumas diferenças entre os arquivos *gbXML* originados de diferentes ferramentas autorais BIM. Além disso, foram também observadas diferenças entre valores de parâmetros de entrada ao comparar o levantamento manual e o automatizado a partir de arquivo *gbXML*, principalmente, nos parâmetros relacionados às áreas de parede externa por orientação. Dessa forma, resultando em diferenças no valor da predição de carga térmica obtida pelo metamodelo.

Foi possível concluir que os modelos BIM podem ser integrados a um metamodelo de predição de desempenho com o uso do esquema gbXML de uma maneira semi-automática. O trabalho reforça a necessidade de padronização na implementação de ferramentas de exportação para arquivos de formato aberto pelos desenvolvedores de software. Também, indica a possibilidade de uso futuro da ferramenta para auxiliar no processo de etiquetagem energética de edificações brasileiras e auxiliar projetistas nas fases iniciais de projeto.

Palavras-chave: BIM; gbXML; Predição de carga térmica, Integração BIM-BEM. Metamodelo de predição de desempenho; Interoperabilidade.

RESUMO EXPANDIDO

Introdução

A maneira como as edificações são projetadas tem um impacto significativo na respectiva demanda energética futura. Entretanto o projetista deve levar em consideração uma grande gama de variáveis, exigindo o envolvimento de ferramentas computacionais para auxiliá-lo a encontrar uma solução otimizada (HENSEN; LAMBERTS, 2019).

Uma solução promissora para a integração de ferramentas de simulação energética no processo de projeto pode ser alcançada pelo uso de modelos de informação da construção (*Building Information Model* – BIM). A integração de BIMs com modelos de análise energética (*Building Energy Model* – BEM) durante o ciclo de vida pode reduzir o retrabalho e facilitar a avaliação de diferentes alternativas de projeto (ANDRIAMAMONJY ET AL., 2019). Os dois formatos abertos mais amplamente reconhecidos para a integração BIM-BEM são o IFC e o gbXML. Entretanto, ainda existem limitações. Processos de transcrição manual de dados ainda são comuns em fluxos de trabalho entre ferramentas autorais BIM e as de simulação energética (GAO ET AL., 2019; KAMEL; MEMARI, 2019). Gao et al. (2019) concluiu que os métodos baseados em gbXML oferecem o melhor desempenho para processos de transferência de dados, atingindo um nível semiautomático de integração BIM-BEM.

Ferramentas de simulação energética tradicionais requerem um número elevado de parâmetros de entrada, além de exigir um tempo de simulação considerável. Esses aspectos acabam gerando desafios para a integração BIM-BEM. Nesse sentido, o desenvolvimento de metamodelos de predição de desempenho pode ser uma alternativa para a resolução desses desafios. A metamodelagem pode ser entendida como um método de construção de modelos rápidos e simplificados que correlacionam parâmetros de entrada com resultados obtidos por modelos muito mais complexos, como os de ferramentas de simulação energética (ØSTERGÅRD et al., 2017).

A integração de modelos BIM com metamodelos de predição de desempenho poderia permitir um processo mais dinâmico para a avaliação do desempenho térmico de edificação. A integração de modelos BIM com esses metamodelos poderia permitir também um processo de etiquetagem energética mais acessível e consistente, como recomendado pelo trabalho de Li et al (2019).

Nesse contexto, o trabalho pretende explorar a possibilidade de integração entre modelos BIM com um metamodelo de predição de carga térmica. O metamodelo adotado foi desenvolvido previamente com o objetivo de ser incorporado ao processo de definição da classe de eficiência energética do programa de etiquetagem de edificações residenciais brasileiras.

Objetivos

Desenvolver um método para permitir a integração de modelos BIM ao metamodelo de predição de carga térmica da Instrução Normativa do INMETRO para edificações residenciais (INI-R) utilizando arquivos de formato aberto (gbXML).

Objetivos específicos:

- Desenvolver uma ferramenta para extrair e transformar os dados relevantes de arquivos gbXML gerados por ferramentas autorais BIM para o metamodelo usado na INI-R;

- Comparar os arquivos gbXML gerados pelas diferentes ferramentas autorais BIM (Revit, ArchiCAD e OpenBuildings) para um estudo de caso;
- Analisar a aceitabilidade dos diferentes arquivos gbXML pela ferramenta de integração desenvolvida;
- Analisar o impacto das diferenças entre os arquivos gbXML nos valores de predição do metamodelos para diferentes climas brasileiros

Apresentação do artigo
O trabalho foi apresentado na forma de artigo científico publicado em periódico. O artigo tem as seguintes informações principais:

Título: **A metamodel to the Building Information Modeling-Building Energy Modeling integration in the early design stage**
DOI: https://doi.org/10.1016/j.autcon.2020.103422
Autores: M. K. Bracht, A. P. Melo, R. Lamberts

Os principais subcapítulos do artigo serão apresentados resumidamente a seguir:

Proposta de Instrução Normativa INMETRO para edificações residenciais (INI-R)
A proposta de Instrução Normativa do Inmetro para edificações residenciais (INI-R) é consequência da revisão dos Regulamentos Técnicos da Qualidade para o Nível de Eficiência Energética de Edificações Residenciais (RTQ-R) e Comerciais, de Serviços e Públicas (RTQ-C) (BRASIL, 2010, 2012).
Os regulamentos entraram em processo de revisão no ano de 2012 (CB3E, 2018a), resultando nas propostas de procedimentos denominadas Instrução Normativa do Inmetro para edificações comerciais, públicas e de serviço (INI-C) e para edificações residenciais (INI-R) (CB3E, 2018b). A INI-R classifica as edificações residenciais do nível 'A' (mais eficiente) até o nível 'C' (menos eficiente), avaliando a envoltória e o sistema de aquecimento de água. Para realizar a classificação da envoltória das unidades habitacionais, a INI-R apresenta três diferentes métodos de avaliação: prescritivo, simplificado e simulação (CB3E, 2018b). Para proceder com a determinação da classe de eficiência energética no método simplificado, as cargas térmicas integralizadas de refriamento e aquecimento da edificação real são comparadas com os resultados de carga térmica de um caso referência. O caso referência do método proposto na INI-R possui a mesma geometria e orientação solar da edificação em sua condição real e equivale à Classe C de eficiência energética (CB3E, 2018b). A predição das cargas térmicas integralizadas do método simplificado é realizada por metamodelos gerados a partir de simulações energéticas utilizando a ferramenta EnergyPlus (MELO et al., 2016). Assim, o metamodelo desenvolvido para o método simplificado da INI-R, a partir desse momento denominado Metamodelo INI-R, é capaz de predizer a carga térmica de resfriamento e aquecimento da unidade habitacional a partir de 24 parâmetros de entrada relativos a cada zona térmica (CB3E, 2018b). É importante ressaltar que os parâmetros de entrada são levantados para cada ambiente considerado de permanência prolongada da edificação em questão. A INI-R considera os seguintes ambientes como de permanência prolongada: sala de estar, sala de jantar, sala íntima, dormitórios, escritório, sala de TV e ambientes de uso similares aos citados (CB3E, 2018b).

Desenvolvimento da ferramenta de integração

Com o intuito de possibilitar a análise das vantagens e desafios da integração do BIM com modelos de predição caixa-cinza, como o Metamodelo INI-R, é proposto o desenvolvimento de uma ferramenta de integração. A ferramenta de integração objetiva vincular modelos BIM desenvolvidos por diferentes ferramentas autorais BIM ao Metamodelo INI-R por meio do esquema gbXML. A ferramenta de integração foi desenvolvida em linguagem Python, utilizando, principalmente, a biblioteca xml.etree.ElementTree (PYTHON SOFTWARE FOUNDATION, 2019).

Dos 24 parâmetros de entrada do Metamodelo INI-R, optou-se em contemplar no escopo do desenvolvimento da ferramenta de integração apenas as características geométricas e de uso das zonas térmicas da edificação, além de suas condições de exposição. Propriedades térmicas dos materiais e informações relativas ao funcionamento das esquadrias, como o fator de abertura para ventilação, são fixadas pela ferramenta de integração levando em consideração os valores do caso "referência" para o clima da cidade de Florianópolis, apresentado na INI-R (CB3E, 2018b).

Uma limitação encontrada no esquema gbXML durante o desenvolvimento dessa etapa foi a definição dos usos dos espaços encontrados no Building Information Model. Dentro do esquema gbXML é permitido nomear com liberdade o uso pretendido dos espaços da edificação, não existindo assim uma padronização. Dessa maneira, optou-se pelo estabelecimento de um padrão de nomenclatura com o intuito de classificar-se corretamente o uso do espaço. Outra questão encontrada foi a falta de "parametrização" de alguns critérios da INI-R, como por exemplo, a definição da exposição das superfícies. No texto da INI-R que se encontra em processo de revisão, não é apresentado atualmente o limite a ser considerado para definir um piso como "em contato com o solo" ou "entrepiso", por exemplo. Foi estipulado para a ferramenta um limite de 50%, entretanto, é importante adicionar esses limites oficialmente no texto final da INI-R.

Em resumo, a ferramenta de integração é capaz de automatizar os seguintes processos:

1. Leitura dos dados geométricos, condições de exposição e de uso das zonas térmicas do arquivo gbXML exportado de ferramenta autoral BIM, e a transformação desses dados nos parâmetros de entrada do Metamodelo INI-R;
2. Atribuição de valores padrões para os parâmetros relacionados às propriedades térmicas e funcionamento de esquadrias conforme o caso referência da INI-R;
3. Execução do Metamodelo INI-R conforme os parâmetros de entrada levantados e automaticamente atribuídos;
4. Apresentação da estimativa de carga térmica anual por ambiente de permanência prolongada do Building Information Model.

Validação da ferramenta de integração

Com o intuito de avaliar a flexibilidade da ferramenta de integração desenvolvida, assim como a consistência do esquema gbXML proveniente de diferentes ferramentas autorais BIM, foi estabelecida uma etapa de validação.

Essa etapa consiste no desenvolvimento de modelos BIM em três diferentes ferramentas autorais BIM: Autodesk Revit; Graphisoft ARCHICAD; Bentley OpenBuildings Designer CONNECT Edition. Após a finalização da modelagem foi realizada a exportação do modelo BIM para gbXML, permitindo a leitura do arquivo de interoperabilidade pela ferramenta de integração desenvolvida.

Para realizar essa tarefa foi estabelecido um caso teste baseado em uma tipologia residencial de projetos representativos de habitações de interesse social brasileiras levantados por Triana et al (2015). O caso desenvolvido é uma edificação residencial unifamiliar composta por dois dormitórios, uma sala com cozinha integrada e um banheiro.

Para a ferramenta Autodesk Revit, observou-se que a opção de exportação para gbXML "*Use Room/Space Volumes*" se apresenta mais alinhada com o método estipulado na INI-R. No caso do Archicad, duas diferenças principais foram observadas no processo de exportação e no arquivo gbXML gerado: Diferentemente do Autodesk Revit, o condicionamento ou não do ambiente é definido no nível de zona térmica e não de espaço; Todas as portas foram classificadas como "*OperableWindow*". As janelas também são classificadas no gbXML exportado pelo Archicad como "*OperableWindow*", sendo assim tornando impossível realizar a diferenciação desses dois tipos de objetos utilizando apenas esse atributo. Dessa forma, foi necessário deletar as portas antes de realizar o processo de exportação para o correto funcionamento da ferramenta de integração desenvolvida. Já o OpenBuildings da Bentley apresentou duas falhas na exportação: Duas superfícies foram perdidas no processo de transferência de informações que ocorre entre o OpenBuildings e o EnergySimulator e as superfícies do piso foram erroneamente exportadas como "*RaisedFloor*". Dessa forma, foi necessário realizar uma simplificação na modelagem geométrica do telhado da edificação para correção do erro relativo às superfícies perdidas e uma correção diretamente no código do arquivo gbXML para correção do segundo erro.

Ao se realizar a comparação dos três arquivos gbXML originados das ferramentas autorais BIM, observou-se uma diferença na maneira com que as paredes são consideradas e exportadas. No Autodesk Revit as paredes internas de cada zona térmica são modeladas justapostas (*centerline*), desconsiderando as suas espessuras. Enquanto no Archicad e o OpenBuildings, as paredes apresentam um pequeno espaço entre elas (*inside line*), considerando dessa forma sua espessura.

As diferenças entre os valores nos parâmetros de entrada provindo de cada ferramenta autoral BIM e o levantamento manual foram comparados. Foi possível observar que as principais diferenças se concentraram nas áreas de parede externa, reflexo da diferença na forma de consideração das paredes internas (*centerline* ou *inside line*). Dessa forma, a ferramenta Autodesk Revit apresentou as maiores diferenças para o levantamento manual. De forma contrária, os valores de área de cada ambiente do Autodesk Revit se apresentaram mais próximos aos do levantamento manual. Com essas diferenças nos valores de entrada, os resultados de predição do Metamodelo INI-R para diferentes climas brasileiros foram apresentados na forma de gráficos (Figure 12 e Figure 13).

Os erros associados as predições de carga térmica de resfriamento demonstraram que, com a correção do tipo de piso do arquivo proveniente do OpenBuildings, os maiores erros percentuais e as médias de erro foram do Autodesk Revit. Todos os casos mostraram uma tendência de subestimar levemente os valores de carga de resfriamento.

A mesma análise foi realizada para as predições de carga térmica de aquecimento. Como o inverno brasileiro apresenta temperaturas amenas em alguns dos climas analisados, os resultados de carga térmica só foram apresentados para 6 localidades.

De forma geral, os resultados para o arquivo gerado pelo Autodesk Revit apresentaram os maiores valores de erro. Diferente da carga de resfriamento, há uma tendência de superestimar os resultados de predição obtidos dos arquivos gerados pelo Autodesk Revit e OpenBuildings. O arquivo gerado pelo Archicad mostrou a melhor convergência de resultados. Em ambos os casos existe uma forte tendência de redução do erro com o aumento do valor absoluto da previsão de carga térmica.

Discussões e limitações

A ferramenta de integração idealizada foi desenvolvida com sucesso e o processo de validação proposto pode ser realizado. Foram encontradas limitações relacionadas aos padrões de nomenclatura de salas e a necessidade de algumas parametrizações extras no método descrito pela INI-R. Durante o processo de validação, foi necessário realizar simplificações em relação aos modelos BIM antes do processo de exportação para gbXML. No caso da ferramenta Autodesk Revit, nenhuma simplificação foi necessária, ao usar o Graphisoft Archicad foi necessário excluir as portas existentes presentes no modelo BIM. O OpenBuildings exigiu uma maior simplificação da geometria do telhado e uma intervenção manual no código do arquivo gbXML gerado, para corrigir o tipo de exposição do piso do edifício.

As principais limitações do trabalho são apresentadas a seguir: O caso teste proposto possui uma geometria simples; e os parâmetros considerados como fixos constituem uma simplificação da avaliação do desempenho térmico dos edifícios.

Conclusões

O objetivo deste estudo foi desenvolver um método para permitir a integração entre o metamodelo de predição de carga térmica da INI-R à modelos BIM para facilitar o processo de troca de dados. Dessa forma, uma ferramenta de leitura de arquivos gbXML foi proposta e um processo de validação desenvolvido.

Os resultados demonstram a viabilidade de desenvolvimento desta ferramenta de integração, o processo de validação apresentou pequenos erros nos valores de predição de carga térmica quando comparados a um levantamento manual e também considerando as diferentes ferramentas autorais BIM. Houve a necessidade de ajustes manuais nos modelos BIM nos casos utilizando Archicad e OpenBuildings. Portanto, foi alcançado um método de integração BIM-BEM semi-automático usando gbXML, com exceção do caso do processo utilizando o Autodesk Revit onde não houve necessidade de ajuste pelo usuário. Esse resultado reforça a necessidade de implementação padronizada de ferramentas de exportação para formatos abertos pelos fabricantes de software. O conteúdo deste trabalho representa um passo em direção aos estudos que visam o desenvolvimento de um método mais automatizado para a aplicação das normas de etiquetagem de edifícios. Também ajudará as equipes de design na exploração de alternativas de design de uma maneira prática e aberta.

Palavras-chave: BIM; gbXML; Predição de carga térmica, Integração BIM-BEM. Metamodelo de predição de desempenho; Interoperabilidade.

ABSTRACT

The use of energy simulations is not yet fully inserted in the building design process. A promising solution for the integration of energy simulation tools in the design process can be achieved by using building information models (BIM). The integration of BIMs with energy analysis models (BEM) during the life cycle can reduce rework and facilitate the evaluation of different design alternatives. However, complete interoperability in the BIM-BEM integration process has not yet been achieved. Performance prediction metamodels can assist in solving this challenge and allow for quick analysis in the early design phases. Thus, this work presents the process of development and validation of an integration method between Building Information Models and the thermal load prediction metamodel developed for Inmetro's Normative Instruction for residential buildings (INI-R).

The integration method is based on a tool developed in the Python language to extract the data found in the files based on the gbXML scheme, proceed with mathematical and logical transformations, and correctly fill in the parameters of the developed metamodel. One single-family residential building was modeled on three different BIM authoring tools to validate the integration tool developed and test the consistency of the gbXML scheme.

The results demonstrate the feasibility of developing the integration tool, however, they point out some differences between the gbXML files originated from different BIM authoring tools. Also, differences were observed between values of input parameters when comparing the manual and the automated survey from the gbXML file, mainly in the parameters related to the external wall areas. Thus, resulting in differences in the thermal load prediction value obtained by the metamodel.

It was possible to conclude that the BIM models can be integrated to a metamodel of performance prediction using the gbXML in a semi-automatic way. The work reinforces the need for standardization in the implementation of export tools for open file formats by software developers. It also indicates the possibility of future use of the method to assist in the energy labeling process of Brazilian buildings and support designers in the initial design stages.

Keywords: BIM; gbXML; Thermal load prediction; BIM-BEM integration; Performance prediction metamodel; Interoperability

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ABDI	Agência Brasileira de Desenvolvimento Industrial
API	Application Programming Interface
ASHRAE	American Society of Heating, Refrigerating and Air Conditioning Engineers
BIM	Building Information Modelling
CAD	Computer Aided Design
DXF	Drawing Exchange Format
gbXML	Green Building eXtensible Markup Language
IDF	Input Data File
IDM	Information Delivery Manual
IFC	Industry Foundation Classes
INI-C	Instrução Normativa do Inmetro para edificações comerciais, públicas e de serviço
INI-R	Instrução Normativa do Inmetro para edificações residenciais
ISO	International Organization For Standardization
MDIC	Ministério da Indústria, Comércio Exterior e Serviços
MVD	Model View Definition
PSets	Property Sets
RTQ-C	Regulamento Técnico da Qualidade para o Nível de Eficiência Energética de Edificações Comerciais, de Serviços e Públicas
RTQ-R	Regulamento Tëcnico da Qualidade para o Níve de Eficiência Energética de Edificações Residenciais
XML	eXtensible Markup Language
W3C	World Wide Web Consortium

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1 INTRODUCTION

The way buildings are designed has a substantial impact on their future energy demand. Early design decisions may affect the performance of the building during operation. Changes on the construction materials, window openings and sizing can improve the capacity of buildings to operate with passive strategies, as natural ventilation, to provide cooling for its occupants (MÉNDEZ ECHENAGUCIA ET AL., 2015; NEGENDAHL, 2015; ØSTERGÅRD ET AL., 2017). The designer must consider many different aspects and strategies about the building environment to achieve an optimized solution. In this way, the development of computational tools is considered essential to assist the design process (HENSEN; LAMBERTS, 2019).

A promising solution related to the integration of building simulation tools into the design process is the use of building information models (BIMs). The integration of BIMs with building energy models (BEMs) throughout the building life cycle is aimed at reducing the amount of reworking and simplifying the evaluation of different parameters, from the early design stages to the occupation of the building (ANDRIAMAMONJY ET AL., 2019). However, there are limitations regarding the BIM-BEM integration topic. Manual information transcription processes still occur in workflows related to energy simulation tools. These processes take a lot of time and effort, reflecting on potential errors and misassumptions in the workflow (GAO ET AL., 2019; KAMEL; MEMARI, 2019).

Tradicional energy simulation tools require a high number of input parameters and present computation times that generate challenges regarding the BIM-BEM integration during the design process. The development of performance prediction metamodels can help to overcome this issue. Metamodeling can be understood as a method for constructing fast and simplified models that correlate inputs to outcomes obtained by more complex mathematical models, such as energy simulation tools (ØSTERGÅRD ET AL., 2017).

Integrating BIMs with prediction metamodels could enable a more dynamic and effortless process to evaluate the thermal performance of buildings. Furthermore, some energy efficiency labels worldwide are based on prediction metamodels. The integration of these metamodels to BIM authoring tools could enable a more robust and replicable method for classifying and issuing energy efficiency labels. Thus, leveraging the insertion of labeling in more building design processes and increasing the results consistency, as recommended by Li et al (2019).

One example of such prediction metamodel was adopted in Brazil. The Inmetro Normative Instruction proposal for residential buildings (INI-R) is part of the Brazilian labelling program for buildings. In its method, the integrated cooling and heating thermal loads of the actual building are compared with a baseline building. The prediction of the integrated thermal loads is performed by metamodels, developed based on energy simulations, adopting Artificial Neural Networks techniques.

In this context, this work aims to explore the possibility of integrating building information models with a thermal load prediction metamodel, using the previously developed metamodel for INI-R's thermal load prediction process.

1.1 OBJECTIVES

1.1.1 Main objectives

Development of a method to enable the integration between Building Information Models and the metamodel for INI-R's thermal load prediction metamodel using an open file format (gbXML).

1.1.2 Specific objectives

a) To develop an algorithm to extract and transform the relevant data from gbXML files generated by BIM authoring tools into the metamodel used in the new Brazilian labeling proposal for dwellings;
b) To compare gbXML files generated by different BIM authoring tools (Revit, ArchiCAD and OpenBuildings) for a case study;
c) To analyze the acceptance of the different gbXML files by the developed integration tool for the case study;
d) To analyze the impact on the differences between the gbXML files in the prediction values of the metamodel for different Brazilian climates.

2 LITERATURE REVIEW

2.1 ENERGY PERFORMANCE IN BUILDINGS

Energy simulation can be understood as a representation of the building in the form of a computational model in a specialized software. It allows detailed analyzes of the building's energy consumption and specific parameters, such as studies of natural and artificial lighting, natural ventilation, dimensioning air conditioning equipment, among others (AL-HOMOUD, 2001).

The processes involving energy simulations are considered as an assisting tool to support the decisions of the design team. It is possible to analyze the impact of each design change, both in geometric and physical properties terms, within the context of the climate of the building site. The sooner the design team starts conducting energy simulations within the building design process, the more impactful are the changes and it will be easier to achieve good results (LAMBERTS ET AL., 2014).

However, these complex simulation tools are based on physical principles and require several detailed input parameters for the building and its surroundings. Often, these parameters are not available in the early design phase or are difficult to obtain accurately. This lack of precision in the input parameters leads, consequently, to a loss in the reliability of the simulation result, distancing the output of the computational analysis from the real situation of the building (BORGSTEIN ET AL., 2016). Also, the use of simulation tools usually requires specialized technical work, making the activity expensive within a traditional design process (ZHAO; MAGOULÈS, 2012).

Already in 2008, Bazjanac (2008) pointed out the following limitations of the traditional thermal performance prediction process:

1. Thermal simulations are very costly and intensive in specialized labor, consuming a long time;
2. The simulation results are not reproducible due to the various simplifications related to the building's geometry and data related to the use and occupation of spaces, that have to be made by the person responsible for the simulation;

3. The architectural and HVAC design must traditionally be well developed to provide the necessary information for the thermo-energetic simulation to be run, reducing the chance of early optimizations in some fundamental aspects of the building and its systems;
4. The preparation of input information for the simulation is manual, laborious, and costly, increasing the chance of errors and thus affecting the quality of the simulation results.

The prediction tools for thermal performance are not fully integrated into the digital design and planning processes, wasting the advantage of the continuous information flow that digital modeling provides. Information related to energy simulation must be manually reinserted, even if it is already available in modern design tools (such as BIM authoring tools) (GAO ET AL., 2019).

The common practice of energy simulation is restricted to the later stages of the design process and the analysis of a single design solution and not a variety of alternatives and options (HENSEN; LAMBERTS, 2019). The insertion of simulations in earlier design phases would allow the comparison of different design alternatives in terms of energy efficiency. These analysis in the initial design phase can help owners and designers to make more informed decisions regarding the characteristics of the building envelope, as well as the air conditioning, water heating, and lighting systems (GARCIA; ZHU, 2015).

Recently, different ways, from the simplest to the most complex, of predicting the energy consumption of buildings have been proposed and applied to a variety of problems (ZHAO; MAGOULÈS, 2012).

2.1.1 Performance prediction models

Energy consumption prediction models development can be divided into three main categories: white-box, black-box, and gray-box models.

The white-box or forward-approach models are based on physical principles to perform thermodynamic and energy behavior calculations of the building. These calculations are performed over time (step-by-step) based on a series of input parameters, regarding climatic data, construction materials, occupancy and operation patterns, energy tariff costs, and HVAC and lighting systems. In this way, the simulation solves a series of equations of heat transfer phenomena and returns the building's energy consumption as a result. It is also possible to extract a series of parameters and intermediate outputs, such as heat transfer rates in specific elements or values of thermal loads of each thermal zone (FOUCQUIER *et al.*, 2013).

White-box models have been under development for over 50 years (FOUCQUIER *et al.*, 2013), giving rise to consolidated simulation engines such as EnergyPlus (ENERGYPLUS, 2019). The increase in the sophistication of techniques and computational power available to researchers and developers allowed white-box models to provide a high degree of precision in predicting results (HARISH; KUMAR, 2016).

A challenge of white-box models refers to the detailed description and understanding of the physical phenomena involved, mainly mechanisms of heat transfer occurring in the building envelope. In other words, the degree of accuracy of the white-box models depends on the complexity of the geometric model, the amount of information inserted in the energy simulation tool, and, also, by the person responsible for the energy simulation, an understanding of the physical phenomena to assess the quality of the results obtained (FUMO, 2014).

Otherwise, black-box models statistically correlate historical energy consumption data with input variables adopted. Thus, to achieve a satisfactory quality of prediction, the prediction models must be based on a large amount of high-quality data. This method is usually adopted to solve one of the three following problems: to predict energy consumption based on simplified variables, to predict energy indexes, or to estimate important parameters related to heat transfer of building elements (ZHAO; MAGOULÈS, 2012).

The most relevant difference between black-box and white-box models is that the first one does not require any physical information and specific geometric or thermal parameters to perform the prediction. The black-box model deducts consumption statistically based on the examples provided during its development, involving no heat transfer or any physical equations in the problem-solving process. The advantage of black-box models is that they can be used when there is no detailing of the building geometry or the physical phenomena involved. However, these models are dependent on a large amount of data to be successfully implemented (FOUCQUIER *et al.*, 2013).

Finally, the gray-box or hybrid models, as the name implies, are a mixture between the two previously presented models, being able to analyze the energetic behavior of the building when the information is incomplete or with some degree of uncertainty involved (ZHAO; MAGOULÈS, 2012).

Two main steps must happen to proceed with the development of the gray-box model. First, a mathematical model of the building and its systems should be developed to ascertain the impacts of different input data on the result of energy consumption. Then, statistical analysis should be employed to identify and quantify the necessary parameters to estimate energy performance in a satisfactory manner (FUMO, 2014).

The great advantage of gray-box models is the reduction of the amount of input data needed for the prediction of the determined output, while still maintaining a physical interpretation of the phenomenon. A more general description of the geometry and its thermal parameters is sufficient, allowing its application in cases in which the input data are still incomplete or with reduced detail, for example, in the early design phases (FOUCQUIER *et al.*, 2013). Table 1 summarizes the three different prediction methods.

Table 1 – Comparison between the three different prediction models.

Methods	Building geometry	Training data	Physical interpretation
White-box	Detailed description of the geometry is required	No training needed	Results can be interpreted physically
Black-box	Detailed description of the geometry is not required	A large amount of data collected over a long period of time is required	There are several difficulties to interpret results in physical terms
Gray-Box	An approximate description of the geometry is sufficient	A small amount of data collected over a short period of time is required	Results can be interpreted physically

Source: Adapted from Foucquier et al., 2013.

Amasyali e El-Gohary (2018) claim that different prediction models meet different needs. There is no perfect model for all cases, and it is necessary to develop specific models for each application.

Artificial neural networks are the most used artificial intelligence method for predicting the energy consumption of buildings. The advantage of this method is the ability to solve non-linear and complex problems such as those involved in forecasting energy consumption. In recent years, artificial neural networks have been used to predict energy consumption in different situations, such as heating/cooling thermal loads, energy consumption, usage/occupation estimates, among others (ZHAO; MAGOULÈS, 2012).

Artificial neural networks can learn from examples, tolerate noise, and, after being trained, can predict consumption results and identify patterns and relationships between input parameters and results (KALOGIROU; BOJIC, 2000).

The parameters to perform model training can be obtained from measurements in the field, questionnaires, data collection of energy bills, or even by energy simulations (ZHAO; MAGOULÈS, 2012).

Several researchers (YOKOYAMA; WAKUI; SATAKE, 2009; KALOGIROU; BOJIC, 2000; NETO; FIORELLI, 2008) developed neural network models to predict the demand for cooling, heating, or energy consumption of buildings. Most of these authors, however, considered a low number of different geometries to form their training database, reducing the applicability of their prediction metamodels to the geometries for which they were designed.

Melo et al. (2016) compared the multilinear regression method used in the simplified method of the Technical Regulation of Quality for the Level of Energy Efficiency of Residential Buildings to artificial neural networks to predict the thermal performance of a wide variety of typologies and different geometries of dwellings, both naturally ventilated and mechanically conditioned. The results showed a significant improvement in the prediction results when using the artificial neural networks in face of the multilinear regression previously used in the technical regulations of the Brazilian Labeling Program.

It is important to note that all artificial neural networks are trained using a specific database, that is, for a new strategy or different constructive typology to be correctly evaluated, it must be previously included in the database used. If this criterion is met, the method is able to accurately estimate the energy consumption of buildings (MELO, 2012).

2.2 BIM – BUILDING INFORMATION MODELLING

The ISO 19650-1:2018 standard defines Building Information Modelling (BIM) as the use of a shared digital representation of a built asset to facilitate design, construction and operation processes to form a reliable basis for decisions (INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, 2018). This representation exists in the form of a three-dimensional object-oriented model that facilitates interoperability and the exchange of information between different software tools. BIM tools allow parametric modeling and provide opportunities for spatial visualization, simulations of building behavior, and more efficient project management. BIM's collaborative character is often cited in the literature (EL-DIRABY; KRIJNEN; PAPAGELIS, 2017; MIETTINEN; PAAVOLA, 2014). By extending its application between different phases of the building's life cycle, a new level of information exchange between the stakeholders becomes viable. The collaboration provided is cited as a factor in reducing design errors and increasing productivity (MIETTINEN; PAAVOLA, 2014).

According to Costa et al. (2013), a Building Information Model consists of two main components: 1. A three-dimensional and parametric graphic reproduction of the building's geometry; 2. A database in which all the information, properties, and relationships of the building's elements are saved. These two main components together make the digitally represented elements understand their function, how they behave, and how they are eventually related to other objects.

It is important to differentiate the concepts of Building Information Modelling and Building Information Model. The General Services Administration, the institution that manages public buildings in the USA, presents them in a way that the first consists of the verb, that is, the process of developing and using an information model, not only to extract documentation but also to simulate the construction and operation phases of a building. The second, the noun, is understood as the result of the process previously presented (GSA, 2007).

Succar (2009) presents the idea that the BIM methodology consists of processes, technologies, and people, linked together with the use of procedures, standards, and best practices. Thus, reinforcing that BIM is not just a technology, but a much extensive change in the culture of organizations.

The BIM methodology could facilitate that the consultants from different disciplines to be involved in the earlier stages of building design. It would enable the proposal and evaluation of alternative solutions, guided by Life Cycle Analysis and simulated performance, considerably optimizing design alternatives under the most diverse aspects (ELEFTHERIADIS; MUMOVIC; GREENING, 2017). Otherwise, Miettinen & Paavola (2014) introduce a more critical point of view, which stated that all new technologies promise to improve production activities. This potential is always presented in a futuristic view of the advantages that will be achieved when the new technology is fully implemented. In the case of the construction industry, the main concern is to improve the productivity and efficiency of the processes. BIM, with its promises to reduce design errors, increase design quality, optimize communication and collaboration between all stakeholders, emerges as a great solution to the main problems in the industry. This view is called by the authors “BIM utopia” or idealized goals of BIM. Eastman et al. (2011) cite the fact that the term BIM has been popularized by software vendors as a "buzzword", making it susceptible to variations in interpretation and confusion.

Most of these BIM promises are based on the idea of interoperability and the complete integration of information produced in the construction industry processes, made possible by Information Technologies in Construction, and by established standards. It is discussed, however, how much that promise can be achieved in practice. A more realistic view is to interpret BIM as a set of multidisciplinary software and instruments that will become more and more integrated. However, it is impossible to define the final level of integration to be achieved between the tools, removing the more utopian concept that all tools would exchange data without any loss in any process to which they were submitted (MIETTINEN; PAAVOLA, 2014).

As previously discussed, BIM allows its application in the different phases of the building's life cycle. The first researches on the subject focused mainly on improvements in the building design, planning, and budgeting process (ANDRIAMAMONJY; SAELENS; KLEIN, 2019). The main benefits sought when implementing the BIM methodology are still focused on automating the modeling process, improving documentation, and communication between the design and construction teams. However, the use of BIM has been expanding as researchers and users perceive other potentials to be explored (KAMEL; MEMARI, 2019).

Andriamamonjy, Saelens & Klein (2018) proposes, based on a scientometric review, a division of the BIM theme into six main research areas:

1. Benefits of BIM and its adoption: two more general and interconnected themes, since a more comprehensive adoption of the BIM methodology depends on a clear and objective way of quantifying its advantages;
2. Management: covers a wide range of management problems that occur in the construction process and has the potential to be reduced with the use of BIM. Topics related to occupational safety management, waste, suppliers, and maintenance are some examples;
3. Construction monitoring and as-built modeling: studies that deepen the use of different remote sensing technologies to monitor the progress of building construction and automate the modeling of existing buildings;
4. Interoperability: the ability to exchange information between different software is crucial for the construction industry and the maturity of BIM. When functional, interoperability allows the exchange of digital information between different disciplines, reducing rework and the use of traditional design documents. Problems related to the theme arise when certain data do not have the potential to be correctly exported and read by the tools or when the software uses proprietary information models;
5. Reduction of incorporated energy: the potential benefits of integrating BIM with life cycle analysis are investigated;
6. Energy simulation: the integration between BIM and energy simulation and prediction tools is studied and its challenges and potential benefits are addressed.

The development of BIM promises to facilitate the insertion of energy simulations during the different stages of the building design process. Due to its characteristic of acting as a database, it allows information from multiple disciplines to be inserted into the model, as well as the thermophysical and geometric characteristics of the building, potentially facilitating the simulation. However, the lack of proper implementation of standards and interoperability solutions are presented as factors of difficulty in carrying out the integration process and end up reflecting on the increase in research in relation to the theme (KRYGIEL; NIES, 2008).

2.3 BIM INTEGRATION WITH THERMO-ENERGY PERFORMANCE PREDICTION TOOLS

BIM promises to integrate the energy analysis tools throughout the design process, reducing reworks and making them more accessible for the evaluation of different parameters, from the early design stages until during the occupation of the building (ANDRIAMAMONJY; SAELENS; KLEIN, 2019).

Traditionally, energy simulation is carried out only after the initial phases of the architectural project are already completed, being performed by a specialist. This professional manually inserts a series of data and recreates the building's geometry based on two-dimensional drawings, models, and spreadsheets within the simulation tool. According to Andriamamonjy et al (2019), the integration of energy simulation with BIM removes manual processes and drastically reduces the rework required to perform energy simulations. Also, documentation and standardization of the energy analysis data decrease the chance of errors and assumption changes during the process.

The integration of energy simulation and BIM occurs when using the design information inserted in the Building Information Model (for example, building geometry, internal thermal loads, material properties, and systems) to establish the input parameters for the simulation tools. In this way, providing a reduction in time and cost to perform the simulation, as well as more consistent and reproducible data entry (GAO; KOCH; WU, 2019).

Bazjanac & Crawley (1999) demonstrated some potential advantages with the use of interoperability between Building Information Models with energy simulation tools through the first versions of the IFC scheme (Industry Foundation Classes). They cited aspects related to cost and time reduction, as well as reducing duplicate information and errors in the execution of the energy simulation as the main advantages.

Schlueter & Thesseling (2009) argue about the need to use energy simulation tools in the early design phases and highlight the absence of methods for the integration of Building Information Models with the simulation tools at the time. The authors developed a plugin using the Application Programming Interface (API) of the Autodesk Revit tool to integrate the BIM model with a heat and loss gain prediction tool, based on a metamodel used in the German energy conservation regulation. The results presented a variation of less than 5% was found in the prediction values among the prototype and the traditional simulation tools. This study constitutes one of the first presentations of the benefits of BIM for energy simulation.

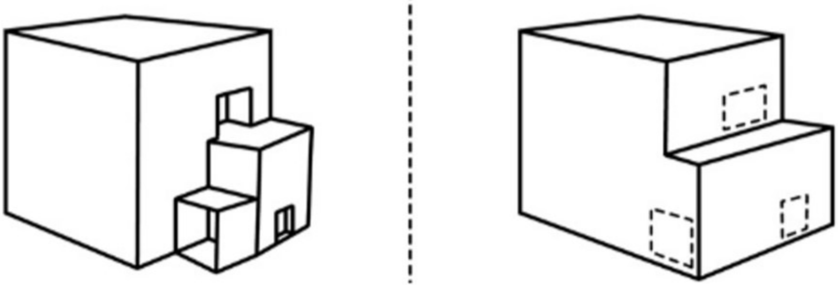
Hamedani & Smith (2015) explored the potential outcomes related to the integration of BIM and energy simulations in the early design phases. The authors argued that there was a deficiency in available methods to integrate prediction tools to the BIM authoring tools.

O'Donnell et al. (2013) concluded that the main benefits of the integration between BIM and the thermal performance prediction tools are:

1. Minimize the amount of time and cost to prepare the building model for the energy simulation;
2. Provide quick generation of project alternatives;
3. Increase the geometric accuracy of the energy simulation models;
4. Improvement of the energy performance of the proposed buildings using an integrated method when compared to the practice based on manual data exchanges and two-dimensional drawings.

One of the main differences between the data of a traditional BIM architectural model and a model for energy analysis is the way that the building's geometry is declared and represented. An architectural BIM model typically contains detailed, high-level information about all elements of the building. The internal and external walls, for example, are defined representing all three-dimensional details of their shape. A energy analytical model is defined geometrically from a thermal point of view. That is, the geometry is simplified in the form of several two-dimensional planes. Most energy simulation tools apply heat transfer calculations in a one-dimensional way, so the transfer is considered to occur only perpendicularly to each surface, and heat transfers in the other dimensions are ignored (GAO; KOCH; WU, 2019). Also, walls and other surfaces must be subdivided to allow calculations of heat transfer between different thermal zones, construction patterns, and exposure conditions (internal or external walls, for example). This behavior in the treatment of surfaces is called 2nd Level Space Boundary, being mainly used for the exchange of information related to energy simulation[1]. Otherwise, the 1st Level Space Boundary doesn't subdivide the surfaces, and its use is more restricted to architectural processes and surveying of quantities (WEISE *et al.*, 2011). When the simplification process is carried out manually, this activity is performed by the person responsible for the energy simulations. Thus, the specialist performs simplifications and subjective adjustments in the building geometry to enable its analysis and reduce the simulation time, as shown in Figure 1. It is important to note, however, that with each change in the architectural design, this model must be re-analyzed and its modifications passed on to the simplified model (NEGENDAHL, 2015).

Figure 1 – Differences between a geometric (left) and analytical model (right).



Source: Adapted from PINHA, 2017.

This particularity in the difference in the declaration of geometry reflects the difficulty of exchanging the geometric information contained in a BIM model to the energy simulation tools. Because, to remove the manual input of the person in charge of energy modeling, all these transformations must be carried out by algorithms adapted to the different types and construction assemblies found around the world.

Recently, there has been a movement by BIM tools developers to offer energy performance analysis tools integrated with their BIM authoring tools. Autodesk offers Insight 360 integrated with Revit (AUTODESK, 2019), Graphisoft integrates EcoDesigner Star with Archicad (GRAPHISOFT, 2019) and Bentley offers OpenBuildings Energy Simulator together with OpenBuildings Designer (BENTLEY, 2019). However, all of these performance analysis tools are integrated with BIM

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[1] There are also the 3rd, 4th and 5th Level Space Boundary, as defined by Bazjanac (2010). However, they will not be discussed in this work.

authoring tools using proprietary data formats, not solving the interoperability problems between different modeling and performance prediction tools. Thus, researchers have been proposing alternatives in search of solutions and improvements to allow interoperability between these tools in a more open way (PINHA, 2017).

2.3.1 Interoperability in the BIM context

Interoperability is understood as the possibility of communication, exchange, and use of data between two (or more) software (ABANDA; BYERS, 2016). In the case of buildings, there is a loss of information at every transfer of construction documents (architect to energy consultant, the design team to the main contractor, main contractor to the building administrator, etc) (COSTA *et al.*, 2013).

This exchanging and using data are crucial for a collaborative environment, such as a building project. The interoperability between BIM tools makes it possible to share information between the different disciplines involved, reducing the use of traditional documents and enabling the collaboration and optimized communication promised by the introduction of the BIM methodology in civil construction processes (ANDRIAMAMONJY; SAELENS; KLEIN, 2019).

In the context of the integration of energy simulation in design processes, the lack of interoperability between the design and simulation tools ends up generating a large consumption of work and time, distancing users from carrying out simulations and resulting in decisions based only on the designer intuition (KIM, Hyunjoo; ANDERSON, 2013).

Most of the information needed for energy analysis is produced during the design phase by the team of architects and engineers. If this information is captured and shared with the simulation software, the work required to gather and check the information is drastically reduced. It is pointed out by Kim e Anderson (2013) that the time to interpret and reconstruct a geometry of a Building Information Model into an energy simulation program can correspond to 50% of the total time required to perform the complete energy simulation process.

Thus, two alternatives appear more clearly as schemes for exchanging information in the field of BIM and energy efficiency simulation: the IFC and the gbXML.

2.3.1.1 Industry Foundation Classes

The Industry Foundation Classes (IFC) is a product data model geared to the needs of the construction industry, internationally accepted and supported by the ISO-16739 standard (EASTMAN *et al.*, 2011). It emerged from the “Industry Alliance for Interoperability” consortium founded in 1995 among twelve companies interested in developing tools and techniques that would make it possible to integrate the different software available on the market. After successive changes and evolutions, this private alliance has become a non-profit organization known since 2008 as buildingSMART, responsible, therefore, for the development and maintenance of the IFC scheme (BUILDINGSMART, 2019).

The IFC aims to enable data exchanges during the entire life cycle of buildings. Consequently, the scheme becomes quite complex and presents redundancies in the form of a declaration of elements (EASTMAN *et al.*, 2011).

The IFC data schema is decoupled from the programming language and, therefore, is available in several formats, for example: ISO STEP-EXPRESS (related to ISO 10303-21) and XML (Extensible Markup Language). As the IFC is complex and comprehensive, some information exchanges do not require the whole scheme, specific parts of the code can be exchanged using a “Model View Definition (MVD)” (CEMESOVA; HOPFE; MCLEOD, 2015). The MVD is a transcription into the technical domain of the necessary information collected by the Information Delivery Manual (IDM) method. The IDM is a method defined by ISO 29481-1 (INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, 2016) as a standardized way of gathering and documenting the information needed to carry out a process within the construction industry (MACIEL, 2018). Thus, an MVD emerges based on these requirements gathered and defines a subset of the IFC scheme in a way that is interpretable by computational tools, satisfying the different information exchange requirements of the construction industry (BUILDINGSMART, 2018).

2.3.1.2 gbXML

gbXML was developed to facilitate the transfer of necessary information for energy analysis and simulations (EASTMAN *et al.*, 2011). Thus, because its objective is restricted to a specific information exchange process, it offers better support for the integration between BIM and energy simulation tools (CEMESOVA; HOPFE; MCLEOD, 2015), mainly because of its ability to incorporate thermal information from the building components and thermal zones (ABANDA; BYERS, 2016).

The gbXML scheme is supported by the construction industry and widely adopted by software vendors such as Autodesk, Trimble, Graphisoft, and Bentley. It is currently present in more than 40 energy simulation tools. It was developed based on XML (eXtensible Markup Language), a computer language that allows computer programs to exchange information ideally independent of human interference (gbXML, 2019).

XML was developed in 1996 as part of the World Wide Web Consortium (W3C) based on some objectives where the following are highlighted (W3C, 2008):

1. XML must be fully adapted to the Internet;
2. XML must support a wide variety of applications;
3. The development of tools that process XML documents must be simple;
4. XML documents must be interpretable by humans and reasonably clear;
5. XML documents must be simple to create.

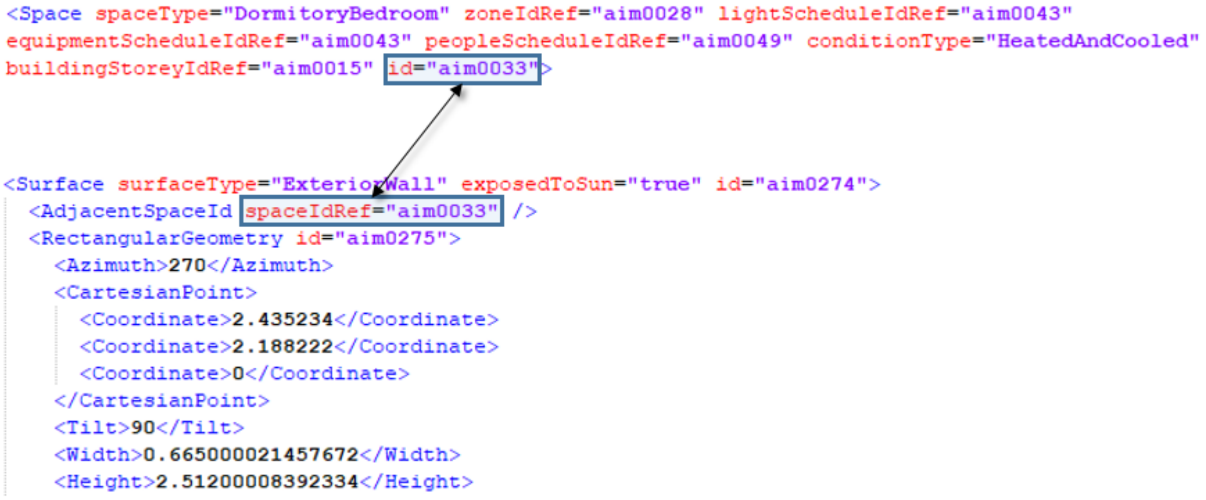
Thus, it is possible to open an XML document and understand its basic structure without having advanced programming knowledge. An XML schema describes the structure of an XML document. The gbXML scheme consists of more than 500 types of elements and attributes to describe various aspects of the building related to parameters for energy simulation (gbXML, 2019). gbXML is presented as a tree structure, as follows:

- *gbXML*
  - *Campus*
    - *Building(s)*
      - *Space(s)*
        - *More nested elements...*
    - *Surface(s)*
      - *Opening(s)*
    - *Construction(s)*

- *Layer(s)*
- *Material(s)*
- *Meter(s)*
- *Zone(s)*
- *Schedule(s)*
- *Result(s)*
- *DocumentHistory*

Contrary to what one might imagine, the elements of surfaces, constructions, and usage patterns are not declared within the building description, but independently. A shared attribute is used to connect them to the description of the building. In Figure 2 an example of a connection between a space and an external wall is presented using the attribute 'id'.

Figure 2 – Shared attribute connecting an external wall to a space.



```
<Space spaceType="DormitoryBedroom" zoneIdRef="aim0028" lightScheduleIdRef="aim0043"
equipmentScheduleIdRef="aim0043" peopleScheduleIdRef="aim0049" conditionType="HeatedAndCooled"
buildingStoreyIdRef="aim0015" id="aim0033">


<Surface surfaceType="ExteriorWall" exposedToSun="true" id="aim0274">
  <AdjacentSpaceId spaceIdRef="aim0033" />
  <RectangularGeometry id="aim0275">
    <Azimuth>270</Azimuth>
    <CartesianPoint>
      <Coordinate>2.435234</Coordinate>
      <Coordinate>2.188222</Coordinate>
      <Coordinate>0</Coordinate>
    </CartesianPoint>
    <Tilt>90</Tilt>
    <Width>0.665000021457672</Width>
    <Height>2.51200008392334</Height>
```

Source: Elaborated by the author.

Compared to IFC, which tries to cover all the exchange processes of a building, gbXML is specially developed to facilitate the transformation of data from a BIM tool to an energy analysis tool. Thus, gbXML accepts only rectangular shapes, which is usually adequate for the energy simulation of most types of buildings (GAO; KOCH; WU, 2019).

The main differences between the IFC and gbXML schemes are summarized in Table 2. According to Kamel e Memari (2019), the two data models are developed with different approaches. IFC uses a bottom-up approach, and gbXML, a top-down approach. The top-down approach consists of first elaborating the general design of the system and proceeding to detail its parts as in a tree. In the case of the bottom-up approach, the pieces that constitute the whole are declared individually and form the systems based on associations promoted among themselves (JALAEI; JRADE, 2015). Both theoretically allow the transfer of material-related properties, limited data from air conditioning systems, and information from thermal zones (KAMEL; MEMARI, 2019).

Table 2 – Comparison between gbXML and IFC schemes for energy simulation.

Caractheristics	gbXML	IFC
Geometry representation	Only rectangular geometry	Any geometry
Data structure	XML	IFC, PKZIP and XML
Data structure approach	Top-down approach with relatively more complex representation	Bottom-up approach with relatively more straight forward representation
Domain of application	Mostly energy simulation domain	Different domains such as building construction to building operation
Capability of defining thermal zones	Yes	Yes
Location (Weather data)	Yes	No
Standard for minimum content for a certain type of model and using subsets	No	Yes – there is MVD standard for IFC and IDM capabilities
Material thickness	Yes	Yes
Limited data related to HVAC system	Yes	Yes

Source: Adapted from KAMEL & MEMARI (2019).

Osello et al. (2011) performed comparative interoperability tests between Autodesk Revit and energy simulation software (including Ecotect, IES-VE, TRNSYS) using three different interoperability schemes: IFC, gbXML, and DXF (Drawing Exchange Format). Also, they defined a set of best practices for the development of BIM models that would facilitate the data exchange for conducting energy simulations. In this comparison, gbXML presented the best support for the exchange of information among the three schemes studied. The gbXML scheme was able to transmit the building geometry, the building components, the building location and orientation, the thermal zones, and the shading devices of the model developed in Revit to the simulation tools. Table 3 shows a comparison between the three schemes of one of the case studies demonstrated in the work. It is important to note that the tests developed in the article were performed with the IFC2x3 version. Currently, the IFC4 version is already available and documented by BuildingSmart. However, few commercial BIM tools have incorporated the new possibilities for data exchange made possible by the most updated version of IFC (ANDRIAMAMONJY; SAELENS; KLEIN, 2019).

Table 3 – The interoperability test results of a case study.

Property	DXF	IFC	gbXML
Drawing units	X	-	X
Thermal zone	-	X	X
Geometry	X	X	X
Building components	-	-	X
Location	-	-	X
Building type	-	-	X
Building servisse	-	-	-
Building materials	-	-	-
Material thicknesses	X	X	X

Source: Adapted from OSELLO et al. (2011).

gbXML, compared to IFC, within the specific domain of energy simulations, presents a higher level of development, including in information transfers not only data related to the geometry of the building but also the location, the type of building, and the construction data of the elements. However, information related to materials, for example, still needs to be re-entered manually in the format (GAO; KOCH; WU, 2019).

2.3.2 Current applications and challenges for the integration of BIM and energy simulation

Full interoperability between BIM and energy simulation tools, despite efforts, is not yet fully achieved. Losses of data and information, inconsistencies in the geometric transformations of the building envelope, and different ways of modeling BIM elements are still common barriers in the processes of data exchange between BIM and energy simulation tools (KAMEL; MEMARI, 2019).

Kim & Woo (2011) compared the differences in the results of energy simulations using the manual approach with a process based on BIM tools using the gbXML scheme. The results showed that despite the use of BIM promising to facilitate the insertion of energy simulation, the lack of data, and the use of automatic assumptions caused significant differences between the results. Assumptions regarding the air conditioning system were responsible for most of the differences in the outcomes. There were also problems with surface transformations, where a ceiling element was transformed into an external shading element during the data exchange process. With the manual correction of the mistaken assumptions and transformation errors, the difference between the energy consumption prediction results of the two methods were reduced to only 2.2%.

Prada-Hernández et al. (2015) analyzed the interoperability process between Autodesk Revit and eQUEST and IES-VE simulation tools using a case study of a single-family building as a "basic model" and a mixed-use multi-story building as a "complex model". Several modifications and simplifications in the geometry of the Building Information Model had to be carried out within the BIM authoring tool to enable the correct exchange of geometry. In this way, the results demonstrated that the interoperability between the tools still does not occur consistently as promised by different software developers.

Shadram & Mukkavaara (2018) proposed a framework to integrate a BIM model developed in Autodesk Revit with OpenStudio using gbXML to perform an optimization between embodied and operational energy. The authors observed the high computational use required to perform all the necessary simulations and the processes involved in exchanging data, making its practical application unfeasible to support the design process.

It is important to highlight that the gbXML scheme can store and, theoretically, transmit information that was not found in the previously reported data exchange processes. However, the commercial tools developed to allow the writing and reading of the interoperability files are not able to map this information. For example, information related to occupation schedules are covered by the gbXML scheme. Nonetheless, OpenStudio is unable to read the information contained in the file and, consequently, this information is lost in the export and import process (KAMEL; MEMARI, 2019).

Three main strategies were mapped by Andriamamonjy, Saelens & Klein (2019) to overcome the integration problems:

1. Proprietary tool-chain;
2. Middleware;
3. Exchange requirement identification.

The first strategy uses proprietary tools made available by the developer of the BIM authoring tool (usually the Application Programming Interface) to develop a method of data exchange between the Building Information Model and the energy simulation tool. The disadvantage is that the data exchange occurs entirely based on a proprietary data model, often being only compatible with the developer's software in specific versions (ANDRIAMAMONJY; SAELENS; KLEIN, 2019).

Asl et al. (2015), for example, proposed a performance optimization tool based on the Autodesk Revit API, Dynamo (a visual programming tool from Autodesk), and integrations with the Green Building Studio (Autodesk cloud service based on the DOE-2.2 simulation engine), and a daylight analysis in the cloud, also from Autodesk.

The middleware strategy, on the other hand, is based on public and open data schemes such as IFC and gbXML and inserts intermediate software in the process, where visualizations of the exported model data, corrections, and data enrichment can be carried out. Karola et al. (2002), developed a tool to facilitate the implementation of IFC reading in civil construction software. Lawrence Berkeley National Laboratory uses the software as an intermediate step in its process for converting IFC files to IDF (EnergyPlus input data file (ENERGYPLUS, 2019)).

O’Donnell et al. (2011) proposed an intermediate data model based on XML called SimModel, where the information available in the IFC, gbXML, and OpenStudio tool files are aligned with the data requirements of the energy simulation tools. The authors' ideal goal would be for SimModel to be incorporated into the standard IFC data model.

Oh et al. (2011) developed in MATLAB a gbXML to IDF file converter that allows the automatic creation of the building geometry, while the other information necessary for the execution of the EnergyPlus simulation needs to be manually entered in the interface of the intermediate tool.

The latter strategy aims to enable the exchange of information by extending the capabilities of the IFC scheme to cover all the data necessary for the execution of the energy simulation. This strategy is based on the flexibility of the IFC scheme when accepting customizable Property Sets (Psets). Thus, some studies (GUPTA *et al.*, 2014; WELLE; HAYMAKER; ROGERS, 2011) suggest new Property Sets to expand the IFC scheme, covering the data necessary to carry out the proposed activity. This extension of the scheme can be formalized using the previously mentioned IDM methodology. Pinheiro et al. (2018) proposed a method based on IDM and MVD to organize and exchange the information requirements, mainly related to geometry building and basic descriptions of air conditioning equipment, to perform energy simulations using EnergyPlus or Modelica.

The main limitation of this last strategy is the slow adoption by BIM authoring tools developers of the IFC4 version and the possibility of using customizable MVDs. Thus, the practical application of this strategy and workflow is momentarily challenging (ANDRIAMAMONJY; SAELENS; KLEIN, 2019).

Kamel e Memari (2019) carried out a comprehensive summary and condensation of the main challenges involving the integration of BIM and energy simulation tools, which is briefly presented below:

1. The simulation tools need to implement support for all parameters available in the BIM interoperability files;
2. The interoperability files must cover all the necessary parameters for carrying out energy simulations;
3. BIM authoring tools, such as Revit, create subsurfaces and small spaces when exporting the gbXML file, causing a difference between the number of thermal zones and elements exported compared to the ones initially modeled, making it difficult for the average user to understand the process;
4. Although interoperability schemes make it possible to transfer more information, BIM authoring tools do not export all the necessary data;
5. Some information required to perform the energy simulation is not actively provided by the user, so a standard value is set usually based

on ASHRAE manuals, such as those of ASHRAE Standard 90.1 (ASHRAE, 2016).

Gao, Koch & Wu (2019) argue in their review article that there is still no solution for the automatic creation of models for energy simulation from Building Information Models. They conclude that gbXML-based methods currently perform better and reach a semi-automatic level of integration between BIM to energy simulation tools. Thus, some information is automatically transferred to the energy simulation tool, with the remaining to be entered manually.

2.4 FINAL REMARKS

The literature review exposes the difficulties involved in predicting the energy consumption of buildings. Thus, different models are presented to perform the prediction, passing through models based on the resolution of physical equations, depending on a large amount of input data, up to purely statistical models, enabling the prediction from a few parameters.

From another point of view, BIM appears as a great promise to enable and facilitate the integration of energy simulation tools within the design process, providing a reduction in rework and transparency in the exchange and storage of information. However, challenges regarding the current possibilities of interoperability schemes and the implementation failures of the export and import modules of the BIM and energy simulation tools are presented.

Much of the integration problem is caused by the enormous amount of input data required to predict the thermal load of buildings. Therefore, the opportunity to perform the integration between Building Information Models and alternative and simplified methods for prediction of thermal load would allow a more automated and dynamic process of prediction. Thus, gray-box models can present great feasibility in their integration with BIM interoperability schemes, especially with gbXML, due to its data structure focused on conducting energy analysis and simulations.

3 ARTICLE PRESENTATION

Title: A metamodel to the Building Information Modeling-Building Energy Modeling integration in the early design stage

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Authors: M. K. BRACHT, A. P. MELO, R. LAMBERTS

Abstract

Full interoperability between BIM and energy simulation tools has not yet been achieved. Performance prediction metamodels can help to overcome this issue and serve as an investigation tool in the early design stage. This paper describes the development and validation of a tool to integrate building information models (BIMs) and a previously developed metamodel to predict the thermal load of dwellings through gbXML. The results obtained show the feasibility of developing the proposed tool. However, inconsistencies between gbXML files from different BIM authoring tools were observed. There was a need for manual adjustments to the building information models before export to gbXML. This finding reinforces the need for the standardized implementation of exportation tools for open interoperability formats by software manufacturers. It also indicates the possibility for the future use of this tool to support the Brazilian energy labeling certification process and assist building designers in the early design stage.

Keywords: Building information modeling; gbXML; Thermal load prediction; BIM-BEM integration; Performance prediction metamodel; Interoperability

3.1 INTRODUCTION

The design of energy-efficient buildings is a complex process and involves a wide range of professionals with different backgrounds and perspectives. The early design phase, in particular, is characterized by the variability in the building parameters, often presenting multidisciplinary and contrasting objectives, thus shaping a vast design space. The decisions taken in this phase are the ones that most strongly impact the building performance (MÉNDEZ ECHENAGUCIA *et al.*, 2015;

NEGENDAHL, 2015; ØSTERGÅRD; JENSEN; MAAGAARD, 2017). A significant number of variables, ranging from the climatic conditions of the location where the building is inserted to the thermal properties of the construction materials used, affect the thermal performance of buildings (NEGENDAHL, 2015). Given the magnitude of the problem, the development of computational tools is considered essential to support the design process (HENSEN; LAMBERTS, 2019).

Although computational tools are used to evaluate the thermal energy performance of buildings, the building energy modeling process is not fully incorporated into the digital design process. It requires manual information transcription processes, increasing the time spent in creating energy analysis models and the chance of errors in simulation results (GAO; KOCH; WU, 2019). A promising solution to this problem is the use of building information models (BIMs). The integration of BIMs with building energy models (BEMs) throughout the building life cycle is aimed at reducing the amount of reworking and facilitating the evaluation of different parameters, from the early design stages to the occupation of the building (ANDRIAMAMONJY; SAELENS; KLEIN, 2019). Interoperability is understood as the possibility of communication, exchange, and use of data between two (or more) software applications (ABANDA; BYERS, 2016). The literature proposes different strategies to enable a robust method of data exchange between BIMs and energy simulation tools (ANDRIAMAMONJY; SAELENS; KLEIN, 2019; ASL *et al.*, 2015; GUPTA *et al.*, 2014; KAROLA *et al.*, 2002; O'DONNELL, James *et al.*, 2011; PINHEIRO *et al.*, 2018; WELLE; HAYMAKER; ROGERS, 2011).

The two most widely acknowledged schemas for the interoperability of building information models through energy analysis are IFC and gbXML. The *Industry Foundation Classes* (IFC) is an international standard maintained by buildingSMART, focused on the needs of the AECOO (Architectural, Engineering, Consulting, Owner, Operator) industry. The IFC aims to enable data exchanges during the entire life-cycle of buildings (CEMESOVA; HOPFE; MCLEOD, 2015). It has become very comprehensive and complex; therefore, it is difficult to define and check information exchange requirements for each specific situation (CEMESOVA; HOPFE; MCLEOD, 2015; PINHEIRO *et al.*, 2018). To overcome this issue, buildingSMART developed the Model View Definition (MVD) to support the definition of customized exchange requirements. The main limitation of this method is related to the BIM software applications as it still do not support custom MVDs and the newer IFC4 schema version (ANDRIAMAMONJY; SAELENS; KLEIN, 2019). Oppositely, *gbXML* is only focused on data exchange required to perform energy analysis and simulations (VAN DESSEL; MAILE; O'DONNELL, 2019). The *gbXML* schema accepts only rectangular shapes and simplified geometry, which is considered acceptable for most building typologies (GAO; KOCH; WU, 2019). Also, it is less complex and more straightforward than the IFC schema, being supported by many BIM software applications and BEM tools (CEMESOVA; HOPFE; MCLEOD, 2015; VAN DESSEL; MAILE; O'DONNELL, 2019).

However, despite research efforts, full interoperability between BIM and BEM tools has not yet been completely achieved. Data and information losses, inconsistencies in the geometrical transformations and diverse modeling techniques of building elements are still common barriers in the data exchange processes between BIMs and BEMs (GAO; KOCH; WU, 2019; KAMEL; MEMARI, 2019). Gao et al. (2019) concluded that gbXML-based methods currently offer the best performance for data transfer processes and reach a semi-automatic level of data exchange between BIM and energy simulation tools. In this manner, some data is automatically transferred to the BEM while the remaining data need to be manually inserted.

A significant challenge to overcome the BIM-BEM integration barriers is the high number of input parameters, both geometric and semantic, required to run traditional energy simulation tools. The development of performance prediction metamodels can help to overcome this issue. Metamodeling can be understood as a method for constructing fast and simplified models that correlate inputs to outcomes obtained by more complex mathematical models, such as energy simulation tools (ØSTERGÅRD; JENSEN; MAAGAARD, 2017). These metamodels can be developed through different methods (ranging from multilinear regression to artificial neural network techniques) and one of their advantages is the ability to perform a prediction from a reduced number of parameters and with a shorter execution time (FOUCQUIER *et al.*, 2013; FUMO, 2014; ZHAO; MAGOULÈS, 2012). Artificial neural networks are one of the most used artificial intelligence methods for predicting the energy consumption of buildings. The advantage of this method is the ability to solve non-linear and complex problems such as those involved in forecasting energy consumption. In recent years, artificial neural networks have been used to predict energy consumption in different situations, such as heating/cooling thermal loads (BRE; ROMAN; FACHINOTTI, 2020;

MELO *et al.*, 2016), total building energy consumption (KALOGIROU; BOJIC, 2000; NETO; FIORELLI, 2008; YOKOYAMA; WAKUI; SATAKE, 2009), and considering natural ventilation strategies (SALLES OLINGER *et al.*, 2020; VRACHIMI; MELO; CÓSTOLA, 2017).

The opportunity to integrate building information models with prediction methods based on metamodels would allow an automated and dynamic prediction process. Improved interoperability using schemas such as gbXML would further facilitate the analysis of performance indices that need to be evaluated in the early design phases (ØSTERGÅRD; JENSEN; MAAGAARD, 2016). Furthermore, the ability to link prediction metamodels with BIM authoring tools could generate a robust and replicable method for classifying and issuing energy efficiency labels, as well as reducing errors in the data transcription between the software interfaces, as recommended by Li et al. (2019).

The aim of this study was to explore the possibility of integrating building information models with a thermal load prediction metamodel. The metamodel adopted was developed with the aim of its incorporation in the energy efficiency class definition process of the Brazilian labelling program for residential buildings.

The paper is organized into 6 sections as follows: Section 3.2 describes the thermal load prediction metamodel adopted and the normative instruction proposal that it incorporates. Section 3.3 presents the development of the integration tool. To evaluate the flexibility of the tool developed, as well as the consistency of the gbXML scheme, Section 3.4 establishes a validation test case and reports the results obtained. Section 3.5 discusses the results of Sections 3.3 and 3.4, as well as the limitations of this research, and outlines some issues to be addressed in future work. Lastly, a summary of the main findings is provided in Section 3.6.

3.2 INMETRO NORMATIVE INSTRUCTION PROPOSAL FOR RESIDENTIAL BUILDINGS (INI-R)

The Inmetro Normative Instruction proposal for residential buildings (INI-R) originates from the revision of the Regulation for Energy Efficiency Labeling of Commercial, Services and Public Buildings (RTQ-C) and Residential Buildings (RTQ-R) (BRASIL, 2012, 2010). The regulations provide guidelines for the definition of energy efficiency classes ranging from 'A' (most efficient) to 'E' (least efficient), based on two different methods: a simplified and a simulation-based. The metamodel used in the simplified RTQ-R method is based on the multilinear regression method. However, this method is not recommended to deal with nonlinear variables. Melo et al. (2016) compared the multilinear regression method used in the simplified RTQ-R method with artificial neural networks (ANNs) for the prediction of the thermo-energetic performance of a wide variety of typologies and different geometries of residential buildings, both naturally ventilated and mechanically conditioned. The results demonstrated a significant improvement in the prediction outcomes with ANNs, paving the way for a revision of the regulations and the inclusion of ANN-based metamodels.

The regulations were revised in 2012 (CB3E, 2018a), resulting in the proposed procedures of the so-called Inmetro Normative Instruction for commercial, public and service buildings (INI-C) and residential buildings (INI-R) (CB3E, 2018b). INI-R classifies residential buildings from level 'A' (most efficient) to level 'C' (least efficient) and ranks them from the assessment of both the envelope and the water heating system. To rate the housing envelope, INI-R presents three different evaluation methods: prescriptive, simplified and simulation (CB3E, 2018b).

In the simplified method, the integrated cooling and heating thermal loads of the actual building are compared to those of a baseline building. The baseline building of the proposed method in INI-R has the same geometry and solar orientation as the building in its real condition, while the thermal properties of the materials and window characteristics follow standardized values that are equivalent to the Level C of energy efficiency (CB3E, 2018b). The prediction of the integrated thermal loads of the simplified method is performed by metamodels developed using ANN method. The database used for training the metamodels was generated from energy simulations through the EnergyPlus program (MELO *et al.*, 2016). Thus, the proposed metamodels developed for the simplified INI-R method, henceforth called the metamodel, can predict the cooling and heating thermal loads of the building from 27 input parameters relative to each thermal zone (CB3E, 2018b). It is important to note that the input parameters are collected for each room considered as a longer-stay area, which, in the INI-R, are the following: living room, dining room, bedrooms, office, TV room, and similar spaces (CB3E, 2018b). Besides the parameters related to the thermal zones, there are 4 parameters used to describe the climate data of the building location (the following are Portuguese abbreviations): TMA (annual average temperature), dpT (standard deviation of mean temperature), AMA (average annual amplitude), and dpA (standard deviation of amplitude) (VINÍCIUS BAVARESCO *et al.*, 2017). These parameters are related to the 2014 proposal for the Classification of the Brazilian Climates by Roriz (2014). The formulas used to obtain these parameters for each location are given in Table 4.

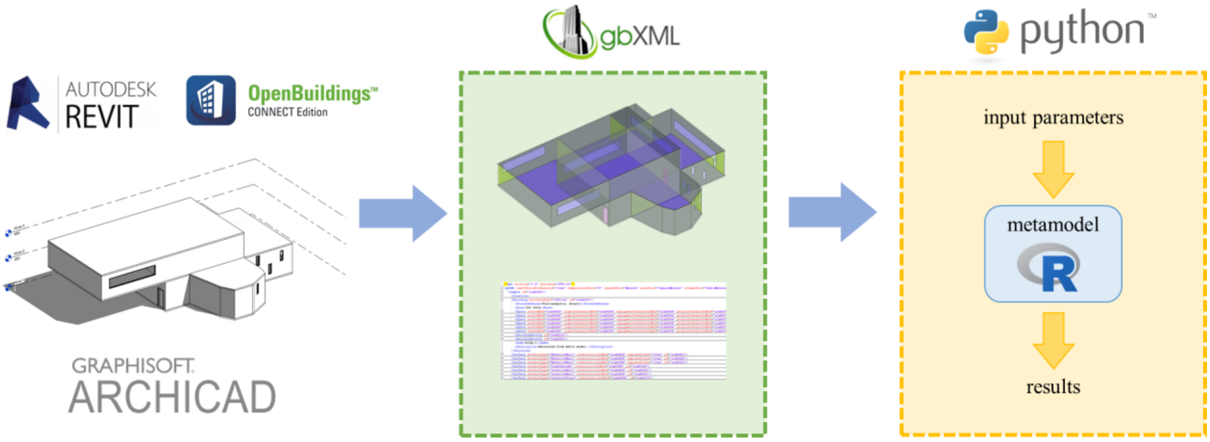
Table 4 – Climate-related input parameters and the formulas used to calculate them (RORIZ, 2014)**.**

Climate variable	Formula
Tmax: Mean monthly maximum temperature	
Tmin: Mean monthly minimum temperature	
Tmed: Mean monthly temperature	$Tmed\ =\ (Tmax + Tmin)/2$
TMA: Annual average temperature	$TMA = \left[\sum_{n=1}^{12} Tmed_{(n)}\right] \Big/ 12$
Amp: Average monthly amplitude	$Amp = Tmax - Tmin$
AMA: Average annual amplitude	$AMA = \left[\sum_{n=1}^{12} Amp_{(n)}\right] \Big/ 12$
dpT: Standard deviation of mean temperature	$dpT = \left\{\left[\sum_{n=1}^{12} T\left(Tmed_{(n)} - TMA\right)^2\right] \Big/ 11\right\}^{0.5}$
dpA: Standard deviation of amplitude	$dpA = \left\{\left[\sum_{n=1}^{12} T\left(Amp_{(n)} - AMA\right)^2\right] \Big/ 11\right\}^{0.5}$

3.3 INTEGRATION TOOL DEVELOPMENT

To enable the analysis of the advantages and challenges of integrating BIM with a metamodel, the development of an integration tool is proposed. The integration tool aims to link building information models (BIMs) developed with different BIM authoring software to the metamodel through the gbXML schema. The metamodel's prediction script was developed using the R programming language and is presented in Appendix A. A simplified scheme of the workflow associated with using the integration tool is shown in Figure 3.

Figure 3 – Simplified scheme of the proposed integration tool.



The integration tool was developed in Python language, mainly using the xml.etree.ElementTree library (PYTHON SOFTWARE FOUNDATION, 2019). During the development of the algorithm, it was important to consider the need for the integration tool to present a high degree of flexibility, allowing its operation considering the different geometric shapes and building typologies of residential buildings, and also the input data acquisition methods and criteria presented in the INI-R (CB3E, 2018b).

The metamodel has a total of 27 input parameters, ranging from the façade area for each orientation to the thermal transmittance of the building elements. However, based on the limitations related to the interoperability between BIM authoring software and energy simulation tools, only the geometric characteristics of the model and the building thermal zones, along with the surface exposure conditions, were included. The thermal properties of the materials and information related to the operation of the windows, such as the opening factor for ventilation, are fixed by the integration tool taking into account the standard values of the baseline building for the climate of the city of Florianópolis, presented in INI-R (CB3E, 2018b). The parameters obtained automatically by the integration tool are shown in Table 5, which also shows the maximum and minimum limits of application of the input parameter values for the metamodel. The other fixed parameters can be seen in Table 6, together with the assumed values based on the baseline building.

Table 5 – Input parameters of the metamodel to be automatically obtained from gbXML (CB3E, 2018b)**.**

Parameters	**Limits of the method**	
	Minimum	**Maximum**
Room	Bedroom	Living room
Floor height to the ground	0	50 m
Façade area – north	0	150 m²
Façade area – south	0	150 m²
Façade area – east	0	150 m²
Façade area – west	0	150 m²
Area of the room	6 m²	300 m²
Window to wall ratio – north	0.10	0.90
Window to wall ratio – south	0.10	0.90
Window to wall ratio – east	0.10	0.90
Window to wall ratio – west	0.10	0.90
Ceiling height	2.50 m	5.00 m
Raised-floor	No	Yes
Floor exposure	Slab on Grade	Interior floor
Roof exposure	Roof	Interior floor

Table 6 – Input parameters and fixed values based on the baseline building (CB3E, 2018b)**.**

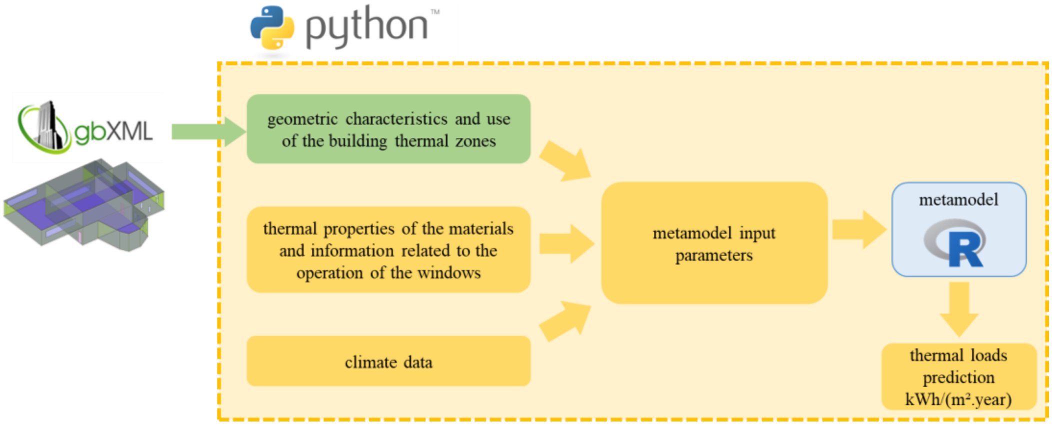
Parameter	**Baseline building**
Roof - solar absorptance	0.60
External walls - solar absorptance	0.60
Roof - thermal capacity	Low (CT < 50 kJ/m².k)
Roof - thermal transmittance	2.02 W/m².K
External walls - thermal capacity	Average (50 < CT < 200 kJ/m².k)
External walls - thermal transmittance	3.65 W/m².K
Floor - thermal capacity	Low thermal capacity
Opening factor for ventilation	0.50
Opening height factor for ventilation	1/“ceiling height”
Solar heat gain coefficient	0.87
Windows - thermal transmittance	5.7 W/m².K
Use of internal shading devices	No

The initial data acquired directly from the gbXML file is transformed by the integration tool developed, resulting in a table with the input parameter values needed for the use of the metamodel (Figure 4). For example, the class corresponding to surfaces in the gbXML schema has an attribute called surfaceType. This attribute makes the declaration, based on the BIM software export process, of the surface type. Within the scope of the metamodel input parameters there are the following relevant surface types:

1. ExteriorWall
2. SlabOnGrade
3. Roof
4. InteriorFloor
5. RaisedFloor
6. OperableWindow

Thus, it is possible to filter out each of these element types and proceed with the area calculations and other related parameters. The surfaces are defined within the gbXML schema by an entity formed by a set of points with XYZ coordinates, an azimuth value and the thermal zone to which the surface relates, along with a set of other parameters. The integration tool applies mathematical and logical transformations to these parameter values, determining the surface area, the orientation range (north, south, east or west) and in which thermal zone this information must be present for the metamodel to be executed correctly.

Figure 4 – Complete scheme detailing the internal operation of the proposed integration tool.



A limitation encountered in the gbXML schema was the definition of space uses provided in the building information model. Within the gbXML schema, it is possible to freely name the intended use of the building spaces. Therefore, in order to reduce errors in the classification of space uses, a nomenclature standard was established for the space name.

Another issue found was the lack of "parameterization" of some INI-R criteria, such as the definition of surface exposure. In the text of the INI-R, which is currently being reviewed, the boundary to be considered when defining a floor as "in contact with the ground" or "between floors", for example, is not presented. A limit of 50% has been set for the tool, however, it is important to officially add these limits to the final text of INI-R.

The integration tool can automatically read all input parameters from the metamodel listed in Table 1 and establishes the default values from Table 2 for the other parameters. Also, it performs the activation algorithm of the metamodel and returns the prediction results for the cooling and heating thermal loads for each room. In short, the integration tool can automate the following processes:

1. Collection of the geometric data, exposure conditions and use of thermal zones from the gbXML file exported from BIM authoring software and transformation of this data into the input parameters of the metamodel;
2. Assignment of default values for the parameters related to the thermal properties and operation of windows as in the INI-R baseline building;
3. Execution of the metamodel according to the input parameters collected and automatically-assigned;
4. Presentation of the estimated annual thermal load for each room considered in the building information model.

The full Python algorithm of the integration tool is provided in Appendix B.

3.4 INTEGRATION TOOL VALIDATION

To evaluate the flexibility of the integration tool developed, as well as the consistency of the gbXML schema originating from different BIM authoring software programs, a validation step was established. This step involved the development of low complexity building information models by the same user using three different BIM authoring software programs: Autodesk Revit 21.0.0.383 20200220_1100(x64);

Graphisoft ARCHICAD 22.0.0 BRA R1(6021); and Bentley OpenBuildings Designer CONNECT Edition Update 6 – Version 10.06.00.64. After the conclusion of the modeling, the model was exported to gbXML, allowing the interoperability file to be read by the integration tool developed. Therefore, it was possible to isolate and analyze the differences in the input parameter values of the metamodel as a result of exporting to gbXML from different BIM software programs. To accomplish this task, a test case was established based on a typology representative of social housing projects in Brazil, as described by Triana et al. (2015).

The case study is a single-family residential building consisting of two bedrooms, a living room with an integrated kitchen and a bathroom, as seen in Figure 5. The geometric characteristics of the rooms considered are shown in Table 7. The parameter values were manually collected according to the methods stipulated in the INI-R (CB3E, 2018b). The physical properties are considered fixed according to the INI-R baseline building (Table 6).

Figure 5 – Perspective view and floor plan of the building (TRIANA; LAMBERTS; SASSI, 2015)**.**

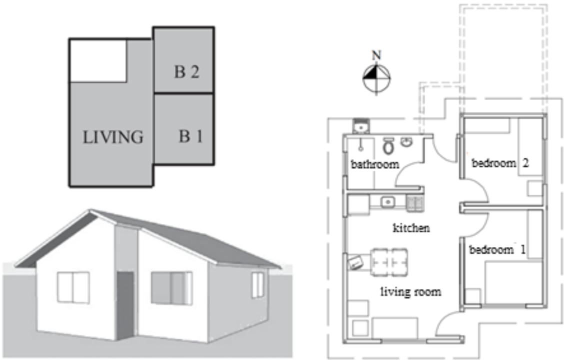


Table 7 – Input data for the building for the metamodel.

Parameter	Room considered		
	Living room	Bedroom 1	Bedroom 2
Space use	Living room	Bedroom	Bedroom
Floor height to the ground	0 m	0 m	0 m
Façade area – north	3.0125 m²	0 m²	6.5125 m²
Façade area – south	9.3375 m²	6.5125 m²	0 m²
Façade area – east	2.550 m²	7.7500 m²	7.2375 m²
Façade area – west	11.9375 m²	0 m²	1.3375 m²
Area of the room	20.046 m²	8.076 m²	7.541 m²
Window to wall ratio – north	0	0	0

Parameter	**Room considered**		
	Living room	**Bedroom 1**	**Bedroom 2**
Window to wall ratio – south	0.1606	0.2303	0
Window to wall ratio – east	0	0	0.2072
Window to wall ratio – west	0.1005	0	0
Ceiling height	2.50 m	2.50 m	2.50 m
Raised-floor	No	No	No
Floor exposure	Slab on Grade	Slab on Grade	Slab on Grade
Roof exposure	Roof	Roof	Roof

The integration tool developed automatically transforms the gbXML files of each BIM software program into the input parameters of the metamodel. The values of the input parameters found are then compared and the points of deviation resulting from differences in the gbXML files or export failures are identified. Lastly, the thermal load predictions using the different sources of input data (manually collected and from the different BIM software programs) are compared to evaluate the impact of the differences in the input values on the prediction value, firstly for the location of Florianópolis and then for 10 other locations in Brazil. The input values for the 4 climate-related parameters for the 11 locations are given in Table 8.

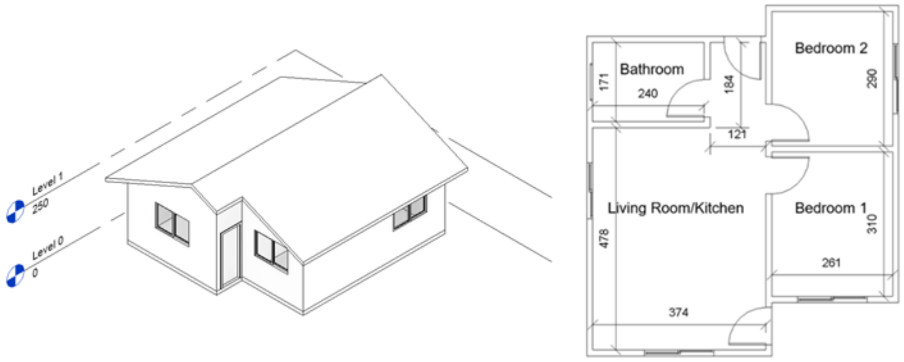
Table 8 – Input values for the climate-related parameters for the 11 different locations in Brazil.

Location	**TMA**	**dpT**	**AMA**	**dpA**
Porto Alegre	21.07	4.10	5.90	1.94
Santa Maria	19.80	4.51	5.58	2.10
Urubici	10.88	1.88	2.49	0.74
Florianópolis	21.47	3.01	5.09	1.07
Curitiba	18.28	2.80	5.75	1.78
São Paulo	21.13	1.84	6.56	0.65
Rio de Janeiro	24.54	1.97	7.32	1.25
Brasília	22.61	0.86	7.18	0.60
Salvador	26.89	1.28	4.43	0.99
Teresina	29.27	0.95	9.58	1.98
Belém	28.71	0.32	7.05	0.26

3.4.1 Autodesk Revit

Figure 6 shows the modeling results for the single-family building using Autodesk Revit for the perspective views and floor plan.

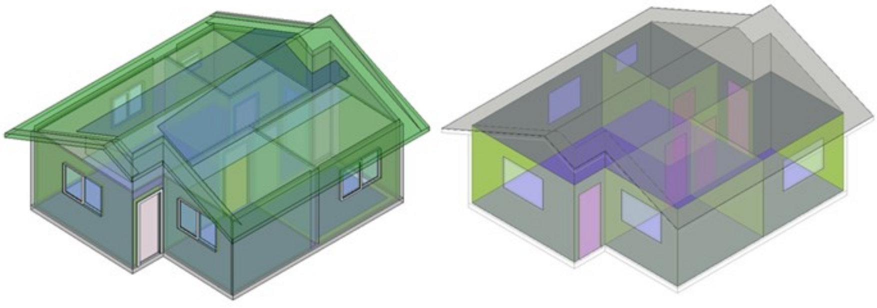
Figure 6 – Residential building modeled in Autodesk Revit 2019.



a) Perspective view b) Floor plan

When exporting the building information model to a gbXML file, Autodesk Revit allows two options: Use Energy Settings and Use Room/Space Volumes (Figure 7).

Figure 7 – Analytical energy models generated from Autodesk Revit.



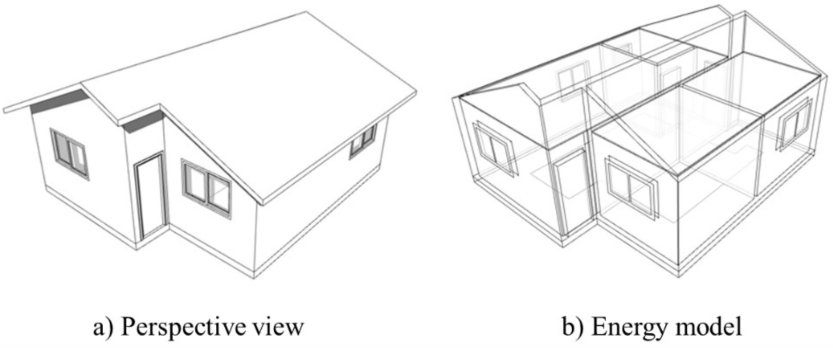
a) Use Energy Settings b) Use Room/Space Volumes

The "Use Energy Settings" option creates a larger amount of spaces and surfaces than originally modeled in the Autodesk Revit, as previously reported by Kamel and Memari (2019). This type of behavior is not consistent with the thermal zone definition established by INI-R. Also, information on the level to which each space belongs (for example, ground floor, first floor, and roof) is not translated from the BIM to the gbXML file. Otherwise, the "Use Room/Space Volumes" option defines the number of spaces as originally modeled in the BIM authoring software. Besides, it translates the level information related to the spaces. This option is associated with the method recommended by INI-R.

3.4.2 Graphisoft Archicad

Figure 8 shows the modeling results for the single-family building using Graphisoft Archicad.

Figure 8 – Residential building modeled in Archicad



a) Perspective view b) Energy model

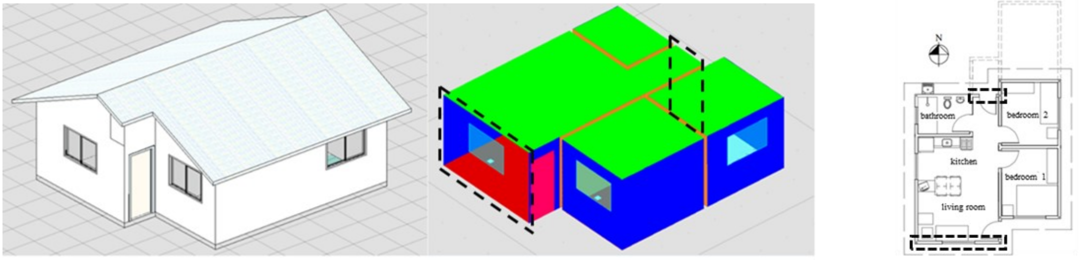
Two major differences arose in the export process and the generating of the gbXML file using Archicad. In contrast to Autodesk Revit, the room conditioning status is set at the thermal zone level and not at the space level, and all doors were classified as “OperableWindow”. Windows are also classified in the gbXML file exported by Archicad as “OperableWindow”, consequently windows cannot be distinguished from doors using only this attribute.

3.4.3 Bentley OpenBuildings

Lastly, the building was modeled using Bentley OpenBuildings, where the exportation to gbXML occurs at an intermediate interface called Energy Simulator. The Energy Simulator interface is integrated with OpenBuildings and the energy analysis model can be viewed before exporting, allowing adjustments. Also, it supports direct integration with the EnergyPlus simulation engine.

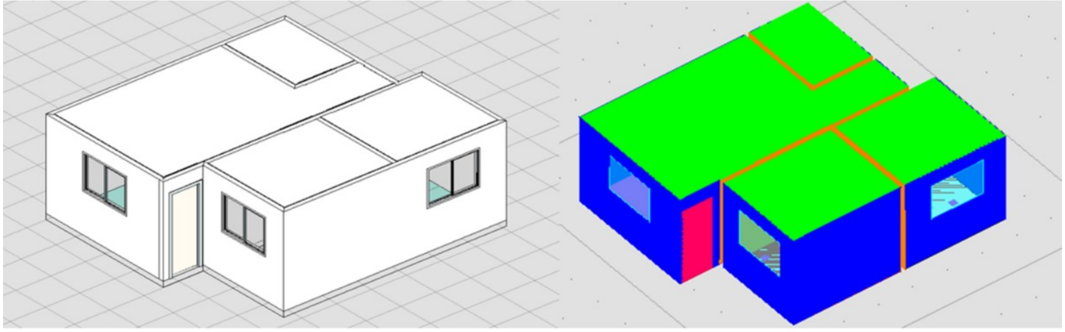
There was a loss of information in the process of transferring data between OpenBuildings and Energy Simulator. Due to the geometry, two surfaces of the living room were not converted – the south façade (next to the building’s main entrance) and north façade (on the building's backdoor) (Figure 9). The dashed lines indicate the two surfaces that were not converted. Therefore, it was necessary to simplify the geometry of the roof and external walls to allow its proper exportation to the energy analysis model (Figure 10).

Figure 9 – Residential building modeled in OpenBuildings



a) Perspective view b) Energy model with failure c) Floor plan with failures indication

Figure 10 – Residential building modeled with a simplified method in OpenBuildings



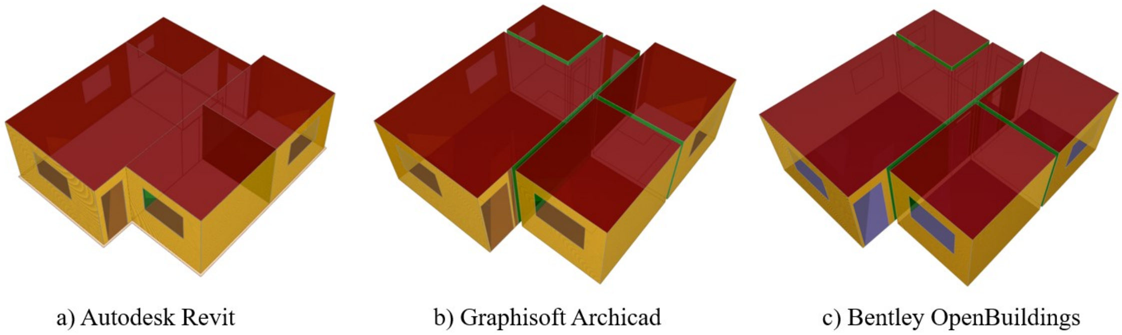
a) Perspective view b) Energy model corrected

During the exportation to gbXML, the floor surfaces lost their definition of "SlabOnGrade" and were exported as "RaisedFloor". Also, windows are automatically defined as "FixedWindow" and not as "OperableWindow" as considered by the Autodesk Revit and Archicad tools. The "OperableWindow" definition is recognized as more consistent with the nature of these openings.

3.4.4 Comparison between survey methods and gbXML files

On comparing the three gbXML files originating from the different BIM software programs using the web viewer Spider gbXML Viewer 'Maevia', it was noted that the ways in which the interior walls are considered and exported differ. In Autodesk Revit, the internal walls of each thermal zone are modeled considering their centerline, disregarding their thickness while in Archicad and OpenBuildings the faces of the internal walls have a small distance between them and thus their thickness is considered (Figure 11).

Figure 11 – Images obtained from the gbXML files using the online tool “Spider gbXML Viewer ‘Maevia’”.


a) Autodesk Revit b) Graphisoft Archicad c) Bentley OpenBuildings

In Autodesk Revit, the definition of internal walls using a centerline has been previously noted and reported as a limitation of the gbXML schema by O’Donnell et al. (2019). However, in the other software programs the faces of each wall are considered respecting the wall thickness and its impact on building geometry. This finding demonstrates that this behavior of the gbXML schema changes accordingly to the way the export processes are implemented by the different software manufacturers. It is important to mention that this behavior cannot be changed by different export settings, being inherited by the BIM authoring software adopted.

Lastly, tables were prepared to compare the values of the input parameters obtained manually and using the integration tool with the gbXML file originated from the different BIM authoring software programs. To correctly read the gbXML files originating from Archicad, it was necessary to delete the doors modeled before the exporting process, as the doors were classified erroneously as “OperableWindow”. In the case of OpenBuildings, the simplified building modeling was used; however, the manual correction of the floor exposure was not performed and thus the impact of this difference on the thermal load prediction value could be analyzed. Autodesk Revit was the only software program that required no modeling simplification or direct interference with the gbXML file. Table 9,Table 10 andTable 11 show comparatively the input parameter values for each building space analyzed.

Table 9 – Living room input data for the metamodels according to the data source.

Parameter	Data source			
	Manual	**Archicad**	**OpenBuildings**	**Revit**
Room	Living room	Living room	Living room	Living room
Floor height to the ground	0 m	0 m	0 m	0 m
Façade area – north	3.0125 m²	3.025 m²	3.025 m²	3.3535 m²
Façade area – south	9.3375 m²	9.35 m²	9.35 m²	9.7089 m²
Façade area – east	2.55 m²	2.55 m²	2.875 m²	2.8888 m²
Façade area – west	11.9375 m²	11.95 m²	11.925 m²	12.3214 m²
Area of the room	20.046 m²	20.1036 m²	20.0662 m²	20.046 m²
Window to wall ratio – north	0	0	0	0
Window to wall ratio – south	0.1606	0.1604	0.1604	0.1545
Window to wall ratio – east	0	0	0	0
Window to wall ratio – west	0.1005	0.1004	0.1006	0.0974
Ceiling height	2.5 m	2.5 m	2.5 m	2.5 m
Raised-floor	No	No	Yes	No
Floor exposure	Slab on Grade	Slab on Grade	Interior floor	Slab on Grade
Roof exposure	Roof	Roof	Roof	Roof

Table 10 – Bedroom 1 input data for the metamodels according to the data source.

Parameter	Data source			
	Manual	**Archicad**	**OpenBuildings**	**Revit**
Room	Bedroom	Bedroom	Bedroom	Bedroom
Floor height to the ground	0 m	0 m	0 m	0 m
Façade area – north	0 m²	0 m²	0 m²	0 m²
Façade area – south	6.5125 m²	6.525 m²	6.525 m²	6.8703 m²
Façade area – east	7.75 m²	7.75 m²	7.75 m²	8.1138 m²
Façade area – west	0 m²	0 m²	0 m²	0 m²
Area of the room	8.076 m²	8.091 m²	8.091 m²	8.076 m²
Window to wall ratio – north	0	0	0	0
Window to wall ratio – south	0.2303	0.2299	0.2299	0.2183
Window to wall ratio – east	0	0	0	0
Window to wall ratio – west	0	0	0	0
Ceiling height	2.5 m	2.5 m	2.5 m	2.5 m
Raised-floor	No	No	Yes	No
Floor exposure	Slab on Grade	Slab on Grade	Interior floor	Slab on Grade
Roof exposure	Roof	Roof	Roof	Roof

Table 11 – Bedroom 2 input data for the metamodels according to the data source.

Parameter	Data source			
	Manual	Archicad	OpenBuildings	Revit
Room	Bedroom	Bedroom	Bedroom	Bedroom
Floor height to the ground	0 m	0 m	0 m	0 m
Façade area – north	6.5125 m²	6.525 m²	6.525 m²	6.8703 m²
Façade area – south	0 m²	0 m²	0 m²	0 m²
Façade area – east	7.2375 m²	7.25 m²	7.25 m²	7.5988 m²
Façade area – west	1.3375 m²	1.2103 m²	1.675 m²	1.6705 m²
Area of the room	7.541 m²	7.569 m²	7.569 m²	7.541 m²
Window to wall ratio – north	0	0	0	0
Window to wall ratio – south	0	0	0	0
Window to wall ratio – east	0.2072	0.2069	0.2069	0.1974
Window to wall ratio – west	0	0	0	0
Ceiling height	2.5 m	2.5 m	2.5 m	2.5 m
Raised-floor	No	No	Yes	No
Floor exposure	Slab on Grade	Slab on Grade	Interior floor	Slab on Grade
Roof exposure	Roof	Roof	Roof	Roof

The main difference observed was that between the values found for the original façade areas of Table 7 and those calculated by the integration tool from the coordinates of the polygons found in the gbXML files. In this case, maximum errors of up to 25.23% are found for the west façade area of Bedroom 2 from the OpenBuildings gbXML file, however, this is a relatively small area (1.3375 m²). In other instances, Autodesk Revit constantly shows larger façade area values, with an average difference of 6.34% compared to -0.70% for Archicad and 3.25% for OpenBuildings. The façade areas in Table 7 were manually calculated using the dimensions of the internal wall surfaces. The results obtained with the integration tool and also observed in the Spider web viewer gbXML Viewer indicate that the Revit-generated gbXML file considers the centerline of the walls for the definition of the contour points and their respective coordinates. However, the other software programs consider the interior face of each wall, reaching input parameter values closer to the behavior stipulated by the INI-R. This difference is also reflected in the window to wall ratio (WWR) parameter for the façade of each orientation, calculated based on the façade area.

In contrast, when analyzing the area for each room, the values provided by the gbXML file originating from Autodesk Revit were closest to those of the manual survey. In the other cases, the values were slightly higher, although the difference is considered small in percentage terms (maximum difference found was 0.37% for the area in the case of Room 2 for both OpenBuildings and Graphisoft Archicad).

With these differences in the metamodel input parameter values, the resulting values for the cooling and heating thermal load predictions for each room for the Florianópolis location are shown in Table 12 and Table 13, respectively.

Table 12 – Cooling loads for each room using data for the location of Florianópolis.

Room	Cooling load (kWh/(m².year))			
	Manual	**Archicad**	**OpenBuildings**	**Revit**
Living room	184.21	183.84	237.92	184.11
Bedroom 1	41.46	41.43	48.28	41.37
Bedroom 2	49.03	48.98	51.37	48.55
Total	274.65	274.25	337.57	274.03

Table 13 – Heating loads for each room using data for the location of Florianópolis.

Room	Heating load (kWh/(m².year))			
	Manual	**Archicad**	**OpenBuildings**	**Revit**
Living room	0	0	5.83	0.01
Bedroom 1	2.56	2.56	30.04	2.62
Bedroom 2	1.85	1.84	28.73	1.97
Total	4.41	4.40	64.60	4.60

The difference in the input parameter values resulted in a difference in the cooling and heating thermal load predictions for each room when comparing the data collection methods and the different gbXML files tested. The predicted values for the gbXML file originating from Archicad were the closest to the values found using the manual survey, only slightly underestimating the integrated cooling and heating thermal loads (-0.16% and -0.23%, respectively). As expected, the prediction from the gbXML file exported by OpenBuildings showed the biggest differences compared with the manual survey due to the difference in the consideration of the floor exposure. The Autodesk Revit gbXML file provided slightly underestimated values for the cooling thermal load (-0.24%) and overestimated the values for the heating thermal load (4.31%). With the exception of the OpenBuildings case, where there was an export failure in defining the building floor exposure type, all heat load predictions produced very consistent results.

With the manual correction of the OpenBuildings export failure, the test case was extended for the other 10 locations listed in Table 8. The cooling and heating prediction results are presented in the form of charts, highlighting the percentage error with an increase in the prediction value for the 3 different BIM authoring software used. The cooling and heating load prediction values are shown for each room, BIM authoring software and location in Appendices C and D, respectively.

The errors associated with the cooling load predictions can be observed in Figure 12. Table 14 presents the average, minimum (representing the greatest underestimated error), and maximum (representing the greatest overestimated error) percentage error. With the correction of the floor exposure definition of the file generated by OpenBuildings, the highest percentage and average error values are found in the cases using the gbXML generated by Autodesk Revit. This behavior is mainly due to the difference in the consideration of the internal walls in the exportation process carried out with Autodesk Revit compared to other software programs, as mentioned previously. With larger façade areas greater heat transfers occur and also the thermal transmittance value of the external walls adopted was low. All software programs showed a tendency to slightly underestimate the cooling load values, but the errors remained within acceptable limits of less than 2.5%. There is, as expected, a tendency for the error to reduce with an increase in the absolute value of the cooling load prediction.

Figure 12 – Percentage error for each BIM authoring software with an increase in the cooling load prediction value

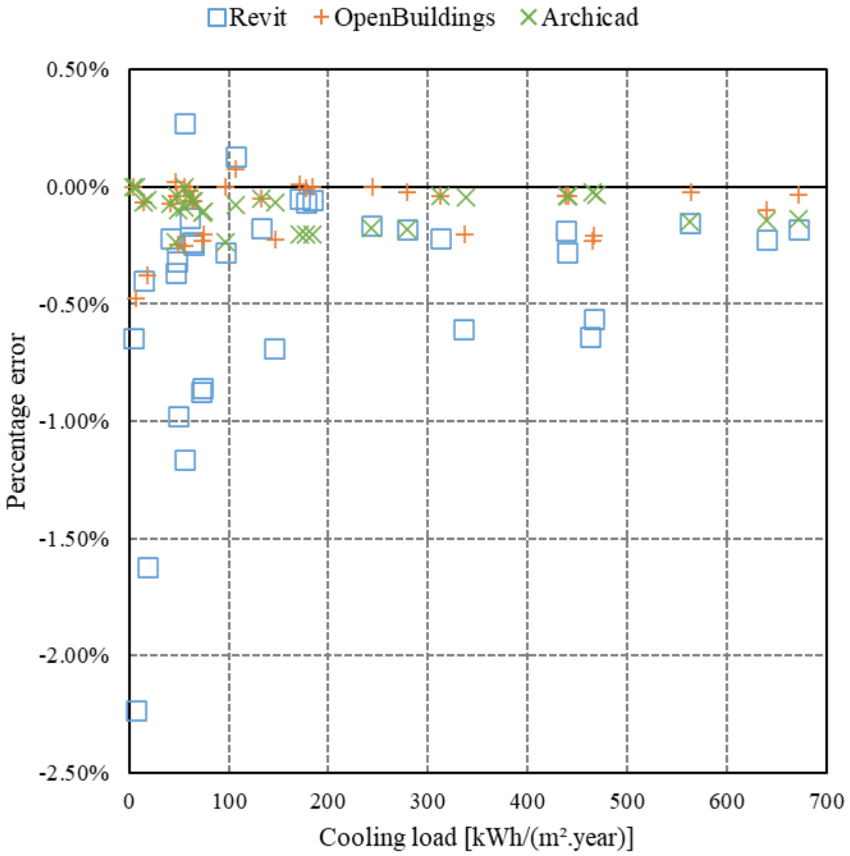


Table 14 – Minimum, maximum, and average percentage error for the cooling load prediction value for each BIM authoring software.

BIM Authoring Software	Percentage error		
	Minimum	**Average**	**Maximum**
Archicad	-0.24%	-0.09%	0.00%
OpenBuildings	-0.48%	-0.10%	0.08%
Revit	-2.23%	-0.44%	0.27%

In comparison with the scatter plot for the cooling loads, that for the heating loads (Figure 13) shows much lower load prediction values, reflecting a greater demand for cooling given the climate in Brazil. Thus, higher error values were obtained due to the much smaller prediction values. The climate conditions in most the Brazilian regions requires the air conditioning system more for cooling during the year, since there are hard summers and mild winters. According to the results, only 6 locations presented the need of heating: Florianópolis (only the bedrooms), Santa Maria, Urubici, São Paulo, Porto Alegre, and Curitiba. Once again the results for the file generated by Autodesk Revit showed the highest error values, reaching a maximum of 13.04% at an estimated heating load of only 0.26 kWh/(m².year). In contrast to the cooling load, there is a tendency toward overestimation in the prediction results obtained from the files generated by Autodesk Revit and OpenBuildings (Table 15). The file generated by Archicad shows good convergence with the values obtained using the manually collected input parameter values, with errors below 2% in all cases. There is a strong tendency for the error to reduce with an increase in the absolute value of the thermal load prediction.

Figure 13 – Percentage error for each BIM authoring software with an increase in the heating load prediction value.

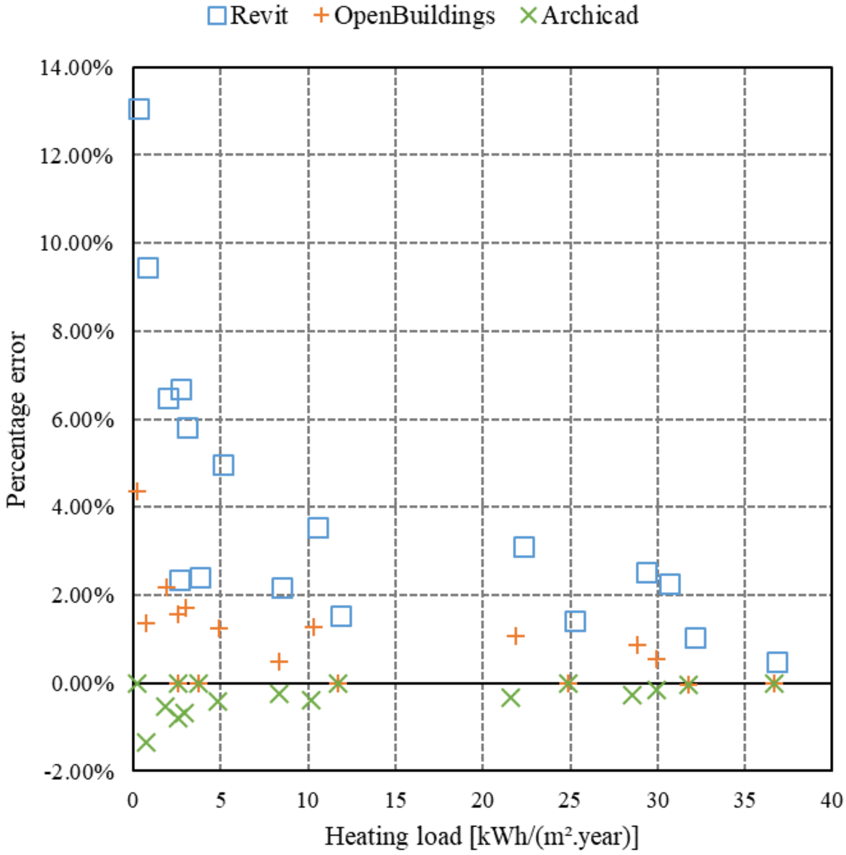


Table 15 – Minimum, maximum, and average percentage error for the heating load prediction value for each BIM authoring software.

BIM Authoring Software	Percentage error		
	Minimum	Average	Maximum
Archicad	-1.35%	-0.31%	0.00%
OpenBuildings	-0.03%	0.98%	4.35%
Revit	0.49%	4.07%	13.04%

The possibility of using a metamodel for integrated thermal load prediction facilitated the integration between the BIM authoring software programs and the prediction results using an open interoperability format. The integration tool developed responded well to the different sources of gbXML files, showing small differences in the thermal load prediction values obtained. It is important to note, however, that fully automatic interoperability cannot be achieved for the test case developed using different BIM authoring software, with the exception of the Autodesk Revit case. Simplifications in the building information models were applied before the exporting process to gbXML, although the degree of intervention required was notably diverse when considering the different BIM authoring software programs used.

3.5 DISCUSSION AND LIMITATIONS

The idealized integration tool was successfully developed and the proposed validation process could be performed. Limitations related to room naming standards and the need for some extra parameterization in the method described by INI-R were encountered. During the validation process, it was necessary to perform simplifications regarding the building information models before the exporting process to gbXML. In the case of the Autodesk Revit tool, no simplification was needed, while using Graphisoft Archicad it was necessary to delete the existing doors present in the model. OpenBuildings required greater simplification of the roof geometry and also manual intervention in the gbXML file code generated, to correct the type of building floor exposure.

The importance of the correct implementation of the export tools by the developers of the BIM software was noted, for example, from the export failure in the case of the doors using Archicad. Kamel and Memari (KAMEL; MEMARI, 2019) call this step of the BIM-BEM integration process “Map BIM data to a readable file for a

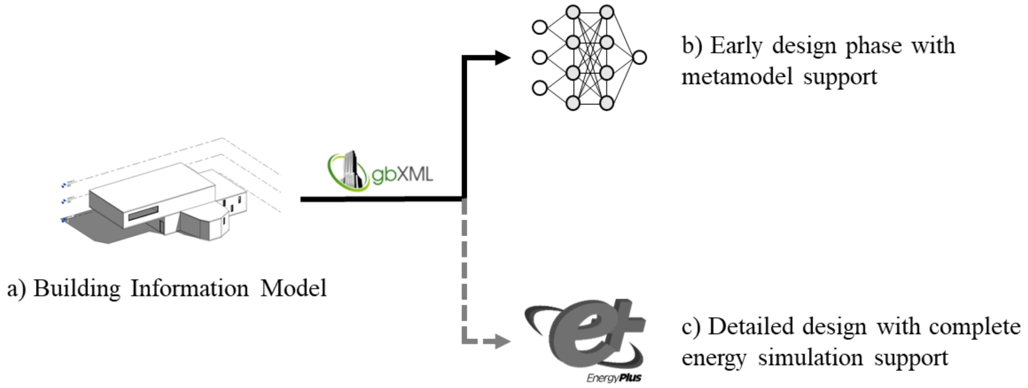
BEM Tool". In other words, failures occur in transforming the data contained within the proprietary format of the BIM authoring software to the interoperability format chosen, in this case, the gbXML schema. Even though the gbXML schema may be complete from a building description standpoint, many of the export failures and differences in the prediction results occurred due to the diversity of considerations and levels of implementation employed by software manufacturers. This demonstrates the importance of the gbXML export tool implementation process in BIM software, besides the need to develop more complete and robust interoperability schemes.

Some limitations of this study should be noted. The proposed test building has a simple geometry, however, it is considered important to validate the integration tool for common cases adapted to the reality of the Brazilian construction industry, where it would have greater application capacity. The parameters taken from the INI-R baseline building and considered fixed constitute a simplification of the evaluation of the thermal performance of the buildings. Also, it is important to mention that the quantitative comparison between the developed approach and different interoperability alternatives was not the aim of this study, however, this comparison is an important approach for future studies.

Given the points raised above, the integration tool developed allows the semi-automatic integration of building information models with a method for predicting the thermal performance with a fast response. By taking advantage of this feature, it is possible to implement additional algorithms to vary the values of the parameters considered fixed (Table 6) within the minimum and maximum limits accepted by the metamodel, allowing the prediction results to be presented in the form of interactive graphs (for example, parallel coordinates plots) in a dashboard. However, the dashboard approach will only be effective if the way in which it is presented is based on in-depth research into the needs and preferences of the different designers involved in the design process. This did not lie within the scope of this paper, but will be considered as an important topic for future studies.

An overall scheme of the process in the context of building design is shown in Figure 14. In the early design phases, the integration with metamodels allows the fast exploration of alternative values for the parameters, leading to a more detailed definition of the target building. More complete building information models (e.g., with the values defined for the thermal properties) could be integrated with complete simulation tools during the design phase, for the simulation of the behavior and evaluation of more complex solutions. However, the development of robust methods for the integration of BIM authoring tools and energy simulation software is crucial for this to occur effectively.

Figure 14 – Scheme of the complete integration process during the design phases.



3.6 CONCLUSIONS

The aim of this study was to evaluate the possibility of integrating a thermal load prediction metamodel to building information models to facilitate the data exchange process. Thus, a tool was developed to validate the viability of this integration using gbXML and it was submitted to validation tests. The results demonstrate the feasibility of developing this integration tool, showing minor errors in the thermal load prediction values when compared to a manual survey and also considering the different BIM authoring tools (maximum error underestimation of 2.23% for cooling and maximum overestimation error of 13.04% for heating). There was a need for manual adjustments to the building information models before export to gbXML, in the Archicad and OpenBuildings cases. Therefore, a fully automatic BIM-BEM integration method using gbXML for all BIM authoring software tested was not achieved. This result reinforces the need for the standardized implementation of exportation tools for open interoperability formats by software manufacturers. The content of this paper represents a step toward studies aimed at developing a more automated method for the application of labeling regulations for buildings. It will also aid design teams in the exploration of design alternatives in a practical and open manner during the different stages of design development.

CONCLUSIONS

This work discussed about the challenges faced when inserting energy simulation tools into the digital design process using BIM. Different BIM-BEM integration strategies and types of prediction models defined by the literature were presented. Thus, a method to integrate BIM authoring tools with a metamodel using the gbXML scheme was proposed and evaluated.

A single-family residence was modeled on three different authoring tools as a case study. It was possible to notice a difference in the assertion of the walls when comparing the file obtained using Autodesk Revit to the others. For the correct operation of the integration tool, it was necessary to perform adjustments manually on the BIM models or directly in the code of the generated gbXML file. This demonstrates the great need to increase awareness among developers of BIM authoring tools to improve their exporting tools, standardizing behaviors, and making better use of the current possibilities offered by open interoperability schemes.

The results of the thermal load prediction when using the integration tool showed small deviations in comparison to the manual survey. The proposed integration method allows for a semi-automatic integration between BIM and BEM. It opens possibilities for further automation of the evaluation process for issuing energy efficiency labels.

In this way, the developed method can be embedded in the Brazilian buildings labeling process, decreasing the number of parameters to be manually inputted by the user. Furthermore, the algorithm can be adapted to be available directly as a plug-in in the BIM authoring tools, facilitating the evaluation of the building design performance. Automation of the process, together with the consistency of considerations, can enable greater democratization of energy labeling and building performance prediction, contributing to an improvement in the energy efficiency of buildings.

Future studies should continue to explore progress into interoperability standards, particularly with the continued evolution and insertion of updated versions of IFC and other interoperability schemes by software manufacturers. Significant limitations of the study, such as the lack of automatic insertion of information related to materials and the operation of openings, must be addressed. However, it is essential to consider the level of certainty of this information presented within the BIM models and to enable easy evaluation of alternative values to the designer. Also, the automatic creation of baseline models of performance standards is an essential field of study to allow the analysis of more complex buildings using energy simulation in a more agile and rigorous way.

The speed of execution of the metamodel with the semi-automatic integration opens the possibility of introducing the proposed method in the initial stages of the building design. However, studies focused on the development of more intuitive graphical user interfaces for the presentation of results must be also carried out. Moreover, the integration of prediction metamodels directly into the environment of BIM authoring tools, using APIs or visual programming, must be studied to evaluate the methods preferred by designers.

REFERENCES

ABANDA, F. H.; BYERS, L. An investigation of the impact of building orientation on energy consumption in a domestic building using emerging BIM (Building Information Modelling). **Energy**, vol. 97, p. 517–527, 2016. DOI 10.1016/j.energy.2015.12.135. Available at: http://dx.doi.org/10.1016/j.energy.2015.12.135.

AL-HOMOUD, M. S. Computer-aided building energy analysis techniques. **Building and Environment**, vol. 36, no. 4, p. 421–433, 2001. DOI 10.1016/S0360-1323(00)00026-3. Available at: https://doi.org/10.1016/S0360-1323(00)00026-3. Accessed on: 31 Mar. 2019.

AMASYALI, K.; EL-GOHARY, N. M. A review of data-driven building energy consumption prediction studies. **Renewable and Sustainable Energy Reviews**, vol. 81, p. 1192–1205, Jan. 2018. DOI 10.1016/j.rser.2017.04.095. Available at: http://dx.doi.org/10.1016/j.rser.2017.04.095. Accessed on: 1 Mar. 2019.

ANDRIAMAMONJY, A.; SAELENS, D.; KLEIN, R. A combined scientometric and conventional literature review to grasp the entire BIM knowledge and its integration with energy simulation. **Journal of Building Engineering**, vol. 22, p. 513–527, 2019. DOI 10.1016/j.jobe.2018.12.021. Available at: https://doi.org/10.1016/j.jobe.2018.12.021.

ASHRAE. ASHRAE STANDARD 90.1. 2016. Available at: https://www.ashrae.org/technical-resources/bookstore/standard-90-1. Accessed on: 19 Aug. 2019.

ASL, M. R.; ZARRINMEHR, S.; BERGIN, M.; YAN, W. BPOpt: A framework for BIM-based performance optimization. **Energy and Buildings**, vol. 108, p. 401–412, Dec. 2015. DOI 10.1016/j.enbuild.2015.09.011. Available at: http://dx.doi.org/10.1016/j.enbuild.2015.09.011. Accessed on: 27 Mar. 2019.

AUTODESK. Autodesk Insight 360. 2019. Available at: https://insight360.autodesk.com/oneenergy. Accessed on: 31 Mar. 2019.

BAZJANAC, V. IFC BIM-Based Methodology for Semi-Automated Building Energy Performance Simulation. 2008. **CIB-W78 25th International Conference on Information Technology in Construction** [...]. Santiago, Chile: [*s. n.*], 2008. Available at: https://www.osti.gov/servlets/purl/938422. Accessed on: 20 Mar. 2019.

BAZJANAC, V. Space boundary requirements for modeling of building geometry for energy and other performance simulation. 2010. **CIB W78 2010 - Applications of IT in the AEC Industry (ISSN: 2706-6568)** [...]. [*S. l.*: *s. n.*], 2010. Available at: https://itc.scix.net/paper/w78-2010-127. Accessed on: 18 Dec. 2020.

BAZJANAC, V.; CRAWLEY, D. B. **The implementation of Industry Foundation Classes in simulation tools for the building industry**. [*S. l.*: *s. n.*], 1999. Available at: https://eetd.lbl.gov/sites/all/files/publications/lbnl-40681.pdf. Accessed on: 25 Mar. 2019.

BENTLEY. AECOsim Building Designer. 2019. Available at: https://www.bentley.com/pt/products/product-line/building-design-software/openbuildings-designer. Accessed on: 31 Mar. 2019.

BORGSTEIN, E. H.; LAMBERTS, R.; HENSEN, J. L. M. Evaluating energy performance in non-domestic buildings: A review. **Energy and Buildings**, vol. 128, p. 734–755, 15 Sep. 2016. https://doi.org/10.1016/j.enbuild.2016.07.018.

BRASIL. Regulamento Técnico da Qualidade para o Nível de Eficiência Energética de Edificações Residenciais (Technical Quality Regulation for the Energy Efficiency Level of Residential Buildings). 2012. Available at: http://www.pbeedifica.com.br/sites/default/files/projetos/etiquetagem/residencial/downloads/RTQR.pdf. Accessed on: 12 May 2020.

BRASIL. Regulamento Técnico da Qualidade para o Nível de Eficiência Energética de Edifícios Comerciais, de Serviços e Públicos (Technical Quality Regulation for the Energy Efficiency Level of Commercial, Service and Public Buildings). 2010. Available at: http://www.pbeedifica.com.br/sites/default/files/projetos/etiquetagem/comercial/downloads/Port372-2010_RTQ_Def_Edificacoes-C_rev01.pdf. Accessed on: 12 May 2020.

BRE, F.; ROMAN, N.; FACHINOTTI, V. D. An efficient metamodel-based method to carry out multi-objective building performance optimizations. **Energy and Buildings**, vol. 206, p. 109576, Jan. 2020. DOI 10.1016/j.enbuild.2019.109576. Available at: https://linkinghub.elsevier.com/retrieve/pii/S0378778819323047.

BUILDINGSMART. buildingSMART - History. 2019. Available at: https://www.buildingsmart.org/about/about-buildingsmart/history/. Accessed on: 26 Feb. 2019.

BUILDINGSMART. Specifications: Model View Definition. 2018. Available at: http://www.buildingsmart-tech.org/specifications/ifc-view-definition. Accessed on: 10

Aug. 2018.

CB3E. Novo método de avaliação energética de edificações com base em energia primária (New energy assessment method for buildings based on primary energy). 2018a. Available at: http://cb3e.ufsc.br/etiquetagem/desenvolvimento/atividades-2012-2016/trabalho-1/pesquisas. Accessed on: 16 Aug. 2019.

CB3E. Proposta de Instrução Normativa Inmetro para a Classe de Eficiência Energética de Edificações Residenciais (Proposed Inmetro Normative Instruction for the Energy Efficiency Class of Residential Buildings). 2018b. Available at: http://www.procelinfo.com.br/main.asp?View=%7B02A05065-. Accessed on: 12 May 2020.

CEMESOVA, A.; HOPFE, C. J.; MCLEOD, R. S. PassivBIM: Enhancing interoperability between BIM and low energy design software. **Automation in Construction**, vol. 57, p. 17–32, 2015. DOI 10.1016/j.autcon.2015.04.014. Available at: http://dx.doi.org/10.1016/j.autcon.2015.04.014. Accessed on: 3 Jul. 2017.

COSTA, A.; KEANE, M. M.; TORRENS, J. I.; CORRY, E. Building operation and energy performance: Monitoring, analysis and optimisation toolkit. **Applied Energy**, vol. 101, p. 310–316, 2013. https://doi.org/10.1016/j.apenergy.2011.10.037.

EASTMAN, C.; TEICHOLZ, P.; SACKS, R.; LISTON, K. **BIM handbook: A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers, and Contractors**. 2º edition. Hoboken, New Jersey: John Wiley & Sons, Inc., 2011.

EL-DIRABY, T.; KRIJNEN, T.; PAPAGELIS, M. BIM-based collaborative design and socio-technical analytics of green buildings. **Automation in Construction**, 2017. DOI 10.1016/j.autcon.2017.06.004. Available at: http://dx.doi.org/10.1016/j.autcon.2017.06.004. Accessed on: 20 Jul. 2017.

ELEFTHERIADIS, S.; MUMOVIC, D.; GREENING, P. Life cycle energy efficiency in building structures: A review of current developments and future outlooks based on BIM capabilities. **Renewable and Sustainable Energy Reviews**, vol. 67, p. 811–825, 2017. DOI 10.1016/j.rser.2016.09.028. Available at: http://dx.doi.org/10.1016/j.rser.2016.09.028.

ENERGYPLUS. EnergyPlus. 2019. Available at: https://energyplus.net/. Accessed on: 22 Aug. 2019.

FOUCQUIER, A.; ROBERT, S.; SUARD, F.; STÉPHAN, L.; JAY, A. State of the art in building modelling and energy performances prediction: A review. **Renewable and**

Sustainable Energy Reviews, vol. 23, p. 272–288, 2013. DOI 10.1016/j.rser.2013.03.004. Available at: http://dx.doi.org/10.1016/j.rser.2013.03.004. Accessed on: 12 Feb. 2019.

FUMO, N. A review on the basics of building energy estimation. **Renewable and Sustainable Energy Reviews**, vol. 31, p. 53–60, 2014. DOI 10.1016/j.rser.2013.11.040. Available at: http://dx.doi.org/10.1016/j.rser.2013.11.040. Accessed on: 12 Feb. 2019.

GAO, H.; KOCH, C.; WU, Y. Building information modelling based building energy modelling: A review. **Applied Energy**, vol. 238, p. 320–343, 2019. https://doi.org/10.1016/j.apenergy.2019.01.032.

GARCIA, E. G.; ZHU, Z. Interoperability from building design to building energy modeling. **Journal of Building Engineering**, vol. 1, p. 33–41, 2015. https://doi.org/10.1016/j.jobe.2015.03.001.

GBXML. gbXML - About GreenBuildingXML. 2019. Available at: http://www.gbxml.org/About_GreenBuildingXML_gbXML.

GRAPHISOFT. Archicad EcoDesigner Star. 2019. Available at: https://www.graphisoft.com/archicad/ecodesigner_star/. Accessed on: 31 Mar. 2019.

GSA. **GSA BIM Guide Overview**. Washington, DC: [*s. n.*], 2007. Available at: www.gsa.gov/bim.

GUPTA, A.; CEMESOVA, A.; HOPFE, C. J.; REZGUI, Y.; SWEET, T. A conceptual framework to support solar PV simulation using an open-BIM data exchange standard. **Automation in Construction**, vol. 37, p. 166–181, 2014. DOI 10.1016/j.autcon.2013.10.005. Available at: http://dx.doi.org/10.1016/j.autcon.2013.10.005. Accessed on: 27 Mar. 2019.

HAMEDANI, M. N.; SMITH, R. E. Evaluation of Performance Modelling: Optimizing Simulation Tools to Stages of Architectural Design. **Procedia Engineering**, vol. 118, p. 774–780, 2015. DOI 10.1016/j.proeng.2015.08.513. Available at: https://linkinghub.elsevier.com/retrieve/pii/S1877705815021682. Accessed on: 25 Mar. 2019.

HARISH, V. S. K. V; KUMAR, A. A review on modeling and simulation of building energy systems. **Renewable and Sustainable Energy Reviews**, vol. 56, p. 1272–1292, 2016. DOI 10.1016/j.rser.2015.12.040. Available at: http://dx.doi.org/10.1016/j.rser.2015.12.040. Accessed on: 12 Feb. 2019.

HENSEN, J. L. M.; LAMBERTS, R. **Building Performance Simulation for Design and Operation**. Second edition. | Abingdon, Oxon ; New York, NY : Routledge, 2019.: Routledge, 2019. DOI 10.1201/9780429402296. Available at: https://www.taylorfrancis.com/books/9780429688546.

INTERNATIONAL ORGANIZATION FOR STANDARDIZATION. **ISO 19650-1:2018 Organization and digitization of information aboutbuildings and civil engineering works, including buildinginformation modelling (BIM) - Information managementusing building information modelling - Part 1: Conceptsand principles**. [*S. l.*]: BSI, 2018.

INTERNATIONAL ORGANIZATION FOR STANDARDIZATION. **ISO 29481-1:2016 - Building information models - Information delivery manual - Part 1: Methodology and format**. [*S. l.*: *s. n.*], 2016.

JALAEI, F.; JRADE, A. Integrating building information modeling (BIM) and LEED system at the conceptual design stage of sustainable buildings. **Sustainable Cities and Society**, vol. 18, p. 95–107, 2015. DOI 10.1016/j.scs.2015.06.007. Available at: http://dx.doi.org/10.1016/j.scs.2015.06.007. Accessed on: 20 Aug. 2018.

KALOGIROU, S.; BOJIC, M. Artificial neural networks for the prediction of the energy consumption of a passive solar building. **Energy**, vol. 25, no. 5, p. 479–491, May 2000. DOI 10.1016/S0360-5442(99)00086-9. Available at: https://doi.org/10.1016/S0360-5442(99)00086-9. Accessed on: 25 Mar. 2019.

KAMEL, E.; MEMARI, A. M. Review of BIM's application in energy simulation: Tools, issues, and solutions. **Automation in Construction**, vol. 97, no. June 2017, p. 164–180, 2019. DOI 10.1016/j.autcon.2018.11.008. Available at: https://doi.org/10.1016/j.autcon.2018.11.008.

KAROLA, A.; LAHTELA, H.; HÄNNINEN, R.; HITCHCOCK, R.; CHEN, Q.; DAJKA, S.; HAGSTRÖM, K. BSPro COM-Server—interoperability between software tools using industrial foundation classes. **Energy and Buildings**, vol. 34, no. 9, p. 901–907, Oct. 2002. DOI 10.1016/S0378-7788(02)00066-X. Available at: https://www.sciencedirect.com/science/article/pii/S037877880200066X. Accessed on: 27 Mar. 2019.

KIM, H.; ANDERSON, K. Energy Modeling System Using Building Information Modeling Open Standards. **Journal of Computing in Civil Engineering**, vol. 27, p. 203–211, 2013. DOI 10.1061/(ASCE)CP.1943-5487.0000215. Available at:

https://ascelibrary.org/doi/10.1061/%28ASCE%29CP.1943-5487.0000215.

KIM, S.; WOO, J. H. Analysis of the differences in energy simulation results between Building Information Modeling (BIM)-based simulation method and the detailed simulation method. 2011. **Proceedings - Winter Simulation Conference** [...]. [*S. l.*: *s. n.*], 2011. p. 3545–3556. https://doi.org/10.1109/WSC.2011.6148049.

KRYGIEL, E.; NIES, B. **Green BIM: Successful Sustainable Design with Building Information Modeling**. 1ª edição. Indianopolis, Indiana: Wiley Publishing, Inc, 2008.

LAMBERTS, R.; DUTRA, L.; PEREIRA, F. O. R. **Eficiência Energética na Arquitetura**. 3ª edição. Rio de Janeiro: ELETROBRAS/PROCEL, 2014.

LI, Y.; KUBICKI, S.; GUERRIERO, A.; REZGUI, Y. Review of building energy performance certification schemes towards future improvement. **Renewable and Sustainable Energy Reviews**, vol. 113, p. 109244, Oct. 2019. DOI 10.1016/j.rser.2019.109244. Available at: https://linkinghub.elsevier.com/retrieve/pii/S1364032119304447.

MACIEL, A. R. **Automação do processo de corte e dobra de armaduras para estruturas de concreto integrada ao processo BIM**. 2018. 184 P. f. Universidade de São Paulo, São Paulo, 2018.

MELO, A. P. **Desenvolvimento de um método para estimar o consumo de energia de edificações comerciais através da aplicação de redes neurais**. 2012. 189 f. UFSC, 2012. Available at: http://www.labeee.ufsc.br/sites/default/files/publicacoes/teses/TESE_AnaPaulaMelo.pdf. Accessed on: 13 Mar. 2019.

MELO, A. P.; FOSSATI, M.; VERSAGE, R. de S.; SORGATO, M. J.; SCALCO, V. A.; LAMBERTS, R. Development and analysis of a metamodel to represent the thermal behavior of naturally ventilated and artificially air-conditioned residential buildings. **Energy and Buildings**, vol. 112, p. 209–221, 2016. https://doi.org/10.1016/j.enbuild.2015.12.021.

MÉNDEZ ECHENAGUCIA, T.; CAPOZZOLI, A.; CASCONE, Y.; SASSONE, M. The early design stage of a building envelope: Multi-objective search through heating, cooling and lighting energy performance analysis. **Applied Energy**, vol. 154, p. 577–591, 2015. https://doi.org/10.1016/j.apenergy.2015.04.090.

MIETTINEN, R.; PAAVOLA, S. Beyond the BIM utopia: Approaches to the development and implementation of building information modeling. **Automation in**

Construction, vol. 43, p. 84–91, 2014. DOI 10.1016/j.autcon.2014.03.009. Available at: http://dx.doi.org/10.1016/j.autcon.2014.03.009. Accessed on: 13 Feb. 2019.

NEGENDAHL, K. Building performance simulation in the early design stage: An introduction to integrated dynamic models. **Automation in Construction**, vol. 54, p. 39–53, 2015. DOI 10.1016/j.autcon.2015.03.002. Available at: http://dx.doi.org/10.1016/j.autcon.2015.03.002. Accessed on: 20 Nov. 2018.

NETO, A. H.; FIORELLI, F. A. S. Comparison between detailed model simulation and artificial neural network for forecasting building energy consumption. **Energy and Buildings**, vol. 40, no. 12, p. 2169–2176, Jan. 2008. DOI 10.1016/j.enbuild.2008.06.013. Available at: https://linkinghub.elsevier.com/retrieve/pii/S0378778808001448. Accessed on: 28 Mar. 2019.

O'DONNELL, J.; SEE, R.; ROSE, C.; MAILE, T.; BAZJANAC, V.; HAVES, P. SimMODEL: A domain data model for whole building energy simulation. 2011. **12th Conference of International Building Performance Simulation Association** [...]. Sydney: [*s. n.*], 2011. p. 382–389. Available at: http://www.ibpsa.org/proceedings/BS2011/P_1223.pdf. Accessed on: 27 Mar. 2019.

O'DONNELL, J. T.; MAILE, T.; ROSE, C.; MRAZOVIĆ, N.; MORRISSEY, E.; REGNIER, C.; PARRISH, K.; BAZJANAC, V. **Transforming BIM to BEM: Generation of Building Geometry for the NASA Ames Sustainability Base BIM**. [*S. l.*: *s. n.*], 2013. Available at: https://simulationresearch.lbl.gov/sites/all/files/lbnl-6033e.pdf. Accessed on: 25 Mar. 2019.

O'DONNELL, J.; TRUONG-HONG, L.; BOYLE, N.; CORRY, E.; CAO, J.; LAEFER, D. F. LiDAR point-cloud mapping of building façades for building energy performance simulation. **Automation in Construction**, vol. 107, p. 102905, Nov. 2019. DOI 10.1016/j.autcon.2019.102905. Available at: https://linkinghub.elsevier.com/retrieve/pii/S092658051830565X.

OH, S.-M.; KIM, Y.-J.; PARK, C.-S.; KIM, I.-H. Process-driven BIM-based optimal design using integration of EnergyPlus, genetic algorithm, and pareto optimality. 2011. **12th Conference of International Building Performance Simulation Association** [...]. Sydney: [*s. n.*], 2011. p. 894–907. Available at: http://www.ibpsa.org/proceedings/BS2011/P_1354.pdf. Accessed on: 27 Mar. 2019.

OSELLO, A.; CANGIALOSI, G.; DALMASSO, D.; DI PAOLO, A.; LO TURNO, M.;

PIUMATTI, P.; VOZZOLA, M. Architecture data and energy efficiency simulations: BIM and inteoperability standards. 2011. **Proceedings of Building Simulation 2011: 12th Conference of International Building Performance Simulation Association** [...]. Sydney: [*s. n.*], 2011. p. 2210–2217. Available at: https://www.researchgate.net/publication/266169217. Accessed on: 27 Mar. 2019.

ØSTERGÅRD, T.; JENSEN, R. L.; MAAGAARD, S. E. Building simulations supporting decision making in early design – A review. **Renewable and Sustainable Energy Reviews**, vol. 61, p. 187–201, 2016. DOI 10.1016/j.rser.2016.03.045. Available at: http://dx.doi.org/10.1016/j.rser.2016.03.045. Accessed on: 20 Aug. 2018.

ØSTERGÅRD, T.; JENSEN, R. L.; MAAGAARD, S. E. Early Building Design: Informed decision-making by exploring multidimensional design space using sensitivity analysis. **Energy and Buildings**, vol. 142, p. 8–22, 2017. https://doi.org/10.1016/j.enbuild.2017.02.059.

PINHA, A. P. **Integração entre BIM e BPS: desafios na avaliação de desempenho ambiental na era do projeto e processos digitais**. 2017. 100 f. f. USP, 2017.

PINHEIRO, S.; WIMMER, R.; O'DONNELL, J.; MUHIC, S.; BAZJANAC, V.; MAILE, T.; FRISCH, J.; VAN TREECK, C. MVD based information exchange between BIM and building energy performance simulation. **Automation in Construction**, vol. 90, p. 91–103, 2018. https://doi.org/10.1016/j.autcon.2018.02.009.

PRADA-HERNÁNDEZ, A. V.; ROJAS-QUINTERO, J. S.; VALLEJO-BORDA, J. A.; PONZ-TIENDA, J. L. Interoperability of Building Energy Modeling (BEM) with Building Information Modeling (BIM). 2015. **SIBRAGEC ELAGEC 2015** [...]. [*S. l.*: *s. n.*], 2015. p. 519–526. DOI 10.13140/RG.2.1.3807.3042. Available at: https://www.researchgate.net/publication/282814185.

PYTHON SOFTWARE FOUNDATION. xml.etree.ElementTree — The ElementTree XML API. 2019. Available at: https://docs.python.org/3/library/xml.etree.elementtree.html. Accessed on: 12 May 2020.

RORIZ, M. Classificação de climas do Brasil – Versão 3.0 (Classification of climates in Brazil - Version 3.0). 2014. Available at: http://www.labeee.ufsc.br/sites/default/files/Climas_v3.pdf. Accessed on: 12 May 2020.

SALLES OLINGER, M.; MELO, A. P.; NEVES, L. O.; LAMBERTS, R. Surrogate Model

Development for Naturally Ventilated Office Buildings. 16., 23 Mar. 2020. **Proceedings of Building Simulation 2019: 16th Conference of IBPSA** [...]. Rome, Italy: IBPSA, 23 Mar. 2020. vol. 16, p. 1396–1403. https://doi.org/10.26868/25222708.2019.210542.

SCHLUETER, A.; THESSELING, F. Building information model based energy/exergy performance assessment in early design stages. **Automation in Construction**, vol. 18, no. 2, p. 153–163, 2009. DOI 10.1016/j.autcon.2008.07.003. Available at: https://doi.org/10.1016/j.autcon.2008.07.003. Accessed on: 25 Mar. 2019.

SHADRAM, F.; MUKKAVAARA, J. An integrated BIM-based framework for the optimization of the trade-off between embodied and operational energy. **Energy and Buildings**, vol. 158, p. 1189–1205, Jan. 2018. DOI 10.1016/j.enbuild.2017.11.017. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0378778817321552. Accessed on: 5 Jul. 2018.

SUCCAR, B. Building information modelling framework: A research and delivery foundation for industry stakeholders. **Automation in Construction**, vol. 18, no. 3, p. 357–375, 2009. DOI 10.1016/j.autcon.2008.10.003. Available at: https://doi.org/10.1016/j.autcon.2008.10.003. Accessed on: 13 Feb. 2019.

TRIANA, M. A.; LAMBERTS, R.; SASSI, P. Characterisation of representative building typologies for social housing projects in Brazil and its energy performance. **Energy Policy**, vol. 87, p. 524–541, 1 Dec. 2015. https://doi.org/10.1016/j.enpol.2015.08.041.

VAN DESSEL, M.; MAILE, T.; O'DONNELL, J. BIM to Building Energy Performance Simulation: An Evaluation of Current Transfer Processes. 2019. **Proceedings of the 16th IBPSA Conference** [...]. [*S. l.*: *s. n.*], 2019. p. 92–99. DOI 10.26868/25222708.2019.210241. Available at: https://doi.org/10.26868/25222708.2019.210241.

VINÍCIUS BAVARESCO, M.; MAZZAFERRO, L.; PAULA MELO, A.; LAMBERTS, R. Classificação de climas brasileiros empregada na atualização dos RTQ para o Nível de Eficiência Energética de Edificações (Classification of Brazilian climates used in updating Technical Regulations for the Energy Efficiency of Buildings). 2017. Available at: http://cb3e.ufsc.br/sites/default/files/Relatorio_GruposClimaticos.pdf. Accessed on: 12 May 2020.

VRACHIMI, I.; MELO, A. P.; CÓSTOLA, D. Prediction of wind pressure coefficients in building energy simulation using machine learning. 2017. **Proceedings of the 15th IBPSA Conference** [...]. San Francisco, CA, USA: [*s. n.*], 2017. p. 2467–2474. DOI

10.26868/25222708.2017.696. Available at: http://www.ibpsa.org/proceedings/BS2017/BS2017_696.pdf.

W3C. Extensible Markup Language (XML) 1.0 (Fifth Edition). 2008. Available at: https://www.w3.org/TR/2008/REC-xml-20081126/. Accessed on: 7 Mar. 2019.

WEISE, M.; LIEBICH, T.; SEE, R.; BAZJANAC, V.; LAINE, T.; WELLE, B. **Implementation Guide: Space Boundaries for Energy Analysis**. [*S. l.*: *s. n.*], 2011.

WELLE, B.; HAYMAKER, J.; ROGERS, Z. ThermalOpt: A methodology for automated BIM-based multidisciplinary thermal simulation for use in optimization environments Article History. **Building Simulation**, vol. 4, no. 4, p. 293–313, 2011. DOI 10.1007/s12273-011-0052-5. Available at: https://link.springer.com/content/pdf/10.1007%2Fs12273-011-0052-5.pdf. Accessed on: 27 Mar. 2019.

YOKOYAMA, R.; WAKUI, T.; SATAKE, R. Prediction of energy demands using neural network with model identification by global optimization. **Energy Conversion and Management**, vol. 50, no. 2, p. 319–327, 2009. DOI 10.1016/j.enconman.2008.09.017. Available at: https://doi.org/10.1016/j.enconman.2008.09.017. Accessed on: 25 Mar. 2019.

ZHAO, H.-X.; MAGOULÈS, F. A review on the prediction of building energy consumption. **Renewable and Sustainable Energy Reviews**, vol. 16, p. 3586–3592, 2012. DOI 10.1016/j.rser.2012.02.049. Available at: https://doi.org/10.1016/j.rser.2012.02.049. Accessed on: 12 Feb. 2019.

APPENDIX A. The prediction script in the R programming language to use the metamodels developed by artificial neural networks.

```
#### PREDICTION SCRIPT ####


#load libraries
library (caret)


#set path to folder
setwd("C:/Users/Matheus/Desktop/ANN_R")
df <- read.csv("inputs.csv")

#heating#
load("heating_model_rsquared_09636238.rna")
heating <- c(heating=(predict(nnetFit, df)))

#cooling#
load("cooling_model_rsquared_09874421.rna")
cooling <- c(cooling=(predict(nnetFit, df)))


df.pred <- cbind(heating, cooling)
df.final <- cbind(df, df.pred)

df.final$heating <- (df.final$heating)^3
df.final$cooling <- (df.final$cooling)^3

df.final[,'heating']=round(df.final[,'heating'],2)
df.final[,'cooling']=round(df.final[,'cooling'],2)

rm(heating, cooling, df, df.pred, nnetFit)
write.csv(df.final, file = "resultados.csv")
```

APPENDIX B. Algorithm of the integration tool developed

```
import xml.etree.ElementTree as ET
import numpy as np
import pandas as pd
import subprocess

def unit_normal(a, b, c):
    x = np.linalg.det([[1,a[1],a[2]],
         [1,b[1],b[2]],
         [1,c[1],c[2]]])
    y = np.linalg.det([[a[0],1,a[2]],
         [b[0],1,b[2]],
         [c[0],1,c[2]]])
    z = np.linalg.det([[a[0],a[1],1],
         [b[0],b[1],1],
         [c[0],c[1],1]])
    magnitude = (x**2 + y**2 + z**2)**.5
    return (x/magnitude, y/magnitude, z/magnitude)

def poly_area(poly):
    if len(poly) < 3:
        return 0
    total = [0, 0, 0]
    N = len(poly)
    for i in range(N):
        vi1 = poly[i]
        vi2 = poly[(i+1) % N]
        prod = np.cross(vi1, vi2)
        total[0] += prod[0]
        total[1] += prod[1]
        total[2] += prod[2]
    result = np.dot(total, unit_normal(poly[0], poly[1], poly[2]))
    return abs(result/2)

def surface_area(surfaces):

    surface_properties = []

    for i in range(len(surfaces)):
        surface_name = surfaces[i].find('{http://www.gbxml.org/schema}Name').text
        surface_space                                                          =
surfaces[i].find('{http://www.gbxml.org/schema}AdjacentSpaceId').attrib['spaceIdRef']
        surface_azimuth                                                        =
float(surfaces[i].find('.//{http://www.gbxml.org/schema}Azimuth').text)
        planargeometry                                                         =
surfaces[i].find('.//{http://www.gbxml.org/schema}PlanarGeometry')
        surface_points                                                         =
planargeometry.findall('.//{http://www.gbxml.org/schema}CartesianPoint')
```

```
        surface_coord = []

        for j in range(len(surface_points)):
            surface_points_xyz = []
            for k in range(3):
                surface_points_xyz.append(float(surface_points[j][k].text))
            surface_coord.append(surface_points_xyz)

        surface_area = poly_area(surface_coord)

        surface_properties.append([surface_name,
                                   surface_space,
                                   surface_area,
                                  surface_azimuth])

    return (surface_properties)

def opening_area(surfaces):

    surface_properties = []

    for i in range(len(surfaces)):
        surface_name = surfaces[i].find('{http://www.gbxml.org/schema}Name').text
        surface_space =
surfaces[i].find('{http://www.gbxml.org/schema}AdjacentSpaceId').attrib['spaceIdRef']
        surface_azimuth =
float(surfaces[i].find('.//{http://www.gbxml.org/schema}Azimuth').text)
        openings =
surfaces[i].findall('.//{http://www.gbxml.org/schema}Opening[@openingType="Operab
leWindow"]') #revit or archicad
        #openings =
surfaces[i].findall('.//{http://www.gbxml.org/schema}Opening[@openingType="FixedW
indow"]') #openbuildings
        for j in range(len(openings)):
            planargeometry =
openings[j].find('.//{http://www.gbxml.org/schema}PlanarGeometry')
            opening_points =
planargeometry.findall('.//{http://www.gbxml.org/schema}CartesianPoint')

            surface_coord = []

            for k in range(len(opening_points)):
                opening_points_xyz = []
                for l in range(3):
                    opening_points_xyz.append(float(opening_points[k][l].text))
                surface_coord.append(opening_points_xyz)

            surface_area = poly_area(surface_coord)
```

```
         surface_properties.append([surface_name,
                         surface_space,
                         surface_area,
                           surface_azimuth])

   return (surface_properties)

def surface_area_orientation(surfaces):

   surfaces_north = [0]
   surfaces_east = [0]
   surfaces_west = [0]
   surfaces_south = [0]

   for i in range(len(surfaces)):

      if surfaces[i][3]<=45 and surfaces[i][3]>=0 or surfaces[i][3]<=360 and
surfaces[i][3]>315:
         surfaces_north.append(surfaces[i][2])
      elif surfaces[i][3]<=135 and surfaces[i][3]>45:
         surfaces_east.append(surfaces[i][2])
      elif surfaces[i][3]<=315 and surfaces[i][3]>225:
         surfaces_west.append(surfaces[i][2])
      elif surfaces[i][3]<=225 and surfaces[i][3]>135:
         surfaces_south.append(surfaces[i][2])

   surfaces_north = np.array(surfaces_north).sum()
   surfaces_east = np.array(surfaces_east).sum()
   surfaces_west = np.array(surfaces_west).sum()
   surfaces_south = np.array(surfaces_south).sum()

   return [surfaces_north, surfaces_east, surfaces_south, surfaces_west]

def safe_div(x,y):
   if y==0: return 0
   return x/y

def wwr_calculator(opening_area,extwall_area):
   wwr=[]
   for i in range(4):
      wwr.append(safe_div(opening_area[i],extwall_area[i]))
   return wwr

def exposition(surfaces_area,space_id,space_area):

   surfaces_area_space = []

   for j in range(len(surfaces_area)):
```

```
            if surfaces_area[j][1]==space_id:
                surfaces_area_space.append(surfaces_area[j][2])

    surfaces_area_space = sum(surfaces_area_space)

    if surfaces_area_space >= 0.5*space_area:
        exp = 1
    else:
        exp = 0

    return exp

tree = ET.parse('Explorer_Unifamiliar_Revit.xml')
print('loading complete')
root = tree.getroot()
campus = root.find('{http://www.gbxml.org/schema}Campus')
building = campus.find('{http://www.gbxml.org/schema}Building')
spaces = building.findall('{http://www.gbxml.org/schema}Space') #archicad or
openbuildings
spaces =
building.findall('{http://www.gbxml.org/schema}Space[@conditionType="HeatedAndC
ooled"]') #only revit
buildingstorey = building.findall('{http://www.gbxml.org/schema}BuildingStorey')

print(spaces)

surfaces = campus.findall("{http://www.gbxml.org/schema}Surface")
surfaces_extwall =
campus.findall("{http://www.gbxml.org/schema}Surface[@surfaceType='ExteriorWall']
")
surfaces_slab =
campus.findall("{http://www.gbxml.org/schema}Surface[@surfaceType='SlabOnGrad
e']")
surfaces_roof =
campus.findall("{http://www.gbxml.org/schema}Surface[@surfaceType='Roof']")
surfaces_floor =
campus.findall("{http://www.gbxml.org/schema}Surface[@surfaceType='InteriorFloor']
")
surfaces_raisedfloor =
campus.findall("{http://www.gbxml.org/schema}Surface[@surfaceType='RaisedFloor']
")
surfaces_openings =
campus.findall('.//{http://www.gbxml.org/schema}Opening[@openingType="Operable
Window"]') #revit or archicad
#surfaces_openings =
campus.findall('.//{http://www.gbxml.org/schema}Opening[@openingType="FixedWin
dow"]') #openbuildings

print(surfaces_extwall)
```

```
print(surfaces_openings[0])

extwall_area = surface_area(surfaces_extwall)
opening_area = opening_area(surfaces_extwall)
slabs_area = surface_area(surfaces_slab)
interiorfloors_area = surface_area(surfaces_floor)
roofs_area = surface_area(surfaces_roof)
raisedfloors_area = surface_area(surfaces_raisedfloor)

print(extwall_area)
print(opening_area)

df = pd.DataFrame(np.nan, index=range(len(spaces)),

columns=['space_storey_name','space_storey_id','space_name','space_id','zona',
                    'wwr_norte','wwr_leste','wwr_sul','wwr_oeste',
                    'area_par_exp_norte','area_par_exp_leste',
                    'area_par_exp_sul','area_par_exp_oeste',
                    'area_zona','ct_par_ext','u_par_ext','ct_cob','u_cob',
                    'u_vid','fs_vid','tipo_pav','pedireito','abspar','abscob',
                    'tamanhoprojecao','hpav','veneziana','hjan','openfac',
                    'pilotis','exp_pis','exp_cob',
                    'TMA','dpT','AMA','dpA'])

building_storey = []
for i in range(len(buildingstorey)):
    building_storey_id = buildingstorey[i].attrib['id']
    building_storey_name =
buildingstorey[i].find('{http://www.gbxml.org/schema}Name').text
    building_storey_level =
float(buildingstorey[i].find('{http://www.gbxml.org/schema}Level').text)


building_storey.append([building_storey_id,building_storey_name,building_storey_le
vel])

for i in range(len(spaces)):
    space_id = spaces[i].attrib['id']
    space_name = spaces[i].find('{http://www.gbxml.org/schema}Name').text
    space_storey_id = spaces[i].attrib['buildingStoreyIdRef']

    for j in range(len(building_storey)):
        if building_storey[j][0]==space_storey_id:
            space_storey_name = building_storey[j][1]
            space_storey_level = building_storey[j][2]

    space_area = float(spaces[i].find('{http://www.gbxml.org/schema}Area').text)
    space_volume = float(spaces[i].find('{http://www.gbxml.org/schema}Volume').text)
    space_height = space_volume/space_area
```

```
extwall_area_space = []

for j in range(len(extwall_area)):
    if extwall_area[j][1]==space_id:
        extwall_area_space.append(extwall_area[j])

opening_area_space = []

for j in range(len(opening_area)):
    if opening_area[j][1]==space_id:
        opening_area_space.append(opening_area[j])

extwall_area_orientation = surface_area_orientation(extwall_area_space)
opening_area_orientation = surface_area_orientation(opening_area_space)

wwr = wwr_calculator(opening_area_orientation,extwall_area_orientation)

exp_pis = exposition(slabs_area,space_id,space_area)
exp_cob = exposition(roofs_area,space_id,space_area)
pilotis = exposition(raisedfloors_area,space_id,space_area)

if "sala" in space_name.lower():
    zona = 0
elif "quarto" in space_name.lower():
    zona = 1
else:
    zona = 2

ct_par_ext = 2 #kJ/m².K
u_par_ext = 3.65 #W/m².K
abspar = 0.6

ct_cob = 1 #kJ/m².K
u_cob = 2.02 #W/m².K
abscob = 0.6

u_vid = 5.7  #W/m².K
fs_vid = 0.87

openfac = 0.5
hjan = 1/space_height
veneziana = 0
tamanhoprojecao = 0

tipo_pav = 0

TMA = 21.47
dpT = 3.01
```

```
    AMA = 5.09
    dpA = 1.07

    df.iloc[i] = [space_storey_name,space_storey_id,space_name,space_id,zona,
                wwr[0],wwr[1],wwr[2],wwr[3],
                extwall_area_orientation[0],extwall_area_orientation[1],
                extwall_area_orientation[2],extwall_area_orientation[3],
                space_area,ct_par_ext,u_par_ext,ct_cob,u_cob,u_vid,fs_vid,tipo_pav,
                space_height,abspar,abscob,tamanhoprojecao,space_storey_level,
                veneziana,hjan,openfac,pilotis,exp_pis,exp_cob,
                TMA,dpT,AMA,dpA]
df
df.to_csv('inputs.csv',encoding='utf-8-sig')
subprocess.check_call(['Rscript', 'prediction.R'], shell=False)
dfcompleto = pd.read_csv('resultados.csv')
dfcompleto
dfedificio = pd.DataFrame(np.nan, index=range(1),
                columns=['ct_par_ext','u_par_ext','ct_cob','u_cob',
                    'u_vid','fs_vid','tipo_pav','abspar','abscob',
                    'tamanhoprojecao','veneziana','hjan','openfac',
                    'heating','cooling'])
df = pd.DataFrame({})
for i in range(1):
    dfedificio=(dfcompleto.loc[[i],['ct_par_ext','u_par_ext','ct_cob','u_cob',
                        'u_vid','fs_vid','tipo_pav','abspar','abscob',
                        'tamanhoprojecao','veneziana','hjan','openfac']])
    dfresultado=(dfcompleto.loc[0:(len(spaces)),['heating','cooling']])
    dfresultadototal=pd.DataFrame({'total heating': [dfresultado['heating'].sum()],'total
cooling':[dfresultado['cooling'].sum()]})
    dftemporario = dfedificio.join(dfresultadototal)
    df = pd.concat([df,dftemporario])
df
```

APPENDIX C. Cooling load prediction values for the 11 locations

Location	BIM Software	Room	Thermal load [kWh/(m².year)]	Percentage error
Florianópolis	Revit	Living room	184.11	-0.05%
Florianópolis	Revit	Bedroom 1	41.37	-0.22%
Florianópolis	Revit	Bedroom 2	48.55	-0.98%
Santa Maria	Revit	Living room	171.21	-0.05%
Santa Maria	Revit	Bedroom 1	64.15	-0.25%
Santa Maria	Revit	Bedroom 2	73.89	-0.86%
Teresina	Revit	Living room	671.76	-0.18%
Teresina	Revit	Bedroom 1	439.43	-0.28%
Teresina	Revit	Bedroom 2	462.91	-0.64%
Belém	Revit	Living room	639.64	-0.22%
Belém	Revit	Bedroom 1	438.77	-0.19%
Belém	Revit	Bedroom 2	466.81	-0.56%
Urubici	Revit	Living room	106.68	0.13%
Urubici	Revit	Bedroom 1	55.91	0.27%
Urubici	Revit	Bedroom 2	60.54	-0.13%
Rio de Janeiro	Revit	Living room	278.85	-0.18%
Rio de Janeiro	Revit	Bedroom 1	132.25	-0.17%
Rio de Janeiro	Revit	Bedroom 2	145.83	-0.69%
São Paulo	Revit	Living room	97	-0.28%
São Paulo	Revit	Bedroom 1	14.97	-0.40%
São Paulo	Revit	Bedroom 2	18.21	-1.62%
Brasília	Revit	Living room	243.59	-0.16%
Brasília	Revit	Bedroom 1	47.2	-0.32%
Brasília	Revit	Bedroom 2	55.13	-1.17%
Porto Alegre	Revit	Living room	177.49	-0.07%
Porto Alegre	Revit	Bedroom 1	63.05	-0.24%
Porto Alegre	Revit	Bedroom 2	72.53	-0.87%
Salvador	Revit	Living room	563.06	-0.15%
Salvador	Revit	Bedroom 1	312.02	-0.22%
Salvador	Revit	Bedroom 2	335.93	-0.61%
Curitiba	Revit	Living room	46.05	-0.37%
Curitiba	Revit	Bedroom 1	4.61	-0.65%
Curitiba	Revit	Bedroom 2	6.13	-2.23%
Florianópolis	OpenBuildings	Living room	184.21	0.00%
Florianópolis	OpenBuildings	Bedroom 1	41.43	-0.07%
Florianópolis	OpenBuildings	Bedroom 2	48.91	-0.24%
Santa Maria	OpenBuildings	Living room	171.32	0.01%
Santa Maria	OpenBuildings	Bedroom 1	64.27	-0.06%
Santa Maria	OpenBuildings	Bedroom 2	74.38	-0.20%
Teresina	OpenBuildings	Living room	672.77	-0.03%

Location	BIM Software	Room	Thermal load [kWh/(m².year)]	Percentage error
Teresina	OpenBuildings	Bedroom 1	440.49	-0.04%
Teresina	OpenBuildings	Bedroom 2	464.82	-0.23%
Belém	OpenBuildings	Living room	639.64	-0.10%
Belém	OpenBuildings	Bedroom 1	438.77	-0.04%
Belém	OpenBuildings	Bedroom 2	466.81	-0.21%
Urubici	OpenBuildings	Living room	106.62	0.08%
Urubici	OpenBuildings	Bedroom 1	55.76	0.00%
Urubici	OpenBuildings	Bedroom 2	60.61	-0.02%
Rio de Janeiro	OpenBuildings	Living room	279.29	-0.02%
Rio de Janeiro	OpenBuildings	Bedroom 1	132.41	-0.05%
Rio de Janeiro	OpenBuildings	Bedroom 2	146.51	-0.22%
São Paulo	OpenBuildings	Living room	97.27	0.00%
São Paulo	OpenBuildings	Bedroom 1	15.02	-0.07%
São Paulo	OpenBuildings	Bedroom 2	18.44	-0.38%
Brasília	OpenBuildings	Living room	243.99	0.00%
Brasília	OpenBuildings	Bedroom 1	47.33	-0.04%
Brasília	OpenBuildings	Bedroom 2	55.64	-0.25%
Porto Alegre	OpenBuildings	Living room	177.6	-0.01%
Porto Alegre	OpenBuildings	Bedroom 1	63.16	-0.06%
Porto Alegre	OpenBuildings	Bedroom 2	73	-0.23%
Salvador	OpenBuildings	Living room	563.79	-0.02%
Salvador	OpenBuildings	Bedroom 1	312.57	-0.04%
Salvador	OpenBuildings	Bedroom 2	337.29	-0.20%
Curitiba	OpenBuildings	Living room	46.23	0.02%
Curitiba	OpenBuildings	Bedroom 1	4.64	0.00%
Curitiba	OpenBuildings	Bedroom 2	6.24	-0.48%
Florianópolis	Archicad	Living room	183.84	-0.20%
Florianópolis	Archicad	Bedroom 1	41.43	-0.07%
Florianópolis	Archicad	Bedroom 2	48.98	-0.10%
Santa Maria	Archicad	Living room	170.95	-0.20%
Santa Maria	Archicad	Bedroom 1	64.27	-0.06%
Santa Maria	Archicad	Bedroom 2	74.45	-0.11%
Teresina	Archicad	Living room	672.07	-0.14%
Teresina	Archicad	Bedroom 1	440.49	-0.04%
Teresina	Archicad	Bedroom 2	465.77	-0.03%
Belém	Archicad	Living room	640.17	-0.14%
Belém	Archicad	Bedroom 1	439.42	-0.04%
Belém	Archicad	Bedroom 2	469.3	-0.03%
Urubici	Archicad	Living room	106.46	-0.08%
Urubici	Archicad	Bedroom 1	55.76	0.00%
Urubici	Archicad	Bedroom 2	60.6	-0.03%
Rio de Janeiro	Archicad	Living room	278.84	-0.18%

Location	BIM Software	Room	Thermal load [kWh/(m².year)]	Percentage error
Rio de Janeiro	Archicad	Bedroom 1	132.41	-0.05%
Rio de Janeiro	Archicad	Bedroom 2	146.74	-0.07%
São Paulo	Archicad	Living room	97.04	-0.24%
São Paulo	Archicad	Bedroom 1	15.02	-0.07%
São Paulo	Archicad	Bedroom 2	18.5	-0.05%
Brasília	Archicad	Living room	243.56	-0.18%
Brasília	Archicad	Bedroom 1	47.33	-0.04%
Brasília	Archicad	Bedroom 2	55.73	-0.09%
Porto Alegre	Archicad	Living room	177.25	-0.20%
Porto Alegre	Archicad	Bedroom 1	63.16	-0.06%
Porto Alegre	Archicad	Bedroom 2	73.09	-0.11%
Salvador	Archicad	Living room	563.09	-0.15%
Salvador	Archicad	Bedroom 1	312.57	-0.04%
Salvador	Archicad	Bedroom 2	337.82	-0.05%
Curitiba	Archicad	Living room	46.11	-0.24%
Curitiba	Archicad	Bedroom 1	4.64	0.00%
Curitiba	Archicad	Bedroom 2	6.27	0.00%

APPENDIX D. Heating load prediction values for the 6 locations

Location	BIM Software	Room	Thermal Load [kWh/(m².year)]	Percentage Error
Florianópolis	Revit	Bedroom 1	2.62	2.34%
Florianópolis	Revit	Bedroom 2	1.97	6.49%
Santa Maria	Revit	Living room	5.08	4.96%
Santa Maria	Revit	Bedroom 1	32.11	1.04%
Santa Maria	Revit	Bedroom 2	29.33	2.52%
Urubici	Revit	Living room	8.51	2.16%
Urubici	Revit	Bedroom 1	36.82	0.49%
Urubici	Revit	Bedroom 2	30.68	2.27%
São Paulo	Revit	Living room	0.26	13.04%
São Paulo	Revit	Bedroom 1	3.83	2.41%
São Paulo	Revit	Bedroom 2	3.09	5.82%
Porto Alegre	Revit	Living room	0.81	9.46%
Porto Alegre	Revit	Bedroom 1	11.88	1.54%
Porto Alegre	Revit	Bedroom 2	10.55	3.53%
Curitiba	Revit	Living room	2.71	6.69%
Curitiba	Revit	Bedroom 1	25.22	1.41%
Curitiba	Revit	Bedroom 2	22.35	3.09%
Florianópolis	OpenBuildings	Bedroom 1	2.56	0.00%
Florianópolis	OpenBuildings	Bedroom 2	1.89	2.16%
Santa Maria	OpenBuildings	Living room	4.9	1.24%
Santa Maria	OpenBuildings	Bedroom 1	31.77	-0.03%
Santa Maria	OpenBuildings	Bedroom 2	28.86	0.87%
Urubici	OpenBuildings	Living room	8.31	0.48%
Urubici	OpenBuildings	Bedroom 1	36.64	0.00%
Urubici	OpenBuildings	Bedroom 2	29.95	0.53%
São Paulo	OpenBuildings	Living room	0.24	4.35%
São Paulo	OpenBuildings	Bedroom 1	3.74	0.00%
São Paulo	OpenBuildings	Bedroom 2	2.97	1.71%
Porto Alegre	OpenBuildings	Living room	0.75	1.35%
Porto Alegre	OpenBuildings	Bedroom 1	11.7	0.00%
Porto Alegre	OpenBuildings	Bedroom 2	10.32	1.28%
Curitiba	OpenBuildings	Living room	2.58	1.57%
Curitiba	OpenBuildings	Bedroom 1	24.87	0.00%
Curitiba	OpenBuildings	Bedroom 2	21.91	1.06%
Florianópolis	Archicad	Bedroom 1	2.56	0.00%
Florianópolis	Archicad	Bedroom 2	1.84	-0.54%
Santa Maria	Archicad	Living room	4.82	-0.41%
Santa Maria	Archicad	Bedroom 1	31.77	-0.03%
Santa Maria	Archicad	Bedroom 2	28.53	-0.28%
Urubici	Archicad	Living room	8.31	-0.24%

Location	BIM Software	Room	Thermal Load [kWh/(m².year)]	Percentage Error
Urubici	Archicad	Bedroom 1	36.64	0.00%
Urubici	Archicad	Bedroom 2	29.95	-0.17%
São Paulo	Archicad	Living room	0.23	0.00%
São Paulo	Archicad	Bedroom 1	3.74	0.00%
São Paulo	Archicad	Bedroom 2	2.9	-0.68%
Porto Alegre	Archicad	Living room	0.73	-1.35%
Porto Alegre	Archicad	Bedroom 1	11.7	0.00%
Porto Alegre	Archicad	Bedroom 2	10.15	-0.39%
Curitiba	Archicad	Living room	2.52	-0.79%
Curitiba	Archicad	Bedroom 1	24.87	0.00%
Curitiba	Archicad	Bedroom 2	21.61	-0.32%