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# Fluxo de Trabalho BIM-to-BEM Automatizado para Avaliação e Etiquetagem de Eficiência Energética de Edificações

Florianópolis
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# Fluxo de Trabalho BIM-to-BEM Automatizado para Avaliação e Etiquetagem de Eficiência Energética de Edificações

Tese submetida ao Programa de Pós-Graduação em Engenharia Civil da Universidade Federal de Santa Catarina como requisito parcial para a obtenção do título de Doutor em Engenharia Civil.

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Luís Filipe Muta

**Fluxo de Trabalho BIM-to-BEM Automatizado para Avaliação e Etiquetagem de Eficiência Energética de Edificações**

O presente trabalho em nível de Doutorado foi avaliado e aprovado, em 4 de março de 2026, pela banca examinadora composta pelos seguintes membros:

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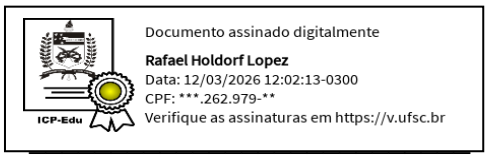
Certificamos que esta é a versão original e final do trabalho de conclusão que foi julgado adequado para obtenção do título de Doutor em Engenharia Civil.

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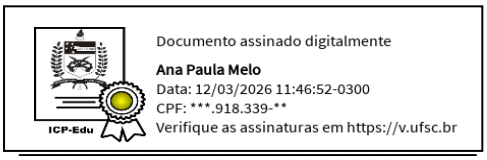


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## RESUMO

Esta tese desenvolve e valida um fluxo de trabalho BIM-to-BEM automatizado aplicável à avaliação e etiquetagem de eficiência energética de edificações por meio de simulação, utilizando o Programa Brasileiro de Etiquetagem de Edificações (PBE Edifica) como referência de demonstração. A pesquisa parte do reconhecimento de que métodos baseados em simulação oferecem maior resolução para representar o comportamento termoenergético das edificações, porém permanecem limitados pelo elevado custo de preparação de modelos, dependência de intervenções manuais e variabilidade interpretativa na tradução de requisitos normativos em configurações de simulação, fatores que reduzem a rastreabilidade e dificultam a aplicação recorrente. Para enfrentar esse problema, o trabalho articula requisitos de informação, diretrizes de modelagem, protocolo de simulação e um pipeline orientado à verificação, correção e enriquecimento de dados exportados. A tese organiza-se em quatro estudos interdependentes: revisão integrativa do cenário brasileiro (28 estudos), revisão sistemática internacional (106 artigos), investigação experimental sobre o efeito da granularidade de modelagem BIM nos resultados de simulação (62 cenários) e proposição de um fluxo BIM-to-BEM automatizado via gbXML, demonstrado em edifício universitário de 8.100 m². A revisão nacional evidencia a predominância de extração de informações geométricas e de soluções pontuais com baixa padronização, enquanto a análise internacional reforça que os desafios de interoperabilidade persistem mesmo em contextos maduros. A investigação experimental demonstra que a granularidade semântica associada às condições internas pode dominar a variabilidade dos resultados (68% entre os extremos) e induzir interpretações inadequadas quando as simplificações não são controladas. Com base nessas evidências, a tese implementa um pipeline automatizado em programação Python que aplica regras de verificação, correção e padronização pós-exportação, integra um protocolo de simulação alinhado aos requisitos normativos e operacionaliza o princípio de "tão detalhado quanto útil" por meio de uma granularidade adaptada ao objetivo da avaliação. A demonstração no edifício universitário gera, em aproximadamente 15 minutos, modelos BEM consistentes para condição real e condição de referência, e calcula a classificação energética. Os resultados sustentam que a estruturação integrada do fluxo reduz significativamente o retrabalho manual, favorecendo consistência metodológica e ampliando transparência e rastreabilidade. Como contribuição científica, a tese propõe e demonstra um fluxo de trabalho automatizado que sistematiza a conversão BIM-to-BEM por meio da articulação entre requisitos de informação, diretrizes de modelagem, protocolo de simulação e pipeline automatizado de pós-processamento, reduzindo a variabilidade procedimental e viabilizando a aplicação de simulação termoenergética em rotinas normativas de etiquetagem com maior agilidade, transparência e escalabilidade. Essa estrutura oferece à academia um modelo replicável para a integração BIM-BEM e à sociedade um caminho para a ampliar a confiabilidade e a eficiência em esquemas de certificação energética obrigatória.



**Palavras-chave**: BIM; BEM; automação; etiquetagem; eficiência energética.

## ABSTRACT

This thesis develops and validates an automated BIM-to-BEM workflow for energy efficiency assessment and buildings labeling through simulation, using the Brazilian Building Energy Labeling Program (PBE Edifica) as a demonstration reference. The research acknowledges that simulation-based methods offer higher resolution to represent the thermoenergetic behavior of buildings, yet remain limited by high model preparation costs, dependence on manual interventions, and interpretative variability in translating regulatory requirements into simulation configurations – factors that reduce traceability and hinder recurrent application. To address this problem, the work articulates information requirements, modeling guidelines, a simulation protocol, and a pipeline oriented toward verification, correction, and enrichment of exported data. The thesis is organized into four interdependent studies: an integrative review of the Brazilian scenario (28 studies), a systematic international review (106 articles), an experimental investigation on the effect of BIM modeling granularity on simulation results (62 scenarios), and a proposition of an automated BIM-to-BEM workflow via gbXML, demonstrated in an 8,100 m² university building. The national review reveals a predominance of geometric information extraction and ad hoc solutions with low standardization, while the international analysis reinforces that interoperability challenges persist even in mature contexts. The experimental investigation demonstrates that semantic granularity associated with internal conditions can dominate result variability (68% between extremes) and induce inadequate interpretations when simplifications are not controlled. Based on this evidence, the thesis implements an automated Python pipeline that applies post-export verification, correction, and standardization rules, integrates a simulation protocol aligned with regulatory requirements, and operationalizes the principle of "as detailed as useful" through granularity adapted to the assessment objective. The demonstration in the university building generates, in approximately 15 minutes, consistent BEM models for actual and reference conditions and calculates the energy rating. The results support that the integrated workflow structure significantly reduces manual rework, promotes methodological consistency and enhances transparency and traceability. As a scientific contribution, the thesis proposes and demonstrates an automated workflow that systematizes BIM-to-BEM conversion through the unprecedented articulation of information requirements, modeling guidelines, simulation protocol, and automated post-processing pipeline, reducing procedural variability and enabling the application of thermoenergetic simulation in regulatory labeling routines with greater agility, transparency, and scalability. This structure offers academia a replicable model for BIM-BEM integration and society as a pathway to expand reliability and efficiency in mandatory energy certification schemes.



**Keywords**: BIM; BEM; automation; certification; energy efficiency.

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## LISTA DE ABREVIATURAS E SIGLAS

| | |
|---|---|
| ACH | *Air Changes per Hour* (Trocas de Ar por Hora) |
| APP | Ambiente de Permanência Prolongada |
| APT | Ambiente de Permanência Transitória |
| BEM | *Building Energy Modeling* (Modelagem Energética de Edificações) |
| BIM | *Building Information Modeling* (Modelagem da Informação da Construção) |
| CAD | *Computer-Aided Design* |
| CON | Montagem Construtiva |
| COP | *Coefficient of Performance* (Coeficiente de Performance) |
| DPE | Densidade de Potência de Equipamentos |
| DPI | Densidade de Potência de Iluminação |
| EUI | *Energy Use Intensity* (Intensidade de Uso Energético) |
| FS | Fator Solar |
| gbXML | *Green Building Extensible Markup Language* |
| HTML | *HyperText Markup Language* |
| IDF | *Input Data File* |
| IFC | *Industry Foundation Classes* |
| INT | Condições Internas |
| IoT | *Internet of Things* (Internet das Coisas) |
| LOD | *Level of Development* (Nível de Desenvolvimento) |
| LOIN | *Level of Information Need* (Nível de Necessidade de Informação) |
| PBE Edifica | Programa Brasileiro de Etiquetagem de Edificações |
| PRCEP | Percentual de Redução do Consumo de Energia Primária |
| RSL | Revisão Sistemática da Literatura |
| SPA | Configuração Espacial |
| ZON | Zoneamento Térmico |

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# 1 INTRODUÇÃO

A mitigação das mudanças climáticas e a busca por modelos de desenvolvimento sustentável situam a gestão da demanda energética como um ponto relevante na agenda global (UN, 2023). Nesse cenário, a transição energética é apresentada como um vetor para a descarbonização, fundamentada na redução do consumo de recursos e das emissões em setores estratégicos (Economidou et al., 2020). As edificações destacam-se entre esses setores devido à sua participação expressiva na demanda de energia e nos impactos ambientais decorrentes (Maduta et al., 2023). Essa conjuntura reforça a avaliação do desempenho energético das edificações como um elemento progressivamente incorporado às políticas públicas (Li et al., 2019).

Tal relevância impulsionou a implementação de marcos legais e de iniciativas voltadas ao estabelecimento de índices mínimos de eficiência energética e à consolidação de esquemas de avaliação e etiquetagem de edificações (Li et al., 2019). Embora os requisitos e as ferramentas variem entre jurisdições, esses esquemas enfatizam, de forma recorrente, transparência e comparabilidade, com procedimentos padronizados para avaliar o uso de energia do estoque edificado (Muta; Melo; Lamberts, 2025). No contexto regulatório, a avaliação de eficiência energética é estruturada para promover conformidade com padrões e critérios predefinidos (Hårsman; Daghbashyan; Chaudhary, 2016). Para favorecer a reprodutibilidade e a ampla aplicabilidade, esses esquemas frequentemente se apoiam em valores prescritivos, parâmetros padronizados e premissas fixas delineadas em normas e manuais técnicos (Hardy; Glew, 2019).

A consolidação dos arcabouços regulatórios aumentou a demanda por métodos de avaliação capazes de lidar com grandes volumes de projetos, mantendo rigor técnico e consistência metodológica (Li et al., 2019). Nesse cenário, destacam-se tanto os métodos de cálculo simplificado, baseados na entrada explícita de características prescritas em formulários ou softwares padronizados (Las-Heras-Casas et al., 2018), quanto os métodos baseados em simulação dinâmica, que utilizam modelos digitais para representar geometria, propriedades de materiais, cargas internas, perfis de ocupação e sistemas técnicos (Muta; Melo; Lamberts, 2025). Dentro desse domínio, o *Building Energy Modeling* (BEM) consolidou-se como abordagem para a criação de representações virtuais e a derivação de métricas de

desempenho energético (Hensen; Lamberts, 2019). Contudo, apesar de sua capacidade de capturar dinâmicas térmicas e perfis temporais com alta resolução, o uso efetivo de simulação para fins de conformidade pode ser dificultado por desafios de preparação de dados, consistência de interpretação e esforço para alinhar a documentação do projeto aos dados de entrada do modelo (Melo et al., 2016).

Essa dependência de atividades intensivas em manipulação e preparo de dados constitui um obstáculo crítico para a aplicação de avaliações de eficiência energética para fins regulatórios, especialmente quando o processo é manual e a diversidade da documentação introduz complexidade adicional (Bracht; Melo; Lamberts, 2021). À medida que os volumes de projetos crescem e as regulamentações evoluem, as ineficiências operacionais tendem a se agravar, elevando o risco de inconsistências e dificultando a manutenção da integridade dos dados (Gonzalez-Caceres et al., 2022). Em contextos que exigem avaliações rápidas e reprodutíveis, como a etiquetagem compulsória, esses fatores reforçam a necessidade de abordagens que reduzam intervenção manual e aumentem o controle sobre o processo (Muta et al., 2026).

Nesse cenário, avanços na Modelagem da Informação da Construção (*Building Information Modeling* – BIM) oferecem caminhos promissores para organizar e integrar a grande quantidade de informações necessárias à avaliação de eficiência energética (Barone et al., 2021). Ferramentas BIM consolidam dados geométricos, espaciais, de materiais e de sistemas em um ambiente digital coordenado, acessível e processável ao longo de diferentes estágios de projeto e construção (Ciccozzi et al., 2023). A adoção de padrões abertos de dados, como *Industry Foundation Classes* (IFC) (Garlet et al., 2026) e *Green Building Extensible Markup Language* (gbXML) (Otero et al., 2020), pode facilitar a transferência de informações do BIM para o BEM, reduzindo redundâncias e apoiando uma interpretação mais consistente dos dados (Gao; Koch; Wu, 2019). Contudo, na prática, a estrutura, a completude e a granularidade dos dados no BIM podem variar significativamente conforme o estágio do projeto, as convenções de modelagem e os requisitos específicos dos esquemas regulatórios (Xu et al., 2023). Como consequência, a dependência de fluxos de trabalho manuais frequentemente persiste, limitando oportunidades de automação e reduzindo a reprodutibilidade das avaliações energéticas (Muta; Garlet; Melo, 2024).

Mesmo com padrões abertos de dados, permanecem desafios de interoperabilidade associados a limitações de ferramentas e de algoritmos de

transformação de dados, resultando em perda de informação ou em saídas genéricas para uso em simulação (Roth; Shelden; Ouellette, 2024). Um problema-chave são as discrepâncias semânticas, nas quais o significado dos dados se perde ou é mal interpretado durante a transferência entre os ambientes BIM e BEM, afetando atributos como propriedades de materiais e condições de contorno (Wu et al., 2023). Essas lacunas podem se manifestar, por exemplo, quando elementos com função específica no BIM são classificados incorretamente no BEM devido a interpretações divergentes de algoritmos ou limitações do padrão aberto de dados (Gao; Koch; Wu, 2019). Para contornar esse tipo de limitação, abordagens recentes investigaram correções automatizadas e enriquecimento semântico para o alinhamento de taxonomia e de atributos necessários à avaliação energética (Kamel; Memari, 2019; Di Biccari et al., 2022). Outras estratégias exploram correspondência por similaridade para reduzir ambiguidades e ajustes manuais em mapeamentos de dados (Forth; Borrmann, 2024), bem como procedimentos de transformação de dados para aumentar a consistência das entradas no modelo BEM (Costa; Sicilia, 2020).

Diante disso, a integração BIM-to-BEM tende a exigir mais do que a simples troca de arquivos, requerendo requisitos de informação e diretrizes de modelagem capazes de padronizar dados para a avaliação energética (Sanhudo et al., 2021), além de um protocolo de simulação que assegure configuração consistente do BEM para fins de conformidade, especialmente para abordagens automatizadas (Choi et al., 2019). Protocolos de simulação contribuem para definir procedimentos de configuração e para aplicar valores prescritivos de bases de dados (e.g., legislação, normas, manuais técnicos, códigos de energia) para equilibrar padronização e flexibilidade conforme tipos de edificações e objetivos de verificação (Albdour et al., 2022). A combinação desses elementos em rotinas automatizadas cria condições para reduzir a intervenção manual e manter o alinhamento regulatório, sobretudo quando os dados de entrada apresentam estrutura e completude compatíveis com as demandas da avaliação energética (Gao; Koch; Wu, 2019).

Embora a estruturação de dados e a automação sejam demandas globais, a validação dessas propostas requer sua aplicação em um arcabouço regulatório concreto. Nesse sentido, esta pesquisa adota o contexto brasileiro, materializado no Programa Brasileiro de Etiquetagem de Edificações (PBE Edifica), como cenário de investigação. O programa, estruturado com padrões mínimos de desempenho (Brasil, 2022; CGIEE, 2025), reflete os desafios internacionais típicos da adoção de métodos

baseados em desempenho. A utilização de simulação em suas rotinas permanece condicionada às mesmas barreiras de preparação de dados e padronização operacional discutidas globalmente (Muta; Melo; Lamberts, 2025). É nesse quadro que a pesquisa investiga a integração BIM-to-BEM, explorando como requisitos de informação, diretrizes de modelagem, protocolos e automação podem compor um fluxo de trabalho reprodutível e escalável para a etiquetagem.

## 1.1 PROBLEMATIZAÇÃO

A incorporação da eficiência energética ao campo regulatório desloca o foco da análise do desempenho como exercício pontual de projeto para um mecanismo de governança que exige comparabilidade entre empreendimentos e estabilidade metodológica entre avaliadores e ferramentas (Geraldi et al., 2025). Essa mudança cria uma tensão estrutural entre duas racionalidades. A racionalidade regulatória privilegia a reprodutibilidade, a verificabilidade e a rastreabilidade, pois as decisões de conformidade dependem de critérios padronizados e defensáveis em auditorias (Pascuas; Paoletti; Lollini, 2017). A racionalidade técnico-operacional, por sua vez, tende a buscar uma representação mais fiel do comportamento termoenergético, em especial quando simulações dinâmicas são utilizadas para capturar efeitos de massa térmica, sazonalidade e perfis horários (Muta; Melo; Lamberts, 2025). A coexistência dessas racionalidades torna o processo de etiquetagem particularmente sensível a inconsistências de interpretação e a variações na preparação dos dados de entrada, sobretudo quando o objetivo é operar em escala (Melo et al., 2016).

A escalabilidade, frequentemente tratada como requisito administrativo, manifesta-se como um problema técnico-informacional. Em esquemas obrigatórios, o aumento do volume de projetos e a evolução contínua de exigências normativas ampliam o custo de manutenção de rotinas manuais, elevando o risco de divergências entre a documentação, as entradas em software e os resultados emitidos (Li et al., 2019). Mesmo quando o cálculo é prescritivo, a execução prática tende a depender de múltiplas transcrições e reinterpretações de dados, o que favorece erros, perda de integridade e baixa transparência do processo (Muta; Garlet; Melo, 2024). Instrumentos concebidos para padronizar a avaliação podem gerar variabilidade operacional, caso a cadeia de dados não seja controlada de forma sistemática (Melo et al., 2014). Em termos de política pública, essa variabilidade enfraquece a função de benchmarking e a previsibilidade do compliance, reduzindo a utilidade da

etiquetagem como instrumento de transformação de mercado (Economidou et al., 2020).

A adoção de simulação dinâmica em contextos de conformidade introduz ganhos potenciais, mas também amplia o espaço de incertezas na modelagem. A simulação dinâmica permite representar interações temporais e dependências entre cargas internas, ventilação, ganhos solares e estratégias de condicionamento (Hensen; Lamberts, 2019). Entretanto, para fins regulatórios, a qualidade do resultado passa a depender menos da capacidade do motor de simulação e mais da consistência com que o modelo é configurado (Hardy; Glew, 2019). Quando a preparação do modelo exige decisões manuais, surgem discrepâncias associadas à escolha de zoneamento, à atribuição de propriedades e à parametrização de sistemas, com impacto direto na comparabilidade dos indicadores (Muta et al., 2026). Esse problema tende a se agravar quando diferentes profissionais e organizações participam da cadeia de produção do modelo, tornando a consistência um desafio socio-técnico e não apenas computacional (Miller et al., 2025).

A digitalização via BIM costuma ser apresentada como resposta natural a essas limitações, pois concentra informações geométricas e semânticas em um ambiente coordenado e passível de extração (Liu et al., 2023). Contudo, a prática mostra que a existência de um modelo BIM não equivale à existência de um conjunto de dados apto à simulação. A variabilidade de estágios de projeto, convenções disciplinares, bibliotecas e estratégias de modelagem produz heterogeneidade na completude e na granularidade dos dados, com efeitos diretos na conversão para o BEM (Xu et al., 2023). Mesmo quando padrões abertos são utilizados, a transferência entre BIM e BEM permanece condicionada ao que é exportável, ao que é interpretável pelos softwares de simulação e ao que é semanticamente preservado no percurso (Muta; Melo; Lamberts, 2025). Assim, a automação encontra um limite prático quando se apoia apenas na troca de arquivos, pois parte relevante do trabalho permanece na interpretação, correção e padronização de dados após a exportação (Bracht; Melo; Lamberts, 2021; Roth; Shelden; Ouellette, 2024).

A interoperabilidade, nesse cenário, não se reduz à compatibilidade de formatos. A principal fragilidade emerge de discrepâncias semânticas, nas quais o significado de atributos e a função de elementos se perde ou é reinterpretado durante a tradução entre esquemas, softwares e taxonomias (Wu et al., 2023). A consequência pode ser a classificação equivocada de superfícies, materiais ou condições de

contorno, além de omissões de atributos, com impacto cumulativo na qualidade do modelo BEM e nos resultados da avaliação (Gao; Koch; Wu, 2019). A presença de esquemas abertos, como IFC e gbXML, reduz as dependências proprietárias, porém não elimina as limitações de abrangência e de suporte das ferramentas. Mesmo versões atualizadas podem permanecer subutilizadas quando ambientes BIM ou BEM não implementam novos atributos semânticos (Porsani et al., 2021). Esse quadro ajuda a explicar por que fluxos semiautomatizados frequentemente ainda exigem correções manuais recorrentes e validações intensivas, especialmente em geometrias complexas ou em modelos com baixa consistência semântica (Alexandrou et al., 2025).

A literatura indica tentativas de endereçar essas lacunas por meio de enriquecimento semântico e correções automatizadas, utilizando dicionários, ontologias e rotinas de mapeamento para padronizar termos e inferir atributos ausentes (Kim et al., 2013; Costa; Sicilia, 2020; Forth; Borrmann, 2024). Apesar desse avanço, persiste a dificuldade de transformar essas soluções em rotinas para os contextos regulatórios, nos quais a transparência do procedimento e a repetibilidade do resultado são requisitos tão relevantes quanto o próprio valor numérico calculado (Carvalho et al., 2021). Além disso, a adoção regulatória tende a demandar rastreabilidade de cada regra aplicada, redução de ambiguidade na atribuição de parâmetros e capacidade de auditar as decisões de transformação do dado, aspectos que nem sempre são priorizados em fluxos orientados à análise de projeto ou a estudos exploratórios (Liu et al., 2023). A fragilidade, portanto, não está apenas na etapa de simulação, mas também no controle do percurso informacional que antecede a simulação e no modo como regras de conformidade são operacionalizadas de forma consistente (Melo et al., 2014; Roth; Shelden; Ouellette, 2024).

O problema torna-se mais evidente quando os requisitos de avaliação evoluem de métricas estáticas para abordagens que consideram perfis temporais e maior integração com o sistema elétrico, como ocorre em revisões recentes de diretivas e em debates internacionais sobre flexibilidade do lado da demanda e desempenho interativo com a rede (Aste et al., 2025). Essa tendência amplia a dependência de dados bem estruturados, de cronogramas coerentes e de configurações de simulação consistentes, reduzindo a margem de tolerância para fluxos baseados em transcrição manual e em suposições implícitas (Muta; Melo; Lamberts, 2025; Aste et al., 2025). Em consequência, a infraestrutura de dados e o

método de transformação entre BIM e BEM passam a integrar o próprio mecanismo regulatório, e não apenas um suporte operacional. Sem esse controle, cresce o risco de que mudanças regulatórias produzam aumento de custo, redução de reprodutibilidade e atraso na emissão de certificações e etiquetas, com efeitos sobre cronogramas de projeto e sobre a efetividade da política pública (Gonzalez-Caceres et al., 2022).

Nesse contexto, a formalização de requisitos de informação, diretrizes de modelagem e protocolos de simulação assume um papel central. Requisitos de informação definem o conjunto mínimo e a estrutura dos dados necessários para produzir modelos energéticos consistentes, orientando o que deve ser representado e em que estágio (Sanhudo et al., 2021). Diretrizes de modelagem reduzem a variabilidade, pois traduzem o requisito em práticas que evitam erros de geometria, interseções ambíguas e divergências de interpretação entre ferramentas, com impacto direto na exportação e na geração de superfícies analíticas (O'Donnell et al., 2019). Protocolos de simulação, por sua vez, convertem normas e manuais em regras explícitas de configuração do BEM, permitindo comparações sob condições de contorno equivalentes e com parâmetros prescritos aplicados de forma reproduzível (Choi et al., 2019). Ainda assim, esses elementos, isoladamente, não resolvem a etapa crítica pós-exportação, quando arquivos gerados por BIM chegam ao ambiente BEM com lacunas semânticas, nomenclaturas genéricas e configurações incompletas para simulação (Barone et al., 2021; Carvalho et al., 2021). Por essa razão, a automação passa a depender de pipelines capazes de integrar validação, correção e enriquecimento, operando regras explícitas alinhadas ao protocolo e reduzindo intervenções manuais (Jansen et al., 2025).

A validação prática desse arranjo metodológico demanda um cenário de aplicação onde a discrepância entre a exigência normativa e a capacidade operacional seja evidente. É sob essa perspectiva que se analisa o PBE Edifica. O contexto nacional reproduz as barreiras discutidas globalmente, apresentando um cenário onde a demanda por conformidade (CGIEE, 2025) contrasta com a baixa padronização dos processos de projeto (Muta; Garlet; Melo, 2024). A dependência de ajustes manuais e a variabilidade na preparação dos modelos, identificadas na literatura internacional, manifestam-se no PBE Edifica como entraves diretos à reprodutibilidade e à escalabilidade da etiqueta (Muta; Melo; Lamberts, 2025; Bracht; Melo; Lamberts, 2021). Dessa forma, o caso brasileiro não é adotado apenas como recorte geográfico,

mas como o meio para investigar se a estruturação de requisitos, diretrizes e automação é capaz de superar a desarticulação técnica típica de esquemas de avaliação obrigatória.

Diante desse conjunto de desafios, a questão central que orienta esta pesquisa é qual arranjo mínimo de processos viabiliza um fluxo BIM-to-BEM consistente para a avaliação de eficiência energética por meio de simulação. Essa questão desdobra-se em três dimensões investigativas. A primeira dimensão investiga quais requisitos de informação e diretrizes de modelagem constituem o núcleo mínimo para produzir modelos BIM compatíveis com a geração e a parametrização de modelos BEM para simulação. A segunda dimensão examina quais operações um pipeline automatizado deve executar para verificar, corrigir e complementar dados exportados, reduzindo intervenção manual e ampliando a rastreabilidade. A terceira dimensão avalia a aplicabilidade do arranjo mínimo proposto em avaliações reais, considerando o esforço operacional, a consistência dos resultados e a possibilidade de auditoria do processo.

## 1.2 HIPÓTESE

A hipótese que orienta esta pesquisa é que a estruturação de um fluxo de trabalho BIM-to-BEM reduz a dependência de ajustes manuais, favorece a consistência metodológica e aumenta a transparência nas avaliações de eficiência energética vinculadas a processos de etiquetagem. Essa hipótese fundamenta-se no reconhecimento de que as barreiras de interoperabilidade entre BIM e BEM decorrem não apenas de limitações técnicas dos formatos de troca de dados, mas também da escassez de estruturas que orientem o processo de modelagem BIM, verifiquem a integridade dos dados exportados e traduzam requisitos normativos em configurações de simulação BEM.

A hipótese desdobra-se em três dimensões complementares. Primeiro, os requisitos de informação e as diretrizes de modelagem orientam a construção de modelos BIM compatíveis com as demandas de simulação energética, reduzindo lacunas de informação e inconsistências estruturais que comprometem a exportação de dados. Segundo, um pipeline automatizado verifica, corrige e complementa os dados exportados, transformando modelos BIM incompletos em modelos BEM compatíveis com os requisitos normativos, reduzindo o tempo de avaliação de uma edificação de horas ou dias para minutos. Terceiro, a aplicação programática

traduzida a partir de um protocolo de simulação reduz a variabilidade interpretativa na implementação de requisitos normativos, favorecendo a comparabilidade dos resultados e a auditabilidade das avaliações.

A validação dessa hipótese depende da demonstração de que o fluxo de trabalho proposto pode ser aplicado de forma sistemática, mantendo consistência nos procedimentos de verificação, correção e enriquecimento de dados, e que os resultados obtidos são rastreáveis e alinhados aos critérios estabelecidos pelo programa de etiquetagem. A hipótese não pressupõe a eliminação completa de intervenções manuais nem a resolução definitiva das limitações de interoperabilidade, mas propõe que a estruturação sistemática do fluxo de trabalho pode reduzir drasticamente essas limitações, facilitando a aplicação da simulação dinâmica em contextos de etiquetagem.

## 1.3 OBJETIVOS

A definição dos objetivos desta pesquisa fundamenta-se na necessidade de estruturar a integração entre BIM e BEM para fins de conformidade normativa. O escopo do trabalho é delineado para responder às lacunas de interoperabilidade e de processo identificadas, organizando-se em um objetivo geral, que apresenta a meta principal, e em objetivos específicos, que detalham os entregáveis técnicos necessários para viabilizar a consistência metodológica da tese.

### 1.3.1 Objetivo Geral

Desenvolver e validar um fluxo de trabalho BIM-to-BEM aplicável aos processos de avaliação e etiquetagem de eficiência energética em edificações.

### 1.3.2 Objetivos Específicos

Para o alcance do objetivo geral, foram definidos os seguintes objetivos específicos:

- Estabelecer requisitos de informação e diretrizes de modelagem orientados às demandas de simulação energética em contextos de etiquetagem.
- Apresentar um protocolo de simulação que traduza os requisitos normativos em configurações de simulação.
- Desenvolver um pipeline capaz de verificar, corrigir e complementar os dados exportados de modelos BIM para modelos BEM.

- Produzir uma avaliação de eficiência energética completa por meio de um estudo de caso, validando a aplicabilidade do fluxo de trabalho BIM-to-BEM.

## 1.4 ESTRUTURA

Esta tese adota uma organização distinta do modelo tradicional. Em vez de reconstruir integralmente todo o percurso investigativo em capítulos convencionais, apresenta uma síntese estruturada a partir de quatro artigos científicos desenvolvidos ao longo do doutorado, disponibilizados integralmente nos apêndices. Dessa forma, o corpo principal concentra-se em elementos conceituais que sustentam o desenvolvimento da pesquisa, enquanto os apêndices preservam a profundidade metodológica e técnica dos estudos originais.

Após a Introdução, inicia-se o bloco de desenvolvimento, no qual cada artigo é apresentado como seção autônoma. Essa apresentação segue uma estrutura estável composta por duas partes. A primeira situa o artigo na trajetória da pesquisa, apresentando informações gerais e o contexto de sua produção. A segunda corresponde ao guia de leitura, estruturado como um roteiro que sintetiza a lógica interna do artigo. Nos guias, a narrativa privilegia a fluidez argumentativa, recorrendo ao referencial bibliográfico apenas quando indispensável, uma vez que os guias apontam diretamente para os artigos. Por meio dos guias, o leitor tem uma visão geral da progressão conceitual, das relações entre seções e dos pontos que conectam o artigo ao desenvolvimento da tese.

Concluída a apresentação dos quatro artigos, a tese reúne o conjunto de resultados na seção de síntese integrativa. Essa seção recompõe o desenvolvimento completo da investigação em uma narrativa única, evidenciando as conexões entre os artigos e consolidando a contribuição científica final da tese. O texto se encerra com as conclusões, que apresentam o fechamento do trabalho, recuperam os resultados centrais e indicam seus desdobramentos potenciais.

# 2 APLICAÇÃO DO BIM NO PROGRAMA BRASILEIRO DE ETIQUETAGEM DE EDIFICAÇÕES: UMA REVISÃO – ARTIGO 1

O primeiro artigo que compõe esta tese intitula-se *BIM application in the Brazilian Building Labeling Program: a review* e foi desenvolvido por Luís Filipe Muta, Liége Garlet e Ana Paula Melo. O trabalho encontra-se publicado no periódico PARC Pesquisa em Arquitetura e Construção, tendo cumprido o trâmite editorial com submissão em 31 de julho de 2023, aprovação em 17 de janeiro de 2024 e publicação em 15 de abril de 2024. Sua referência bibliográfica é:

- MUTA, L. F.; GARLET, L.; MELO, A. P. BIM application in the Brazilian Building Labeling Program: a review. **PARC Pesquisa em Arquitetura e Construção**, Campinas, SP, v. 15, p. e024005, 2024. DOI: 10.20396/parc.v15:00.8674178.

O estudo apresenta uma revisão integrativa da literatura sobre a incorporação do BIM ao PBE Edifica. O texto expõe os benefícios do BIM para a extração, automação e visualização de dados, ao mesmo tempo em que mapeia desafios críticos, como a escassez de práticas padronizadas para a integração com o BEM e a limitada exploração do OpenBIM. A análise aponta lacunas de pesquisa e indica que trabalhos futuros devem priorizar a investigação das complexidades das ferramentas BIM e BEM, a compreensão da sintaxe e a semântica dos dados e a adesão a protocolos e diretrizes de modelagem.

## 2.1 GUIA DE LEITURA DO ARTIGO 1

Esta seção apresenta um guia de leitura destinado a orientar a apreciação do artigo 1, disponibilizado integralmente no APÊNDICE A. O objetivo é oferecer uma compreensão rápida da lógica interna do artigo, destacando os pontos que estruturam sua argumentação e são particularmente relevantes para a tese. O guia de leitura não substitui a leitura do artigo, mas sinaliza onde se encontram os elementos críticos que sustentam a pesquisa.

### 2.1.1 Introdução

A seção *Introduction* contextualiza a pesquisa ao conectar a demanda por sustentabilidade às políticas públicas brasileiras, com foco no PBE Edifica. Destaca-se a transição para a obrigatoriedade da etiquetagem em edifícios públicos federais, estabelecida pela Instrução Normativa nº 2/2014 (Brasil, 2014). Esse marco regulatório intensifica a necessidade de métodos de avaliação eficientes em substituição à aquisição manual de dados. A problematização metodológica fundamenta-se na premissa de que o BIM mitiga a fragmentação do processo de projeto e as omissões de dados nas avaliações de eficiência energética.

### 2.1.2 Método

A seção *Method* detalha o protocolo de revisão. A estratégia de busca precisou ser expandida para o *Google Scholar* devido à escassez de estudos indexados internacionalmente sobre o tema, com apenas um registro na *Scopus* (Bracht, Melo e Lamberts, 2021). O levantamento resultou na seleção de 28 publicações pertinentes. A literatura foi organizada segundo uma taxonomia focada em três fluxos de trabalho principais. O primeiro abrange o *BIM as a tool for data extraction*. O segundo engloba o *Use of scripting/programming*. O terceiro trata da *BIM-BEM Integration*, que é subdividida nas categorias *Direct integration*, *Direct export* e *Indirect export*.

### 2.1.3 Desenvolvimento

A seção *Energy efficiency labeling of buildings in Brazil* traça a evolução normativa do PBE Edifica até a Portaria nº 309/2022 (Brasil, 2022), responsável por centralizar os critérios de avaliação energética. A análise comparativa entre o método simplificado e o método de simulação evidencia a necessidade de abordagens integradas. O diagnóstico aponta que o BIM contribui para a redução da fragmentação dos dados e do esforço manual durante a avaliação energética.

O tópico *Building Information Modeling* conceitua o BIM como uma metodologia de integração de tecnologias, processos e pessoas, baseada em Sacks et al. (2018). No cenário brasileiro, destacam-se a Estratégia BIM BR (Brasil, 2018) e a Lei nº 10.306/2020 (Brasil, 2020) como impulsionadoras do uso do BIM em obras públicas. O texto aborda barreiras práticas, como a escassez de normas específicas

e os desafios de interoperabilidade. Argumenta-se que as simulações energéticas devem ser antecipadas para as fases de concepção, o que evidencia o descompasso entre o potencial teórico do BIM e as atuais limitações de aplicação no país.

A seção *BIM in the Brazilian Building Energy Labeling Program* expõe que os modelos BIM podem centralizar os dados necessários para a avaliação energética. A utilização prática dessa capacidade depende de métodos consistentes de intercâmbio de dados e da interoperabilidade entre os softwares.

A subseção *BIM as a tool for data extraction* agrupa estudos sobre a aceleração da preparação de dados energéticos via modelos BIM. Observa-se a redução do tempo de preparação em comparação aos fluxos baseados em CAD. A extração de dados isolada não soluciona os desafios de consistência da informação. O processo torna-se efetivo quando o modelo BIM apresenta um conjunto mínimo de dados estruturados em parâmetros compatíveis com os métodos de avaliação.

A subseção *Use of scripting/programming* aborda iniciativas de automação da avaliação energética a partir de modelos BIM por meio de programação. Os ganhos em agilidade do processo contrastam com limitações associadas ao uso de templates proprietários, à necessidade de múltiplas rotinas e aos desafios de conversão para formatos abertos. A automação depende de uma estruturação informacional coerente para operar de forma consistente.

A subseção *Direct integration* examina o uso de conexões nativas e plugins para vincular ferramentas BIM e BEM. Apesar de facilitar a transferência de dados, as ferramentas BIM operam com parâmetros configuráveis restritos, limitando a representação das condicionantes energéticas. Essas integrações mostram-se adequadas para análises preliminares, mas são insuficientes para o atendimento pleno aos requisitos formais da etiquetagem de eficiência energética.

A subseção *Direct export* analisa os fluxos de transferência de arquivos de dados abertos, com ênfase no padrão gbXML. Evidenciam-se problemas como falhas na interpretação geométrica de modelos BEM e perda de dados semânticos entre diferentes combinações de softwares. A exportação de dados do BIM para o BEM sem tratamento posterior raramente resulta em um modelo funcional.

A subseção *Indirect export* discute estratégias de uso de softwares intermediários para a conversão de arquivos, como gbXML ou IFC para IDF. Cada etapa intermediária adiciona complexidade e introduz inconsistências. A multiplicação

de ferramentas para a conversão de dados não soluciona os desafios de interoperabilidade e amplia a necessidade de tratamentos posteriores aos modelos.

### 2.1.4 Discussão

A seção *Discussion* sintetiza o uso do BIM no contexto do PBE Edifica. A análise bibliométrica dos 28 trabalhos indica predominância de dissertações e artigos de eventos, com escassas publicações em periódicos. Observa-se uma inclinação para métodos prescritivos em detrimento de abordagens baseadas em simulação. A Figura 1 ilustra o panorama e evidencia a distância entre o potencial do BIM para apoiar fluxos analíticos e o foco no método prescritivo nas publicações mapeadas.

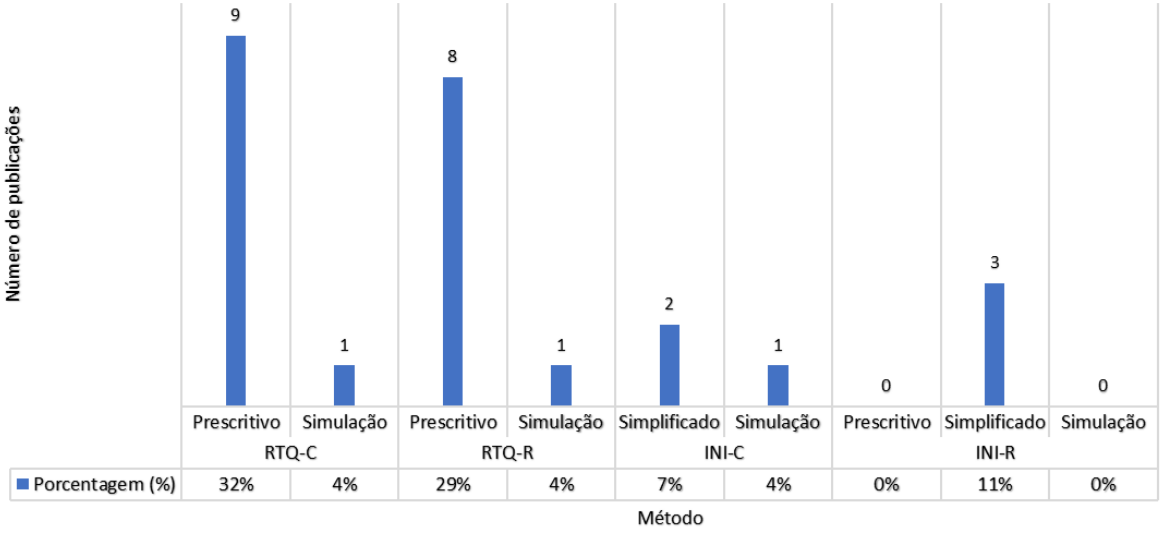



Figura 1 – Quantidade de publicações por método de avaliação
Fonte: Adaptado de Muta, Garlet e Melo (2024).

A síntese dos fluxos de trabalho (Figura 2) articula os softwares, os formatos de dados, as camadas intermediárias e os métodos de avaliação. A representação evidencia padrões recorrentes, como o uso predominante do Revit e do padrão gbXML. Constata-se a presença de etapas intermediárias que tornam os fluxos suscetíveis à perda de dados.

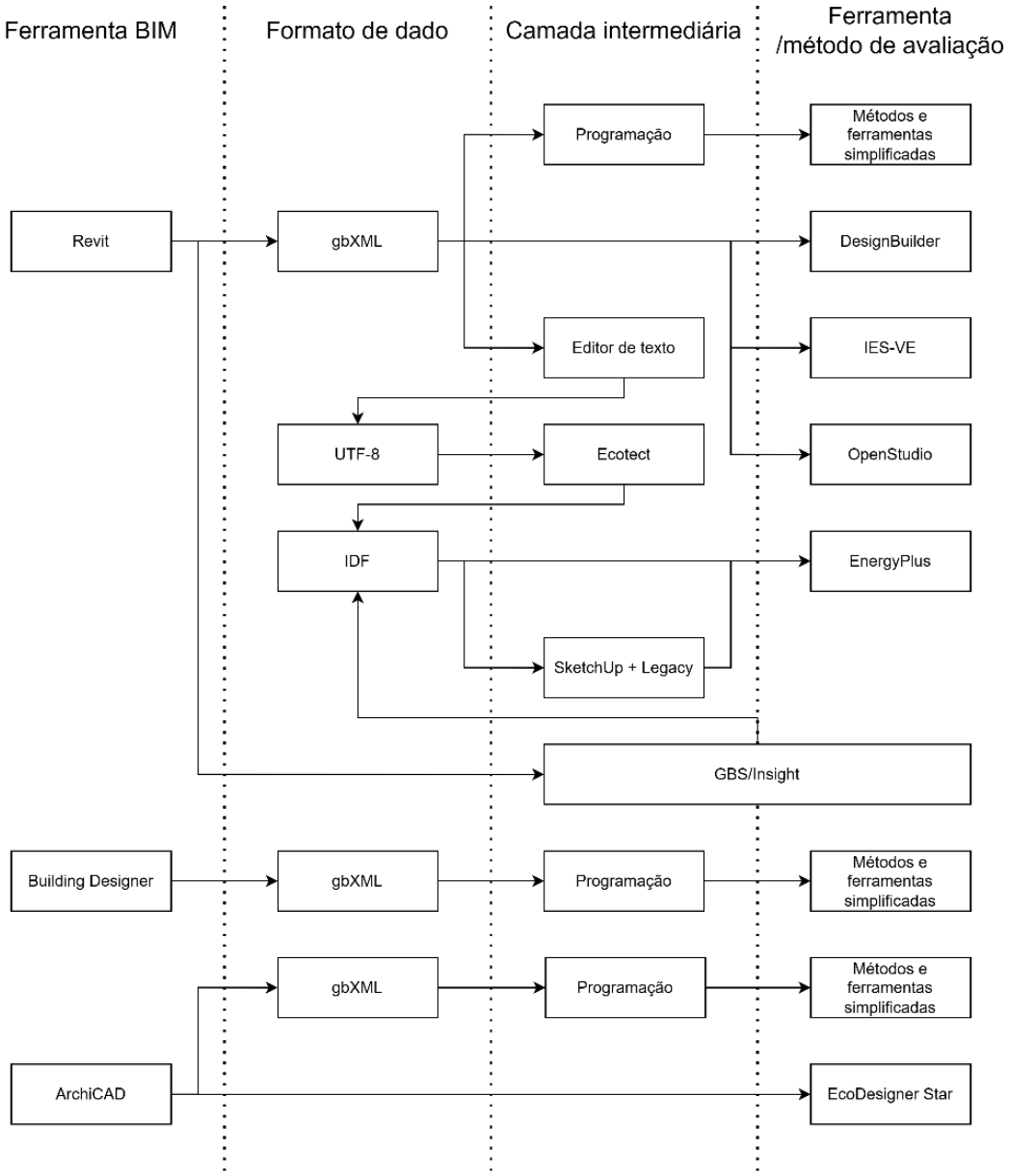



Figura 2 – Fluxos de trabalho BIM para etiquetagem do PBE Edifica
Fonte: Adaptado de Muta, Garlet e Melo (2024).

Os diagnósticos transversais conectam cada rota às respectivas limitações práticas. A extração de dados transfere a responsabilidade para a qualidade da modelagem. A programação apresenta obstáculos na interoperabilidade de formatos abertos. A integração direta restringe a profundidade analítica, a despeito da agilidade processual. A interoperabilidade demanda procedimentos sistemáticos de verificação. A exportação de arquivos mostra-se insuficiente para alcançar a consistência necessária à avaliação e etiquetagem energética.

As limitações estruturais contextualizam o cenário de fragmentação. A baixa adoção de padrões abertos (OpenBIM), a inexistência de processos de auditoria de modelos e a formação profissional restrita criam um ambiente propício ao uso de modelos idealizados em experimentos acadêmicos. Tais modelos são pouco representativos da complexidade do mundo real, o que resulta em baixa generalização e aplicabilidade prática na literatura analisada.

A análise aponta para desafios persistentes na integração BIM-BEM. Apesar dos avanços tecnológicos, a incerteza quanto à qualidade da informação e a falta de padronização na modelagem dificultam a consolidação da técnica. A mitigação de perdas informacionais e o alinhamento das avaliações ao rigor normativo dependem do estabelecimento de fluxos de trabalho estruturados e verificáveis, transcendendo a adoção isolada de novas ferramentas.

### 2.1.5 Conclusão

A seção *Conclusions* ratifica esse panorama ao constatar que, apesar dos esforços, o uso do BIM na avaliação energética ainda orbita predominantemente em torno de fluxos prescritivos, com a automação ocorrendo de forma pontual e a interoperabilidade permanecendo como um obstáculo crítico. A superação desse estágio exige investir em fluxos OpenBIM e em programação voltada à simulação. Destaca-se que o avanço da área depende de um aprofundamento rigoroso em diretrizes de modelagem, requisitos de informação e na semântica dos dados.

# 3 APRIMORANDO A AVALIAÇÃO E ETIQUETAGEM DE DESEMPENHO ENERGÉTICO EM EDIFICAÇÕES: UMA REVISÃO DE ABORDAGENS BASEADAS EM BIM – ARTIGO 2

O segundo artigo que integra esta tese intitula-se *Enhancing energy performance assessment and labeling in buildings: A review of BIM-based approaches* e foi desenvolvido por Luís Filipe Muta, Ana Paula Melo e Roberto Lamberts. O trabalho foi publicado no periódico internacional *Journal of Building Engineering* (v. 103, 112089, 2025), tendo cumprido o trâmite editorial com submissão em 23 de outubro de 2024, aprovação em 10 de fevereiro de 2025 e publicação em 12 de fevereiro de 2025. Sua referência bibliográfica é:

- MUTA, L. F.; MELO, A. P.; LAMBERTS, R. *Enhancing energy performance assessment and labeling in buildings: A review of BIM-based approaches*. ***Journal of Building Engineering***, v. 103, p. 112089, 2025. DOI: 10.1016/j.jobe.2024.112089.

Diferentemente do primeiro artigo, que focou no cenário nacional, este trabalho amplia o escopo para uma perspectiva global, apresentando uma Revisão Sistemática da Literatura (RSL) baseada na análise de 106 publicações. O estudo investiga como o BIM pode mitigar falhas nos esquemas de avaliação e etiquetagem energética, categorizando as contribuições do BIM em seis abordagens principais. Além de demonstrar como essas abordagens podem aumentar a confiabilidade e a eficiência das avaliações de eficiência energética, o estudo aponta lacunas críticas na área de pesquisa.

## 3.1 GUIA DE LEITURA DO ARTIGO 2

Esta seção apresenta o guia de leitura do artigo 2, cuja versão integral encontra-se no APÊNDICE B. O objetivo é oferecer uma compreensão clara da lógica interna do artigo, destacando os pontos estruturantes da tese. O guia não substitui a leitura integral do artigo, mas indica onde se localizam os elementos conceituais, metodológicos e críticos que fundamentam a contribuição à pesquisa.

### 3.1.1 Introdução

A seção *Introduction* contextualiza a estrutura global de avaliação e etiquetagem energética e aponta as fragilidades dos esquemas vigentes baseados em processos manuais. Dentre os desafios críticos, destaca-se a lacuna de desempenho, definida conceitualmente como a divergência sistemática entre a eficiência teórica calculada em projeto e o consumo energético medido durante a operação (Hardy; Glew, 2019). A lacuna de desempenho fundamenta a investigação. As limitações dos métodos atuais justificam a transição para fluxos em BIM como estratégia para elevar o rigor técnico da avaliação e da etiquetagem energética.

### 3.1.2 Método

A seção *Method* apresenta o propósito da revisão e a formação do conjunto de artigos analisados. A Figura 3 sintetiza o percurso metodológico, desde o processo de seleção até o refinamento da amostra de 106 artigos examinados.

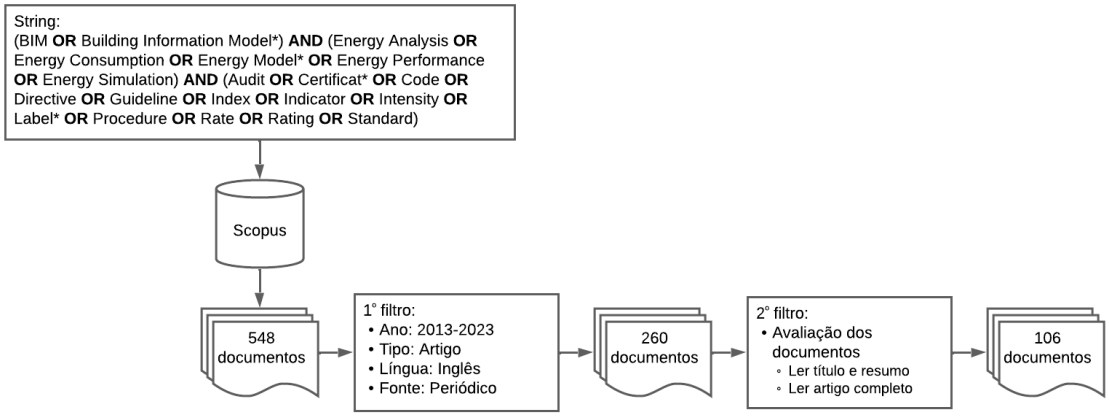



Figura 3 – Fluxograma do processo de amostragem
Fonte: Adaptado de Muta, Melo e Lamberts (2025).

A revisão organiza a literatura em grupos temáticos estruturais. O processo de análise identifica abordagens recorrentes, como o BIM como repositório de dados, técnicas para geração de modelos BIM, integração BIM-BEM, otimização multiobjetivo e gêmeos digitais. Esses eixos destacam o papel do BIM como articulador entre a aquisição de dados, a simulação, a avaliação e a etiquetagem energética.

### 3.1.3 Desenvolvimento

A seção *Energy performance labeling shortcomings* detalha as barreiras que limitam a eficácia da etiquetagem energética. O texto categoriza os problemas em três frentes principais. A primeira aborda a lacuna de desempenho. A segunda trata da falta de confiabilidade nos dados. A terceira examina a dependência de processos manuais onerosos. A desconexão entre a fase de projeto e a avaliação gera inconsistências, justificando a transição para fluxos digitais estruturados.

A abordagem *BIM as a data repository* responde às inconsistências dos métodos manuais ao explorar a capacidade do modelo digital de centralizar informações geométricas, construtivas e operacionais de forma coordenada. Essa centralização depende intrinsecamente de diretrizes claras e de bibliotecas organizadas para funcionar como uma base de dados estruturada em fluxos de avaliação.

A seção *Enhanced BIM model generation techniques* discute o uso de tecnologias de captura da realidade, como varredura a laser e termografia, na automação da criação de modelos digitais de edificações existentes. A precisão dos dados de entrada afeta diretamente a simulação energética. Essas técnicas reduzem o esforço de levantamento manual, contudo não eliminam a necessidade de estruturação semântica dos dados para interpretação por ferramentas BEM. A geometria compõe apenas uma parte do processo, enquanto a interoperabilidade e a estruturação da informação representam os principais obstáculos.

A seção *BIM-BEM direct integration* examina ferramentas operadas por conexões nativas ou plugins. O ganho em agilidade operacional nessas abordagens frequentemente resulta em menor autonomia sobre as variáveis de simulação. A rigidez dos perfis de uso e dos parâmetros predefinidos restringe a aplicabilidade dessa integração em contextos regulatórios, onde a aderência a critérios normativos sobrepõe-se à necessidade de rapidez.

A abordagem *BIM-BEM open data standards* aponta os formatos interoperáveis gbXML e IFC como elementos estruturais para a transparência dos fluxos de trabalho. Os padrões abertos apresentam-se como uma alternativa ampla às restrições das integrações proprietárias, suportando avaliações energéticas auditáveis e flexíveis. A Figura 4 organiza os benefícios, as limitações e as estratégias vinculadas ao uso de padrões abertos.

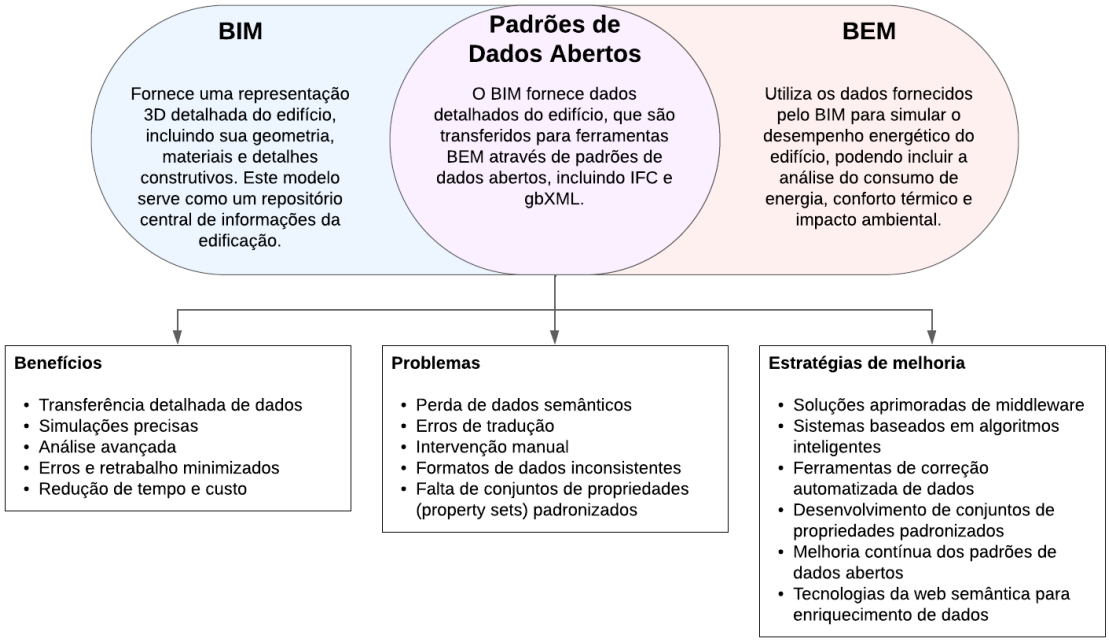



Figura 4 – Síntese da abordagem BIM-BEM via padrões abertos de dados
Fonte: Adaptado de Muta, Melo e Lamberts (2025).

A adoção desses padrões enfrenta perdas geométricas e semânticas, exigindo tratamento pós-exportação para viabilizar a interoperabilidade. A estruturação informacional consolida-se como o eixo da integração entre BIM e BEM.

A seção *BIM-based multi-objective optimization* examina o uso de algoritmos genéticos em conjunto com ferramentas BIM e BEM para o balanceamento de objetivos conflitantes, como a eficiência energética e os custos construtivos. A integração tecnológica possibilita a busca automatizada por soluções de alto desempenho, ultrapassando o atendimento aos requisitos mínimos normativos. A complexidade dos algoritmos, entretanto, exige elevada capacidade de processamento e apresenta sensibilidade crítica à qualidade dos dados de entrada, resultando em tempos de análise extensos. A técnica contribui para o refinamento de projetos singulares, mas apresenta limitações de agilidade e escala para aplicação em rotinas abrangentes de avaliação e etiquetagem energética.

A seção *Digital twin for efficient operation* projeta a discussão para a fase de uso e operação, apontando o monitoramento contínuo como mecanismo para mitigar a lacuna de desempenho. A convergência entre o BIM e a Internet das Coisas (IoT) viabiliza a detecção de anomalias e a calibração dinâmica de modelos BEM em substituição às avaliações estáticas. A implementação esbarra em barreiras como os

custos de infraestrutura e a ausência de modelos digitais representativos do estoque construído. A aplicação dessas tecnologias depende da disponibilidade prévia de uma base informacional estruturada.

### 3.1.4 Discussão

A seção *Discussions* analisa a interação das abordagens baseadas em BIM com as limitações estruturais da avaliação energética, com ênfase na qualidade e na consistência dos dados. Parte expressiva das barreiras práticas associa-se à fragilidade da interoperabilidade. O contraste entre a integração BIM-BEM direta e os padrões abertos de dados indica que os fluxos entre ferramentas proprietárias agilizam etapas, mas impõem simplificações que reduzem o controle paramétrico. Os padrões abertos ampliam a transparência e a parametrização para o BEM, embora apresentem obstáculos de interoperabilidade que demandam tratamentos específicos.

As abordagens de otimização multiobjetivo e os gêmeos digitais tornam-se operacionais quando apoiados por modelos BIM estruturados consistentemente. O Quadro 1 posiciona as diferentes abordagens ao longo do ciclo de vida da edificação. A representação aponta o papel transversal dos padrões abertos de dados, aplicáveis às análises de projeto, ao retrofit e à operação.

Quadro 1 – Abordagens baseadas em BIM para avaliação e etiquetagem de eficiência energética

| Fase do ciclo de vida | Abordagens recomendadas | Considerações principais | Resultados esperados |
|---|---|---|---|
| Projeto (novas edificações) | - BIM-BEM via integração direta: Suporta simulações em estágios iniciais, potencialmente orientando o projeto energeticamente eficiente e a avaliação de conformidade.<br>- BIM-BEM via padrões de dados abertos: Podem melhorar a interoperabilidade e facilitar a colaboração ao reduzir erros manuais.<br>- Otimização multiobjetivo baseado em BIM: Ajuda a explorar trade-offs entre eficiência energética, custos e conforto dos ocupantes. | - Vantagens: Pode facilitar processos de projeto iterativos e apoiar a validação de conformidade.<br>- Desafios: Dependência de suposições e dados genéricos, dificuldades em capturar condições operacionais reais. | - Decisões de projeto mais informadas.<br>- Fluxos de trabalho potencialmente melhorados.<br>- Melhor alinhamento com requisitos regulatórios.<br>Coordenação de dados aprimorada entre as partes interessadas. |
| Operação (em uso) | - BIM-to-BEM via padrões de dados abertos: Podem apoiar avaliações contínuas de desempenho energético facilitando a integração de dados.<br>- Gêmeos digitais para operação eficiente: Pode fornecer monitoramento em tempo real, análise de desempenho e oportunidades de engajamento dos ocupantes. | - Vantagens: Pode auxiliar no rastreamento contínuo de desempenho e no planejamento de manutenção proativa.<br>- Desafios: Questões relacionadas à precisão dos dados, integração de sensores e imprevisibilidade do comportamento dos ocupantes. | - Potencial redução da lacuna de desempenho (performance gap).<br>- Insights operacionais aprimorados.<br>- Estratégias proativas para manutenção.<br>- Possíveis melhorias no conforto dos ocupantes. |
| Retrofit (edificações existentes) | - Técnicas aprimoradas de geração de modelos BIM: Visam fornecer modelos as-built mais confiáveis para apoiar o planejamento e simulações de retrofit.<br>- BIM-BEM via padrões de dados abertos: Podem contribuir para a consistência de dados entre softwares.<br>- Otimização multiobjetivo baseado em BIM: Apoia a identificação de potenciais estratégias de retrofit que equilibram custo e eficiência energética. | - Vantagens: Pode fornecer dados de base úteis para esforços de retrofit.<br>- Desafios: Potenciais inconsistências na documentação, variações no uso da edificação e dificuldades na integração com sistemas mais antigos. | - Abordagens de retrofit energético mais eficazes.<br>- Planejamento de retrofit potencialmente econômico.<br>- Centralização de dados aprimorada para a gestão de longo prazo da edificação. |

Fonte: Adaptado de Muta, Melo e Lamberts (2025).

A evolução dos métodos de avaliação energética depende de modelos capazes de preservar os dados da simulação, condição prévia à adoção de soluções avançadas. A consistência do fluxo BIM-BEM transcende a seleção de ferramentas e fundamenta-se na estruturação e no manuseio da informação ao longo do processo.

### 3.1.5 Conclusão

A seção *Conclusion* enfatiza as fragilidades relacionadas à fragmentação das informações e à lacuna de desempenho. Os obstáculos discutidos configuram-se como problemas de estruturação informacional, vinculados à organização e à transferência de dados para ferramentas BEM. O BIM atua na mitigação de incertezas ao centralizar informações e ampliar a integração por meio de plugins ou padrões abertos. Os desafios de interoperabilidade e calibração de dados, contudo, permanecem. Os avanços na avaliação e na etiquetagem energética dependem de melhorias no tratamento e no intercâmbio de dados.

# 4 DESVIO DE DESIGN: COMO A GRANULARIDADE DA MODELAGEM BIM COMPROMETE A AVALIAÇÃO DE DESEMPENHO ENERGÉTICO EM FLUXOS DE TRABALHO INTEGRADOS BIM-TO-BEM – ARTIGO 3

O terceiro artigo que compõe esta tese intitula-se *Design misdirection: how BIM modeling granularity compromises energy performance assessment in integrated BIM-to-BEM workflows* e foi desenvolvido por Luís Filipe Muta, Giovanni Francesco Giuzio, Ana Paula Melo e Annamaria Buonomano. O trabalho foi publicado no periódico *Energy & Buildings* (v. 351, 116739, 2026), tendo cumprido o trâmite editorial com submissão em 6 de agosto de 2025, aprovação em 16 de novembro de 2025 e publicação em 17 de novembro de 2025. Sua referência bibliográfica é:

- MUTA, L. F.; GIUZIO, G. F.; MELO, A. P.; BUONOMANO, A. *Design misdirection: how BIM modeling granularity compromises energy performance assessment in integrated BIM-to-BEM workflows*. ***Energy & Buildings***, v. 351, p. 116739, 2026. DOI: https://doi.org/10.1016/j.enbuild.2025.116739

Em continuidade ao posicionamento estratégico definido na revisão sistemática, este estudo desloca a investigação da viabilidade tecnológica para a sensibilidade informacional do fluxo de trabalho. Uma vez estabelecido que a integração por padrões abertos é o caminho mais adequado para o contexto regulatório, tornou-se necessário examinar como a variabilidade na estruturação dos dados de entrada (granularidade) afeta a estabilidade dos resultados da simulação. Por meio de um experimento paramétrico controlado com 62 cenários, o trabalho investiga os riscos de *design misdirection* causados por inconsistências na modelagem. O objetivo central desta etapa não foi buscar a precisão absoluta através do detalhamento máximo, mas sim identificar os níveis mínimos de informação semântica e geométrica necessários para assegurar a consistência técnica em processos de avaliação de eficiência energética.

## 4.1 GUIA DE LEITURA DO ARTIGO 3

Esta seção apresenta o guia de leitura do artigo 3, disponibilizado integralmente no APÊNDICE C. O objetivo é oferecer uma compreensão da lógica interna do estudo, destacando os pontos que estruturam sua argumentação e são

particularmente relevantes para a tese. O guia não substitui a leitura integral do artigo, mas indica onde se encontram os elementos conceituais, metodológicos e analíticos que sustentam sua contribuição à tese.

### 4.1.1 Introdução

A seção *Introduction* estabelece a granularidade da modelagem BIM[1] como alicerce da investigação. Diferentes níveis de granularidade influenciam a consistência das informações transferidas ao BEM, mesmo em fluxos baseados em padrões abertos de dados. O desempenho do processo BIM-BEM depende do controle explícito sobre o grau de informação do modelo BIM.

A seção *Context* relaciona a granularidade da modelagem BIM às incertezas da fase de projeto. Estruturas tradicionais, a exemplo do Nível de Desenvolvimento (*Level of Development* – LOD), privilegiam representações geométricas e frequentemente omitem atributos necessários à simulação energética. Decisões nas etapas iniciais introduzem variações que afetam a confiabilidade dos modelos exportados. A granularidade de modelagem atua como elemento estruturante para estabilizar os fluxos BIM-BEM.

A seção *Approach and objectives* delineia a estratégia experimental para isolar e mensurar o impacto da modelagem nos resultados da simulação. O conceito de granularidade distingue-se de padrões como o LOD e o Nível de Necessidade de Informação (*Level of Information Need* – LOIN) ao priorizar atributos semânticos operacionais, frequentemente negligenciados em estruturas focadas em geometria e documentação genérica. A seção detalha o fluxo automatizado em Python via gbXML para testar os quatro domínios de modelagem e formaliza as perguntas de pesquisa. Essas questões estruturam a busca por compensações entre o esforço de modelagem e a consistência dos resultados.

[1] Nesta pesquisa, o termo “granularidade de modelagem BIM” descreve o nível de especificação das informações que influenciam a simulação energética, incluindo atributos espaciais, construtivos, operacionais e de zoneamento térmico. A expressão foca na adequação informacional necessária ao BEM, indo além da ênfase geométrica ou documental típica de LOD ou LOIN.

### 4.1.2 Método

A seção *Method* apresenta o panorama do experimento. A Figura 5 ilustra o mapa metodológico organizado em quatro etapas, sendo elas a definição do arquétipo, a construção da matriz paramétrica, a execução do fluxo BIM-BEM e a análise dos dados.

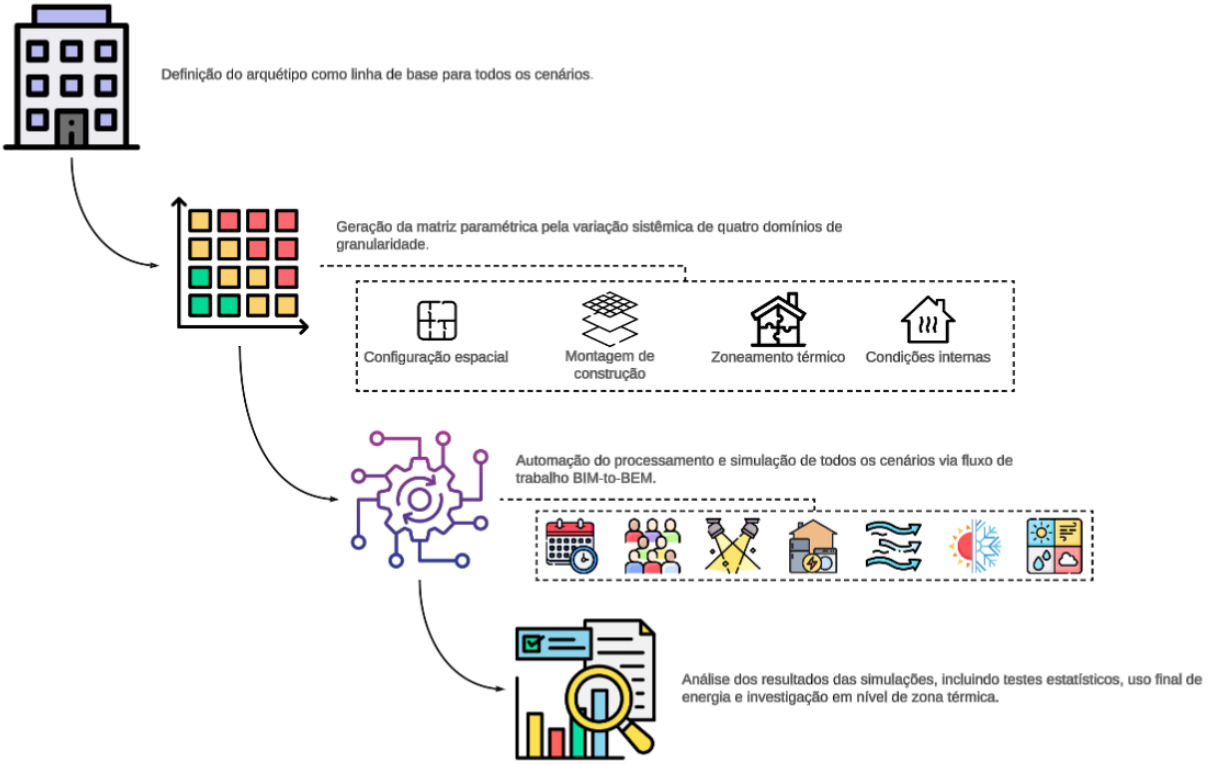



Figura 5 – Representação esquemática do fluxo metodológico do artigo 3
Fonte: Adaptado de Muta et al. (2026).

A subseção *Archetype definition* descreve o objeto de referência adotado na pesquisa, correspondente a uma edificação universitária de cinco pavimentos (Figura 6), inspirada no Projeto DEO (CBCS, 2021) e parametrizada com base na Portaria nº 309/2022 (Brasil, 2022). A apresentação abrange a organização espacial, a composição da envoltória e os sistemas. As condições de contorno padronizam os cenários do experimento e reduzem as interferências de variáveis externas.

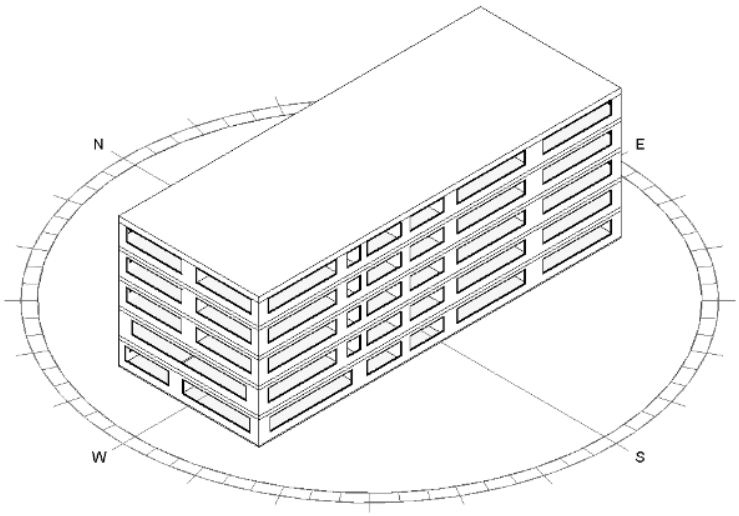



Figura 6 – Vista isométrica do arquétipo
Fonte: Adaptado de Muta et al. (2026).

A subseção *Parametric study* apresenta a estrutura organizadora das granularidades de modelagem BIM. O escopo abrange quatro domínios de granularidade, classificados como Configuração Espacial (SPA), Montagem Construtiva (CON), Zoneamento Térmico (ZON) e Condições Internas (INT). Cada domínio representa uma dimensão específica da informação necessária ao BEM. O Quadro 2 sintetiza os níveis adotados em cada domínio na pesquisa, variando de representações esquemáticas a configurações específicas.

Quadro 2 – Síntese dos domínios e níveis de granularidade de modelagem BIM

| Domínio | Nível | Descrição |
|---|---|---|
| Configuração espacial | SPA-1 | Envoltória simplificada; ausência de divisórias internas, portas ou espaços técnicos/entreforros; abertura envidraçada (janela) única por fachada/pavimento. |
| | SPA-2 | Envoltória com divisórias internas e portas preliminares, permitindo zoneamento térmico funcional; janelas modeladas em fita ou agrupadas; ausência de entreforros. |
| | SPA-3 | Layout definitivo com todas as divisórias, janelas e portas posicionadas individualmente; funções definidas dos ambientes; ausência de entreforros. |
| | SPA-4 | Idêntico ao SPA-3, com a adição de entreforros modelados como zonas térmicas independentes. |
| Montagem construtiva | CON-1 | Ausência de camadas de materiais explícitas no BIM; construções genéricas sem propriedades térmicas; dados térmicos atribuídos esquematicamente via templates. |
| | CON-2 | Todas os materiais modelados explicitamente no software BIM, com camadas definidas por espessura, condutividade, densidade e calor específico. |
| Zoneamento térmico | ZON-1 | Cada pavimento é modelado como uma única zona térmica. |
| | ZON-2 | Diferenciação entre zonas térmicas internas e perimetrais (core and shell) por pavimento. |
| | ZON-3 | Cada pavimento subdividido em zonas funcionais, refletindo a diversidade de uso típica. Ambientes com as mesmas funções são agrupados na mesma zona térmica. |
| | ZON-4 | Cada ambiente modelado como uma zona térmica individual, permitindo resolução máximo de cargas internas. |
| Condições internas | INT-1 | Cargas internas e taxas de renovação de ar uniformes baseadas nas diretrizes regulatórias brasileiras (Brasil, 2022). |
| | INT-2 | Cargas internas e taxas de renovação de ar baseadas em média ponderada; metodologia idêntica ao INT-1, mas utilizando o conjunto de dados do INT-3 como base de cálculo. |
| | INT-3 | Cargas internas e taxas de renovação de ar diferenciadas por tipo de ambiente, baseadas nas normas ASHRAE 90.1 e 62.1 (ASHRAE, 2022a, 2022b). |

Fonte: Adaptado de Muta et al. (2026).

A explicitação das dependências entre os domínios estrutura a subseção. O domínio CON é independente e combinável com os demais. Os domínios SPA e ZON possuem relação direta, uma vez que níveis elevados de zoneamento térmico exigem resolução espacial compatível. Por exemplo, a combinação de SPA-1 com ZON-4 é inviável por não proporcionar a definição de uso de ambientes requerida pelo zoneamento térmico. O nível INT-3 aplica-se apenas quando há zoneamento por ambiente a partir de ZON-3, ao passo que INT-1 e INT-2 funcionam de forma transversal. Essas relações fundamentam a matriz de cenários paramétricos (Figura 7), que sintetiza as combinações viáveis e resulta em 62 cenários avaliados, demonstrando a interação entre as variações espaciais e térmicas no conjunto experimental.

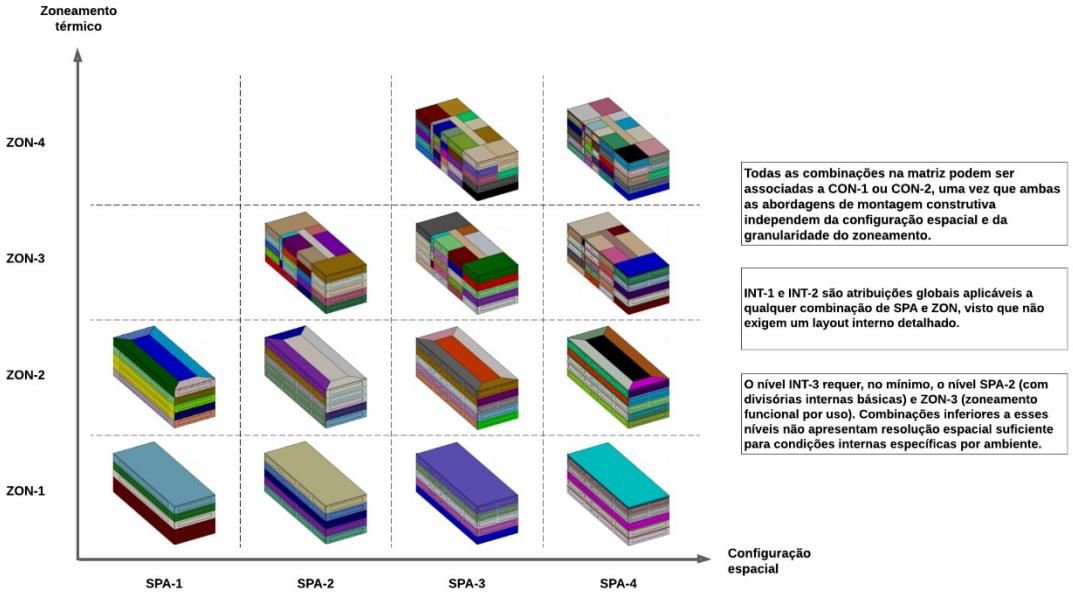



Figura 7 – Matriz de cenários paramétricos
Fonte: Adaptado de Muta et al. (2026).

A subseção *BIM-BEM workflow* descreve o processamento de cada cenário da matriz. A Figura 8 sintetiza o fluxo em estágios encadeados, desde a exportação do modelo BIM em formato gbXML até o pós-processamento das simulações. As etapas de conversão, limpeza e enriquecimento ocorrem via rotinas em Python para mitigar limitações de interoperabilidade e aplicar os parâmetros das condições internas antes da simulação. Essa padronização reduz a variabilidade atrelada ao modelador e ao usuário, propiciando o processamento uniforme dos cenários.

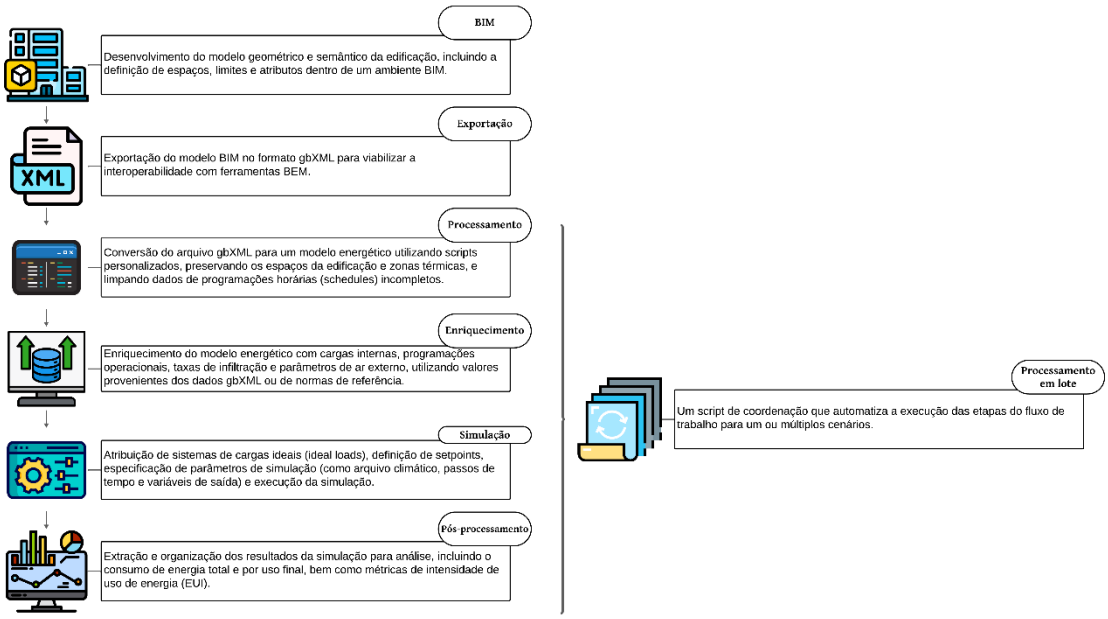



Figura 8 – Representação esquemática do fluxo de trabalho BIM-BEM
Fonte: Adaptado de Muta et al. (2026).

A subseção *Data analysis* detalha o método de análise dos resultados das simulações. A Figura 9 organiza o processo em cinco estágios, partindo da variação global da Intensidade de Uso Energético (*Energy Use Intensity* – EUI) até as análises em nível de zona térmica. Os estágios englobam a caracterização da amplitude dos resultados, a inspeção visual por domínio, a quantificação formal por meio de testes estatísticos, a estratificação condicional e a desagregação da EUI por usos finais e ambientes. Essa sequência direciona a análise e explicita a repercussão das escolhas de granularidade nas métricas de desempenho energético das edificações.

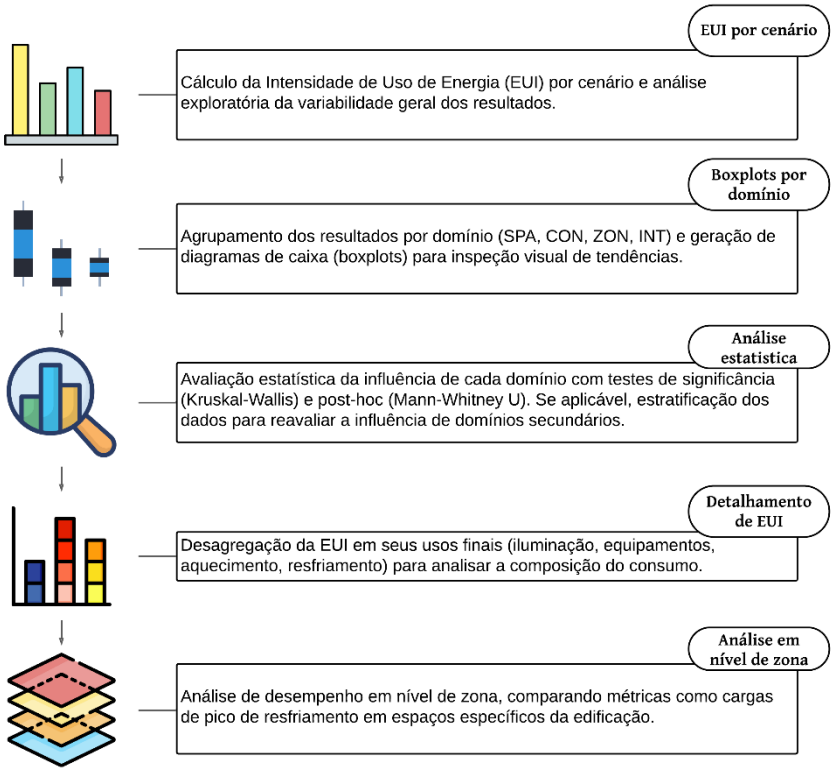



Figura 9 – Fluxo da análise de dados
Fonte: Adaptado de Muta et al. (2026).

### 4.1.3 Resultados

A seção *Results* analisa a influência da granularidade da modelagem BIM nos resultados do BEM. A Figura 10 e a Figura 11 evidenciam que os 62 cenários agrupam-se em três faixas distintas de EUI. A segregação observada nos boxplots indica que a definição das cargas internas (domínio INT) atua como o principal fator de organização dos resultados em três patamares primários, independentemente das configurações de SPA, CON ou ZON. O domínio INT funciona como o eixo de separação primário dos cenários. Os demais domínios modulam a variabilidade dentro de cada faixa, sem desconstruir o padrão dominante estabelecido por INT.

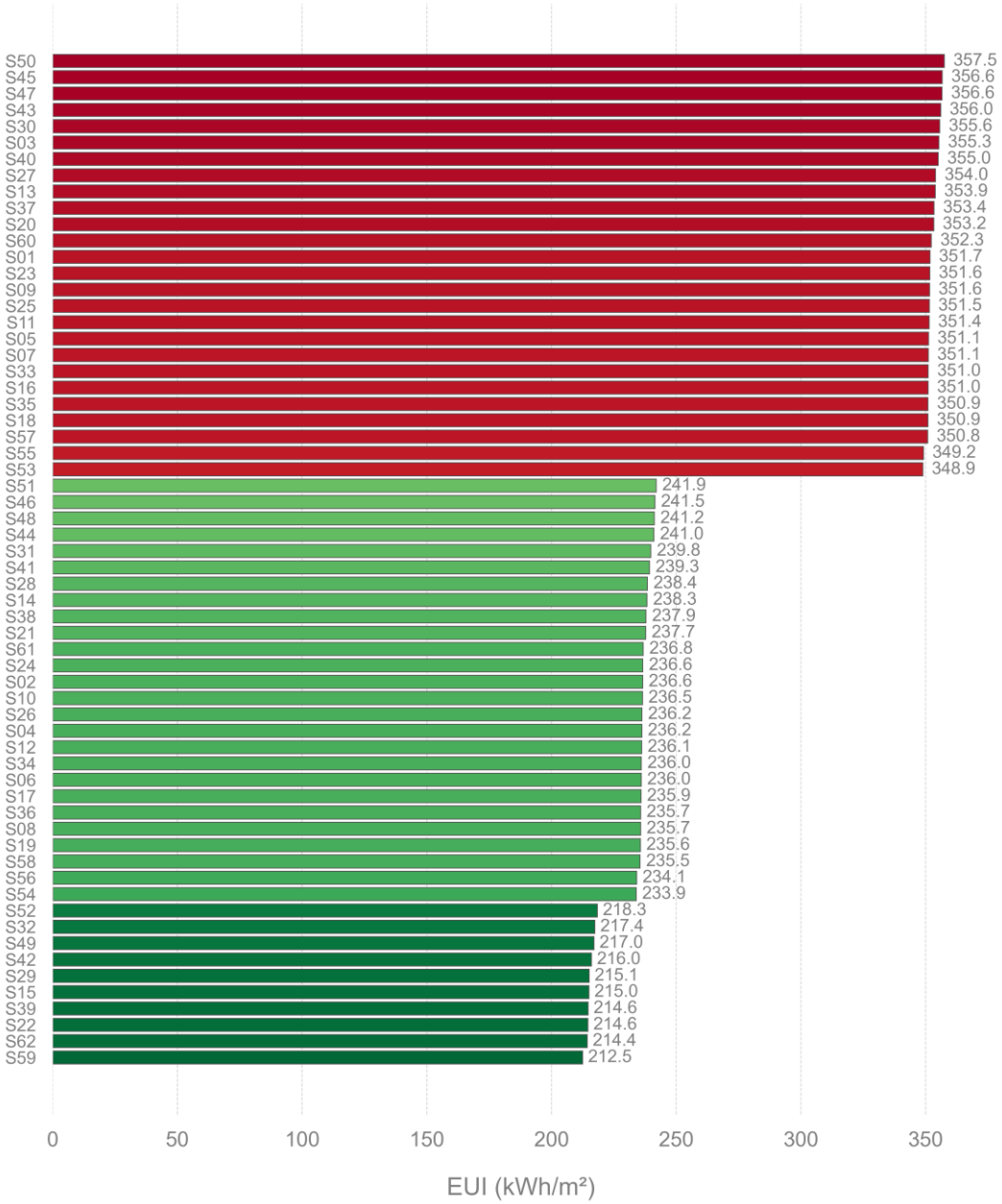



Figura 10 – Distribuição da EUI por cenário
Fonte: Muta et al. (2026).

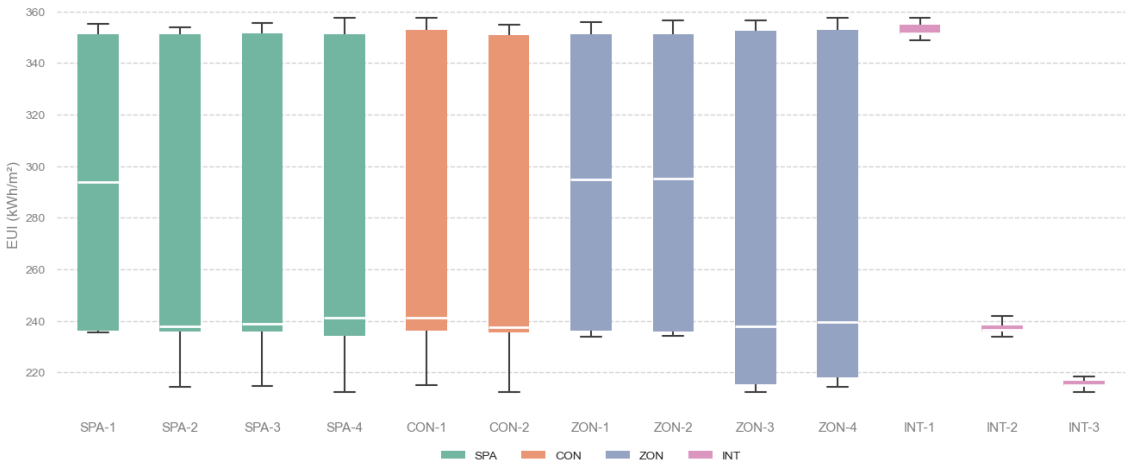



Figura 11 – Efeito da granularidade de modelagem BIM na EUI por níveis de domínios
Fonte: Muta et al. (2026).

O comportamento dos domínios SPA, CON e ZON nos patamares fixados por INT é examinado nas Figura 12, Figura 13 e Figura 14. A análise distingue dois fenômenos principais na simulação, sendo eles o aumento da dispersão dos dados e a alteração do valor central da EUI.

O aumento da granularidade de SPA e ZON amplia a dispersão dos resultados, sem alterar a média de consumo. Os cenários mais granulares apresentam maior variância nos boxplots, comportamento validado pelo teste de Levene. No nível INT-1, a variação de dispersão do SPA apresenta significância estatística ($p = 0,007$). A ampliação da granularidade espacial e de zoneamento eleva a sensibilidade do modelo a pequenas variações e introduz ruído nos resultados, sem promover necessariamente a mudança no patamar da previsão de consumo.

O domínio CON atua na alteração do valor central da simulação. A modificação na granularidade de CON desloca a mediana da EUI. A análise estatística demonstra que CON é o único domínio secundário capaz de alterar os resultados do BEM de forma significativa ($p < 0,05$) em todos os níveis de INT testados, incluindo o grupo INT-3 ($p = 0,028$).

Decisões sobre SPA e ZON afetam a dispersão dos dados, enquanto o domínio CON altera o valor central calculado. Em faixas estreitas de resultados, como o intervalo de 348,7 a 357,3 kWh/m² em INT-1, a distinção entre a atribuição de propriedades térmicas a elementos BIM genéricos (CON-1) e a modelagem explícita de camadas de materiais (CON-2) permanece nítida. A metodologia de incorporação dos dados térmicos atua como fator determinante para a alteração do consumo

energético calculado. O detalhamento de SPA e ZON funciona majoritariamente como fonte de variabilidade.

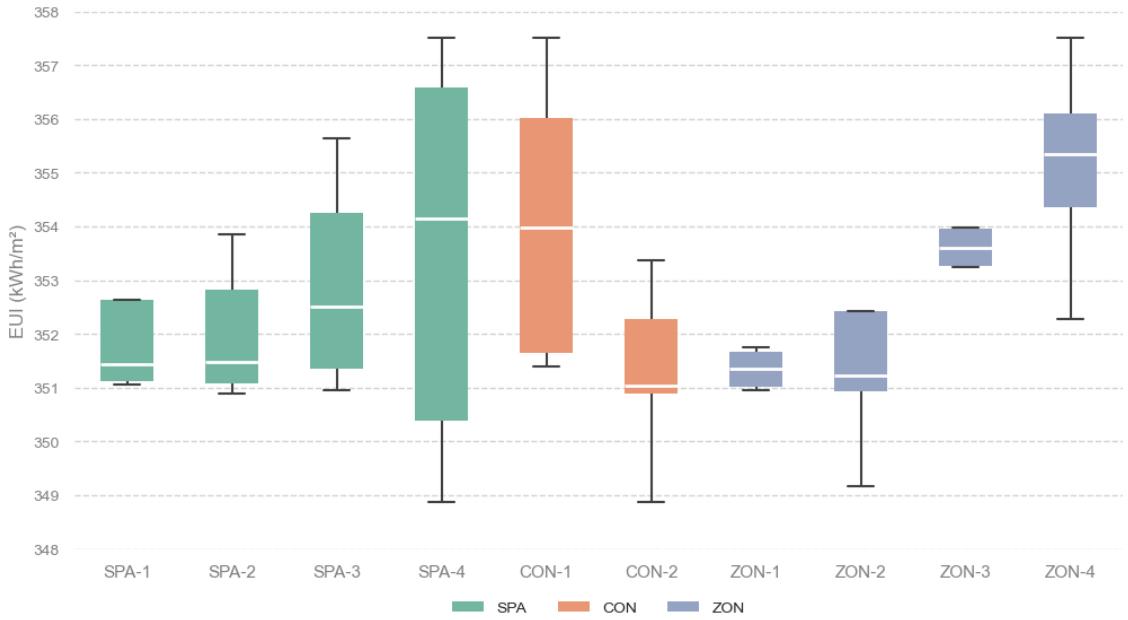



Figura 12 – Influência da granularidade de SPA, CON e ZON na variabilidade da EUI sob INT-1
Fonte: Muta et al. (2026).

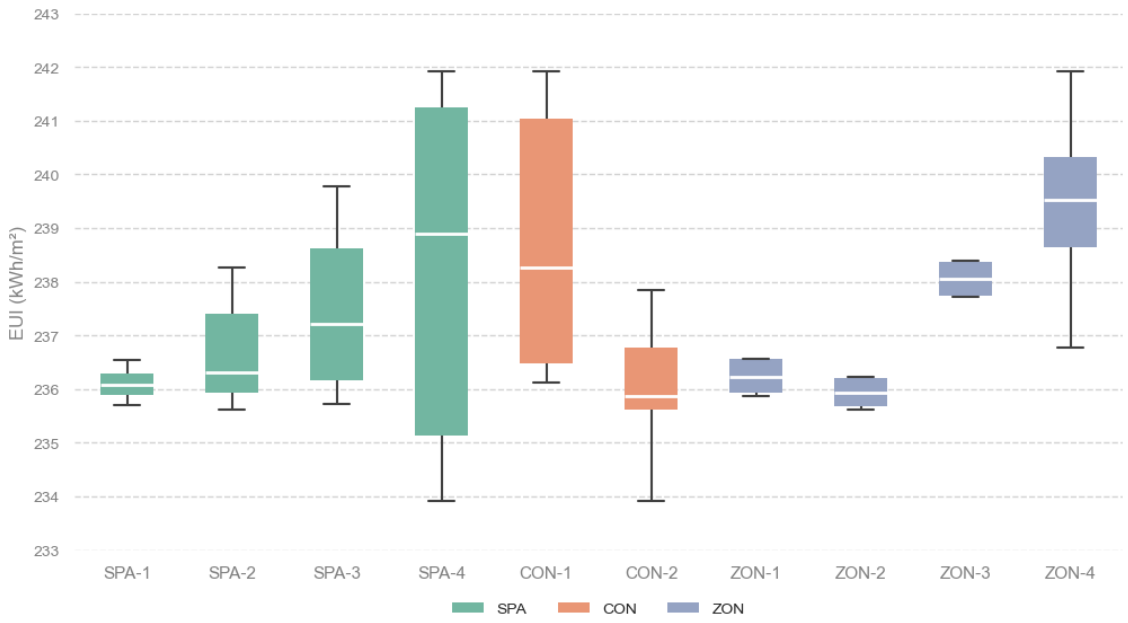



Figura 13 – Influência da granularidade de SPA, CON e ZON na variabilidade da EUI sob INT-2
Fonte: Muta et al. (2026).

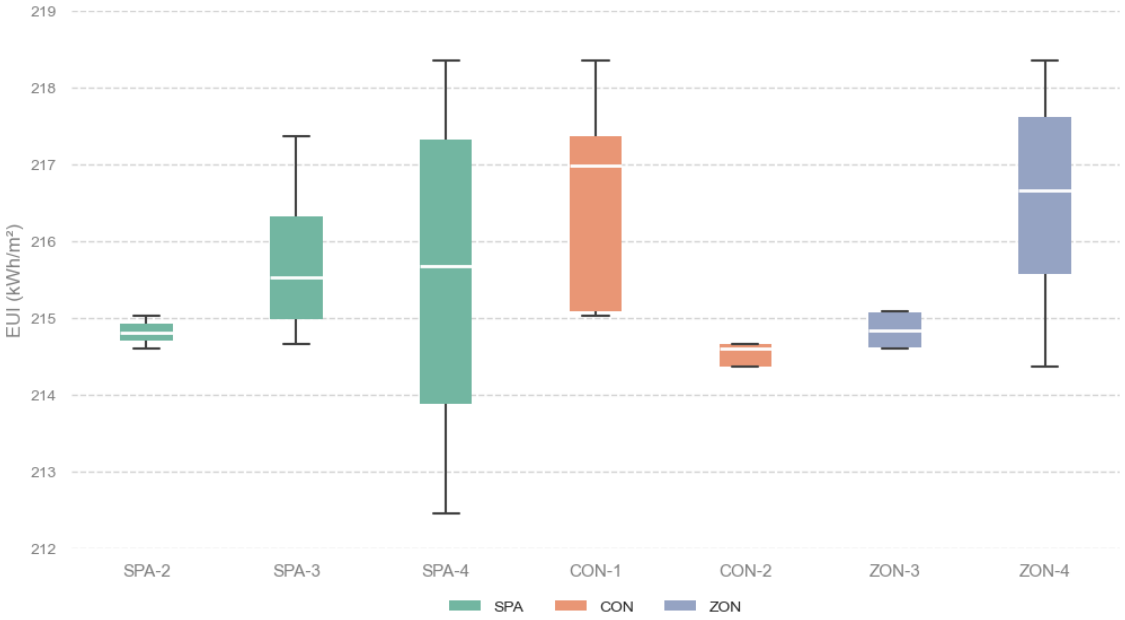



Figura 14 – Influência da granularidade de SPA, CON e ZON na variabilidade da EUI sob INT-3
Fonte: Muta et al. (2026).

A decomposição do consumo (Figura 15) elucida a mecânica das diferenças de patamares entre os níveis de INT. A variação da EUI concentra-se no sistema de resfriamento. O cenário simplificado (INT-1) superestima o consumo em até 64% em comparação ao cenário mais granular (INT-3). A globalização de perfis de ocupação pressupõe a simultaneidade de cargas, com pessoas e equipamentos operando concomitantemente e com a mesma intensidade em toda a edificação. Esse fator inflaciona artificialmente a demanda térmica de resfriamento. Os sistemas de iluminação e equipamentos apresentam cargas mais estáveis e menor impacto de variação.

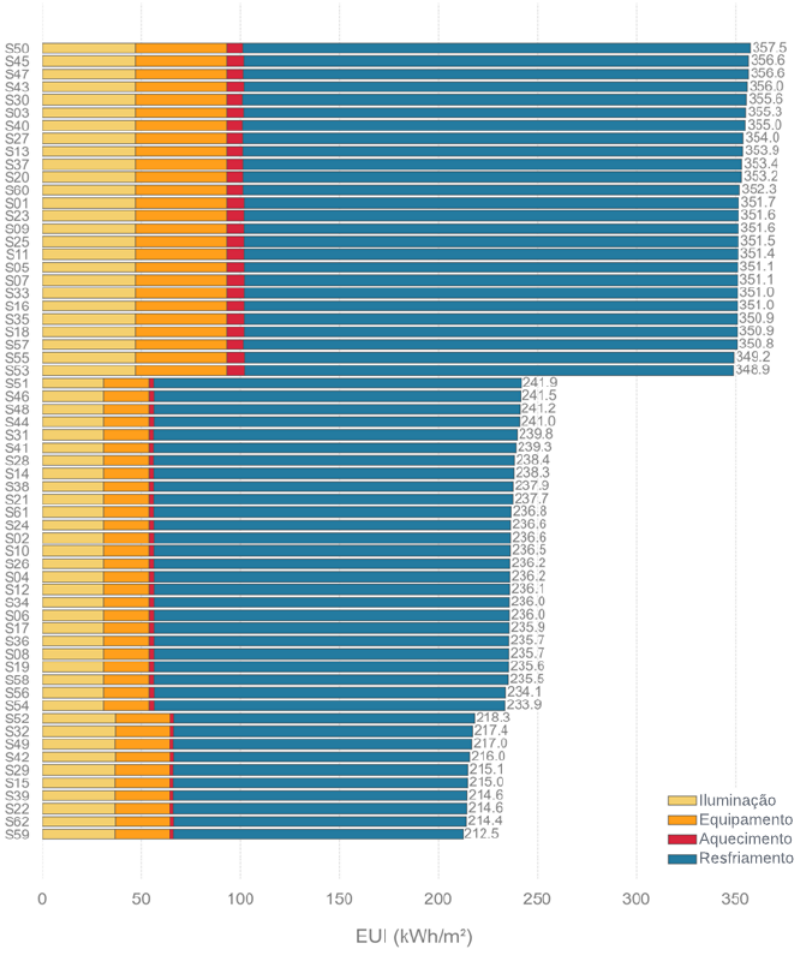



Figura 15 – Decomposição da EUI por cenário
Fonte: Adaptado de Muta et al. (2026).

A Figura 16 demonstra o risco de *design misdirection*. A comparação entre o comportamento de uma biblioteca e de uma sala de aula expõe a alteração na hierarquia dos ambientes em decorrência da granularidade. A aplicação de perfis globais simplificados (INT-1) ou ponderados (INT-2) posiciona a biblioteca como o ambiente de maior consumo, com pico de 59,0 kW. A adoção do nível mais granular (INT-3) reduz a carga da biblioteca para 19,7 kW e revela a sala de aula como o ambiente de maior densidade de carga crítica.

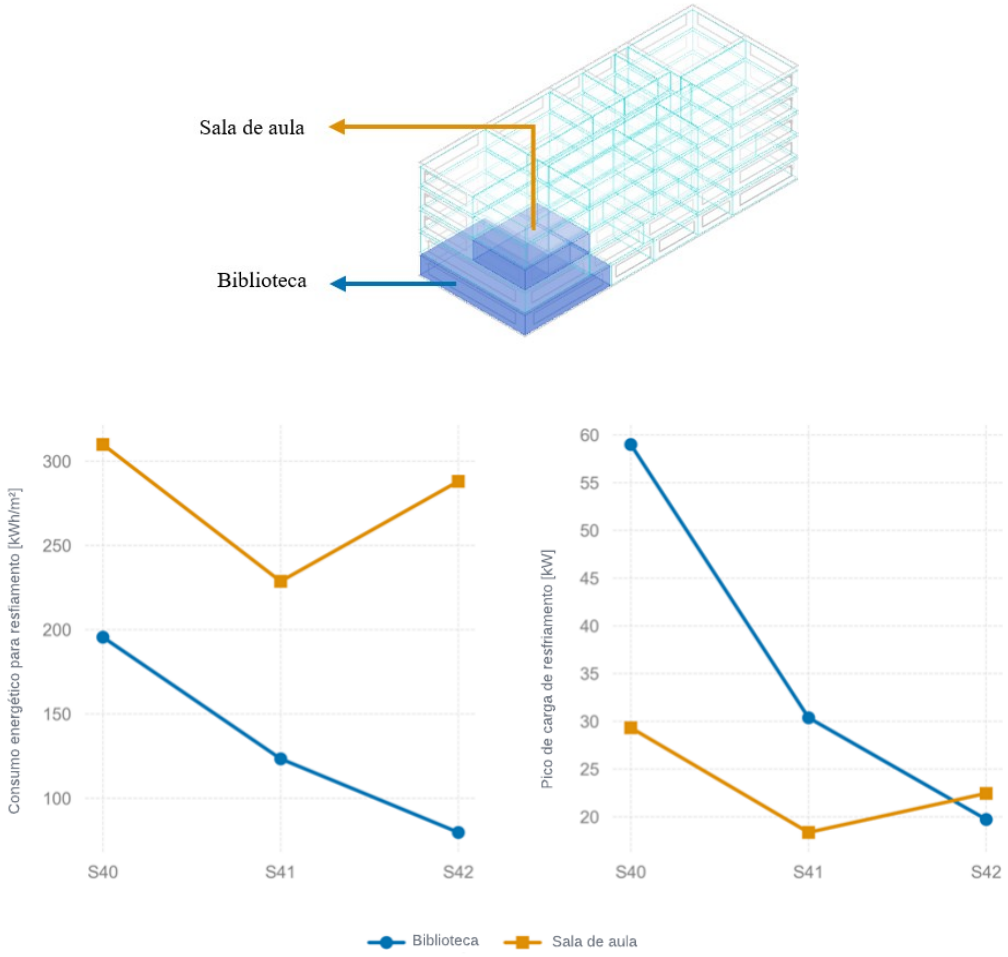



Figura 16 – Impacto da granularidade de INT nas cargas de resfriamento anuais e de pico em ambientes selecionados
Fonte: Adaptado de Muta et al. (2026).

A seleção inadequada do nível de granularidade induz a erros no dimensionamento de sistemas. O uso de médias ponderadas, frequente em processos de etiquetagem, tende a ocultar picos de carga em ambientes densos, como salas de aula, em virtude da diluição com áreas de baixa carga, como corredores. A granularidade de INT define a magnitude do consumo do edifício e determina o diagnóstico de desempenho energético.

Esse comportamento em nível de ambiente reforça que a granularidade de INT afeta a magnitude global da EUI e reorganiza a distribuição interna das cargas. Essa dinâmica modifica a interpretação do desempenho do edifício e a aplicação de dados semânticos na modelagem. Decisões associadas a INT influenciam o valor final da simulação e a lógica de identificação de ambientes críticos, com implicações

diretas no dimensionamento, nos diagnósticos e nos ajustes de projeto. Os resultados posicionam o domínio INT como o elemento dominante da variabilidade, constatação que fundamenta a seção *Discussion*.

### 4.1.4 Discussão

A seção *Discussion* evidencia que o domínio INT não requer maximização constante. Seu efeito dominante demonstra a importância da seleção de níveis adequados de granularidade para cada finalidade. A granularidade semântica exerce influência sobre a simulação. Essa influência não estabelece uma diretriz para modelagens exaustivamente minuciosas, sobretudo em contextos regulatórios focados em consistência e escalabilidade em detrimento de calibrações finas.

Simplificações ou agregações do domínio INT alteram o valor global da EUI e a identificação de espaços críticos. A inversão de resultados entre a biblioteca e a sala de aula ilustra que granularidades inadequadas distorcem a análise de desempenho. O nível mais granular, contudo, não se mostra estritamente necessário em todos os cenários.

O domínio CON é retomado sob essa perspectiva metodológica. As diferenças entre construções explícitas e atribuições programáticas indicam que escolhas procedimentais de modelagem geram incertezas. A elevação da granularidade sem critérios definidos aumenta o esforço sem promover a consistência dos resultados, em especial nos fluxos automatizados.

O modelo conceitual da Figura 17 organiza essas percepções e diferencia o “Platô Espacial”, a “Saturação Semântica” e a “Escada de Crescimento”. O aumento do refinamento espacial ou semântico além do limite necessário não resulta em melhorias proporcionais nas saídas da simulação. Em determinados casos, o esforço adicional em uma dimensão não altera a resposta do modelo. Em outras situações, a carência de base geométrica e espacial inviabiliza o uso de dados semânticos refinados.

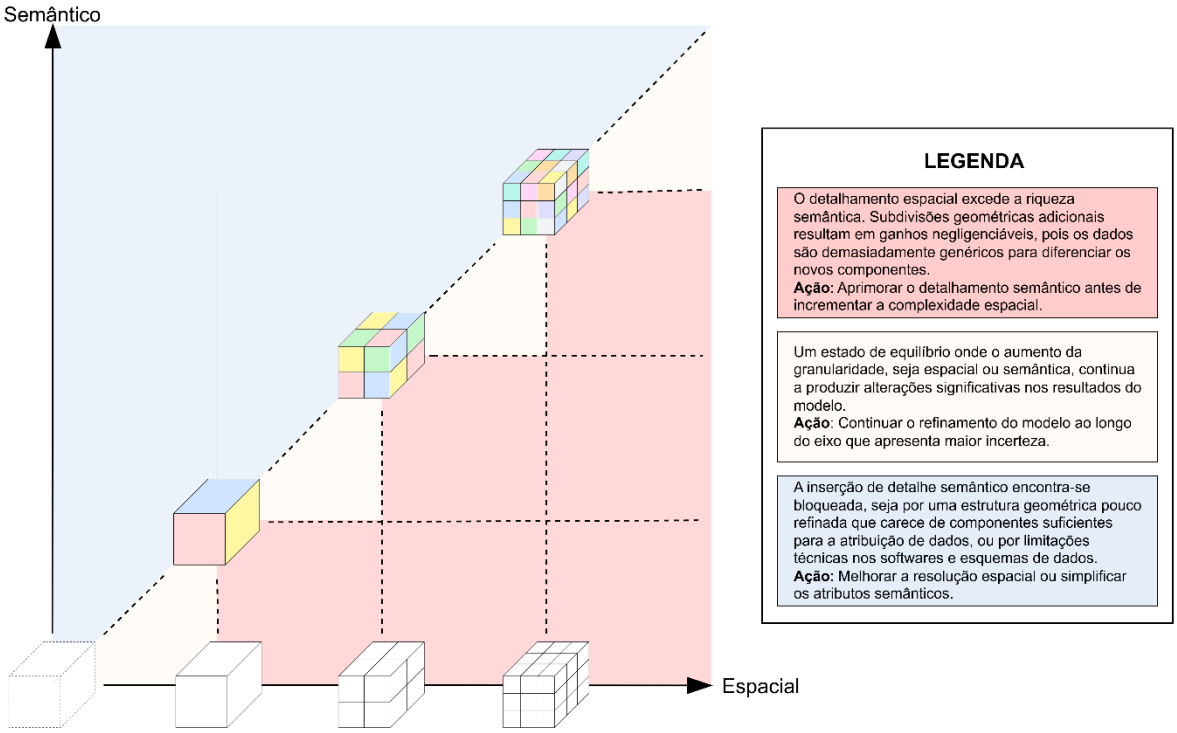



Figura 17 – Modelo conceitual de granularidade espacial e semântica
Fonte: Adaptado de Muta et al. (2026).

O propósito principal afasta-se da busca pela granularidade máxima e direciona-se a um nível adequado para o equilíbrio entre utilidade, consistência e viabilidade operacional. No contexto da etiquetagem compulsória, evita-se a aplicação de modelos orientados à calibração fina em favor do ganho de escala, da padronização e da rapidez de processamento. Em avaliações regulatórias, a prioridade recai sobre fluxos consistentes para a comparação homogênea de edifícios, distanciando-se da reprodução exata do comportamento real em operação.

### 4.1.5 Conclusão

A seção *Conclusion* sintetiza os resultados e articula a influência da granularidade de modelagem BIM na confiabilidade das simulações energéticas. Destaca-se a predominância do domínio INT em relação aos demais domínios de granularidade nos resultados quantitativos. A relação entre o esforço de modelagem e a consistência dos resultados das simulações apresenta comportamento estruturalmente não linear.

O modelo conceitual (Figura 17) distingue a granularidade espacial da granularidade semântica. Esse enquadramento teórico divide os resultados em três

estados. A utilidade do modelo apoia-se no equilíbrio entre o detalhe espacial e geométrico disponível e a riqueza dos dados semânticos atribuídos. A formulação fornece uma base para a orientação de diretrizes de modelagem em fluxos BIM-BEM.

O escopo de validade dos achados é delimitado no encerramento do artigo. A análise fundamenta-se em um arquétipo universitário único, situado em um clima específico e avaliado sob um sistema de cargas ideais. Tais fatores restringem a generalização para outras tipologias, regiões e configurações de sistemas de condicionamento de ar.

Essas limitações configuram fronteiras metodológicas e indicam direções para trabalhos futuros. As recomendações englobam a aplicação da abordagem em novos contextos, o estudo de métricas adicionais de desempenho e a consolidação de protocolos padronizados para a operacionalização estratégica da granularidade de modelagem.

# 5 VIABILIZANDO SIMULAÇÕES DINÂMICAS ESCALONÁVEIS PARA A ETIQUETAGEM DE DESEMPENHO ENERGÉTICO DE EDIFICAÇÕES: UM FLUXO DE TRABALHO BIM-TO-BEM AUTOMATIZADO – ARTIGO 4

O quarto trabalho que compõe esta tese intitula-se *Enabling Scalable Dynamic Simulation for Building Energy Performance Certification: An Automated BIM-to-BEM Workflow* e foi desenvolvido por Luís Filipe Muta, Ana Paula Melo, Giovanni Francesco Giuzio e Annamaria Buonomano.

Apresentado na forma de um manuscrito de artigo científico, este estudo consolida a proposição metodológica da tese ao propor e validar um fluxo de trabalho BIM-to-BEM, estruturado para atender às demandas da avaliação e etiquetagem energética. Diferentemente das etapas de revisão e de testes paramétricos controlados, este trabalho instrumentaliza a solução técnica ao integrar requisitos de informação, diretrizes de modelagem, um protocolo de simulação e um pipeline desenvolvido em Python.

A pesquisa validou a proposta por meio de um estudo de caso em um edifício universitário real de 8.100 m², caracterizado por uma geometria em forma de “X” e alta diversidade de uso. Os resultados demonstram a capacidade do pipeline de corrigir erros de interoperabilidade, realizar enriquecimentos semânticos e gerar automaticamente modelos BEM exigidos pelo método de simulação energética, completando a avaliação em aproximadamente 15 minutos.

## 5.1 GUIA DE LEITURA DO ARTIGO 4

Esta seção apresenta o guia de leitura do artigo 4, disponível integralmente no APÊNDICE D. O objetivo é oferecer uma compreensão clara da lógica interna do estudo, destacando os elementos que estruturam o fluxo BIM-to-BEM. O guia não substitui a leitura integral do artigo, mas indica como cada parte contribui para a construção do método e para a avaliação da sua contribuição técnica.

### 5.1.1 Introdução

A seção *Introduction* contextualiza a etiquetagem energética mandatória como um processo regido por imperativos de consistência e reprodutibilidade. O texto estabelece a distinção conceitual entre a modelagem para predição do consumo real e a avaliação de conformidade regulatória, evidenciando a tensão entre método e

aplicação. Sustenta-se que a superioridade analítica da simulação dinâmica esbarra no tratamento manual de dados, posicionando a automação como infraestrutura essencial para a aplicação do método em escala regulatória.

A seção *Background* articula a demanda por eficiência regulatória às limitações dos processos de troca de dados, desvinculando a interoperabilidade de uma visão puramente instrumental. A integração BIM-to-BEM é abordada como um desafio de preservação semântica, dependente de requisitos de informação, diretrizes de modelagem e protocolos de simulação. A revisão do estado da arte demonstra que a persistência de inconsistências geométricas e semânticas inviabiliza a aplicação direta entre BIM e BEM exclusivamente via padrões abertos, fundamentando a necessidade de um pipeline capaz de auditar e enriquecer a informação antes da simulação.

A seção *Approach and objectives* marca a transição do diagnóstico para a proposição, apresentando a arquitetura da solução estruturada em duas fases: a preparação do modelo no ambiente BIM e a sua tradução automatizada para o ambiente BEM. Os quatro componentes do fluxo operam de forma integrada: os requisitos de informação e as diretrizes de modelagem atuam preventivamente na origem dos dados (BIM), enquanto o protocolo de simulação e o pipeline gerenciam a complexidade da simulação no destino (BEM). O segmento justifica o uso estratégico do esquema gbXML e define as questões de pesquisa, convertendo os objetivos em critérios de validação baseados em escalabilidade, consistência e transparência.

### 5.1.2 Método

A seção *Method* apresenta a visão sistêmica da proposta. A hierarquia entre os componentes é sintetizada visualmente na representação esquemática (Figura 18). O texto foca em explicar a função lógica de cada etapa no arcabouço da pesquisa, demonstrando como a integração entre os requisitos, as diretrizes, o protocolo e a automação forma uma estrutura coesa para atender aos objetivos do estudo.

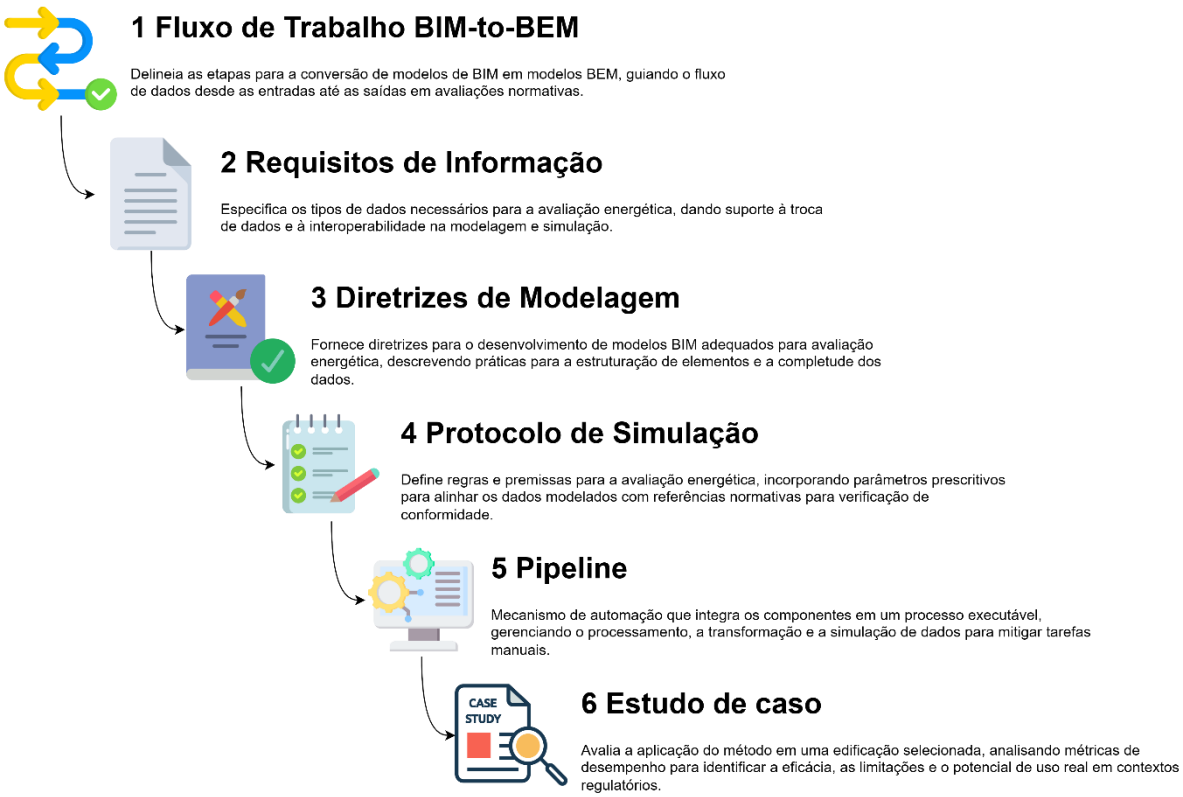



Figura 18 – Representação esquemática do fluxo metodológico do artigo 3

### 5.1.3 Fluxo BIM-to-BEM

A subseção *BIM-to-BEM workflow* detalha a operacionalização do produto proposto. O fluxo de trabalho (Figura 19) mapeia a sequência de tarefas, entradas e saídas do processo, descrevendo o encadeamento lógico que transforma dados brutos em métricas da etiquetagem energética. O fluxo organiza-se em uma linha do tempo dividida em etapas preparatórias e de implementação, avançando desde a definição de regras abstratas (consulta a bases regulatórias) até a execução prática, que culmina na exportação do arquivo gbXML e na execução do script de automação. Essa estruturação linear fundamenta a capacidade do método de minimizar intervenções manuais e promover a consistência dos dados ao longo da avaliação energética.

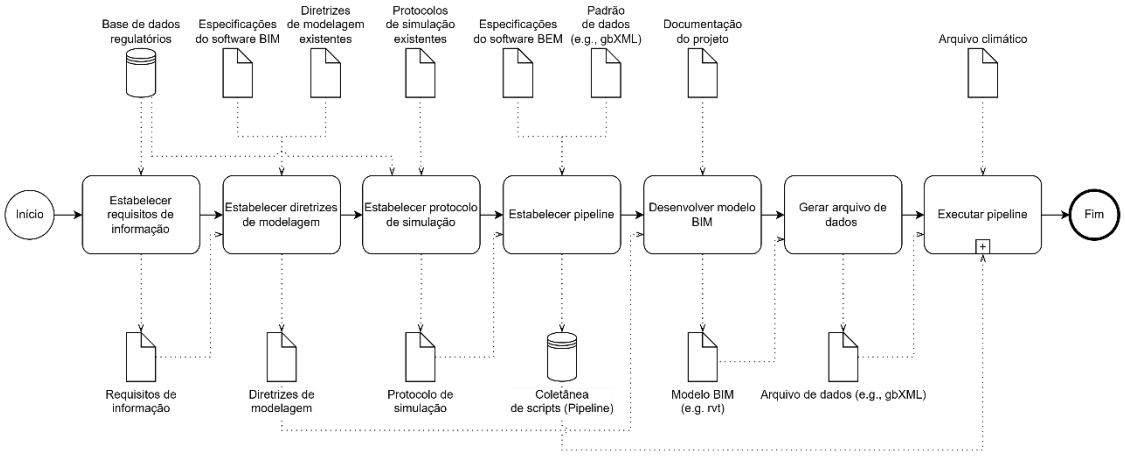



Figura 19 – Fluxo de trabalho BIM-to-BEM para avaliação e etiquetagem energética

### 5.1.4 Requisitos de informação

A seção *Information requirements* organiza os dados necessários em categorias que podem ser lidas como o escopo mínimo de informações que o fluxo precisa receber. O Quadro 3 oferece uma visão sintética dessa estrutura e permite reconhecer que o método não depende apenas da geometria, mas também de um conjunto articulado de atributos físicos, operacionais e de uso, condição necessária para que a simulação dinâmica produza indicadores para fins de etiquetagem energética.

Quadro 3 – Síntese dos requisitos de informação para a etiquetagem

| Categoria | Requisito de informação | Descrição |
|---|---|---|
| Localização | Latitude e longitude | Coordenadas de localização. |
| Orientação | Orientação solar | Orientação da edificação em relação ao Norte Verdadeiro. |
| Geometria da edificação | Elementos geométricos | Dimensões e posicionamento de paredes, pisos, coberturas, aberturas e elementos de sombreamento. |
| Materiais da envoltória opaca | Camadas de materiais e propriedades térmicas | Valores de espessura, condutividade térmica, densidade, calor específico e absortância solar. |
| Elementos de envidraçamento | Propriedades termo-ópticas | Valores de fator solar (FS) e transmitância térmica (U). |
| Ganhos internos | Ocupantes, DPI e DPE | Densidade de ocupação, densidade de potência de iluminação (DPI) e densidade de potência de equipamentos (DPE). |
| Trocas de ar | Infiltração e ar externo para ventilação | Caracterização da infiltração de ar não controlada e especificação do ar externo. |
| Sistema de ar-condicionado | Parâmetros de desempenho | Coeficiente de performance (IDRS) do sistema de ar-condicionado, juntamente com as temperaturas de setpoint para resfriamento e aquecimento. |
| Agendas operacionais | Horas de operação diárias, semanais e anuais | Agendas de ocupação, iluminação, equipamentos e operação do ar-condicionado. |

A descrição subsequente de cada categoria do quadro mostra como esses requisitos se relacionam às decisões de modelagem e ao comportamento do modelo energético. Os parâmetros de localização e orientação situam o edifício em um contexto climático e solar específico, o que orienta a seleção do arquivo climático. Os itens associados à geometria e aos materiais caracterizam o volume, as superfícies de troca térmica da envoltória. Ganhos internos, trocas de ar e desempenho do sistema de condicionamento de ar definem o regime de cargas e as condições de operação, enquanto os horários de uso estruturam o perfil temporal de ocupação, iluminação, equipamentos e sistemas. Observa-se que, em conjunto, esses requisitos estabelecem a base sobre a qual o pipeline e o protocolo de simulação operam, tornando explícito o tipo de informação que deve estar presente e estruturada no BIM.

### 5.1.5 Diretrizes de modelagem

A seção *Modeling guidelines* estabelece como o modelo BIM deve ser organizado para que os requisitos de informação sejam concretizados e explorados no fluxo. O Quadro 4 sintetiza essa orientação em passos sequenciais, associando cada um a um objetivo, a requisitos de informação e a diretrizes específicas.

Quadro 4 – Síntese das diretrizes de modelagem BIM para etiquetagem

| Etapa | Objetivo | Requisito de informação relacionado | Diretriz de modelagem |
|---|---|---|---|
| Configurações globais | Definir o contexto climático e solar do projeto. | Localização e orientação | Atribuir coordenadas geográficas (latitude/longitude) e alinhar o Norte do Projeto ao Norte Verdadeiro. |
| Modelagem geométrica | Criar a envoltória física da edificação. | Geometria da edificação | Modelar elementos contínuos da envoltória (paredes, coberturas, lajes) assegurando a delimitação adequada dos volumes internos. |
| Propriedades físicas | Atribuir propriedades térmicas aos componentes da envoltória. | Materiais da envoltória opaca e elementos de envidraçamento | Criar composições de materiais em múltiplas camadas com propriedades térmicas definidas. |
| Definição do espaço analítico | Traduzir a geometria física em superfícies e volumes analíticos. | N/A (etapa de processo) | Posicionar objetos de espaço/zona em todas as áreas ocupáveis para capturar os limites volumétricos para análise energética. |
| Atribuição de dados semânticos | Preencher as zonas analíticas com dados de uso e operação. | Ganhos internos, trocas de ar, sistema de ar-condicionado e agendas operacionais | Atribuir atributos de ocupação, iluminação e equipamentos aos objetos de espaço/zona com base na função. |
| Geração e exportação do modelo analítico | Gerar o modelo energético final e exportá-lo como um arquivo gbXML. | N/A (etapa de processo) | Gerar o modelo analítico de energia abstraindo a geometria física e exportar para padrão aberto (gbXML). |

As diretrizes estruturam os pontos críticos que afetam a interoperabilidade BIM-to-BEM. A configuração global exige a vinculação do modelo a uma localização e orientação coerentes para viabilizar o processamento do arquivo climático. A modelagem geométrica determina a construção de uma envoltória contínua, sem lacunas ou interseções ambíguas, condição essencial para a geração correta de superfícies analíticas. A representação das propriedades de materiais opacos e transparentes deve assegurar a equivalência de desempenho no BEM, admitindo-se o uso de estratégias indiretas de modelagem caso o software BIM não disponha de todos os parâmetros térmicos nativos.

Na definição das zonas analíticas, espaços de uso semelhante devem ser agrupados em volumes coerentes com a lógica de simulação, evitando segmentações que aumentam a complexidade do modelo BEM sem ganhos de precisão. A atribuição de dados semânticos consolida os atributos críticos que o pipeline transformará em entradas de simulação. Por fim, a geração e exportação do modelo para o padrão gbXML exige a verificação prévia do fechamento dos volumes, das atribuições de

zonas e materiais, e da compatibilidade das opções de exportação, visando reduzir ajustes manuais posteriores.

### 5.1.6 Protocolo de simulação

A seção *Simulation protocol* descreve as regras de configuração e as premissas de cálculo que orientam a avaliação de desempenho. O protocolo estrutura-se em uma sequência de três etapas (Figura 20): geração dos modelos, configuração das simulações e classificação da eficiência.

A avaliação regulatória baseia-se na comparação entre um modelo de condição real e um de referência. Para viabilizar essa análise, o protocolo prescreve a derivação de ambos os cenários a partir de um único modelo BIM, delegando ao pipeline a tarefa de operacionalizar as diferenças paramétricas entre os modelos. Essa diretriz visa mitigar a subjetividade inerente ao processo de modelagem e à configuração manual do BEM.

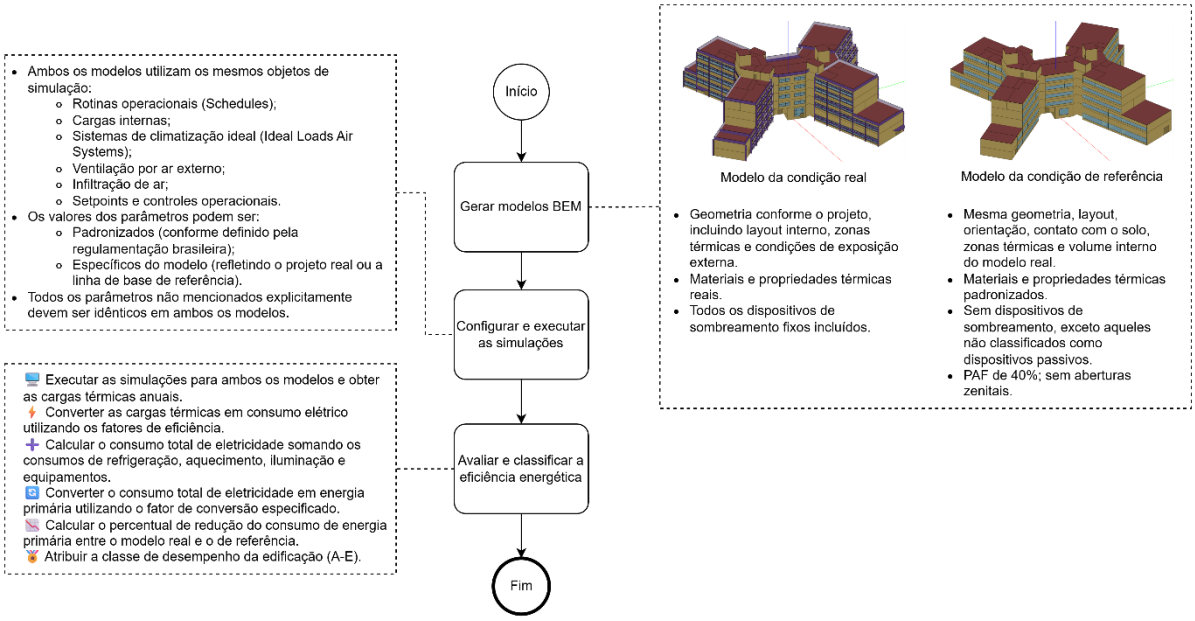



Figura 20 – Síntese do protocolo de simulação

### 5.1.7 Pipeline

A seção Pipeline descreve a automação por meio de rotinas em Python que aplicam as regras do protocolo de simulação. O algoritmo transforma o arquivo gbXML em dois modelos BEM completos (real e de referência), executa as simulações e converte os resultados na classificação energética (Figura 21). A automação atua diretamente nos gargalos de interoperabilidade BIM-to-BEM, realizando a validação, a correção e o enriquecimento semântico dos dados, estruturando-se em três rotinas principais: *Real condition model routine*, *Reference condition model routine* e *Energy simulation and assessment routine*.

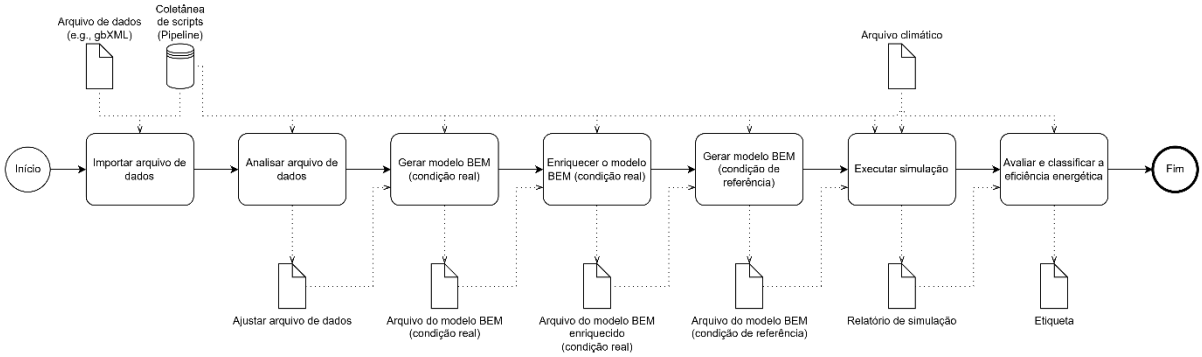



Figura 21 – Pipeline para avaliação e etiquetagem

A subseção *Real condition model routine* detalha a lógica de tratamento de dados que converte o arquivo geométrico exportado em um modelo BEM funcional. O núcleo estruturante dessa etapa é o mecanismo de classificação espacial (Figura 22), que utiliza um dicionário de correspondência semântica para traduzir a taxonomia nativa do gbXML diretamente para as categorias de ocupação (APP e APT) exigidas pelo protocolo de simulação.

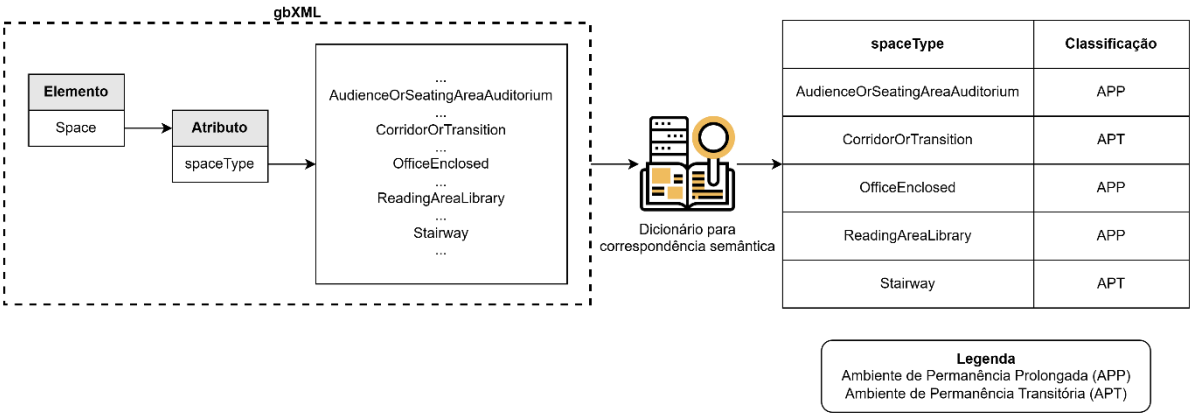
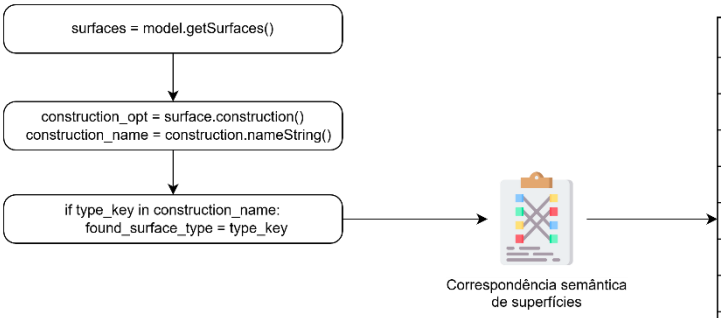



Figura 22 – Esquema do dicionário de correspondência semântica

A partir dessa classificação, o pipeline enriquece o modelo BEM, atribuindo automaticamente as cargas internas, os parâmetros de ventilação, as configurações de sistemas idealizados e os horários de operação (cujos valores paramétricos detalhados encontram-se documentados no artigo). Na sequência, a seção descreve as rotinas de verificação que impactam diretamente a coerência física da simulação. O algoritmo padroniza a nomenclatura das construções e emprega um fluxo de correspondência semântica (Figura 23) para corrigir falhas recorrentes da exportação gbXML, resolvendo divergências entre a função inferida no modelo BIM e o tipo de superfície e condição de contorno interpretadas no BEM.




| Surface type | Outside boundary condition | Sun exposure | Wind exposure |
|---|---|---|---|
| InteriorWall | Surface | NoSun | NoWind |
| ExteriorWall | Outdoors | SunExposed | WindExposed |
| Roof | Outdoors | SunExposed | WindExposed |
| InteriorFloor | Surface | NoSun | NoWind |
| UndergroundWall | Ground | NoSun | NoWind |
| UndergroundSlab | Ground | NoSun | NoWind |
| Ceiling | Surface | NoSun | NoWind |
| Air | Surface | NoSun | NoWind |
| SlabOnGrade | Ground | NoSun | NoWind |
| RaisedFloor | Outdoors | NoSun | WindExposed |

Figura 23 – Correspondência semântica e correção de atribuições de tipo de superfície

A subseção *Reference condition model routine* detalha o ajuste do modelo BEM para refletir o cenário de linha de base. O texto descreve a substituição programática das composições de paredes, coberturas e pisos reais por construções com propriedades térmicas normativas. O pipeline também aplica a razão janela-parede de referência (recriando janelas com transmitância e fator solar específicos), normaliza a densidade de potência de iluminação e remove elementos de sombreamento e claraboias. A distinção clara entre os aspectos que são padronizados e os que permanecem herdados do modelo real é o ponto de atenção desta etapa.

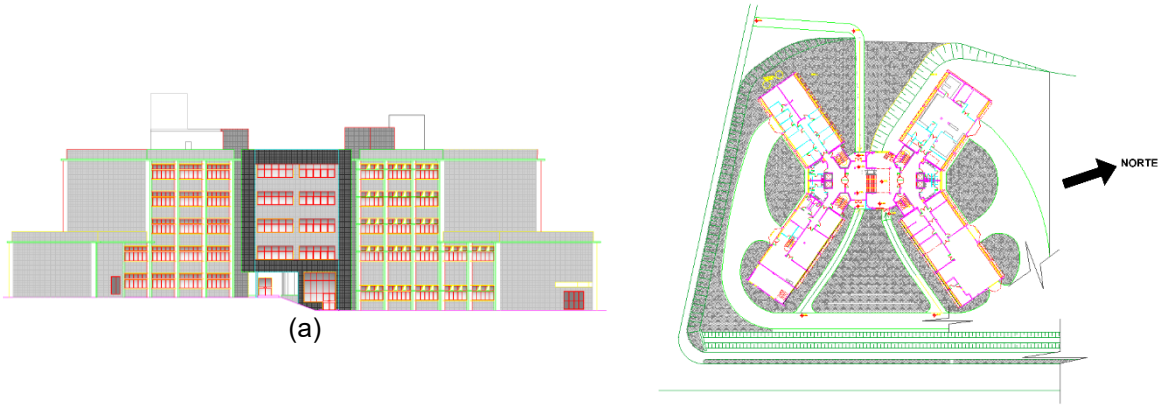
A subseção *Energy simulation and assessment routine* apresenta a lógica de cálculo que converte os resultados brutos da simulação em indicadores de desempenho. O texto demonstra como o pipeline extrai os dados simulados e processa automaticamente as métricas necessárias para emitir a classificação energética da edificação.

A configuração das variáveis de saída segue estritamente o protocolo de simulação. O texto detalha o processamento dessas grandezas e a aplicação dos fatores de conversão para transformar a demanda térmica em consumo de energia elétrica e, posteriormente, em energia primária, culminando no cálculo do Percentual de Redução do Consumo de Energia Primária (PRCEP).

A seção também evidencia a interdependência entre os dados geométricos extraídos dos relatórios de simulação e a definição dos limites de classificação da etiqueta. O pipeline extrai do arquivo de saída da simulação o volume e a área da envoltória para calcular o fator de forma da edificação. Esse processamento demonstra que os intervalos para a obtenção das etiquetas (faixas A a E) não são estáticos, mas calculados dinamicamente em função de um “coeficiente i”, que depende diretamente da geometria e da zona bioclimática na qual a edificação está inserida.

### 5.1.8 Estudo de caso

A seção *Case study* apresenta o objeto selecionado para a validação do fluxo de trabalho BIM-to-BEM. A escolha de um edifício universitário de 8.100 m² atua como um mecanismo de teste de estresse para a automação. A sua geometria — caracterizada pelo formato em "X", por desníveis no pavimento térreo e por coberturas em diferentes cotas (Figura 24) — desafia o pipeline com uma diversidade de informações superior à encontrada em volumetrias retangulares simples.




(a) (b)

Figura 24 – Fachada principal (leste) do objeto de estudo (a); e planta de implantação (b)

Em relação à materialidade e aos parâmetros operacionais do objeto de estudo, a seção estabelece a hierarquia entre os dados reais de projeto e as exigências da regulamentação. O texto esclarece que o modelo digital deve adotar os valores operacionais padronizados estipulados pelo protocolo de simulação (como a densidade de equipamentos e a eficiência mínima exigida para os sistemas de condicionamento de ar), sobrepondo-se às especificações originais do projeto arquitetônico.

Por fim, a caracterização do estudo de caso é encerrada com a definição das condições meteorológicas. O emprego de um arquivo climático futuro para Florianópolis (década de 2050, RCP 8.5) alinha a avaliação e a etiquetagem à real expectativa de vida útil da edificação, submetendo o modelo ao estresse térmico previsto pelos cenários de mudanças climáticas.

### 5.1.9 Resultados

A seção *Results* demonstra como o método responde às falhas de interoperabilidade e valida o fluxo de trabalho, apresentando o panorama geral que conecta as cinco etapas de transformação de dados (Figura 25).

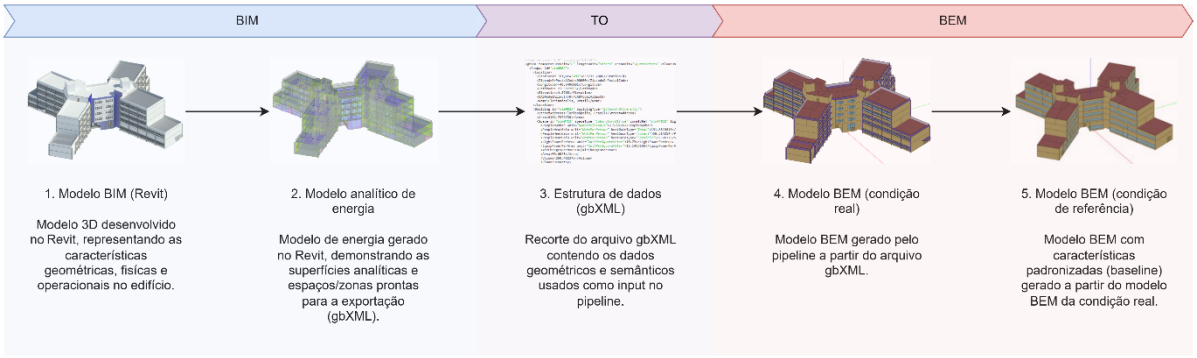
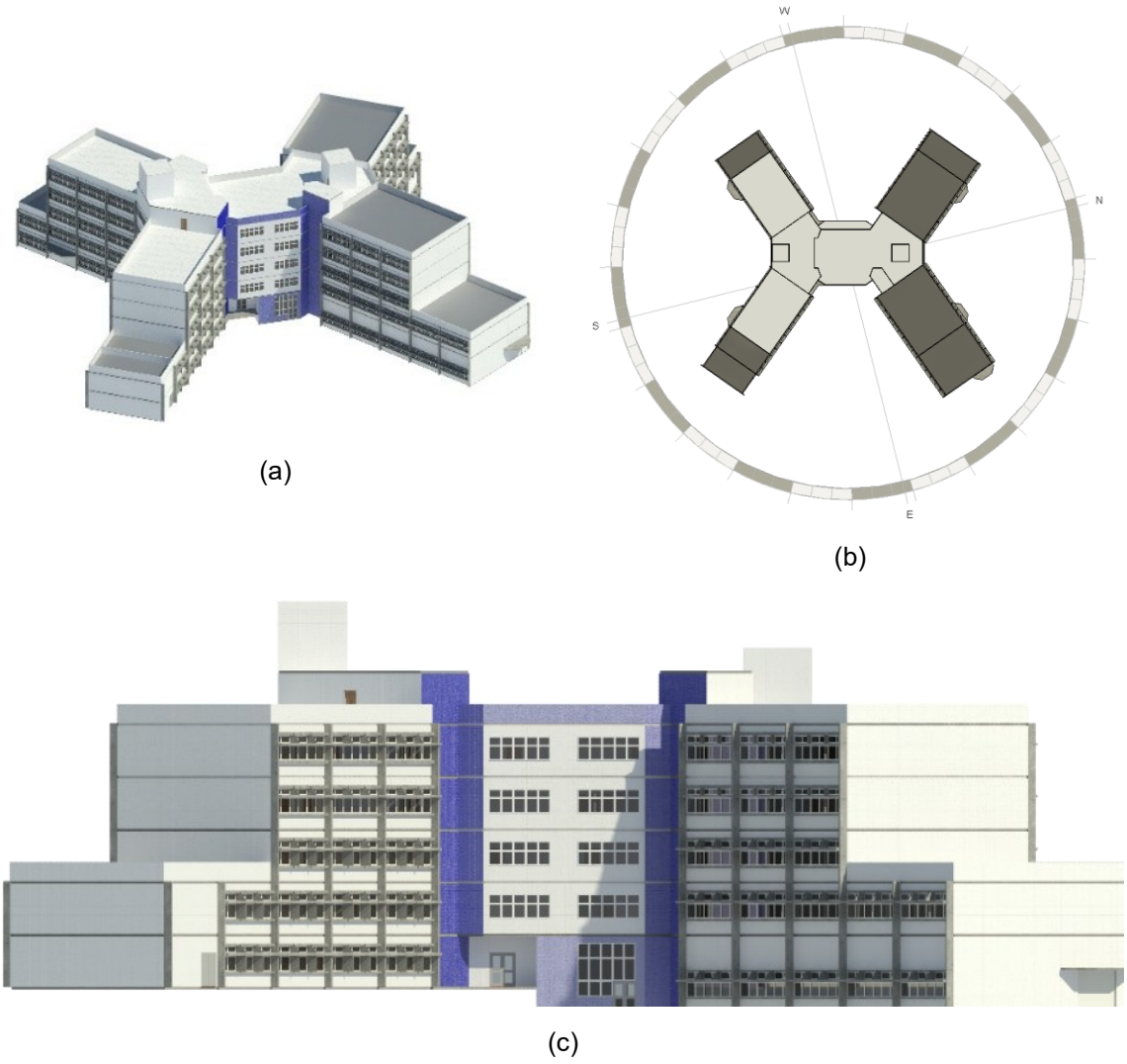



Figura 25 – Panorama da implementação do fluxo de trabalho BIM-to-BEM

A caracterização do objeto de estudo evidencia a complexidade do modelo BIM, composto por 139 ambientes distribuídos em cinco pavimentos (Figura 26). Essa magnitude atesta que a validação ocorre em uma edificação com diversidade funcional real, e não em um protótipo simplificado.




(a)

(b)

(c)

Figura 26 – Representação do modelo BIM ilustrando (a) geométrica 3D, (b) vista superior e (c) fachada leste.

Os resultados iniciais da tradução expõem as limitações dos algoritmos nativos, discutindo distorções de classificação semântica que não são passíveis de correção direta na ferramenta BIM. O texto exemplifica esse fenômeno com a rotulação incorreta de lajes do pavimento térreo como piso elevado (*RaisedFloor*) em vez de piso sobre o solo (*SlabOnGrade*) (Figura 27). A ocorrência demonstra que a interoperabilidade nativa exige tratamento pós-exportação mesmo quando o modelo analítico de energia é geometricamente coerente.

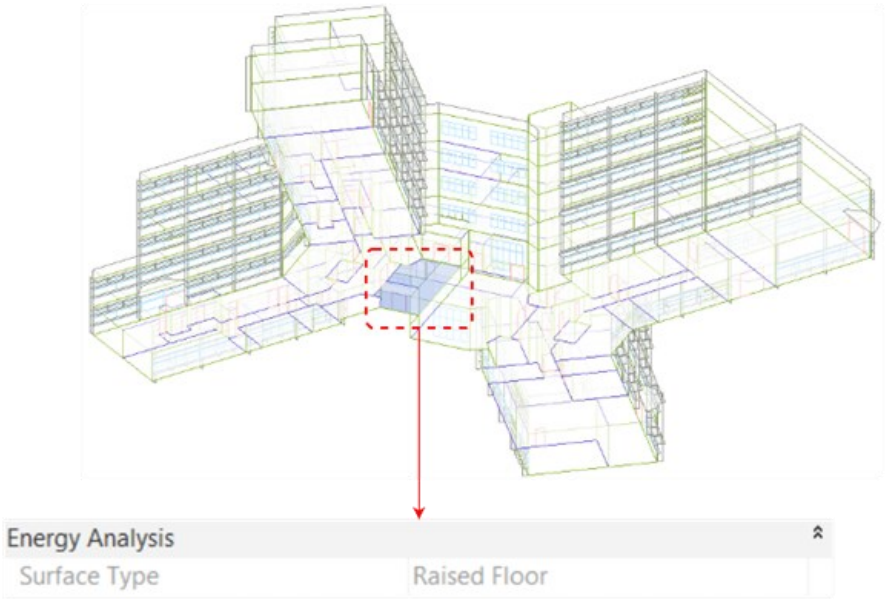



Figura 27 – Evidência de erro de classificação de superfície

Em relação às propriedades dos materiais, a seção detalha a correção de inconsistências semânticas no arquivo gbXML. O módulo de exportação da ferramenta BIM atribui erroneamente o parâmetro de absortância infravermelha (enumerador “ExtIR”) às composições construtivas, enquanto o protocolo de simulação exige a absortância solar (enumerador “ExtSolar”). A Figura 28 documenta a substituição automática desse enumerador realizada pelo pipeline, uma intervenção programática indispensável para preservar a coerência física da simulação.

```
<Construction id="aim14698" constructionIsSchematic="false">
  <U-value unit="WPerSquareMeterK">1.7270537</U-value>
  <Absorptance unit="Fraction" type="ExtIR">0.2</Absorptance>

<Construction id="aim14698" constructionIsSchematic="false">
  <U-value unit="WPerSquareMeterK">1.7270537</U-value>
  <Absorptance unit="Fraction" type="ExtSolar">0.2</Absorptance>
```

Figura 28 – Evidência de substituição automática da enumeração ExtIR por ExtSolar para construções opacas externas

A rotina de geração do modelo da condição real atesta a integridade da tradução geométrica do gbXML para o ambiente BEM (Figura 29). A importação processou com êxito um volume expressivo de dados espaciais – 1.669 superfícies,

1.089 aberturas e 64 montagens construtivas – preservando a integridade estrutural da edificação original.

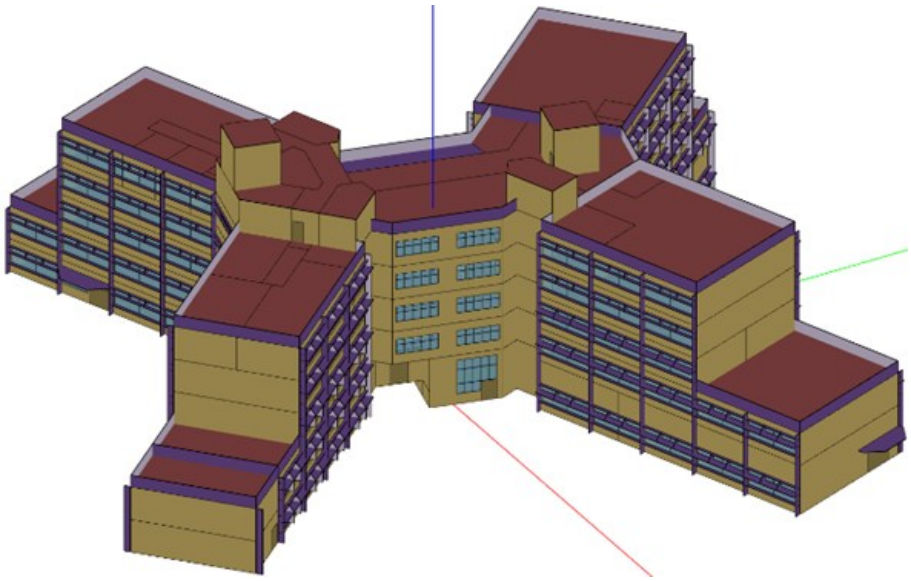


Figura 29 – Representação 3D do modelo BEM da condição real

A etapa de enriquecimento semântico evidencia a operacionalização do dicionário de correspondência (Figura 30). O pipeline populou automaticamente as zonas térmicas com base no protocolo de simulação: 76 zonas foram classificadas como APP, recebendo cargas completas de ocupação e equipamentos, além de setpoints de 21 ºC (aquecimento) e 24 ºC (resfriamento); e 63 zonas foram definidas como APT, recebendo apenas cargas de iluminação. A estrutura de dados resultante deriva diretamente da lógica semântica programada na ferramenta.

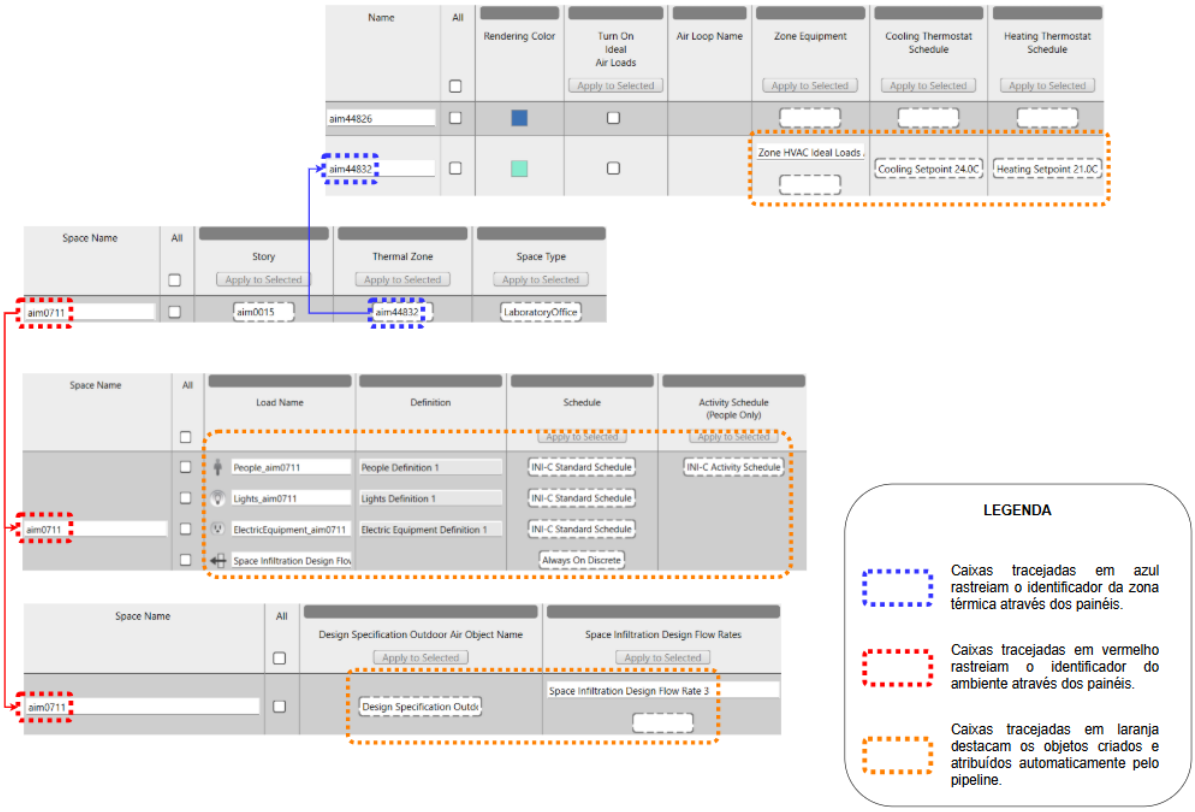



Figura 30 – Evidência de enriquecimento semântico de uma zona térmica APP

Nas rotinas de verificação do modelo real, o pipeline corrigiu distorções semânticas herdadas da exportação BIM, alterando 24 superfícies que apresentavam inconsistências de classificação (como *RaisedFloor*, *UndergroundWall* e *SlabOnGrade*). A intervenção automatizada retificou a condição de contorno de ambiente externo (*Outdoors*) para contato com o solo (*Ground*), ajustando simultaneamente os atributos físicos de exposição solar e ventilação (Figura 31).

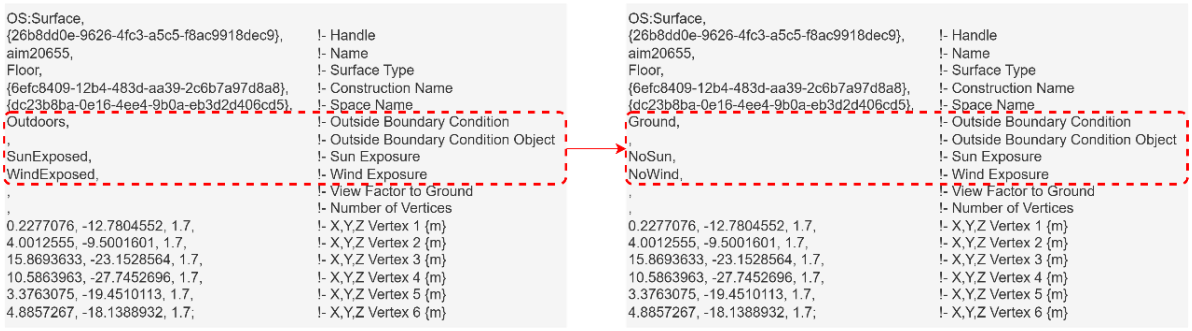



Figura 31 – Evidência da correção automatizada da condição de contorno externa para superfície em contato com o solo

A gestão das interfaces internas destaca a capacidade do pipeline de identificar superfícies ambíguas no modelo e realizar sua conversão automática para limites de ar (*Air Boundary*) (Figura 32). A operação garante a continuidade térmica entre os ambientes, substituindo barreiras sólidas pelas interfaces de mistura simples (*Simple Mixing*) exigidas para simular as trocas de ar entre zonas adjacentes.

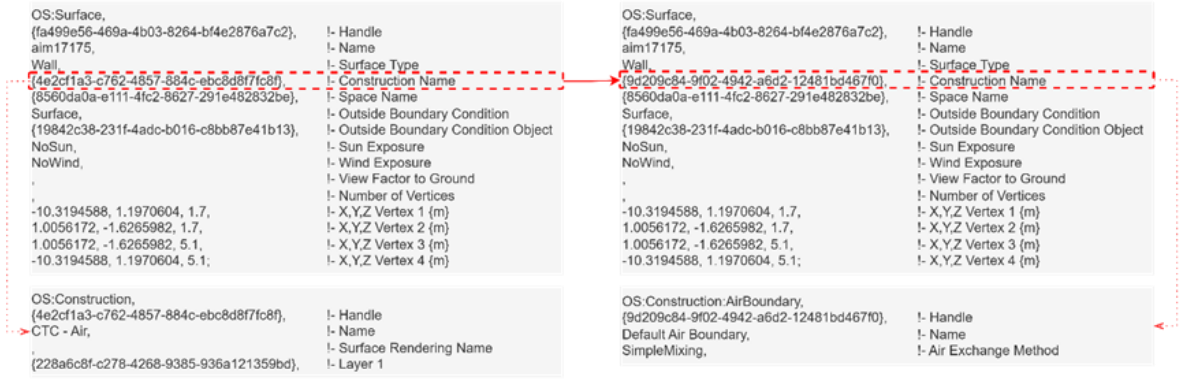



Figura 32 – Criação e atribuição automatizada de construção de limite de ar para superfície de ar

A geração automatizada do modelo BEM da condição de referência atesta a magnitude de intervenção e reprogramação do pipeline (Figura 33). Preservando a geometria de base, o algoritmo substituiu programaticamente as construções originais por montagens com propriedades térmicas normativas em 383 pisos, 40 coberturas e 1.335 paredes. Simultaneamente, o processo executou a remoção integral de 618 superfícies de sombreamento externo e substituiu todos os vidros originais por 118 novos objetos de envidraçamento, ajustando dinamicamente as fachadas para atingir a exata proporção padronizada de 40% de razão janela-parede.

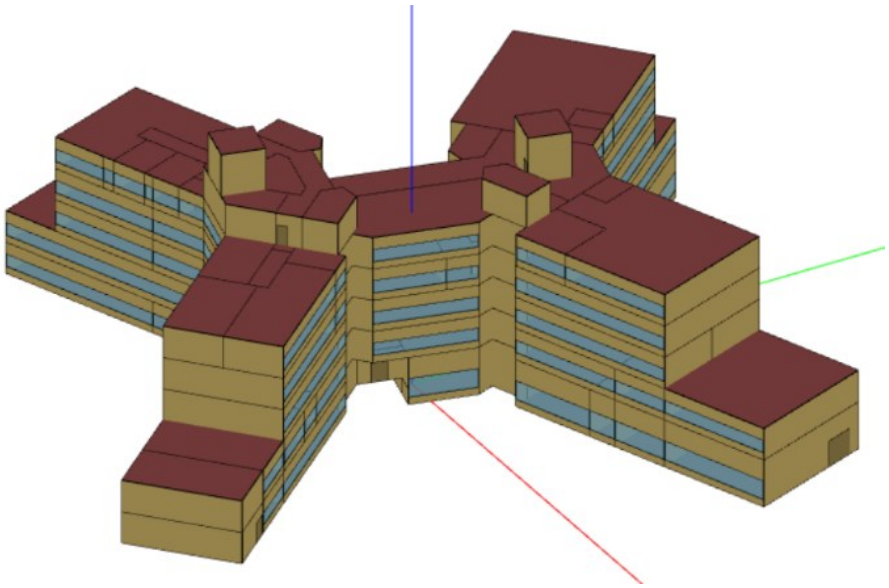


Figura 33 – Representação 3D do modelo BEM da condição de referência

Para atestar a integridade paramétrica do modelo, a Figura 34 atua como um painel de verificação das definições previamente detalhadas no protocolo de simulação. O texto documenta a substituição sistemática das camadas de material originais por construções padronizadas e a fixação normativa da densidade de potência de iluminação. Essa etapa evidencia que o modelo gerado opera sob as propriedades físicas e as cargas estritamente exigidas para a avaliação na condição de referência.

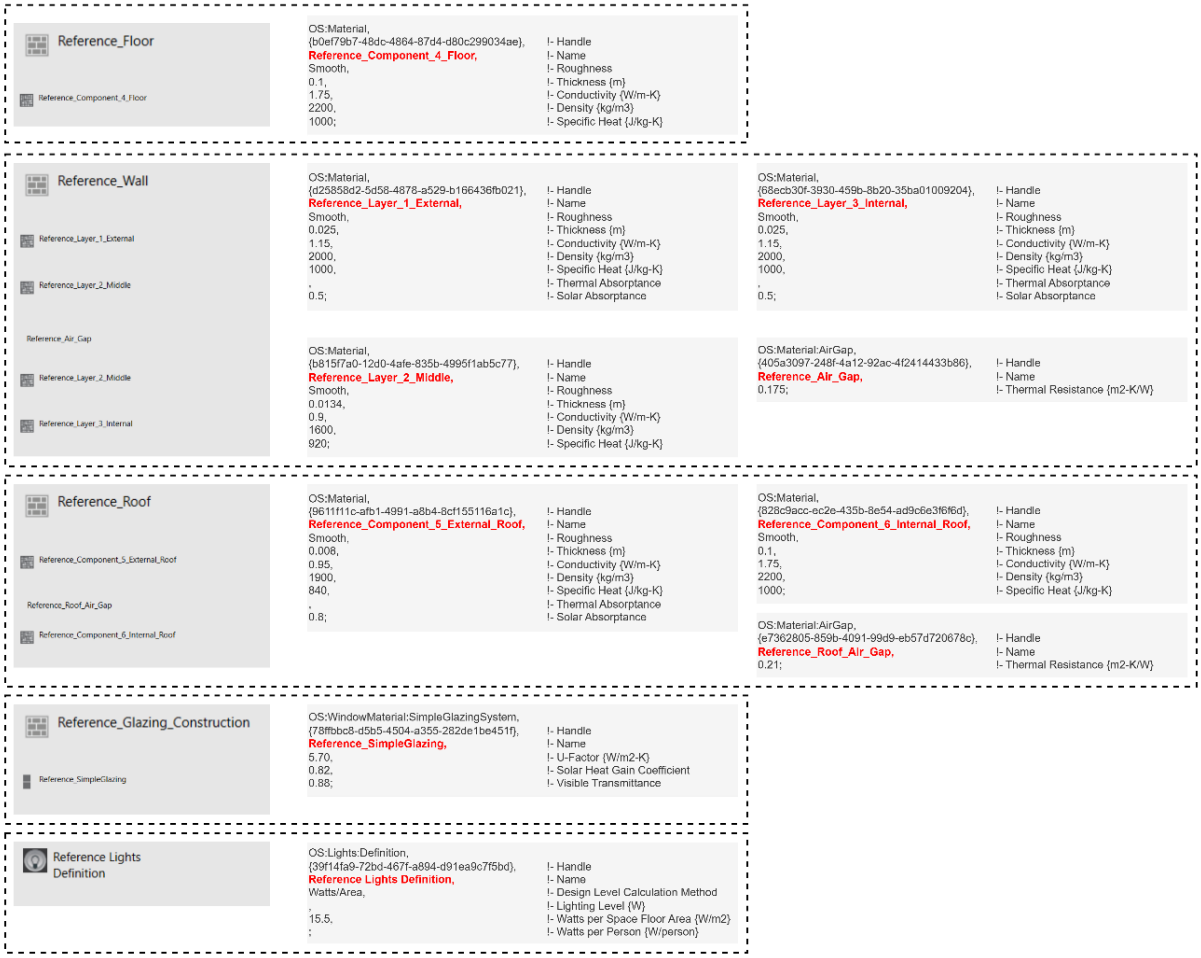
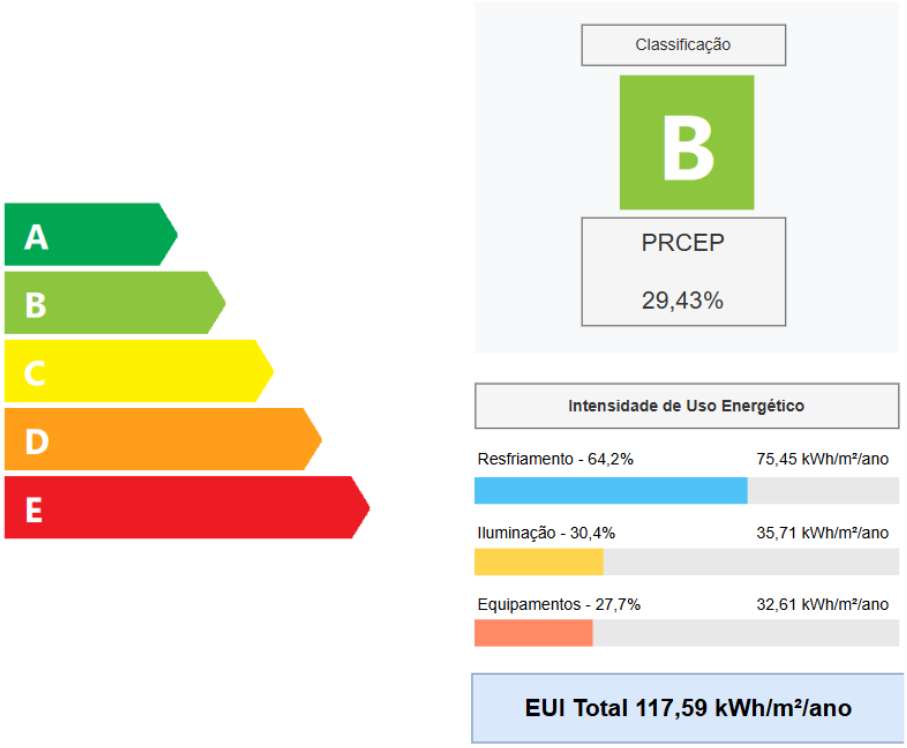



Figura 34 – Evidência da substituição das construções e densidade de potência de iluminação para as condições de referência

A fase final dos resultados compreende a execução dinâmica das simulações e a classificação energética da edificação. O pipeline integrou o arquivo climático e executou autonomamente os cálculos para ambos os cenários (real e de referência), sem intervenção manual. A decomposição dos indicadores (Figura 35) quantitativos demonstra uma redução expressiva nas cargas de resfriamento e de iluminação no modelo real em relação à linha de base. O consumo referente a equipamentos, por sua vez, permaneceu idêntico entre os cenários, refletindo a conformidade com a premissa normativa que impõe densidades de potência equivalentes em ambos os modelos.




| Componente | Modelo de referência | Modelo real | Diferença |
|---|---|---|---|
| Resfriamento | 126,23 kWh/m²/ano | 75,45 kWh/m²/ano | ↓ 50,78 kWh/m²/ano (-40,2%) |
| Iluminação | 51,58 kWh/m²/ano | 35,71 kWh/m²/ano | ↓ 15,88 kWh/m²/ano (-30,8%) |
| Equipamentos | 32,61 kWh/m²/ano | 32,61 kWh/m²/ano | 0% |
| Total | 166,64 kWh/m²/ano | 117,59 kWh/m²/ano | ↓ 49,04 kWh/m²/ano (-29,4%) |
| PRCEP | 0% | 29,43% | ↓ 29,43% |

Como interpretar os resultados:

- PRCEP (Percentual de Redução do Consumo de Energia Primária): Métrica de eficiência global.
- PRCEP Positivo (+): Sua edificação consome MENOS energia que a referência (mais eficiente).
- PRCEP Negativo (-): Sua edificação consome MAIS energia que a referência (menos eficiente).
- EUI (Intensidade de Uso de Energia): Consumo de energia por metro quadrado por ano.
- EUI de "Resfriamento" utiliza a área condicionada; "Iluminação" e "Equipamentos" utilizam a área total da edificação.
- EUI "Total" utiliza a área total da edificação para comparação padronizada.
- Valores com ↓: Redução no consumo comparado à referência (positivo).
- Valores com ↑: Aumento no consumo comparado à referência (negativo).

Figura 35 – Classificação energética e métricas de consumo

Por fim, a seção encerra expondo a eficiência operacional da ferramenta por meio de uma análise temporal. O ciclo completo de processamento do pipeline – abrangendo a importação do arquivo gbXML, a geração dos dois modelos BEM completos, a execução das simulações e a emissão das métricas de classificação energética – foi concluído em aproximadamente 15 minutos. A constatação final transmitida pelos resultados é que a automação converteu uma tarefa historicamente

intensiva em um fluxo computacional ágil, mitigando o gargalo imposto pela construção e configuração manual de modelos em processos de etiquetagem.

### 5.1.10 Discussão

A seção *Discussion* desloca a análise dos resultados específicos do edifício para uma reflexão crítica sobre os pilares de automação, informática e interoperabilidade na etiquetagem energética. O texto responde à questão central da pesquisa e avalia as implicações da automação de fluxos complexos em contextos normativos, ponderando sobre os desafios e as oportunidades encontrados.

A eficácia das diretrizes de modelagem é debatida, desafiando a percepção de que o fluxo BIM-to-BEM é inerentemente instável. Argumenta-se que parte dos insucessos documentados na literatura decorre da ausência de uma metodologia estruturada, e não exclusivamente de falhas tecnológicas. A validação em uma edificação de geometria complexa indica que regras claras de modelagem são uma condição básica para minimizar ambiguidades e aumentar a utilidade dos dados de entrada antes da exportação.

Em relação às limitações da interoperabilidade, estabelece-se uma distinção crítica entre falhas de origem humana e restrições intrínsecas aos softwares. A consistência do modelo não depende exclusivamente da habilidade do projetista, visto que os algoritmos de exportação incorrem frequentemente em erros de interpretação dos esquemas de dados. Ocorrências como a classificação equivocada de superfícies e o uso incorreto de enumeradores do padrão aberto demonstram que a confiança exclusiva na exportação nativa é inviável. Essa perspectiva fundamenta a necessidade do pipeline como uma camada de verificação e correção, estruturada para mitigar inconsistências e elevar a confiabilidade física dos dados no BEM.

A discussão aborda ainda o papel do pipeline no enriquecimento semântico e na promoção da equidade do processo de etiquetagem. A geração automatizada do modelo de referência atua para mitigar a subjetividade humana na aplicação dos parâmetros normativos. O valor dessa abordagem reside na auditabilidade e na transparência da comparação entre o cenário real e o de referência, e não necessariamente na previsão exata do consumo energético absoluto.

Por fim, avaliam-se a eficiência temporal e as limitações do método. Os tempos de processamento evidenciam que a simulação dinâmica tem potencial para deixar de ser um gargalo na etiquetagem, ressalvando-se as restrições inerentes ao

fluxo, como a dependência estrita das diretrizes de modelagem. O fechamento aponta caminhos para trabalhos futuros e reitera a conclusão de que metodologias de correção automatizada constituem etapas intrínsecas ao processo BIM, configurando-se como parte integrante da estruturação e da verificação de modelos direcionados à avaliação energética.

### 5.1.11 Conclusão

A seção *Conclusion* sintetiza a validação do fluxo de trabalho proposto, retomando a questão central e as subquestões da pesquisa. O texto estabelece que a viabilidade da etiquetagem em larga escala no contexto BIM-to-BEM reside na adoção de um fluxo estruturado em múltiplos estágios, visto que os desafios de interoperabilidade inerentes aos softwares atuais persistem. O argumento central sustenta que o sucesso do processo não depende exclusivamente da ferramenta de modelagem, mas da articulação estratégica entre requisitos de informação, diretrizes de preparação de dados e um pipeline de pós-processamento capaz de auditar, corrigir e enriquecer os modelos digitais.

Em relação à preparação dos dados, conclui-se que os requisitos e as diretrizes de modelagem atuam como a fundação necessária para a integração geométrica de projetos complexos, embora se mostrem insuficientes para evitar erros nativos da exportação. Para endereçar essas lacunas, o pipeline consolida-se como um recurso multifuncional que atua simultaneamente na varredura e correção de inconsistências, no enriquecimento semântico e na aplicação programática de regras.

A avaliação do impacto do fluxo estrutura-se sobre o tripé de escalabilidade, consistência e transparência. A redução drástica do tempo de processamento viabiliza a análise dinâmica em volume, promovendo resultados que são consequência direta das diretrizes do protocolo de simulação e mitigando a variabilidade da intervenção manual. A contribuição principal consolida-se na proposição de uma estrutura replicável que, a despeito das limitações e dependências procedimentais, converte a avaliação e etiquetagem energética em um processo dinâmico embasado em dados.

# 6 SÍNTESE INTEGRATIVA DA TESE

A apresentação individual dos estudos nos capítulos anteriores permite, neste momento, recompor a unidade da investigação. Mais do que uma coletânea de artigos com objetivos específicos, a tese consolidou uma trajetória incremental que partiu da identificação de lacunas conceituais para resultar na demonstração de um fluxo de trabalho BIM-to-BEM operacional. O conjunto da obra construiu uma narrativa interdependente voltada a: (i) compreender criticamente o uso do BIM no contexto da avaliação e etiquetagem energética de edificações; (ii) situar esse debate na cena internacional; (iii) investigar em profundidade um ponto técnico sensível, a granularidade da modelagem BIM; e (iv) propor um fluxo de trabalho BIM-to-BEM, instanciado no contexto do PBE Edifica e orientado à viabilidade de aplicação em condições compatíveis com rotinas de avaliação e etiquetagem.

A investigação iniciou-se com o diagnóstico do cenário nacional, o qual revelou um descompasso crítico: embora o potencial do BIM fosse teoricamente reconhecido, a sua aplicação prática no âmbito do PBE Edifica permanecia fragmentada em soluções pontuais e dependente de intervenções manuais. A revisão do estado da arte evidenciou que o uso da metodologia se restringia, majoritariamente, à extração geométrica ou a automações isoladas por meio de programação visual, sem a consolidação de um fluxo contínuo. Essa fase foi determinante para demonstrar que a barreira para a adoção em larga escala não era puramente tecnológica; ficou claro que a alta incidência de falhas de interoperabilidade e a dependência de softwares proprietários eram sintomas de uma lacuna estrutural, caracterizada pela ausência de requisitos de informação e de diretrizes de modelagem específicas. Concluiu-se, portanto, que a incipiência local decorria não da falta de ferramentas, mas da inexistência de um método sistematizado capaz de alinhar a modelagem BIM às exigências formais da etiquetagem.

Diante da insuficiência de referências locais, a expansão da análise para o contexto internacional buscou situar o debate em um patamar de maior maturidade. Essa etapa foi crucial para compreender que as dificuldades de integração não eram exclusividade do cenário brasileiro, mas reflexo de desafios globais associados à confiabilidade de dados e à variabilidade de procedimentos. O exame de abordagens avançadas – como a otimização multiobjetivo e os gêmeos digitais – permitiu um filtro metodológico determinante para a pesquisa: embora tecnicamente sofisticadas, essas

estratégias mostraram-se pouco aderentes aos ritos de uma avaliação mandatória, que exige reprodutibilidade e auditabilidade acima da exploração de cenários.

Dessa forma, a investigação consolidou a integração por meio de padrões de dados abertos como a alternativa mais coerente para a etiquetagem normativa, ainda que tenha exposto suas fragilidades intrínsecas. A constatação de que falhas de interoperabilidade e perdas semânticas persistiam mesmo em mercados consolidados reforçou a tese de que a tecnologia, por si só, não resolveria o problema. Esse panorama validou a premissa de que a viabilidade do fluxo dependeria menos da sofisticação do software e mais da estruturação de diretrizes de modelagem rigorosas e da adoção consciente de simplificações, preparando o terreno para a investigação da granularidade que viria a seguir.

Definida a estratégia de interoperabilidade por meio de padrões abertos, a pesquisa deparou-se com a necessidade de validar a confiabilidade desse processo na prática. A literatura indicava que perdas de informação eram inerentes ao intercâmbio de dados, mas não havia clareza sobre quais perdas comprometiam a avaliação energética. O terceiro estágio da investigação consistiu, portanto, em uma análise de sensibilidade para mensurar o impacto de diferentes estratégias de modelagem nos resultados da simulação. O experimento paramétrico revelou uma assimetria determinante, visto que o refinamento geométrico teve influência marginal sobre o desempenho, ao passo que a variação na granularidade semântica provocou oscilações de até 68% nos indicadores de consumo.

Essa etapa foi fundamental para identificar e caracterizar o fenômeno do *design misdirection* (artigo 3). As evidências demonstraram que, quando o modelo evolui geometricamente mas mantém dados operacionais genéricos, ele cria uma falsa percepção de acurácia. O diagnóstico energético resultante pode apontar erroneamente quais zonas são críticas, não por falha do motor de cálculo, mas pela insuficiência da representação semântica para refletir a heterogeneidade das cargas e perfis entre os ambientes do modelo. Esse achado expôs uma fragilidade central, uma vez que a sofisticação visual do modelo geométrico não garante – e muitas vezes mascara – a consistência analítica dos resultados.

A partir dessas evidências, a tese avançou para uma reflexão estrutural sobre a compatibilização entre os domínios. Reconheceu-se uma discrepância de escala, pois, enquanto o BIM permite uma modelagem geométrica de alta fidelidade, o BEM opera com abstrações físicas simplificadas. Constatou-se, portanto, a incoerência de

exigir um modelo BIM com elevado nível de granularidade geométrico e espacial se o motor de simulação possui um limite de interpretação inferior a essa complexidade. Somado a isso, o próprio rito da etiquetagem impõe o uso de dados operacionais padronizados, tornando ineficaz a tentativa de incorporar especificidades extremas no modelo BIM.

Esse raciocínio consolidou o princípio da granularidade adaptativa, mencionada no artigo 3 como “tão detalhado quanto útil”. O estudo fundamentou que a consistência do fluxo não reside na transferência integral da complexidade do BIM, mas em uma curadoria técnica na qual a geometria deve ser simplificada para respeitar os limites de abstração do BEM e atender às limitações de interoperabilidade, enquanto a semântica deve ser rigidamente controlada para alinhar-se aos padrões normativos. Essa conclusão estabeleceu a premissa lógica para a estruturação informacional do fluxo de trabalho, pois, se a geometria e o zoneamento excessivo geram ruído sem agregar valor ao cálculo e a norma padroniza o uso, torna-se mandatório estabelecer requisitos que filtrem a forma e controlem a formulação dos dados no BIM antes da exportação para o BEM.

Com as bases teóricas consolidadas, o estágio final da pesquisa converteu as reflexões conceituais em um artefato operacional. A resposta aos desafios de interoperabilidade materializou-se no desenvolvimento de um fluxo BIM-to-BEM que integrou requisitos de informação, diretrizes de modelagem e um pipeline automatizado. A estratégia central ultrapassou a simples automação de tarefas e focou no tratamento deliberado da informação, incorporando a lógica normativa diretamente na rotina de processamento para prover a estrutura técnica padronizada que se mostrou ausente nas etapas anteriores.

O princípio da granularidade adaptativa orientou a própria estruturação informacional do fluxo de trabalho. Visto que a etapa anterior demonstrou estatisticamente que o refinamento geométrico exerce influência marginal sobre os resultados, as diretrizes de modelagem foram definidas para recomendar a simplificação da geometria e do zoneamento no software de autoria. Essa abordagem permitiu alinhar o modelo BIM às características intrínsecas da etiquetagem, método que opera com valores semânticos globais. Dessa forma, o sistema foi projetado para receber uma geometria otimizada para a interoperabilidade, enquanto a complexidade semântica é gerenciada pelo algoritmo, o que assegura que o diagnóstico reflita o

desempenho da edificação e não as escolhas subjetivas de atribuição de dados do modelador.

Nesse arranjo, estabelece-se uma relação de complementaridade entre os dados inseridos no BIM e o enriquecimento realizado pelo pipeline. A injeção automática de parâmetros normativos não dispensa o rigor na construção do modelo no software de autoria, pois os requisitos de informação garantem a integridade da forma e a correta classificação dos ambientes, alicerces estruturais sem os quais a automação não consegue operar. Além disso, o sistema mantém a flexibilidade para transcender o recorte do PBE Edifica, pois, embora a estratégia atual priorize a aplicação de padrões normativos, a arquitetura do pipeline permite herdar definições operacionais diretamente do arquivo gbXML caso o objetivo da análise exija fidelidade a um projeto executivo específico.

A validação experimental confirmou que essa estruturação reduz drasticamente a dependência de ajustes manuais e mitiga as barreiras de interoperabilidade. O sistema mostrou-se capaz de gerar modelos consistentes e corrigir falhas de forma autônoma, evidenciando que a agilidade e a replicabilidade na etiquetagem decorrem não apenas da evolução das ferramentas, mas da clareza metodológica que define como modelar e como processar a informação. Fechou-se, assim, o ciclo da investigação ao provar que a integração consistente depende de um ecossistema onde o método precede e orienta a automação.

Em suma, a tese partiu de um panorama fragmentado sobre o uso do BIM no contexto da etiquetagem, conforme evidenciado no primeiro artigo, avançou para uma contextualização internacional e para uma análise do papel da granularidade de modelagem, e culminou na proposição de um fluxo de trabalho BIM-to-BEM estruturado e demonstrado em aplicação. Essa trajetória evidenciou que a integração entre BIM e BEM não depende apenas de trocas de arquivos, mas também de um ecossistema informacional e do desenvolvimento de um artefato para automatizar processos. Ao consolidar esses pilares, os resultados obtidos sustentam a hipótese de que tal estrutura reduz significativamente a dependência de intervenções manuais, favorece consistência metodológica e amplia a transparência das avaliações no escopo investigado. Adicionalmente, a síntese reforça que a escalabilidade pretendida para avaliações normativas não decorre apenas de automação, mas do alinhamento entre escolhas de modelagem, incluindo simplificações deliberadas, regras do

protocolo e rotinas de verificação, correção e enriquecimento de dados que tornam a conversão BIM-to-BEM mais robusta e escalável.

# 7 CONCLUSÃO

Esta tese tratou da integração entre BIM e BEM como meio de viabilizar avaliações de eficiência energética por meio de simulação em contextos de etiquetagem e conformidade normativa. O foco recaiu sobre o recorte BIM-to-BEM com o uso de gbXML e sobre a necessidade de tornar o processo menos dependente de ajustes manuais e mais consistente na tradução de requisitos normativos em configurações de simulação. Os quatro artigos reunidos como apêndices foram organizados de modo a construir uma trajetória única – do diagnóstico do cenário e da sistematização do campo, passando pela análise de fatores que afetam resultados, com ênfase na granularidade, até a implementação e validação de um fluxo integrado.

A questão central que orientou a pesquisa – quais elementos estruturais e operacionais compõem um fluxo de trabalho BIM-to-BEM aplicável a processos de etiquetagem – foi respondida por meio de três dimensões investigativas, tratadas de forma complementar ao longo dos estudos.

Na dimensão (i), referente à requisitos de informação e diretrizes de modelagem BIM, a tese consolidou que a compatibilidade com o BEM depende de um conjunto mínimo de informações e decisões de modelagem que reduzam lacunas e ambiguidades desde a origem do processo. A literatura analisada e a discussão construída no recorte brasileiro convergiram para a necessidade de explicitar requisitos relacionados à organização espacial, à geometria e às suas adjacências, às características da envoltória, às aberturas e sombreamentos, e às informações de uso e ocupação que afetam cargas internas e padrões de operação. Nesse enquadramento, diretrizes de modelagem não são tratadas como prescrição de valores, mas como orientação para estruturar o modelo de modo que a exportação e a posterior parametrização do BEM ocorram de forma previsível e verificável, compatível com o objetivo da avaliação e fundamentado nas evidências de sensibilidade paramétrica obtidas no artigo 3.

Na dimensão (ii), relativa às operações necessárias em um pipeline, a tese mostrou que um fluxo BIM-to-BEM aplicável não se limita à exportação do modelo, exigindo uma camada operacional de tratamento pós-exportação. A proposta de pipeline reúne rotinas orientadas a três funções: verificar (identificar inconsistências estruturais e semânticas no arquivo exportado), corrigir (ajustar entidades, relações e atributos que inviabilizam ou degradam o modelo BEM) e enriquecer (preencher

informações necessárias ao BEM e ao protocolo de simulação quando não estiverem devidamente representadas no arquivo de troca). Essa camada operacional permite reduzir variações procedimentais e tornar explícitas regras de transformação frequentemente realizadas de forma manual e pouco rastreável, mantendo o foco em na transparência do processo e na repetibilidade das etapas.

Na dimensão (iii), que trata da aplicabilidade do fluxo em contexto real, a tese reuniu evidências por meio de um estudo de caso, conduzindo uma avaliação completa com a geração do modelo BEM real e do modelo BEM de referência conforme o procedimento normativo adotado no recorte. Essa etapa permitiu examinar o fluxo como processo integrado (BIM → exportação gbXML → verificação, correção e enriquecimento semântico → parametrização conforme protocolo de simulação → execução da simulação → classificação energética), reforçando a viabilidade de aplicação quando requisitos, diretrizes, protocolo e pipeline são concebidos como componentes interdependentes. A aplicabilidade, nesse sentido, é sustentada menos por um resultado isolado e mais pela capacidade do fluxo de organizar decisões, tornar rastreáveis as transformações do modelo e reduzir o esforço operacional associado à preparação do BEM para simulação energética.

A hipótese da pesquisa estabeleceu que a integração de requisitos de informação, diretrizes de modelagem, protocolo de simulação e pipeline reduziria a dependência de ajustes manuais, favorecendo a consistência metodológica e a transparência. O conjunto dos estudos sustenta essa hipótese no escopo investigado, ao tratar a interoperabilidade como um problema simultaneamente técnico e metodológico: formatos de troca, como gbXML, têm limitações conhecidas, porém a perda de qualidade do BEM decorre também da ausência de estrutura para orientar a modelagem, avaliar integridade do exportado e padronizar a tradução de regras normativas para a simulação. Adicionalmente, a discussão sobre granularidade reforçou que a consistência da avaliação é sensível a decisões semânticas, por exemplo, associadas ao zoneamento e às condições internas, tornando particularmente relevantes a presença de um protocolo e de rotinas de verificação que reduzam a arbitrariedade e a variabilidade interpretativa.

Os resultados da tese permanecem condicionados ao recorte metodológico e ao contexto de aplicação. A adoção de gbXML como meio principal de interoperabilidade implica dependência do comportamento do exportador e da qualidade do modelo BIM de origem, o que pode demandar adaptações do pipeline

conforme o ecossistema de modelagem utilizado e conforme práticas de modelagem adotadas. Além disso, a validação por estudo de caso, ainda que suficiente para demonstrar a aplicabilidade do processo no escopo proposto, não substitui validações adicionais em outras tipologias, níveis de complexidade e condições de uso. Por fim, como em avaliações normativas, parte do resultado depende de decisões de parametrização, especialmente ligadas a uso e ocupação, o que reforça a necessidade de rastreabilidade e padronização via protocolo, sem eliminar completamente a necessidade de julgamento técnico.

Como continuidade natural, recomenda-se ampliar a validação do fluxo de trabalho proposto para diferentes tipologias e contextos regulatórios, testando a robustez das rotinas de verificação, correção, enriquecimento e a estabilidade do protocolo sob variações de modelagem e de dados disponíveis. Também é pertinente aprofundar a integração com dados medidos para calibração quando aplicável, além de expandir o escopo de métricas conforme o objetivo da avaliação (por exemplo, incorporando dimensões de conforto térmico e estratégias passivas como ventilação natural), preservando o princípio central da tese: processos rastreáveis, reproduzíveis e alinhados a requisitos normativos.

Esta tese consolida que um fluxo BIM-to-BEM aplicável a avaliações de etiquetagem exige, simultaneamente, uma camada estrutural (requisitos de informação, diretrizes de modelagem e protocolo de simulação) e uma camada operacional (pipeline de verificação, correção e enriquecimento), articuladas e validadas em aplicação real. Nesse arranjo, a contribuição central está em organizar o processo como um método completo e auditável, capaz de reduzir retrabalho e tornar mais consistente a transposição do modelo BIM e o modelo BEM necessário à simulação.

Por fim, a pergunta central foi respondida ao explicitar os elementos estruturais e operacionais do fluxo e ao demonstrar sua aplicação. A hipótese foi sustentada no escopo investigado, ao evidenciar que a integração entre requisitos, diretrizes, protocolo e pipeline reduz a dependência de ajustes manuais e aumenta a consistência e transparência do procedimento. O objetivo geral foi alcançado com o desenvolvimento e validação do fluxo BIM-to-BEM, e os objetivos específicos foram atendidos com: (1) definição de requisitos e diretrizes orientadas à simulação, (2) proposição de protocolo de simulação adaptável ao objetivo da pesquisa, (3)

desenvolvimento do pipeline para verificar/corrigir/complementar exportações gbXML e (4) validação por estudo de caso com avaliação completa.

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# APÊNDICE A

ARTIGO 1

BIM APPLICATION IN THE BRAZILIAN BUILDING LABELING PROGRAM: A REVIEW

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## Contrato de Autoria Compartilhada

Esse documento atesta que todos os coautores do artigo intitulado *Enhancing energy performance assessment and labeling in buildings: A review of BIM-based approaches*, publicado na PARC Pesquisa em Arquitetura e Construção, **CONCORDAM** com o seu uso como parte da tese de doutorado de Luís Filipe Muta, orientado pela professora Ana Paula Melo do Programa de Pós-Graduação em Engenharia Civil (PPGEC) da Universidade Federal de Santa Catarina (UFSC) e coorientado pela professora Annamaria Buonomano do Departamento de Engenharia Industrial da Università degli Studi di Napoli Federico II.

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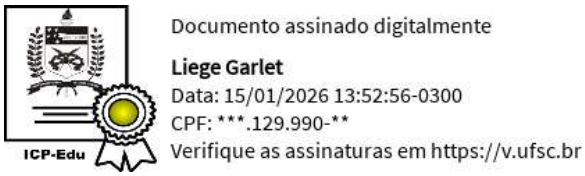


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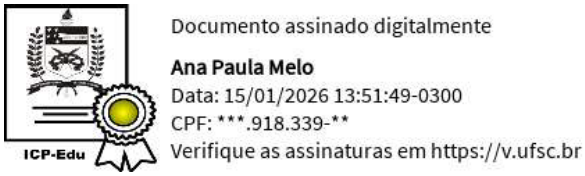


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# BIM APPLICATION IN THE BRAZILIAN BUILDING LABELING PROGRAM: A REVIEW

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## Abstract

This study presents a comprehensive literature review on integrating Building Information Modeling (BIM) within the Brazilian Building Labeling Program (PBE Edifica), focusing on challenges, workflows, and research gaps. Emphasizing the advantages of BIM in PBE Edifica, this research highlights its effectiveness in data extraction, automation, and visualization tasks. Challenges encompass the absence of standardized practices for integrating BIM with Building Energy Modeling (BEM), interoperability issues, and limited exploration of universal standards, such as Industry Foundation Classes (IFC). The identified challenges involve disparities in simulation outcomes, concerns about BIM model reliability for energy assessments, and complexities in direct and indirect BIM-BEM exports. Future research should consider in-depth investigations into BIM tool intricacies, a comprehensive understanding of data syntax and semantics, and strict adherence to modeling guidelines. This study highlights the crucial connection between design processes and energy efficiency by encouraging the exploration of BIM as a methodological approach. Moreover, there is a need to develop standardized guidelines for BIM modeling, enhanced OpenBIM tools to improve interoperability, and the exploration of ontologies and machine learning for optimized data exchange. The research recommends a broader approach to address technical aspects for successfully integrating BIM in building energy assessments within the Brazilian context.

**Keywords**: building information modeling, BIM, Brazilian Building Labeling Program, PBE Edifica.

## 1 Introduction

The building sector consumes 35% of the world's energy and is responsible for emitting 38% of carbon dioxide (CO2) (Unep, 2020). Considering the UN's sustainable development agendas and objectives, immediate actions are required to reduce the environmental impacts of buildings.

Certifications and energy efficiency labels in buildings are public policies adopted in several countries to expand sustainable building stocks and mitigate the environmental impacts of the construction sector (Harter et al., 2020).

In Brazil, the government has created the Brazilian Building Labeling Program (PBE Edifica) and the National Energy Conservation Label (ENCE). The ENCE verifies the energy efficiency class of buildings based on a system that ranges from "A" (i.e., more efficient) to "E" (i.e., less efficient) (INMETRO, 2022). The ENCE classification is obtained through technical quality regulations (RTQs) and normative instructions from Inmetro (INIs), guidelines for evaluating and classifying the energy efficiency of buildings (Brasil, 2013; INMETRO, 2022).

The government has shown interest in making the ENCE compulsory, given the Normative Instruction No. 02/2014, which requires federal public buildings and retrofitted old buildings to obtain the ENCE class A energy efficiency rating (Brasil, 2014). By 2035, labeling may become mandatory for all new buildings in Brazil (EPE, 2020).

Energy labeling promotes information transparency, enhances society's awareness of energy efficiency, assists consumers in making decisions regarding the purchase or rental of a property, and increases sustainable building stocks (Li; Kubicki; Guerriero; Rezgui, 2019).

One way to assess energy efficiency is by Building Energy Modeling (BEM), which involves the use of energy simulation tools capable of estimating the energy consumption and energy performance of a building. BEM tools provide results that are closer to reality but require many inputs (e.g., construction systems, climate, equipment, usage patterns, among others), demanding a considerable amount of time to execute the BEM model and multidisciplinary knowledge from the user (Hensen; Lamberts, 2019).

Several studies have proposed simplified calculation models for the Brazilian Building Labeling Program to make the assessment faster and more accurate (Carlo,

2008; Melo, 2012; Versage, 2015; Mazzaferro, 2021). These proposals, although simplified, still require a significant amount of project data, which, in many cases is more complex to obtain from the projects (Gomes, 2017). Manual data acquisition is a problem in energy labeling because human interference in the process affects data quality, increases the time of the process, and widens the gap between the performance presented on the label and the actual performance of the building (Hårsman; Daghbashyan; Chaudhary, 2016).

In Brazil, several difficulties are reported in the labeling process, such as a large amount of data required for evaluation; detailing errors and omissions of project data; difficulty in obtaining specific properties of construction systems; high time demand; potential for human errors in the process; lack of media exposure for labeling; and insufficient enforcement of Normative Instruction No. 02/2014 (Gomes, 2017; Ohlweiler et al., 2019; Muta, 2022).

The mentioned aspects hinder the dissemination of labeling in the country. Partially, these challenges originate during the design process. The conventional design process is based on two-dimensional (2D) documentation and is characterized by fragmented phases (Sacks; Eastman; Lee; Teicholz, 2018). Communication between design teams is limited, requiring more effort and time to transmit all the information. There are many manual steps, and information technology needs to be more utilized, leading to errors and omissions of data during the design process (Soliman Junior; Baldauf; Formoso; Tzortzopoulos, 2018).

Design flaws are propagated until the energy efficiency evaluation, one of the last stages performed (Oliveira, 2019). Energy efficiency should be considered in the early design phases, but for that to happen, the project needs to be integrated (Gerrish et al., 2017).

Building Information Modeling (BIM) emerges as a methodology, comprising technologies, people, and processes, capable of enhancing collaboration and flaws throughout the project (Sacks; Eastman; Lee; Teicholz, 2018). BIM tools enable the creation of digital representations of buildings, including various technical and construction-related information inherent to the building (Kim; Asl; Yan, 2015).

In Brazil, using BIM in public works has been encouraged since 2021, according to Law No. 14.133/2021 (Brasil, 2021). Considering Normative Instruction No. 02/2014 and Law No. 14.133/2021, it is evident that labeling and the use of BIM potentially converge in the realm of federal public buildings.

The use of BIM by designers in the country has grown recently, benefiting the civil construction industry. However, there is still room for improvement in energy efficiency (Boldrini, 2020). One significant challenge in building labeling in Brazil is the lack of awareness among designers about labeling requirements (Gomes, 2017; Boldrini, 2020). Moreover, the adoption of BIM in Brazil encounters obstacles, ranging from company organizational structures to challenges in establishing government norms and requirements (Arrotéia; Freitas; Melhado; 2021).

Given the presented context, the following questions have been raised: "What are the difficulties and limitations observed in BIM application in PBE Edifica labeling?"; "What are the most commonly used workflows in the application of BIM/BIM-BEM in PBE Edifica labeling?"; "What are the existing research gaps between BIM and PBE Edifica labeling?".

This research reviewed BIM application in the PBE Edifica labeling. The benefits, limitations, and gaps and the BIM/BIM-BEM workflows were identified. The aim of the review was to present the existing knowledge in the literature to support the development of future research in the field.

## 2 Method

Bibliographic research was carried out to gather scientific information from studies involving the use of BIM in the Brazilian Building Labeling Program. The labeling process is carried out based on the following regulations and normative instructions:

- Technical Regulation of Quality for the Energy Efficiency Level of Commercial, Service, and Public Buildings (In Portuguese: Regulamento Técnico da Qualidade para o Nível de Eficiência Energética de Edificações Comerciais, de Serviços e Públicas – RTQ-C);
- Technical Regulation of Quality for the Energy Efficiency Level of Residential Buildings (In Portuguese: Regulamento Técnico da Qualidade para o Nível de Eficiência Energética de Edificações Residenciais – RTQ-R);
- Inmetro Normative Instruction for the Energy Efficiency Classification of Commercial, Service, and Public Buildings (In Portuguese: Instrução Normativa Inmetro para a Classificação de Eficiência Energética de Edificações Comerciais, de Serviços e Públicas – INI-C);

- Inmetro Normative Instruction for the Energy Efficiency Classification of Residential Buildings (In Portuguese: Instrução Normativa Inmetro para a Classificação de Eficiência Energética de Edificações - INI-R).

The method used in this study was an integrative literature review, which sought to synthesize and analyze the knowledge already produced on a specific topic and evaluate the relevance of the methods employed (Botelho; Cunha; Macedo, 2011).

The method comprises five steps: formulating research questions, sampling the literature, evaluating selected documents, analyzing data, and presenting findings and discussions. The research questions were presented in the Introduction section.

The literature sampling was based on organized search criteria, from a string that included BIM and terms related to the labeling process in the Scopus index: ("BIM" OR "Building Information Model*" OR "Modelagem da Informação da Construção") AND (“Brazilian Energy Labeling” OR “Etiquetagem PBE Edifica” OR "INI-C" OR "INI-R" OR "RTQ-C" OR "RTQ-R").

The search was limited to Portuguese or English publications, including journals, conferences, specialization final projects, master’s theses, and doctoral dissertations. The inclusion criterion for the documents was the use of BIM in the Brazilian labeling process. The exclusion criteria included publications that merely cited BIM or aspects of the Brazilian Building Labeling Program, or those that addressed other labeling systems or methodologies.

The search on Scopus resulted in one paper that met the inclusion criteria. The bases were expanded to include Google Scholar and the repositories of universities and federal institutes that present programs in BIM and energy efficiency in buildings. It is worth noting that, unlike Scopus, Google Scholar does not allow filtering the search by title, abstract, and keywords separately. The search can be conducted on the entire document or the title only. Since filtering by title is too restrictive, a search of the whole document was made.

The search returned 538 publications, of which 28 were approved. Due to the search filter covering all the documents, most of the resulting publications only cited BIM and aspects of the Brazilian Building Labeling Program. There was an exception regarding the search filter; Pereira (2022) – undergraduate thesis – was included in this review because it constitutes the complete work of Pereira and Andrade (2021).

The 28 approved publications were read in full and categorized according to the specific use of BIM in the Brazilian Building Labeling Program. Three primary

categories were identified, which are as follows: BIM as a data extraction tool for labeling, BIM and programming for labeling, and BIM-BEM for labeling.

The category BIM-BEM for labeling was subdivided into three categories, given the variety of BIM-BEM tools and workflows:

- Direct Integration (i.e., the link between BIM and BEM tools occurs through add-ons or APIs, for example, Autodesk's Revit and Insight).
- Direct Export (i.e., from exporting a BIM model to a BEM tool, for example, exporting gbXML from Revit to DesignBuilder).
- Indirect Export (i.e., the link between BIM and BEM tools depends on an intermediate file conversion tool or process, for example, converting Revit's IFC to IDF using OpenStudio and importing it into EnergyPlus).

The raised publications and the bibliometric analysis were both presented in the discussion section.

## 3 Energy efficiency labeling of buildings in Brazil

The discussions on energy efficiency began in the 1980s and culminated in the creation of the Brazilian Labeling Program (PBE). However, the most significant measures for buildings emerged after the energy crisis in 2001 (Altoé et al., 2017). Law 10.295/2001 and Decree 4.059/2001 established the maximum energy consumption levels and minimum energy efficiency levels for machines, equipment, and buildings in Brazil (Brasil, 2001).

In 2003, the National Program for Energy Efficiency in Buildings (Procel Edifica) was established, aiming to promote the conservation and efficient use of natural resources in buildings reduce waste and environmental impacts. The merger of PBE and Procel Edifica led to the creation of the Brazilian Labeling Program for Buildings (PBE Edifica).

PBE Edifica covers energy efficiency labeling of buildings through the National Energy Conservation Label (ENCE). The classification presented in ENCE considers the performance of the building envelope, lighting, air conditioning, and water heating systems. ENCE also provides information on renewable energy generation, rational water use, and carbon dioxide emissions (INMETRO, 2022). It can be issued in the design phase and in the constructed building stage, delimited by residential, commercial, public and service buildings (Brasil, 2022). To obtain the ENCE, the project and the constructed building must be inspected by an Inspection Organization

Accredited (OIA) by Inmetro. The OIA uses the Technical Regulations for Quality (RTQs) or the Inmetro Normative Instructions (INIs) to determine the ENCE classification (INMETRO, 2022).

The RTQs were the first documents to present requirements and procedures for evaluating the energy efficiency classification of buildings in Brazil. The RTQ-C, published in 2009, provides guidelines for assessing commercial, service, and public buildings; and the RTQ-R, published in 2010, provides guidelines for assessing residential buildings (INMETRO, 2013). The RTQs present two evaluation methods: prescriptive, a simplified calculation model based on the application of equations and tables; and a simulation, which employs computational simulation tools to estimate the energy consumption of the building (INMETRO, 2013).

The simulation method provides results closer to reality but requires various design, construction, climate, and building use data, as well as specialized simulation professionals, and demands a significant amount of time to be completed (Hensen; Lamberts, 2019). To simplify the evaluation, research was conducted to create a simplified calculation method based on the statistical technique of multiple linear regression, capable of assessing the thermal performance of building envelopes, which gave rise to the prescriptive approach of the RTQs. The prescriptive method was developed through simplifications and assumptions regarding climate, usage patterns, occupancy, and building type (Carlo; Lamberts, 2010a, 2010b).

PBE Edifica offers complementary materials that assist in the application of the prescriptive method of RTQ-C and RTQ-R. Among these materials, WebPrescritivo stands out, an online interface that adopts the guidelines of RTQ-C to verify the hypothetical ENCE classification based on inputs provided by the user. For RTQ-R, there is a spreadsheet that calculates the energy efficiency of the housing unit based on user-entered data. The prescriptive method requires less time to be applied compared to the simulation method. Moreover, the simplifications and assumptions made while creating it led to discrepancies between the results of those methods. The results obtained through the prescriptive approach may diverge by up to 60% from the results obtained through computational simulation (Melo et al., 2014).

Many studies, conducted by Procel Edifica in partnership with the Brazilian Center for Energy Efficiency in Buildings (CB3E), have been carried out in recent years to bridge the gap between the results of the prescriptive and computational simulation methods. In 2022, Ordinance No. 309/2022 was published, establishing the Normative

Instructions (INIs) that present updated procedures for evaluating and classifying the energy efficiency of commercial, service, and public buildings (INI-C) and residential buildings (INI-R) (INMETRO, 2022).

The INIs include both the simulation and simplified methods, replacing the prescriptive approach of the RTQs. The simplified form in the INIs is based on simplified calculation metamodels to predict the thermal load of the analyzed buildings (INMETRO, 2022). The statistical method adopted in the development of the metamodels was Artificial Neural Networks (ANN), which resulted in discrepancies of less than 1% compared to the computational simulation method (Melo et al., 2016).

Despite the advancements in energy efficiency assessment, some studies have shown difficulties in applying the methods of RTQs and INIs (Gomes, 2017; Leite; Hackenberg, 2020; Muta, 2022). The data acquisition process is laborious and time-consuming, and the fragmented stages of the conventional design process exacerbate the situation (e.g., 2D documentation, and communication gaps). In this context, the BIM methodology can represent a paradigm shift in project development, benefiting the energy efficiency discipline.

## 4 Building Information Modeling

Building Information Modeling (BIM) can have different definitions. This work relies on the concept defined by Sacks, Eastman, Lee and Teicholz (2018), in which BIM is characterized as the integration of modeling technology, processes, and people to produce, communicate, and analyze virtual construction models. BIM models can combine design with construction, manufacturing, assembly, management, maintenance, energy performance monitoring, retrofit, and the building's lifecycle information. Information is inputted into the models, optimizing time through automated modeling processes, as observed in research dating back over 20 years (Bazjanac, 2001). Costs related to building facilities and operations are also reduced when decisions are collectively made in the early stages of the project (Gao; Koch; Wu, 2019).

Despite the capacity to enhance the construction of buildings with reduced costs, BIM projects require paradigm shifts for companies, encompassing changes in processes, technologies, and individuals. The paradigm shift is a process that presents some obstacles. In both developed and developing countries, the main barriers to BIM implementation are similar and relate to the unavailability of standards and guidelines,

lack of BIM training, shortage of qualified personnel, high implementation costs, and lack of BIM research and implementation, interoperability issues, organizational concerns, and, in some cases, a lack of national standards (Liu; Xie; Tivendal; Liu, 2015; Criminale; Langar, 2017; Manzoor et al., 2021; Othman et al., 2021; Arrotéia, Freitas, Melhado, 2021). These barriers are associated with the company and its organization and are related to the design process. However, this scenario has been undergoing recent changes due to the actions of government agencies, as well as the industry, which have resorted to standardization and standard rules for the use of BIM.

Several decrees were enacted in Brazil within the scope of the BIM BR Strategy (Brasil, 2018), whose purpose is to promote an environment suitable for BIM investment and its dissemination in the country. One of these decrees is Federal Decree No. 10.306, which ensures BIM's direct or indirect use in federal public works and civil engineering services. The Brazilian Association of Technical Standards - ABNT - also defined a set of technical standards related to BIM, including requirements for modeling objects, guidelines for libraries, system classification, and information management in construction.

In Brazilian academia, groups of professors and students from various educational institutions carried out actions for digital transformation based on a Curricular BIM Implementation Plan (PIBc). Through a public call, the Built Environment Technology Association (ANTAC) multiplied the number of BIM cells created in the country. The ANTAC BIM Cells Network presented partial results that demonstrate a significant potential for understanding BIM Maturity in education and the latent capacity for incorporating BIM into the undergraduate courses in Architecture and Urbanism, and Civil Engineering (Ruschel; Ferreira, 2022).

Despite the progress, there still needs to be more knowledge about the use of BIM in collaborative processes by designers and other users in the early stages of construction projects (Miettinen; Paavola, 2014). According to Barison and Santos (2016), the BIM workflow in Brazil has emerged differently from the North American model, where the architect manages the entire workflow. In Brazil, developers or clients usually appoint a project coordinator who may also act as a BIM manager, or there may be a specific person for this role. The BIM manager is typically a consultant who assists in implementing BIM within companies. Design offices also have a model manager who coordinates their discipline, modeling guidelines, and tools.

In the Brazilian context, the ideal process for developing BIM models using federated models (i.e., models from each discipline linked to a single integrated/federated central model) begins by organizing project survey data. In this initial stage, the architect, the project owner, and the BIM manager gather to organize the data, project schedules, initial cost information, and project requirements to determine the team of designers and tools to be used. The architect then develops the conceptual model and conducts the feasibility study. Then, the stakeholders decide on the project's structure and specificities (Barison; Santos, 2016). According to this organization, this stage appears to be an opportune moment for including energy simulations of the project, which can help choose the best solutions with the possible reduction of energy consumption. After this stage, the preliminary design phase would follow, involving analyzing processes and formalizing a product.

Some methodologies have attempted to describe the design processes and include energy simulations or environmental sustainability requirements. Stipo (2015) gathered data from several design offices in different parts of the world, aiming to standardize aspects or subprocesses of their sustainable design methods. Despite the small sample size, similarities were identified among them, suggesting a possible generalization. The author proposed a flexible design model for designers to achieve project sustainability. Unlike Barison and Santos (2016), the author refers to creating a conceptual design model for initial energy simulations. Additionally, it is indicated that the design will be refined with detailed energy simulations, and subsequently, construction documentation will be generated, accompanied by a BIM coordination process.

Including Building Information Modeling in processes requiring energy simulation, such as the Brazilian Building Labeling Program, can bring significant benefits. These benefits include the accuracy and consistency of results, identification of project opportunities, reliability resulting from data integration, cost and waste reduction, and facilitating the maintenance and operation of buildings.

## 5 BIM in Brazilian Building Labeling Program

This section presents the selected research in the integrative review, organized according to the type of BIM application in the Brazilian Building Labeling Program. Study that considered BIM tools for optimizing building energy performance and subsequent labeling was also considered.

The computational simulation process for the Brazilian Labeling Program requires the construction of a BEM model for thermal load prediction. BIM models already contain most of the information needed for BEM models, such as location data, geometry, materials, thermal properties, electrical systems, and HVAC (Pinheiro et al., 2018). The obtained information can be used in various ways, for example, for thermal-energy analysis, data systematization, visualizations, and interoperability with other software (Dubljevi´c; Tepavcevi´c; Markoski.; Anđelkovi, 2023).

It is essential to ensure that models are shared in a standard structure for reading and writing, using the same file formats and protocols. The concept of interoperability refers to the ability of different computational systems to exchange data, streamlining the workflow and eliminating the need to manually copy information generated by other programs (Sacks; Eastman; Lee; Teicholz, 2018).

### 5.1 BIM as a tool for data extraction

BIM is frequently regarded as a tool for extracting the necessary data in the Brazilian Labeling Program. Researchers adopting this approach conduct exploratory studies to analyze the potential of BIM in data extraction and apply workflows, as well as templates, in case studies to evaluate the proposed procedures (Oliveira et al., 2011; Wollz Netto, 2015; Ohlweiler et al., 2019; Serra; Filho, 2019; Muta et al., 2022).

Oliveira et al. (2011) propose a BIM workflow for evaluating the building envelope using the prescriptive method of RTQ-C. The authors used Revit, applied the BIM workflow in a case study, and compared it with the traditional CAD workflow. It was found that the BIM workflow reduced the time to evaluate the building envelope by 21 times. Wollz Netto (2015) and Serra and Filho (2019) conducted similar works. However, Wollz Netto (2015) considered the guidelines of the prescriptive method of RTQ-R, and Serra and Filho (2019) incorporated the WebPrescritivo into the workflow.

Ohlweiler et al. (2019) explored the potential of Revit in extracting the necessary data for evaluating the building envelope using the prescriptive method. Data required for the building envelope assessment were extracted from a case study. The quality of the extracted data was analyzed in a sample study involving 29 Architecture and Urbanism students. The building envelope classification, calculated using the data from the Revit program, coincided with the results from the CAD program.

Muta et al. (2022) conducted an exploratory study as did Ohlweiler et al. (2019) but considered the evaluation of the building envelope using the simplified method of INI-C. All the data were obtained and applied in the metamodel to classify the building envelope. The energy assessment using Revit was possible, however, the authors state that data extraction is not the critical point between BIM and Brazilian Building Labeling Program. The main aspect lies in the minimum requirements and guidelines adopted in the construction of the BIM model, which impact the energy evaluation process.

Even with limited use for data extraction, the use of BIM is advantageous for energy efficiency. 3D models facilitate the visualization of geometric details, construction information can be automatically extracted and applied in spreadsheets, web interfaces, or metamodels, and design disciplines can be integrated into a central BIM model, streamlining the decision-making process that impacts the building's energy efficiency (Zemero, 2016; Lopes, 2019; Rosa, 2019; Santos; Salgado, 2019; Muta et al., 2022).

Zemero (2016) used Revit to develop a BIM model, integrating architectural, electrical, hydro-sanitary, and HVAC projects. The project considered sustainability principles, and the energy assessment was conducted using the prescriptive method of RTQ-C with the application of WebPrescritivo. Lopes (2019) and Rosa (2019) showed similar research to Zemero (2016) but focused on existing federal public buildings.

Santos and Salgado (2019) used ArchiCAD to automatically verify natural ventilation requirements specified in RTQ-R. The approach was based on verification rules created from tables with model information. The authors state that automating requirements enables selecting the best design solutions.

Muta et al. (2022) presented modeling requirements and guidelines for developing BIM models, focused on evaluating the building envelope using the simplified method of INI-C. The procedures were devised in an exploratory study and applied in a case study. The required data for the building envelope assessment were obtained from a table generated by a Revit template. The data were exported from Revit and entered into the metamodel to create the building envelope classification.

## 5.2 Use of scripting/programming

Some of the works in this research addressed the integration of BIM with energy efficiency evaluation using programming to partially or fully automate the assessment and labeling process.

Boldrini (2020) presents a proposal for a web interface layout based on user experience design to assist in evaluating the simplified method of INI-R. Based on a survey of the work experience in architectural offices, a user-friendly interface proposal capable of integrating files in open formats (i.e., IFC and gbXML) and evaluating energy efficiency was presented. The author does not suggest programming languages for building the tool and needs to consider the challenges of incorporating two distinct standards as IFC and gbXML.

Teixeira (2018) developed a web interface capable of evaluating the building envelope using the prescriptive method of RTQ-C. The interface was designed in the Hypertext Preprocessor (PHP) language and managed by SQL Server Express, which functions by importing data from Revit. The interface was integrated with a database that allows access to the quantitative tables generated in Revit. For the classification to occur, it is necessary to manually select the available options for lighting and air conditioning systems on the interface. The work was also published in a national journal (Teixeira, Pellanda; Reis; Micelli Júnior, 2018).

Oliveira (2022) developed a script using the visual programming language (VPL) with Dynamo software, integrated with Revit, to address the evaluation of the simplified method of INI-R. The workflow depends on a template that generates nomenclatures for building components and provides a standard project sheet, organizing the results and levels of energy efficiency on a color scale. The tool consists of several scripts that must be executed sequentially to reduce processing time.

Oliveira (2019) also used VPL with the Dynamo program to evaluate the prescriptive method of RTQ-R. The tool optimizes processing by combining Python scripts with Dynamo. The necessary data for the tool's operation are obtained through a template developed in Revit. The device was tested and validated in an extension course, in which architecture students, professors, and professionals participated. The results were compared with those calculated in the performance calculation spreadsheet available on the PBE Edifica website. There were minor differences between the results. The products were published in a national journal by Oliveira,

Bittencourt and Dória (2020), and three conferences by Oliveira, Bittencourt and Dória (2019a); Oliveira, Bittencourt, and Dória (2019b); and Oliveira, Bittencourt, and Dória (2022).

Bracht (2020) developed a semi-automatic integration method between BIM and the metamodel of INI-R. Integration occurs through a tool developed by the author in Python, capable of extracting data from the BIM model in gbXML format and inserting it into the metamodel. Revit, ArchiCAD, and Building Designer were used in the tests of the proposed method. There were interoperability issues while converting the BIM model to the gbXML format (i.e., geometry failures and loss of semantic data), requiring manual corrections for the script to function correctly. The product proposed by Bracht (2020) was published in an international journal by Bracht, Melo and Lamberts (2021).

### 5.3 Direct integration

The publications in this section demonstrate the research that used BIM and BEM tools through direct integration.

Pretti (2018) analyzed the integration of Revit with Green Building Studio (GBS) and Insight, comparing the results of energy analyses from both tools with the results calculated using the prescriptive method of RTQ-C. There were no concerns regarding BIM-BEM interoperability, meaning the BEM simulations were completed without any issues. However, the simulation results could have been more consistent with the building's reality. This led to the conclusion that GBS and Insight offer limited possibilities for users to edit simulation parameters and rely on many standardized data, leading to inconsistencies in the results.

Lopes (2019) presented a study similar to that conducted by Pretti (2018), focusing on designing sustainable buildings in BIM. Through a case study, Lopes (2019) optimized the energy efficiency of a public building using Revit, GBS, and Insight. The building envelope's energy efficiency was evaluated based on the prescriptive method's guidelines of RTQ-C. Lopes affirms that GBS and Insight are simple energy analysis tools intended for early design stages and are not recommended for labeling due to the limited number of available simulation configurations.

Queiróz et al. (2019) analyzed the compatibility of Insight Lighting Analysis, integrated into Revit, in assessing natural lighting considering the guidelines of RTQ-

R. It was concluded that Insight Lighting Analysis is incompatible with the criteria required by RTQ-R because the tool's configurations and outputs are geared towards meeting LEED certification criteria.

Pimentel, Barbosa and Souza (2020) conducted a literature review on using BIM and BEM in labeling. The authors concluded that Insight and GBS are unsuitable for the Brazilian Building Labeling Program because they do not evaluate comfort through natural ventilation, which is necessary for some cases of RTQ-C and RTQ-R. There are also limitations regarding the configurations of parameters used for energy simulation, especially in air conditioning systems.

Gomes (2021) used Revit with GBS to estimate the cooling thermal load - a criterion for evaluating the building envelope using the simulation method of RTQ-R - for a set of single-family buildings. The author concluded that integrating BIM with proprietary format simulation is promising and needs to be explored but clarified that there are limitations. The simulation parameters available for editing are scarce, especially in characterizing the air conditioning system, which affects the results of the building envelope evaluation.

Pereira and Andrade (2021) conducted a preliminary study to verify if Revit and ArchiCAD, along with their respective energy analysis tools (i.e., Revit's GBS and ArchiCAD's EcoDesigner Star), meet the requirements for applying the INI-C simulation method. The authors discuss the differences in each tool and conclude that ArchiCAD and EcoDesigner Star from Graphisoft meet more requirements, but both have limitations regarding INI-C demands.

Pereira (2022) used ArchiCAD integrated with EcoDesigner Star to assess the energy efficiency of a federal public building. The tool was chosen based on a preliminary study (Pereira; Andrade, 2021). The author concluded that the simulation results were inconsistent with the building's reality but did not rule out the potential of BIM integration with BEM tools, primarily due to the range of outputs and functions available in the tools.

### 5.4 Direct export

The interoperability between BIM models and labeling assessment through direct export was identified in the works of Zemero (2016), Pretti (2018), Pimentel, Barbosa, and Souza (2020), and Pimentel, Barbosa, and Reis (2021).

Zemero (2016) surveyed Brazil's leading BEM software (i.e., Domus, EnergyPlus, OpenStudio, and DesignBuilder) and evaluated their integrated use between BIM design and PBE Edifica labeling for commercial buildings. The gbXML format was exported from Revit and imported into the BEM tools. DesignBuilder was the only tool capable of performing the simulation. The other software encountered errors in reading the gbXML files. Pimentel, Barbosa, and Souza (2020) also considered DesignBuilder the most suitable tool for energy simulation using RTQ-C.

Similarly to Zemero (2016), Pretti (2018) tested various solutions for BIM-BEM tool integration while evaluating a commercial building. The author's proposal involved exporting gbXML and IFC files, which were then imported into OpenStudio and IES-VE. Additionally, gbXML was imported into GBS and DesignBuilder. The tests revealed that IES-VE did not import IFC and did not simulate the imported gbXML. OpenStudio could not import any of the formats. The author compared the results of successful simulations and found differences in area values and energy consumption (i.e., lighting, equipment, and air conditioning). Information loss or recognition issues occurred in the BIM-BEM interoperability process. The DesignBuilder tool showed the most data loss during importing gbXML files, failing to recognize the HVAC system specified in Revit and doubling the building's area, which impacted the simulation results.

Pimentel, Barbosa, and Reis (2021) analyzed a building through simulation by exporting a gbXML file from the Revit program to the DesignBuilder program. The BEM model presented geometry flaws and data loss, resulting in rework. The simulation results in DesignBuilder were compared with simulations performed exclusively in the BEM domain (i.e., the building was developed and simulated directly in DesignBuilder and OpenStudio/EnergyPlus, without importing the gbXML file from Revit). The variations between the total consumption results in the three simulations were less than 1%.

### 5.5 Indirect export

The works of Pretti (2018) and Pimentel, Barbosa, and Souza (2020) identified the interoperability between BIM models and labeling assessment through computational simulation and indirect export.

Pimentel, Barbosa, and Souza (2020) presented a file conversion workflow from gbXML to Input Data File (IDF), which is the format used by EnergyPlus. The

authors used a text editor to convert gbXML to 8-bit Unicode Transformation Format (UTF-8), and then Autodesk Ecotect Analysis was used to convert UTF-8 to IDF. The authors had to validate and correct errors in the converted model using SketchUp and Legacy OpenStudio plugin. It was concluded that this flow is not viable for the authors' context, mainly due to the software cost, training, and time required.

Pretti (2018) presented different solutions for indirect integration. GBS and Insight were used to convert gbXML from Revit to IDF and InPage Document (INP). IDF was used for simulation in EnergyPlus and OpenStudio, while INP was used for simulation in eQUEST. OpenStudio did not import the IDF, and eQUEST imported the INP but did not load the geometry data from the model. The BIM-BEM flow was incipient and had constant failures in the model's geometry and data loss. Only the EnergyPlus generated from gbXML conversion through GBS provided coherent results, but the IDF file required manual adjustments. All area values presented by the BEM tools diverged from each other and the original BIM model.

## 6 Discussions

This section discusses the research papers that addressed the use of BIM to support the labeling process. The survey considered works published in journals, theses and dissertations, specialization final papers, conference papers, and an undergraduate thesis. The quantity of documents, the authors, the research database, and the type of publication are presented in Table 1.

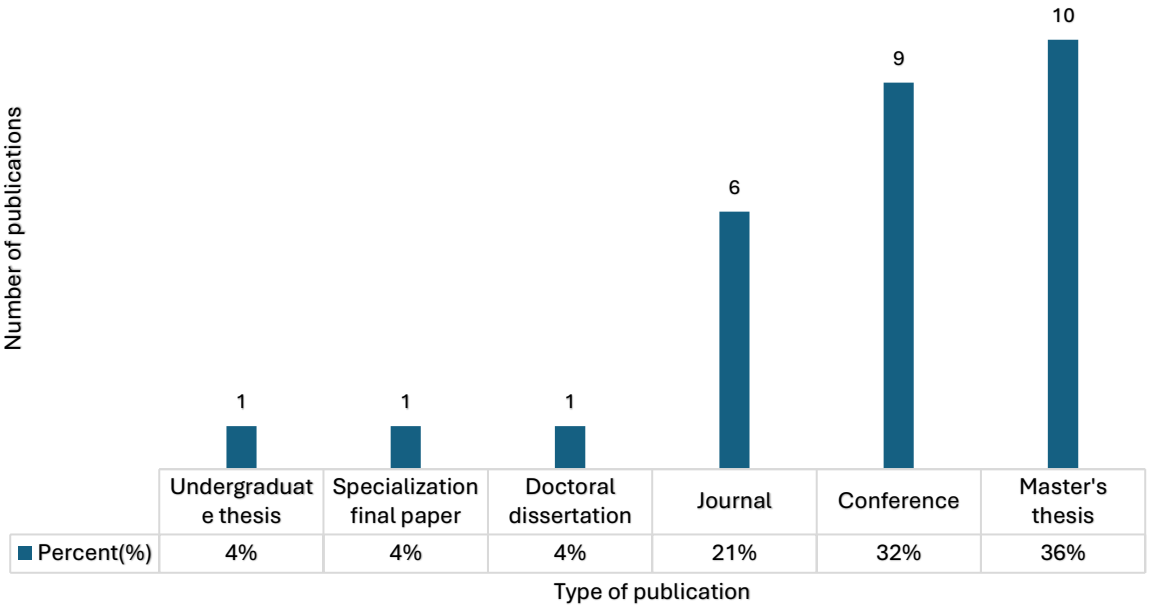
Most of the publications were master's theses (10), followed by conference papers (9). There is one doctoral dissertation, one specialization paper, and six works in journals (Figure 1). It was noted that there was a significant number of publications from the same authors, referring to the same doctoral dissertation. The low number of publications found in the research area (28) indicates a gap for further research.

**Table 1 – Works that contain BIM applied to the Brazilian Building Labeling Program**

| Type of document | Reference | Classification |
|---|---|---|
| Conference | (Oliveira *et al.,* 2011) | data extraction |
| Specialization final paper | (Wollz Netto, 2015) | data extraction |
| Master's thesis | (Zemero, 2016) | data extraction; direct export |
| Master's thesis | (Pretti, 2018) | direct integration; direct export; indirect export |
| Master's thesis | (Teixeira, 2018) | scripting/programming |
| Journal | (Teixeira; Pellanda; Reis; Miceli Júnior, 2018) | scripting/programming |
| Conference | (Santos; Salgado, 2019) | data extraction |
| Conference | (Queiróz *et al.,* 2019) | direct integration |
| Conference | (Oliveira; Bittencourt; Dória, 2019a) | scripting/programming |
| Conference | (Oliveira; Bittencourt; Dória, 2019b) | scripting/programming |
| Conference | (Ohlweiler *et al.,* 2019) | data extraction |
| Master's thesis | (Lopes, 2019) | data extraction; direct integration |
| Master's thesis | (Rosa, 2019) | data extraction |
| Journal | (Serra; Filho, 2019) | data extraction |
| Doctoral dissertation | (Oliveira, 2019) | scripting/programming |
| Master's thesis | (Boldrini, 2020) | scripting/programming |
| Master's thesis | (Bracht, 2020) | scripting/programming |
| Journal | (Pimentel; Barbosa; Souza, 2020) | direct integration; direct export; indirect export |
| Journal | (Oliveira; Bittencourt; Dória, 2020) | scripting/programming |
| Conference | (Pereira; Andrade, 2021) | direct integration |
| Master's thesis | (Gomes, 2021) | direct integration |
| Journal | (Bracht; Melo; Lamberts, 2021) | scripting/programming |
| Journal | (Pimentel; Barbosa; Reis, 2021) | direct export |
| Conference | (Oliveira; Bittencourt; Dória, 2022) | scripting/programming |
| Conference | (Muta *et al.,* 2022) | data extraction |
| Master's thesis | (Oliveira, 2022) | scripting/programming |
| Master's thesis | (Muta, 2022) | data extraction |
| Undergraduate thesis | (Pereira, 2022) | direct integration |

Source: the authors.

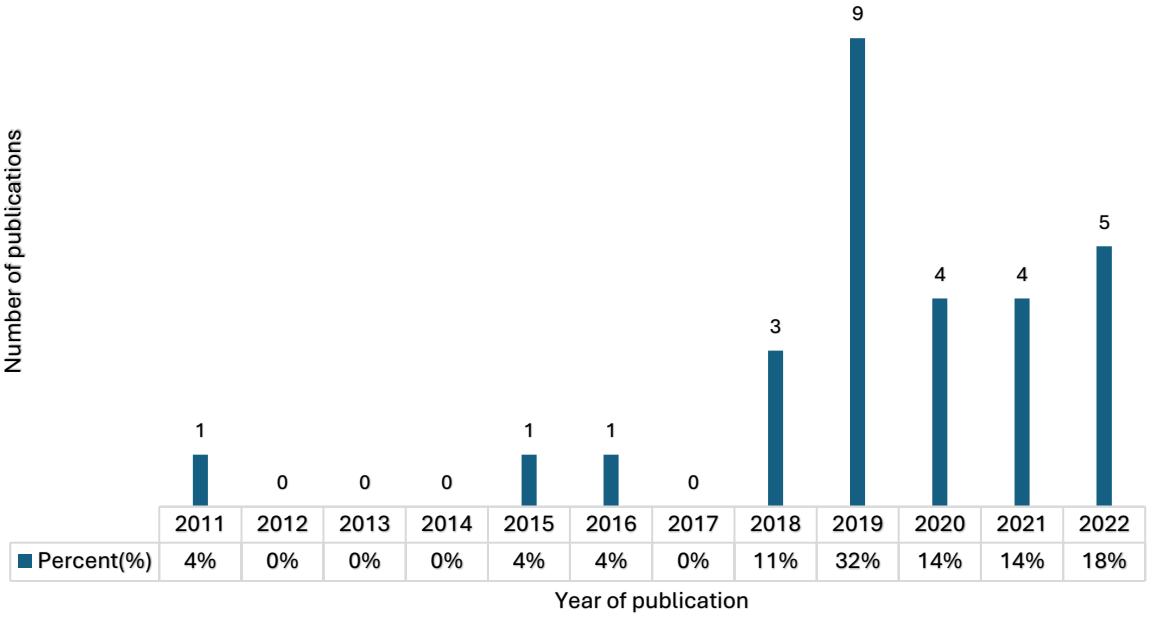
**Figure 1 – Database survey**




Source: the authors.

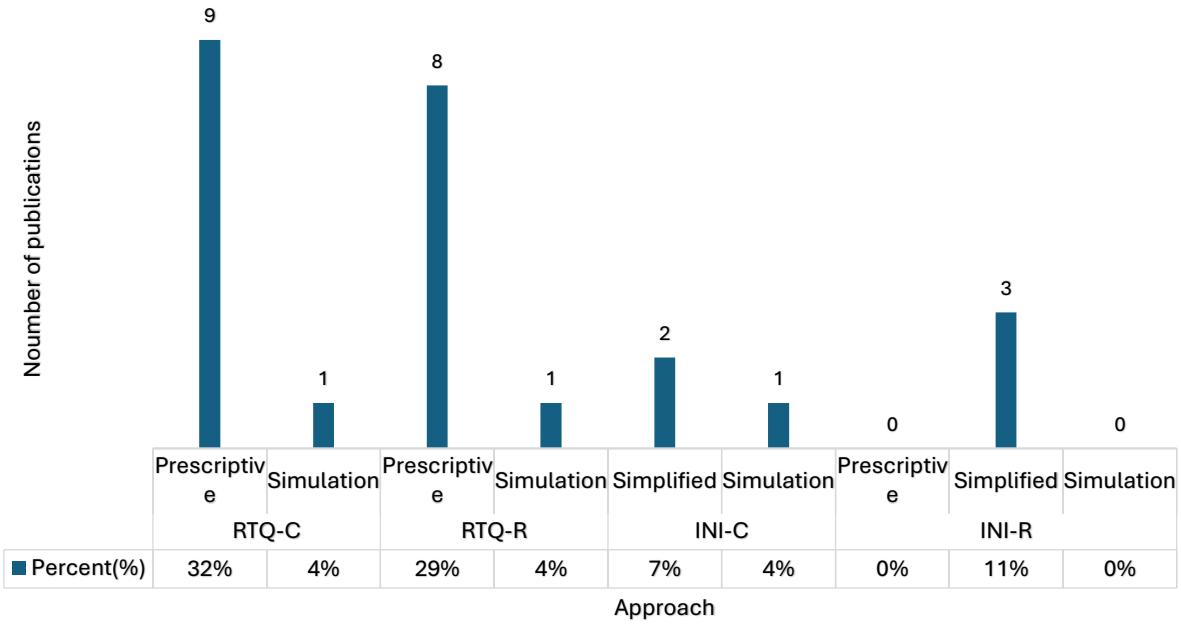
According to the survey (Figure 2), 46% of the research papers were published in 2020, 2021, and 2022, and only 21% applied the INIs, with 50% focused on INI-R and the other 50% on INI-C (Figure 3), demonstrating difficulties due to the recent update of the new Brazilian Building Labeling Program's procedures. The survey also revealed that only three publications (11%) applied the simulation method (Figure 3). However, only one of the studies compared the BIM-BEM simulation with the simulation performed exclusively in the BEM tool to validate the results.

**Figure 2 – Database according to the year**




Source: the authors.

**Figure 3 – Number of works using the labeling process according to the approach**

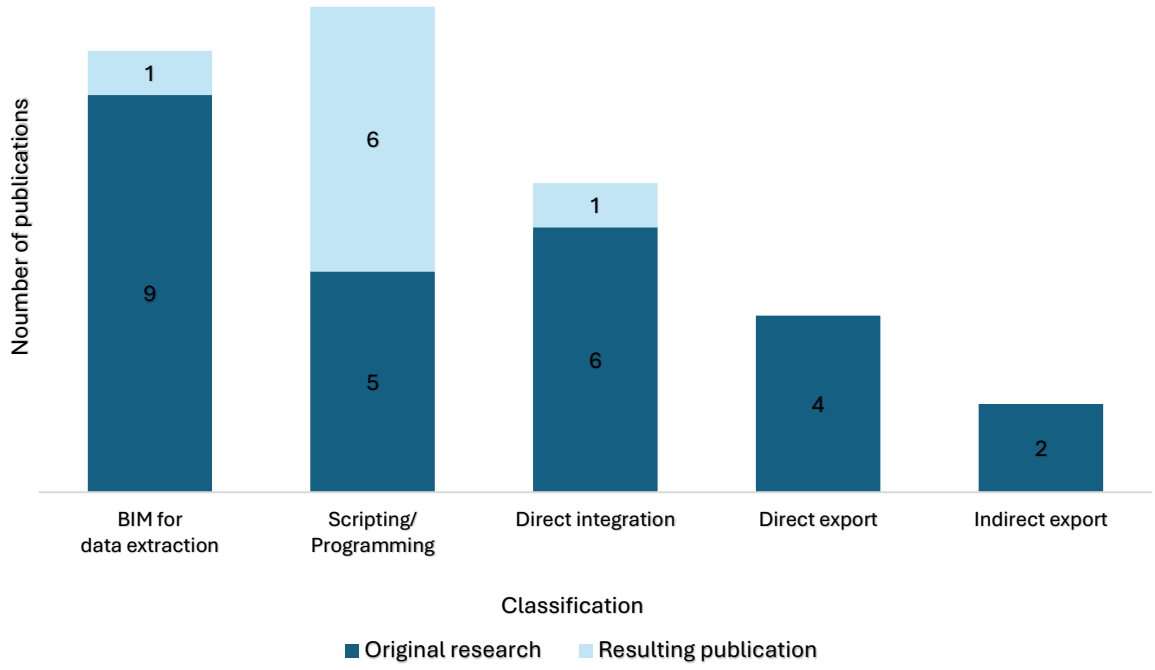



Source: the authors.

Regarding the classifications proposed by this research, the most significant number of publications belongs to the category of works that used scripting or programming to partially or fully automate the evaluation and labeling process.

However, initially, five research papers resulted in other publications from the same researchers. Figure 4 shows the number of research papers per classification, distributed in bars. The dark colors within each typology indicate the number of original research papers, and the light colors represent the resulting publications from the original research.

**Figure 4 – Number of works using the labeling process according to the classification**



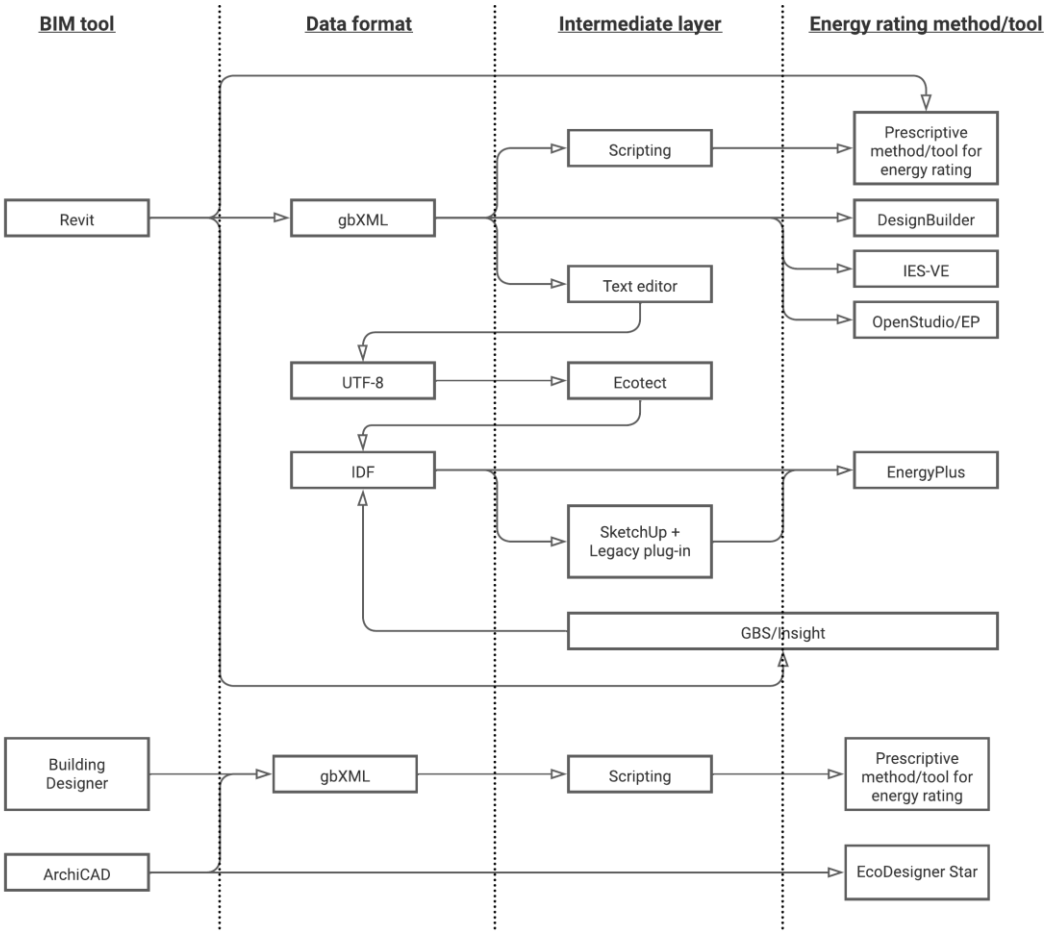

Source: the authors.

The workflow patterns identified in the literature are presented in Figure 5. The structure of the flowchart is divided into four columns. First, the "BIM tool" shows which proprietary BIM tool was used. Second, "Data format" demonstrates the type of file format used in the workflow. Some research did not convert the BIM file into another data format (e.g., exporting the native Revit file to gbXML). Third, the "Intermediate layer" shows the tools/processes used between the BIM domain and the energy efficiency assessment (e.g., developing a script for automatically extracting data from the BIM model). Fourth, the "Energy rating method/tool" presents the set of methods/tools used for energy efficiency assessment (e.g., adopting a prescriptive calculation tool that performs energy efficiency classification based on data from the BIM model).

The box labeled "Prescriptive method/tool for energy rating" refers to the tools and methods used for evaluations by the prescriptive and simplified methods of RTQs and INIs (i.e., calculation spreadsheets, web interfaces, and metamodels). The box labeled "GBS/Insight" occupies two columns of the flowchart because there are two distinct uses: as a tool for energy analysis or as an intermediate application for converting the BIM model into an IDF file.

The prevalent use of BIM for data extraction streamlines the labeling process and brings benefits, including process automation and enhanced visualization. A crucial step is complying with minimum requirements and guidelines for constructing the BIM model. The effectiveness of data extraction relies on accurate adherence to these guidelines, emphasizing the importance of proper modeling practices for reliable and meaningful building assessment. Notably, only a single surveyed study analyzed the need for standardization and establishing minimum requirements and guidelines within BIM modeling for the labeling process.

**Figure 5 – BIM - PBE Edifica labeling workflow identified in the literature review**




Source: the authors.

Scripting and programming for BIM integration with the Brazilian Building Labeling Process indicate a move towards automated approaches. Researchers used various methods, such as web interfaces and diverse programming languages, revealing flexibility and interoperability challenges due to the lack of standardized practices. Validation methods vary across studies, showing a commitment to ensuring tool practicality. Despite promising advancements, the field faces standardization, interoperability, and ongoing tool refinement challenges. This wide range of approaches reflects the evolving interdisciplinary nature of the field, providing opportunities for future developments. As BIM integration with energy assessment progresses, the field remains dynamic, requiring efforts to address challenges and establish common frameworks for continued advancement.

Publications using BIM for data extraction and scripting/programming aligned with the prescriptive and simplified methods of the Brazilian Building Labeling Program have achieved success in obtaining energy label classifications. However, the absence of identified processes for model auditing in the assessed models raises concerns about the accuracy of the evaluation results.

BIM-BEM integration is underexplored, whereby most publications rely solely on proprietary software for data acquisition. The predominant choice for architectural modeling is Autodesk Revit, evident in 24 out of 28 research papers. Graphisoft Archicad is used in only four, while AECOsim Building Designer is used in two studies. The choice of software does not have defined criteria of superiority. Notably, Bracht, Melo and Lamberts (2021) demonstrate greater reliability in Archicad compared to other options. The preference for Revit is driven by its market dominance, coupled with the availability of materials and training, highlighting its influence in shaping choices within the field.

The studies reveal recurring themes and challenges associated with the direct integration of BIM-BEM. In general, seamless interoperability, leads to promising outcomes when employing direct integration of BIM-BEM. However, certain studies highlight disparities between simulation results and actual building performance, attributing these differences to restricted user control over input data for energy simulation. This approach is perceived as more suitable for early design stages rather than for in-depth energy assessments. Nevertheless, some researchers used BEM tools that do not adhere to the requirements of the simulation method, such as applying the direct integration flow with Revit-GBS or ArchiCAD-EcoDesigner Star for envelope

classification. Despite these limitations, there is acknowledgment of the potential of direct integration, and ongoing efforts are required to refine BEM tools and enhance their flexibility.

The exploration of BIM-BEM direct export focuses mainly on transferring gbXML from Revit to tools, such as DesignBuilder, for energy simulations. However, challenges arise, as researchers face errors and recognition issues during gbXML import into BEM tools. Limitations in tools, such as DesignBuilder, especially in recognizing HVAC details and the risk of data loss, raise concerns about reliability. Despite DesignBuilder's consistent favorability, a comparative study revealed slight variations in total consumption results. Other studies pointed to significant challenges, including file import failures and data loss, casting doubt on the reliability of using exported BIM models for energy assessments. Reports of geometry flaws and data loss underscore the need for procedural improvements. While some studies report consistent results, differences in values raise doubts about exported BIM models' reliability. The contradictions reinforce the narrative of the need to standardize BIM modeling procedures. The modeling becomes flexible due to the scarcity of standards, requirements, guidelines, or specific norms for the workflow in the research area. The findings highlight the need for refinement in the export process to enhance reliability and accuracy.

Studies exploring BIM-BEM indirect export methods, for example, converting gbXML into IDF and INP formats, reveal workflow complexities and practicality concerns. Including additional software adds layers of complexity, raising doubts about the viability of such workflows due to software costs, training, and time implications, especially when not supported by standards or OpenBIM tools. Challenges even more severe than direct export emerge, including constant failures in model geometry, data loss, and divergent area values among BEM models and the original BIM model, questioning the accuracy and reliability of results. The identified issues, encompassing software dependencies and data integrity, emphasize the necessity for careful consideration and refinement before widespread adoption of indirect export approaches in practical applications. Open data formats, such as the IFC standard and gbXML, need to be fully exploited, creating a research gap.

Regarding the data exchange format, only two papers mention the universal standard IFC. In a study carried out by Pretti (2018), IES-VE software was used, but did not import the IFC format or simulate the imported gbXML. Further research is

essential for a comprehensive analysis. No papers were found that leverage IFC as the standard for data exchange between BIM and BEM, despite its universal status. The overall scenario indicates the need for a deeper understanding of OpenBIM standards and tools, given the complex nature of the structure and the need for meticulously defined workflows. There are no reports on the use of ontologies, machine learning, or experimentation with more recent proprietary tools (e.g., Autodesk Systems Analysis), nor the use of BuildingSmart tools that enable the IFC standard (e.g., MVD, IfcDoc, IDS), or even BIM model auditing (i.e., geometric and information verification).

Most of the surveyed papers presented superficial analyses, particularly in evaluating BEM tools. Common issues include unexplored reasons for discrepancies in results and limitations in BEM tools, such as constrained editing options for simulation parameters and challenges in achieving smooth interoperability. While some studies hint at promising aspects of BIM-BEM integration, they often overlook significant drawbacks, such as data errors and the need for manual adjustments. These findings highlight the imperative for more comprehensive analyses to address data reliability issues and enhance the understanding of challenges in BIM-BEM integration for achieving accurate results.

In general, the studies do not address technical limitations beyond the use of tools. There needs to be more clarity between the design process and energy efficiency. Most publications that use BIM for data acquisition assume that the model will be built with the necessary information for labeling in a specific template, which is an idealistic scenario.

The Brazilian Building Labeling Program depends on the quality of information and its integration into the design process. Conventional processes that do not integrate energy efficiency become more expensive due to the time required to process data from one professional to another, leading to rework. The high cost generated by inconsistent processes results in a lack of adherence to the market's energy labeling.

Some gaps are identified, stemming from the recent introduction of BIM methodology in the market and the need for its incorporation into the curriculum of Architecture and Urbanism and Civil Engineering undergraduate programs. Other gaps may be reflected by the need for investments in technology, education, policies, and procedures to guide the professionals.

Implementing BIM requires specialized technical skills, including proficiency in BIM software, data interoperability, and awareness of evolving BIM standards. However, initial implementation costs, which encompass software, training, and transitioning from traditional workflows, may pose barriers for smaller organizations or projects. The reliability of data derived from BIM models is contingent on input data quality and adherence to established standards. Inconsistent or inaccurate data could compromise building assessments, including the PBE Edifica.

Additionally, the reviewed studies did not consider legal and contractual issues, such as ownership of BIM models and intellectual property concerns. Overcoming resistance to change from stakeholders within the construction industry and fostering a culture of BIM adoption are significant challenges. Managing sensitive data within BIM models raises concerns about data security and privacy, emphasizing the need for robust protocols to protect confidential information.

A more nuanced exploration of the identified challenges is imperative for successfully integrating BIM with the PBE Edifica. This involves addressing technical limitations comprehensively, emphasizing the crucial link between the design process and energy efficiency, and developing solutions for the identified gaps.

## 7 Conclusions

This work reviewed the literature on the application of BIM in the PBE Edifica's labeling to offer a comprehensive overview, highlighting significant contributions that inform future research. The difficulties and limitations of applying the theme and the workflows used in the application of BIM in labeling were presented.

Most of the studies used the BIM model for manual data export to comply with the prescriptive method. Some solutions were proposed for automating this workflow using scripts/programming. The evaluations are entirely dependent on the reliability of the models, which need to be adequately audited in most cases. While scripting and programming offer flexibility, the absence of standardized practices poses challenges, highlighting the need for common frameworks.

Direct integration of BIM and BEM holds promise but faces challenges related to user control over input data and disparities between simulation results and actual building performance. Examining BIM-BEM export methods, whether direct or indirect, reveals complexities and reliability concerns, emphasizing the need for procedural improvements, standardization, and enhanced export processes.

The BIM model used for the computational simulation assessments shows higher reliability due to the possibility of checking the detailed energy consumption. Moreover, it requires greater expertise in energy efficiency to identify inconsistencies in the results. The direct integration of BIM-BEM revealed the use of tools incapable of performing energy analysis for Brazilian labeling. The immediate export process mainly involves exporting the gbXML from BIM to BEM software. The indirect export process includes an intermediate step between the gbXML and the energy simulation. Both direct and indirect integrations are more costly processes as they involve more software in the process. There is a research gap for other applications that need to be addressed in the works, which use direct integration or OpenBIM workflows and programming to optimize flows in the simulation method.

The publications are focused on applying tools in case studies. There is a shortage of studies that investigate the underlying issues of labeling and how BIM/BIM-BEM will address these problems. Additionally, most of the papers do not examine the limitations of the tools and proposed solutions for interoperability issues, in many cases, not filling the gap between the design process, energy efficiency, and BIM-BEM interoperability.

The scenario indicates that projects are not developed from the perspective of energy performance and integrated processes. The late labeling process creates a gap between the data needed for energy assessment and the data and information presented in the project documentation.

The difficulties and limitations are also due to a need for more knowledge about simulation energy, simulation tools, and techniques. There is a need for a well-mapped process for BIM-BEM and the BIM model's use beyond three-dimensional modeling.

A more detailed exploration and comprehensive understanding of technical limitations, challenges, and potential solutions are imperative for successfully integrating BIM with the PBE Edifica. This involves refining tools and processes and addressing educational, legal, and cultural aspects to ensure a holistic adoption of BIM in building energy assessments.

Future studies should address the use of some direct integration tools not addressed by this research and programming used to automate processes by energy simulation, including IFC flows and OpenBIM tools uses. The absence of exploration into ontologies and machine learning presents potential areas for future research.

Most research utilizes BIM primarily as a digital model or tool, often proposing processes to prepare the model for energy simulation. What is notably lacking is a comprehensive understanding of BIM as a methodological approach. Future studies should conduct more in-depth investigations into the intricacies of the employed tools, fully grasp the syntax and semantics of the data, address information requirements, adhere to modeling guidelines, and meticulously document procedures. This would leverage the structuring of a comprehensive framework to seamlessly integrate BIM into the domain of energy labeling.

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# APÊNDICE B

ARTIGO 2

Enhancing Energy Performance Assessment and Labeling in Buildings: A Review of BIM-Based Approaches

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## Contrato de Autoria Compartilhada

Esse documento atesta que todos os coautores do artigo intitulado *Enhancing energy performance assessment and labeling in buildings: A review of BIM-based approaches*, publicado na *Journal of Building Engineering*, **CONCORDAM** com o seu uso como parte da tese de doutorado de Luís Filipe Muta, orientado pela professora Ana Paula Melo do Programa de Pós-Graduação em Engenharia Civil (PPGEC) da Universidade Federal de Santa Catarina (UFSC) e coorientado pela professora Annamaria Buonomano do Departamento de Engenharia Industrial da Università degli Studi di Napoli Federico II.

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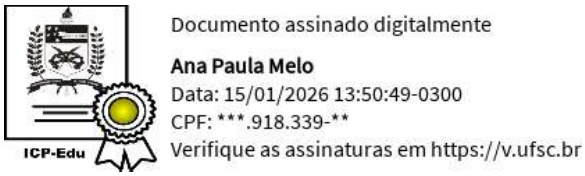


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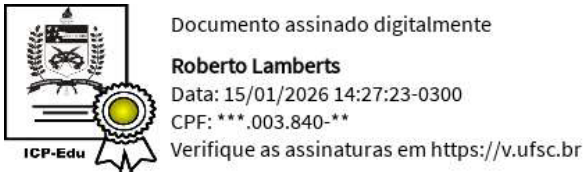


Roberto Lamberts
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Florianópolis, 15 de janeiro de 2026.

## Enhancing Energy Performance Assessment and Labeling in Buildings: A Review of BIM-Based Approaches

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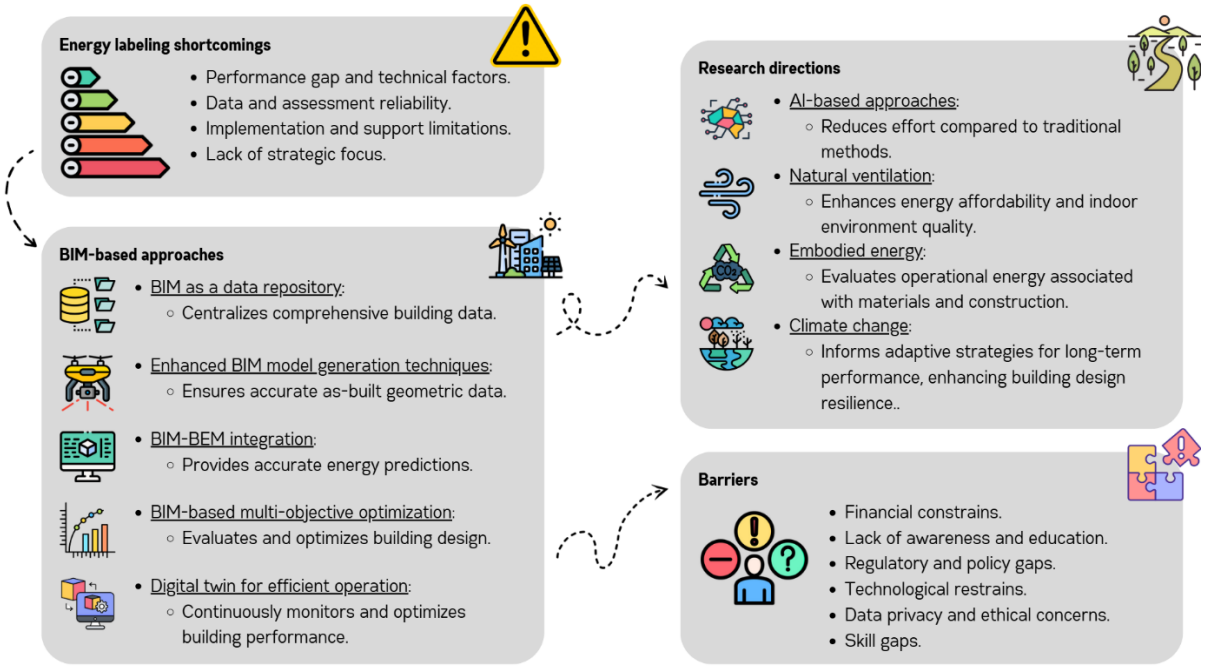
### Abstract

Buildings are central to global efforts to reduce greenhouse gas emissions. However, energy labeling programs, intended to encourage sustainable practices, often encounter challenges such as data inaccuracies, manual processes, and discrepancies between estimated and actual energy consumption. This study examines how Building Information Modeling (BIM) can contribute to improving the accuracy, reliability, and efficiency of energy labeling, addressing existing gaps in current practices. Through a systematic literature review, the research compiles insights from recent studies that demonstrate BIM's potential to centralize and automate building data, reduce errors in energy assessments, and facilitate integration with Building Energy Modeling (BEM) tools for more consistent simulations. The findings indicate that BIM-based methods, including model generation techniques, multi-objective optimization, and digital twin applications, help mitigate the performance gap by enabling data updates, improving interoperability, and offering better occupant behavior modeling. Nevertheless, several challenges remain, such as ensuring data quality, enhancing open data standards, and refining tools to accommodate evolving energy systems. A key novelty of this review lies in synthesizing a broad range of BIM-driven approaches into a cohesive perspective on how energy labeling can be modernized and enriched. By proposing future research paths that further integrate these BIM-based solutions, this study underscores BIM's capacity to streamline labeling processes through advanced analytics and automation, ultimately supporting more informed retrofits, regulatory compliance, and sustainable design strategies. In summary, the review suggests that BIM can enhance current labeling methodologies and contribute to broader sustainability goals in the built environment.

**Keywords**: Building Information Modeling, Energy performance assessment, Energy labeling, Energy efficiency optimization, Performance gap.

## Graphical abstract



## 1 Introduction

Climate change, primarily driven by greenhouse gas emissions, leads to rising global temperatures and extreme weather events [1]. International frameworks such as the Sustainable Development Goals and the Paris Agreement have been established to mitigate these impacts, focusing on reducing greenhouse gas emissions, particularly in high-carbon sectors such as buildings [2]. Given that buildings are responsible for 26% of greenhouse gas emissions and 30% of worldwide energy consumption [3], enhancing energy efficiency within this sector is critical to addressing climate change and achieving sustainability goals [4]. To support these efforts, public policies, including energy codes, minimum energy performance standards, and energy labeling schemes, have been developed to promote sustainable practices and improve energy efficiency in buildings [5].

The European Union (EU) has established energy performance certification and labeling for buildings through the Energy Performance of Buildings Directive (EPBD) [6], first introduced as Directive 2002/91/EC [7] and subsequently revised under Directive 2010/31/EU [8], Directive 2018/844 [9], and the most recent Directive 2024/1275 [10]. This mechanism is relevant for promoting energy efficiency and transparency in energy use [11]. By offering standardized information, energy labeling increases awareness of energy consumption, encourages energy-saving practices, and supports the transition toward more sustainable buildings [12]. It also aids stakeholders in making informed decisions, can enhance the market value of energy-efficient buildings [13], and contributes to energy planning and policy development [14–16].

To connect these benefits to tangible outcomes, accurate and reliable energy labeling schemes are essential. Despite their benefits, energy labeling schemes face several challenges that hinder their effectiveness and widespread adoption. One major issue is the performance gap [17], which refers to the discrepancy between predicted and actual energy consumption in buildings. While the performance gap is a universal issue in energy performance assessment, it significantly impacts the reliability of energy labeling schemes. This gap arises due to various factors, including variations in occupant behavior [18–20], unavailability of design specifications, inadequate maintenance of energy systems, changes made to the building and its systems after initial design and construction, inaccurate or incomplete measurement and data

collection, and limitations in predictive modeling tools [14,21–23]. Addressing the performance gap is crucial for energy labeling to accurately reflect real-world energy performance and to promote effective energy-saving measures.

Besides the performance gap, other challenges affect the energy labeling schemes. The labor-intensive and error-prone manual processes involved in energy assessments [24] can lead to inconsistencies and inaccuracies, especially when compounded by simplifications and default values [14]. Assessing older buildings is particularly challenging due to non-standardized construction practices and missing essential energy-related data [25] and the lack of individual metering makes it difficult to acquire the necessary assessment data [26]. Variations in energy assessors' competency can also result in inconsistent and inaccurate results due to differing methodologies and expertise [27,28]. Additionally, energy labels often lack specific parameters related to thermal comfort, air quality, and other environmental indicators, limiting their utility for informed decision-making [16,29].

Some stakeholders perceive the energy label as an administrative burden rather than a valuable tool, undermining its effectiveness [30]. The lack of enforcement and compliance leads to limited market reach and acceptance, often due to insufficient information, awareness, and perceived value [14]. High costs associated with obtaining the energy label and implementing recommended measures can discourage building owners, especially if the return on investment is unclear [31]. Furthermore, the disconnection between the design phase and subsequent energy performance assessments [14] exacerbates these issues, as reliance on manual data acquisition can be extensive and time-consuming [32]. While many buildings worldwide receive energy labels, few achieve high energy efficiency levels [14]; thus, the focus should be on enhancing the efficiency and performance that buildings can reach, rather than just meeting minimum energy performance standards [21].

Therefore, a central problem lies in the inefficiency of current energy labeling schemes to provide accurate, consistent, and efficient assessments of building energy performance. These schemes are undermined by several factors, including the performance gap, manual and error-prone processes, and the lack of detailed data, particularly in older buildings. Additionally, the high costs associated with obtaining energy labels, combined with insufficient governmental incentives, limit widespread adoption. Finally, the lack of alignment between the design and operational phases of buildings poses additional challenges in ensuring that energy labeling accurately

captures real-world performance. Together, these issues undermine the effectiveness of energy labeling schemes in fostering energy-efficient and sustainable buildings.

Given these challenges, innovative methods that integrate advanced approaches into energy labeling schemes are needed to address inefficiencies and improve data accuracy. Building Information Modeling (BIM) emerges as a promising solution to address these issues. Addressing these challenges requires a comprehensive and standardized approach incorporating detailed and trustworthy building information. BIM can attempt manual, error-prone processes and the lack of accurate data by providing a centralized, detailed digital representation of the building, thus enhancing data accuracy and consistency. Several studies highlight the potential of BIM for the energy performance assessment of buildings [12,33,34]. BIM is a robust, rich-data platform capable of streamlining data acquisition and improving accuracy while minimizing human errors. Recent studies have explored BIM-based approaches to automate manual processes [35,36], further reducing the time required for this step. Given the direct relationship between time, effort, and labeling cost [14], this approach could be instrumental in enhancing the adoption of energy labeling schemes. This improvement in process efficiency helps accelerate delivery and reduce costs associated with energy labeling, potentially meeting stakeholder expectations for more accessible and reliable labeling schemes.

The seamless integration of BIM with Building Energy Modeling (BEM) could also be a promising solution for addressing the issues in energy labeling schemes. By combining the detailed representation provided by BIM with the analytical capabilities of energy simulation, this approach offers a more efficient way to evaluate the energy performance of buildings [37]. BIM's ability to incorporate comprehensive building data, including geometry, materials, and systems, allows for more accurate energy performance assessment [38]. This integration also enhances data consistency and integrity, reducing errors and inconsistencies typically encountered in traditional energy simulations [39]. Additionally, automation through programming offers a promising solution, allowing professionals to create customized workflows that automate tasks from data extraction to simulation execution, minimizing manual effort and enhancing data transfer capabilities [40,41]. Industry developments in the BIM-to-BEM field, such as Autodesk’s Systems Analysis feature in Revit software, which integrates with OpenStudio and EnergyPlus simulation tools, further support this integration by automating processes and enabling model customization through

computational programming [42,43]. Compared to traditional methods, BIM-BEM enables faster and more reliable assessments [44], positioning it as a promising strategy to enhance the efficiency and applicability of energy labeling schemes.

Another strategy for improving energy performance assessments is using BIM-based multi-objective optimization. The design of high-performance buildings involves balancing multiple conflicting objectives, such as optimizing energy efficiency and thermal comfort while minimizing costs. BIM-based multi-objective optimization offers a powerful approach to address these competing demands [45]. By utilizing algorithms like genetic algorithms, designers can evaluate several design alternatives and identify solutions that simultaneously meet multiple performance criteria. This approach addresses specific energy labeling challenges by automating simulations to find optimal design choices, improving alignment between design outcomes and labeling objectives, particularly in terms of sustainability and cost-effectiveness. This approach facilitates the exploration of trade-offs between energy efficiency, cost, and occupant comfort, ensuring that the final design complies with energy labeling standards and maximizes broader sustainability metrics. Thus, this approach can address the challenge of achieving high energy efficiency levels in buildings. However, the complexity of multi-objective optimization, particularly regarding the significant computational resources and time required, presents a challenge [46]. Ensuring the accuracy of input data is equally crucial for reliable outcomes. Additionally, the technical expertise needed to implement these optimization algorithms remains a barrier for many professionals, further increasing the complexity and cost of adopting these advanced solutions [47,48]. By exceeding basic code compliance, this method promotes building designs that go beyond minimum labeling thresholds, addressing a key shortcoming where many labels reflect only minimal standards rather than genuinely high efficiency [14].

Recent innovations, such as BIM-based digital twins, push the capabilities of BIM even further by enabling real-time data monitoring and predictive analytics for ongoing performance optimization [49]. By integrating BIM with Internet of Things (IoT) technologies, these systems create interactive digital replicas of buildings [50], which capture real-time data on desired parameters for continuous monitoring and analysis [51]. Integrating this data with the BIM model allows for dynamic visualization and predictive insights, aiding stakeholders in optimizing operations and addressing maintenance proactively [52,53]. Additionally, these systems provide real-time

feedback on energy consumption patterns to occupants, promoting sustainable behaviors [54]. Advanced predictive modeling and machine learning algorithms can further refine energy management [55], optimizing thermal comfort and reducing the energy use of air-conditioning systems [56]. Despite challenges such as high implementation costs and ongoing maintenance needs, the enhanced data reliability, transparency, and proactive management contribute significantly to closing the performance gap and boosting building energy efficiency [49]. This integration has the potential to enhance energy labeling by allowing labels to capture dynamic performance metrics and reflect actual usage patterns, thereby improving alignment with real-world conditions.

By exploring these BIM-based approaches, this paper offers a holistic view of how various methods can address the core shortcomings of current energy labeling. BIM-BEM facilitates streamlined data transfer, which can reduce manual input errors and help bridge the design–operation disconnect. Multi-objective optimization pushes building performance beyond basic code compliance, offering potential to mitigate the common issue of labels reflecting only baseline performance. Digital twins, through real-time data monitoring, provide insights to address operational variances, such as occupant behavior and maintenance lapses, that can erode labeling accuracy. Together, these strategies show promise in narrowing the performance gap, minimizing manual processes, and contributing to more accurate, cost-effective, and stakeholder-friendly energy labeling.

Despite its potential, several challenges exist in fully realizing BIM's effectiveness in energy labeling. One significant issue is ensuring the quality and completeness of BIM data. The accuracy of BIM-based assessments relies heavily on high-quality input data, which can vary significantly across different stages of a project and require rigorous validation protocols. Additionally, achieving seamless interoperability between BIM and BEM platforms is complex, as it often requires specialized technical knowledge and adaptations to ensure that data transfers accurately between systems [57,58]. This interoperability remains a barrier to efficient data sharing, especially when using BIM in diverse regulatory environments that may require unique adaptations to align with local labeling standards [34–36].

Another barrier is the technical complexity and resource requirements associated with implementing automated BIM workflows for energy labeling. Current BIM tools, while capable of data automation, often require expertise in programming

and workflow customization to fully exploit their capabilities for energy performance assessment. The financial and technical investments necessary for this level of BIM application can be prohibitive for many stakeholders, particularly in regions where resources are limited [37]. Recent industry efforts to facilitate integration between proprietary BIM and BEM tools are promising advances, yet further development is needed to reduce barriers and enhance accessibility [38,39].

These challenges underscore the lack of clear guidelines and practical solutions for effectively implementing BIM in energy labeling. While BIM shows significant promise for addressing many of these issues, its integration into energy labeling is often hindered by non-standardized methodologies, unclear frameworks, and limited practical tools. Consequently, a gap persists between BIM's theorical potential and its real-world application in energy labeling, highlighting the need for further research to bridge these limitations and enhance the accuracy and efficiency of labeling practices.

Although existing reviews occasionally address energy labeling, they often only briefly mention BIM [14,34,59]. Conversely, reviews on BIM's role in enhancing building energy efficiency tend to treat energy labeling superficially [60]. This paper seeks to fill this gap by providing a comprehensive review of BIM applications specifically in the context of energy assessment and labeling, thereby contributing to both academic literature and practical methodologies. It is worth noting that while there is research on the application of BIM-based methods for general energy assessment, studies specifically delving into BIM for energy labeling purposes are relatively few [12,61]. Therefore, a knowledge gap exists regarding the comprehensive integration of BIM into energy performance assessment and labeling of buildings.

The overarching objective of this study is to investigate how BIM can enhance the accuracy, reliability, and efficiency of energy labeling in buildings. To achieve this objective, the paper: identifies the main issues and gaps in current energy labeling schemes; assesses the tangible benefits of leveraging BIM for energy performance assessment and labeling; evaluates the key challenges associated with implementing BIM in labeling processes; and proposes emerging trends and future research directions for seamlessly integrating BIM with energy performance labeling practices. By accomplishing these aims, the study advances academic understanding of BIM-driven energy assessment and labeling and directly supports building engineering practitioners, such as architects, engineers, and facility managers, who seek more

accurate, data-driven methods for energy assessment and labeling. These findings contribute to practical implementations of BIM that promote sustainable building practices, reduce energy consumption, and improve overall building performance. Ultimately, this paper aspires to foster more efficient, reliable, and sustainable approaches to energy labeling, thereby aligning building engineering goals with broader environmental and economic imperatives.

## 2 Method

This study employs a systematic literature review to explore how BIM can enhance the accuracy, reliability, and efficiency of energy performance assessment and labeling in buildings. This systematic approach ensures a comprehensive synthesis of existing research, allowing for the identification of gaps, benefits, challenges, and future directions in the field. Fig. 1 presents the flowchart of the method, illustrating the steps and outcomes.

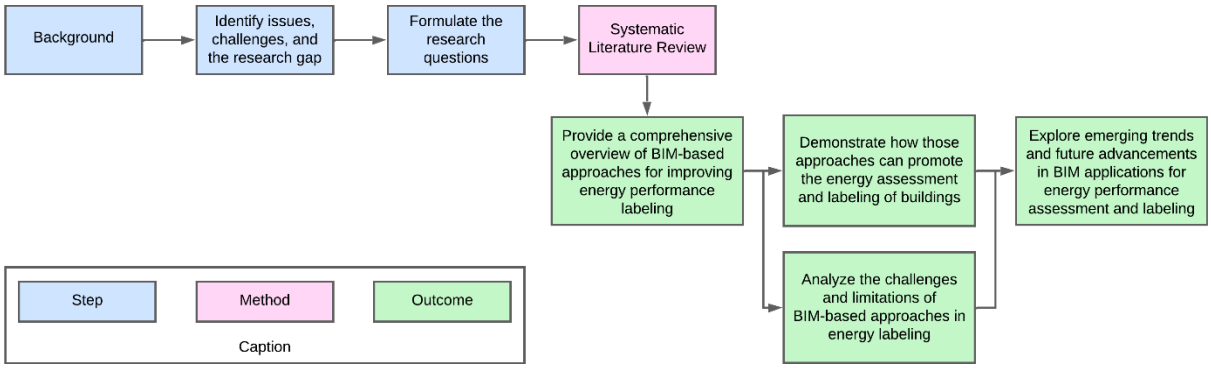



Fig. 1. Flowchart of the method. Source: The authors (2025).

The main questions addressed in this research are:

- What are the current gaps and issues in energy performance assessment and labeling?
- What are the benefits of using BIM for energy performance assessment and labeling?
- What are the key challenges in implementing BIM for energy performance assessment and labeling purposes?
- What are the trends and future directions in using BIM for energy performance assessment and labeling?

To address these questions, a systematic literature search was conducted following established guidelines for systematic reviews. The literature sampling process (Fig. 2) involved a systematic search on BIM and energy-related terms in the Scopus database. To ensure relevance and quality, inclusion criteria were applied: peer-reviewed journal articles published in English between 2013 and 2023, focusing on the application of BIM in energy performance assessment and labeling. Exclusion criteria included conference papers, editorials, book chapters, non-peer-reviewed articles, articles not directly related to BIM and energy performance assessment, and studies lacking sufficient methodological detail or empirical data. The initial search yielded 548 articles. After applying the inclusion and exclusion criteria, 246 articles remained. Titles and abstracts of these articles were screened for relevance to the research questions, excluding 126 articles that did not meet the criteria. The full texts of the remaining 120 articles were then reviewed in detail. Articles were assessed for their contribution to the research questions during the full-text review. This process led to the identification of 106 articles that were deemed relevant and included in the final analysis.

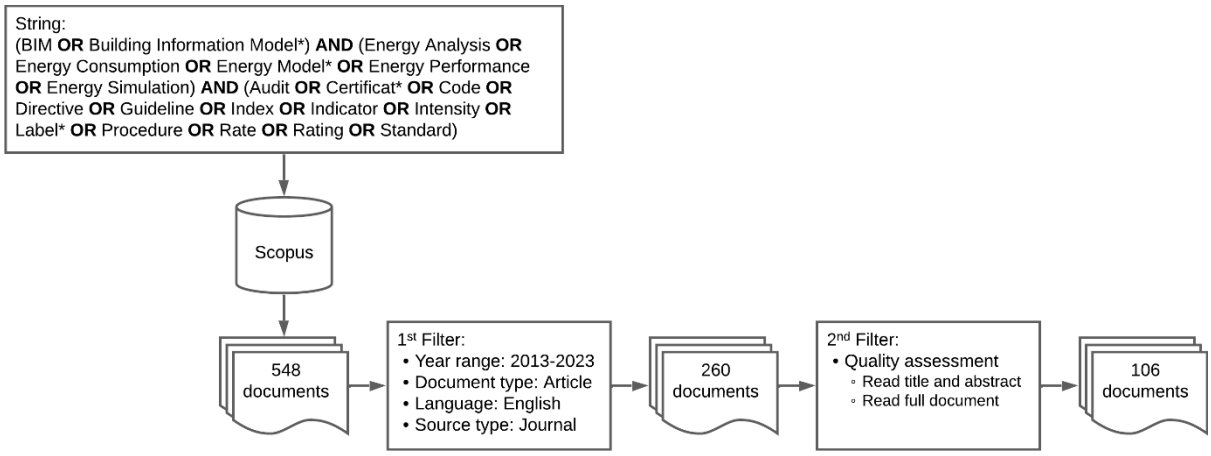



Fig. 2. Flowchart of the sampling process. Source: The authors (2025).

In analyzing each selected article, aspects such as bibliographic information, study objectives and scope, methodology used, key findings related to BIM and energy performance assessment, identified gaps, benefits, challenges, and recommendations for future research were examined. An inductive thematic analysis was conducted to identify recurring themes and patterns across the selected studies. This inductive approach allowed themes to emerge progressively from the data rather than being guided by pre-existing categories.

The inductive thematic analysis involved an iterative process that began with an in-depth reading of each article. The primary focus of this phase was to gain a comprehensive understanding of the material, allowing themes to emerge naturally from the content. As the analysis advanced, various themes related to the use of BIM in energy performance assessment and labeling were identified (e.g., automation, interoperability, 3D laser scanning, energy performance optimization, algorithm and API development, digital twin, IoT, code compliance, among others). The themes were not predefined but evolved as more articles were analyzed, reflecting the diverse applications and challenges of BIM in this context.

Additional aspects were also considered during the analysis to provide a comprehensive view of the research topic. These included identifying the specific phase of the building lifecycle addressed in each study (e.g., design, construction, operation), the software tools, and whether open data standards such as gbXML or IFC were discussed. In addition, the objectives, methods, key conclusions, and personal insights regarding how each study's findings could contribute to building energy labeling were documented and analyzed. These insights were integrated into the subsequent sections of this article.

As themes and patterns were further examined, six primary BIM-based approaches emerged that aligned with the research questions: BIM as a data repository, automated generation of BIM models, BIM-BEM direct integration, BIM-BEM open data standards, BIM-based multi-objective optimization, and digital twin for efficient operation. These approaches surfaced naturally from the analysis, highlighting critical areas where BIM can enhance energy performance assessment and labeling. The inductive nature of this thematic analysis provided a nuanced understanding of the existing literature, capturing the diversity of concepts in the field and effectively addressing the main objective of this research.

## 3 Energy performance labeling shortcomings

Energy labeling is an essential tool for evaluating and certifying the energy performance of buildings based on standardized criteria and guidelines [6]. This framework plays a crucial role in enhancing energy efficiency, reducing energy consumption, and promoting transparency in energy use within buildings [11]. By providing methods to assess the energy performance of buildings, energy labeling schemes aim to raise awareness about energy consumption, encourage the adoption

of energy-saving measures and technologies, and facilitate the transition towards more sustainable and energy-efficient buildings [12].

Energy labels provide clear and standardized information about a building's energy performance, enabling informed decision-making by stakeholders [16]. Buildings with high energy efficiency ratings can have higher market value and attract environmentally conscious buyers or tenants [15]. Furthermore, energy labeling helps buildings meet regulatory standards and plays a crucial role as a database for energy planning and public policy formulation [14].

Countries have implemented energy labeling schemes to suit their regulatory frameworks and building practices. In the United States, programs such as Energy Star and Building Energy Quotient (bEQ) assess and certify buildings' energy performance, offering detailed reports with energy use summaries and improvement suggestions [62–64]. In Brazil, the Brazilian Building Labeling Program (PBE Edifica), applies an alphabetic scale from "A" to "E" to indicate energy efficiency, with specific labels for different building types and systems [62,65]. European Union member states have developed individualized energy labeling schemes aligned with their regulations to promote energy efficiency and transparency [66]. Other countries, including Australia [67], Canada [68], India [69], and Argentina [70], have implemented tailored energy codes or labeling schemes to support energy efficiency and transparency goals [66,71].

Despite their benefits, energy labeling faces several challenges that hinder its effectiveness and widespread adoption. To provide a comprehensive overview of these challenges, Table 1 summarizes the key issues affecting energy performance labeling schemes. Some issues, such as poor documentation and predictive modeling inaccuracies, are commonly rooted in the design stage, while others, like occupant behavior and inadequate maintenance, arise during the operation stage. In many cases, these challenges overlap, with initial design decisions affecting long-term operational outcomes. Each of these challenges will be further discussed in this section.

Table 1 Shortcomings in energy performance labeling schemes.

| Topic | Problem | Description |
|---|---|---|
| Performance gap and technical factors | Performance gap | Variations in occupant behavior, lack of design specifications, inadequate maintenance, post-construction changes, and limitations in predictive modeling can lead to discrepancies between predicted and actual building performance. |
| | Predictive modeling limitations | Limitations in predictive modeling tools can result in inaccurate simulations, contributing to the performance gap. |
| | Disconnect in design and assessment | The gap between design intentions and actual energy performance assessments can lead to inaccurate labeling, as initial design specifications might not be followed or updated throughout the building's lifecycle. |
| | Occupant behavior | Occupant actions and habits significantly affect energy usage, leading to differences between simulated and actual energy consumption due to varying energy awareness and behavior levels |
| | Poor maintenance | Poor maintenance practices or neglect can lead to the degradation of equipment and systems over time, reducing energy efficiency. |
| Data and assessment reliability | Documentation quality | Poor or incomplete documentation of building systems, materials, and maintenance histories can lead to challenges in accurately assessing and maintaining energy performance. |
| | Manual processes | Manual processes in energy performance assessments are labor-intensive and prone to errors, potentially leading to inaccurate data that contributes to the performance gap. |
| | Data availability | In some regions, access to accurate energy consumption data and the infrastructure for energy assessments may be lacking, impeding effective energy assessments and labeling. |
| | Lack of individual metering | Some buildings, especially older ones, may lack individual metering, complicating data acquisition for energy assessments and making it difficult to propose and measure energy-saving strategies. |
| | Assessor competency | Differences in assessor expertise and methodologies result in inconsistent and inaccurate energy performance assessments, affecting the credibility of the energy labels. |
| | Simplifications and default values | Using simplifications and default values in assessments can lead to inaccuracies, affecting the reliability of the energy performance labels. |
| | Inconsistencies in energy label data | Significant discrepancies in energy label data due to different methodologies and assessor expertise highlight the need for standardized assessment procedures to ensure consistency and accuracy. |
| | Non-standardized practices | Older buildings often have non-standardized construction practices and missing energy-related data, making accurate energy assessments and data acquisition difficult. |
| Implementation and support limitations | Lack of technical advice | Inadequate technical support and guidance for implementing energy-saving measures can hinder the effectiveness of energy labeling schemes. |
| | Technical information | Energy labels tend to provide technical information on energy usage and often lack specific details about thermal comfort, air quality, and other environmental indicators, reducing their effectiveness for informed decision-making. |
| | Perception and compliance | Energy labels are often seen as administrative burdens rather than valuable tools, and the lack of enforcement and compliance limits their market acceptance and reach. |

| | | |
|---|---|---|
| | Insufficient information and awareness | Limited information and awareness about the benefits and processes of energy labeling among stakeholders contribute to low market reach and acceptance. |
| | Cost and return on investment concerns | The costs of obtaining energy labels and implementing recommended energy-efficient upgrades deter building owners, especially when the return on investment is uncertain. |
| | Economic disparities | Economic disparities may pose challenges, as low-income populations might not prioritize energy efficiency and the reduction of utility bills when searching for housing. |
| Lack of strategic focus | Efficiency vs. minimum standards | The focus on meeting minimum energy efficiency standards rather than striving for high energy efficiency levels highlights the need to shift towards increasing the stock of highly energy-efficient buildings. |

One major issue is the gap between predicted and actual energy performance in buildings, known as the performance gap [17]. This discrepancy may arise due to variations in occupant behavior, unavailability of design specifications, inadequate maintenance of energy systems, changes made to the building and its systems after its initial design and construction, and inaccurate or incomplete measurement and data collection [14,22,23]. Additionally, limitations in predictive modeling tools, such as insufficient data inputs or oversimplified assumptions about building usage and environmental conditions, can result in inaccurate simulations [21]. These processes, compounded by simplifications and default values, lead to inconsistencies and inaccuracies, impacting the reliability of energy labeling [14]. When design-phase assumptions do not accurately capture real-world conditions, building owners and occupants may struggle to maintain expected efficiency levels during operation [49], exacerbating the performance gap.

Moreover, in some regions, access to accurate energy consumption data and the infrastructure for energy assessments may be lacking, impeding effective energy assessments and labeling. Assessing older buildings with non-standardized construction practices and missing essential energy-related data is particularly challenging. Additionally, some buildings, especially older ones, may lack individual metering, complicating data acquisition for energy assessments and making it difficult to propose and measure energy-saving strategies. Inconsistent and inaccurate results often stem from variability in assessor competency. For instance, studies in Spain and Italy highlight significant discrepancies in energy label data due to differing methodologies and assessor expertise [27,28].

Occupant actions significantly influence energy usage, contributing to the performance gap [18]. Differences in awareness and behavior among occupants can impact how energy is utilized within buildings [19]. A study by [20] reveals that user-dependent factors, especially those related to appliances and cooling practices, lead to substantial discrepancies between simulated and actual energy consumption. This underscores the need for energy labeling to better incorporate individual behaviors and real-world data.

The reliability of energy label data and its reflection of actual energy performance are questioned by some stakeholders. One major issue is the perception of energy labeling as administrative burdens rather than valuable tools, undermining their effectiveness [30]. Furthermore, the lack of enforcement and compliance leads to low market penetration and acceptance, often due to inadequate information, awareness, and perceived value [14]. Additionally, inadequate technical support and guidance for implementing energy-saving measures can hinder the effectiveness of energy labeling schemes. High costs associated with obtaining energy labels and implementing recommended measures can deter building owners, especially if the return on investment is unclear [31]. Additionally, the generality of information provided in energy labels often lacks specific parameters related to thermal comfort, air quality, and other crucial indicators, limiting their utility for informed decision-making [16,29]. Economic disparities may pose challenges, as low-income populations might not prioritize energy efficiency and the reduction of utility bills when searching for housing.

Moreover, energy labeling is highly dependent on the quality of project documentation, yet there is often a disconnect between the design phase and subsequent energy performance assessments [14]. This gap is further exacerbated by the reliance on manual data acquisition, which can be an extensive and time-consuming task [32]. Besides, the cost of obtaining an energy label often depends on the considerable effort required for data collection and verification. When the design stage does not systematically incorporate energy-consumption considerations, stakeholders may have to invest significant resources later to validate and rectify discrepancies discovered during operation. Finally, the focus on meeting minimum energy efficiency standards rather than striving for high energy efficiency levels highlights the need to shift towards increasing the stock of highly energy-efficient buildings.

## 4 BIM as a data repository

The energy labeling process depends greatly on the availability and accuracy of specific building data, often hindered by manual acquisition methods prone to errors [12]. BIM offers a solution by streamlining the building assessment through direct data extraction from digital models, reducing errors and optimizing time and costs. Although widely used during the design stage, it also serves as a comprehensive digital representation of the building, capable of reflecting renovations or operational updates and functioning as a data repository. BIM provides a structured, data-rich, and dynamic framework that can adapt to the complex information needs of energy-efficient projects, from initial design to post-renovation evaluation [72].

BIM serves as a central repository for comprehensive building information, encompassing key data for energy performance assessment, including geometry, material specifications, mechanical systems, and occupancy patterns [73]. Al-Sakkaf et al. [74] demonstrate BIM's potential to represent detailed virtual models essential for the energy performance assessment of heritage buildings. BIM acts as a digital repository, including physical characteristics and energy-related data. Moreover, BIM simplifies documentation generation, thereby streamlining the assessment process for stakeholders [75].

Beyond energy performance, BIM encompasses factors such as environmental comfort and cost estimation [76]. BIM facilitates 3D modeling and extraction of material quantities [77], enabling comprehensive evaluations of carbon footprints and environmental impacts throughout a building's lifecycle [78]. It aids in cost estimation by providing material quantities and construction costs, allowing for data-driven decisions based on lifecycle costs and energy performance criteria [79,80]. The semantic richness of BIM can be exploited for parametric analysis, enhancing the building’s envelope performance and indoor comfort while reducing energy consumption, as demonstrated by Amoruso et al. [81].

The potential of BIM can be harnessed for decision-making. Zhang et al. [82] combined BIM with a Multi-Criteria Group Decision-Making (MCGDM) framework to assess and select energy-efficient retrofit schemes for external walls. BIM was used to create digital building models and calculate heat transfer coefficients for different retrofit options. This information was essential at each process stage, from determining insulation structures and establishing an evaluation index system to

constructing and normalizing assessment matrices. The study integrated Chinese local standards and codes to ensure regulatory compliance. By utilizing BIM's capabilities, the research effectively analyzed energy performance and provided data that facilitated informed decision-making, ultimately optimizing building energy efficiency.

Integrating BIM with Life Cycle Assessment (LCA) and energy simulation supports informed decision-making. As demonstrated by Tushar et al. [83], BIM serves as a collaborative platform for accurately modeling a building's physical features, enabling the assessment of passive design strategies and their impact on embodied and operational energy consumption. This framework allows for automated, data-rich analysis of the environmental impacts of material selection and building operations and advancing sustainable practices [83].

The effectiveness of BIM's data acquisition relies on clear design and information exchange requirements from the project's inception. For instance, Gumbarević et al. [84] proposed a project control method for Nearly Zero-Energy Buildings (NZEBs) using digital representation within the BIM environment. The research underscores the importance of BIM in minimizing information loss, reducing errors, and streamlining tasks related to designing and modeling building elements that affect energy performance. Additionally, it assesses the reliability of energy simulation tools within BIM-authoring software to support energy modeling within the BIM environment.

Similarly, Kamari et al. [85] introduced a BIM-based decision support system to improve the renovation design process, emphasizing sustainability, stakeholder inclusion, and holistic practices. The system enables users to generate, evaluate, and visualize multiple renovation scenarios for Danish dwellings based on input criteria and constraints, primarily on cost. It facilitates comparative analysis through visualizations and iterative adjustments. In a case study, the proposed system generated over 500 scenarios in 30 minutes, demonstrating its effectiveness in exploring alternatives. However, future development should address architectural changes, spatial consistency, building code compliance, and broader validation.

While BIM offers several capabilities, data acquisition can be time-consuming. To address this challenge, approaches using programming languages, such as Python, have been developed to automate data extraction from BIM models [41]. These automated processes streamline energy simulation workflows and enhance

productivity. Another example is the study developed by Zhan et al. [86], which used Dynamo, a visual programming tool, to automate data extraction for environmental performance indicators, including energy consumption, thermal comfort, and material savings. MATLAB further utilizes this data to perform calculations, quantifying the building's performance through a green grade assessment, which evaluates the building's overall environmental performance by quantifying how well it meets sustainability criteria. Visual programming methods can also be employed for code compliance by automating data extraction and calculating building envelope parameters, such as Overall Thermal Transfer Value (OTTV) [87]. These tools optimize evaluation processes by enhancing efficiency and providing support for decision-making.

Automated approaches that rely on BIM as a rich data repository are promising. Andriamamonjy et al. [88] introduced an automated model-based Fault Detection and Diagnosis (FDD) in air handling units using BIM and Modelica to enhance operational efficiency. By utilizing BIM as a central data repository, the study streamlines FDD implementation, reduces manual efforts, and improves fault detection accuracy in building systems. Integrating BIM with Modelica by Python enables automatic generation and calibration of simulation models, enhancing overall system performance and maintenance efficiency.

The energy assessment and labeling process depends on a comprehensive dataset for evaluating building energy performance. Thus, the BIM model must include all required information for accurate assessments. To achieve this, several studies have established guidelines to provide insights into specific information and modeling requirements necessary for developing BIM models suitable for energy-related tasks [89–93]. However, further standardization is needed in this area. Standardized material libraries and data modeling procedures are integral in this process, as they improve interoperability among various software and platforms in the construction industry, facilitating seamless data exchange and collaboration [94]. It is worth noting that IEA-EBC Annex 91 [95], titled 'Open BIM for Energy Efficient Buildings', is addressing this need. Among its various topics, it focuses on developing material libraries and modeling guidelines to streamline energy performance assessment and improve interoperability between BIM and BEM.

Nevertheless, achieving complete standardization in the construction industry presents significant challenges. Variations in language, regional practices, and local

building materials create barriers to a uniform approach. Different countries, and even regions within the same country, may use unique terminologies and construction methods, complicating the development of universally applicable standards. For example, materials and processes commonplace in one region may be absent or untranslatable in another, leading to potential misunderstandings and inefficiencies. Therefore, while aiming for standardization is important to enhance interoperability and collaboration; there must also be a flexible framework that accommodates regional differences. This approach ensures that the benefits of BIM and standardized procedures are realized, without overlooking the local nuances critical for practical implementation in diverse construction contexts.

Despite its limitations, BIM's data-driven nature offers significant advantages for assessing and labeling the energy performance of buildings. Table 2 presents these benefits, challenges, and specific applications of BIM. Additionally, it empowers energy assessors to conduct simulations and performance assessments more efficiently, thereby enhancing result accuracy. As the construction industry undergoes digital transformation, BIM catalyzes shaping energy-efficient building design, construction, and operation by improving data accessibility, optimizing workflows, and streamlining energy performance assessments.

Table 2 Benefits, challenges, and specific applications of BIM.

| **Aspect** | | **Description** | **Reference** |
|---|---|---|---|
| Benefits of BIM | Data accuracy and availability | Reduces manual data acquisition errors and optimizes time and costs through direct data extraction from digital models. | [72] |
| | Comprehensive building information | Provides a central repository for essential building data, including geometry, material specifications, mechanical systems, and occupancy patterns. | [73,74] |
| | Environmental comfort and cost estimation | Facilitates 3D modeling and material quantity extraction for comprehensive evaluations (i.e., carbon footprints, environmental impacts, and lifecycle costs). | [77,79,80] |
| | Decision-making support | Integrates with decision-making frameworks to evaluate energy-efficient retrofit schemes and other assessments. | [82] |
| | LCA integration | Supports the assessment of passive design strategies and the environmental impacts of material selection and building operations. | [83] |
| | Energy assessment and labeling | Enhance energy performance assessment and labeling, improving data accessibility and optimizing workflows. | [75] |

| | | | |
|---|---|---|---|
| Challenges of BIM | Standardization needs | Highlights the need for standardized material libraries and data modeling procedures to improve interoperability. | [89–94] |
| Specific applications of BIM | Project control for NZEBs | Minimizes information loss and errors, supports energy modeling within BIM software. | [84] |
| | Renovation design process | Improves sustainability and stakeholder inclusion, generates multiple renovation scenarios for comparative analysis. | [85] |
| | Fault detection and diagnosis | Integrates BIM with Modelica for automated FDD in air handling units. | [88] |
| Programming approaches of BIM | Automation and programming tools | Uses programming tools like Python and Dynamo for data extraction and environmental performance calculations. | [41,86,87] |

## 5 Enhanced BIM model generation techniques

Assessing energy performance for the energy labeling of existing buildings can be a complex and time-consuming process, as it often requires extensive data collection and manual input into energy simulation tools. Such processes are highly error-prone, increasing the performance gap and raising the cost of energy labels. To address these challenges, researchers have proposed methods to enhance the generation of BIM models for existing buildings, which can then be used for energy performance assessment and labeling.

Streamlining BIM model generation represents a cutting-edge advancement in the field. One prominent method utilizes 3D laser scanning, a technology widely embraced in research for its ability to capture intricate building details and generate detailed point clouds representing internal and external features [96]. This approach mitigates the need for manual data acquisition, a significant advantage, particularly for buildings lacking blueprints.

Some studies propose frameworks for automating BIM model generation using 3D laser scanning [97,98]. This technology captures geometric data and converts it into digital models containing geometric information, material properties, system attributes, and spatial relationships [99]. This synergy, as exemplified in the Chinese rural dwellings case study [97], facilitates efficient building maintenance by creating comprehensive and accurate digital representations. Marzouk et al. [98] also illustrated this approach in a mosque retrofit assessment, converting captured point cloud data into a BIM model that contained geometric information, material properties, and spatial relationships. This BIM model was later converted into a BEM model for energy analysis, guiding retrofitting decisions.

The primary advantage of 3D laser scanning lies in its precision, ensuring accurate capture of the physical environment and providing a solid foundation for BIM development [100]. Decision-makers can utilize these digital models to analyze and optimize energy performance, assess retrofitting options, and predict thermal loads within a virtual environment [101]. This is particularly beneficial in heritage building retrofits, as demonstrated by Nagy and Ashraf [102], who employed 3D laser scanning to create detailed BIM models for energy performance assessment purposes.

The detailed data obtained from 3D laser scanning enhances the credibility of predictions and recommendations during the energy labeling process, as demonstrated in a Norwegian study evaluating cost-effective renovation measures [12]. The precise information provided by 3D laser scanning for BIM models, used in energy simulations and renovation planning, highlights its value in improving the accuracy of energy performance assessments. Another approach involves an indoor multi-sensor acquisition system integrated into a wheeled robot to gather information on 3D geometry, building characteristics, and parameters for energy modeling. This method, demonstrated by Patiño-Cambeiro et al. [103], enables the creation of a detailed BIM model that outlines the building structure, thermal zones, and elements necessary for the building’s energy performance assessment.

Beyond geometric data, other methods offer additional insights. Pérez-Andreu et al. [104] introduced an approach integrating 3D thermal point clouds with RGB and infrared thermography images to construct detailed 3D representations of a building's thermal properties. This method provides compatibility with energy simulation tools through the Green Building XML (gbXML) open data standard, leading to a more streamlined approach for energy simulation and informed decision-making. Additionally, the use of thermography provides visual information about the quality of the building's thermal insulation, revealing thermal bridge locations [25]. Such diagnostics could guide new design-phase solutions or pinpoint operational inefficiencies.

The ability to streamline BEM model creation and enhance energy performance evaluations strengthens the case for automated BIM models. Adán et al. [105] address the challenge of integrating BIM with BEM for accurate energy simulations by automating the generation of 3D thermal models from BIM data and transforming them into standard BEM formats. This not only reduces manual effort and potential errors but also facilitates seamless data exchange among

multidisciplinary teams through open data standards such as Industry Foundation Classes (IFC) [12] and gbXML [104]. Thus, stakeholders (e.g., architects, energy managers) can benefit from centralized, high-quality digital models during the design and operation stages.

However, implementing approaches to automate the generation of BIM models presents challenges and limitations. Factors such as building complexity, occlusions during scanning, and the need for supplementary data can affect effectiveness [98]. The success of these approaches heavily relies on the expertise of practitioners involved in data acquisition, processing, and model development, as highlighted in evaluations of existing building stock [12]. In complex or obstructed indoor environments, ensuring complete and accurate data collection may require multiple scans from different positions [106]. Challenges including inaccessible blind spots such as rooftops underscore the importance of addressing line-of-sight requirements, surface properties, and data volume management [97]. Specialized expertise, equipment costs, and navigation through confined spaces also contribute to these obstacles.

Despite the limitations, integrating technologies such as 3D laser scanning and thermography with BIM shows potential for both design-phase retrofits and ongoing operational improvements in the energy performance labeling of buildings. Table 3 outlines the methods and technologies discussed in this section, along with their respective benefits and challenges. Enhancing the generation of detailed BIM models using these techniques can streamline processes, improving precision and efficiency. This approach accelerates the acquisition of geometric data and BIM model generation, while also facilitating data exportation via open standards to enhance compatibility with energy simulation tools. The synergy between 3D laser scanning technologies and BIM enables accurate digital representations of buildings, empowering decision-makers to optimize energy performance.

Table 3 Overview of enhanced BIM model generation methods, benefits, and challenges.

| Technology/Method | Description | Benefit | Challenge | Reference |
|---|---|---|---|---|
| 3D laser scanning | Utilizes laser technology to capture detailed building geometry and create point clouds for BIM model generation. | -Precision in capturing building details.<br>-Reduces manual data acquisition.<br>-Facilitates accurate energy simulations and retrofit assessments. | -Building complexity, occlusions.<br>-Supplementary data requirements.<br>-Expertise in data processing and model development. | [96–98,100,102] |
| Multi-sensor acquisition | Integrates sensors on a wheeled robot to acquire indoor building data, including geometry and thermal characteristics. | -Detailed BIM models creation.<br>-Outlines building structure and thermal zones.<br>-Enhances energy performance assessment and retrofit planning. | -Challenges in confined spaces navigation.<br>-Data volume management.<br>-Integrating diverse sensor data. | [103] |
| RGB and infrared thermography | Combines RGB and infrared imagery with 3D thermal point clouds to model building thermal properties for energy simulations. | -Enhanced thermal property representation.<br>-Compatibility with energy simulation tools.<br>-Visual inspection of thermal insulation quality. | -Requires specialized equipment and expertise.<br>-Interpretation of thermographic data.<br>-Integration with BIM and BEM tools. | [25,104] |
| Automated BIM model generation and BEM conversion | Automates the generation of BIM models and convert those models into BEM models for energy performance analysis. | -Streamlined workflow.<br>-Reduces manual errors.<br>-Facilitates seamless data exchange with BEM tools. | -Interoperability challenges.<br>-Accuracy depends on BIM model quality.<br>-Adherence to open data standards. | [12,99,101,105] |

## 6 BIM-BEM direct integration

Energy simulation is a common approach for the energy performance assessment and labeling of buildings. However, it faces significant challenges, primarily due to the complexity and accuracy of the required input data, which is often reliant on tedious and error-prone manual entry. These challenges directly impact energy labeling by contributing to inaccuracies and inconsistencies, thereby

undermining its reliability and credibility [60]. Furthermore, this can exacerbate the performance gap, undermining the credibility of label schemes.

While many issues arise from the inherent challenges of the labeling process, they are frequently intensified by inconsistencies between the design and operational stages. For instance, setting accurate model parameters during design is crucial, yet these parameters frequently fail to capture dynamic aspects (e.g., occupant behavior) during operation. Obtaining reliable operation-related inputs remains a significant hurdle in BIM-BEM direct integration, as default schedules and assumptions rarely align with real-world usage patterns. Although primarily intended for design purposes, BIM-BEM integration can also support retrofit and operational phases by incorporating post-occupancy data, helping to refine initial assumptions and bridge the performance gap.

BIM-BEM direct integration is an approach designed to assess and optimize building energy performance, offering significant benefits such as time and cost savings [107]. This method relies on workflows incorporating proprietary tools and plug-ins to ensure smooth data transfer from BIM to BEM, enabling rapid estimation of a building's annual operational energy consumption and facilitating the exploration of design alternatives. Thus, it can inform both the design phase and, to some extent, operational considerations if post-occupancy data are included, though predicting occupant behavior profiles remains challenging.

This integration has been applied in several case studies. Maglad et al. [108] utilized Revit software and the Insight plug-in to test different building materials for the envelope and orientations in an educational building, resulting in a 16.5% reduction in energy consumption in the best scenario. This study highlights the design-phase utility of BIM-BEM direct integration in optimizing energy efficiency through material and orientation selection. Similarly, Rocha et al. [101] used Revit software and the DesignBuilder add-in to improve thermal comfort during winter in an existing building. Here, the operational-phase focus demonstrates how BIM-BEM workflows can address seasonal comfort challenges. In the study by Ali et al. [109], ArchiCAD software and the Energy Evaluation tool were used to optimize window design parameters in high-rise buildings to reduce cooling loads.

Parametric and sensitivity analysis can enhance the exploration of design alternatives and their effects on energy performance. Singh and Sadhu [110] used Revit software and the Green Building Studio cloud-based service to improve energy

performance in a residential building by assessing internal configurations such as orientation, insulation, window-to-wall ratio, and air-conditioning systems. They found that envelope design was the most crucial parameter for energy savings. In a walk-in clinic, the window-to-wall ratio was identified as the most critical factor for energy savings. Sensitivity analysis can also be employed for financial purposes. For example, Truong et al. [111] used Revit software and the Insight plug-in to enhance the energy efficiency and cost-effectiveness of an educational building. This approach identified optimal configurations, empowering designers to make informed decisions towards economic viability and energy-efficient building design.

Several studies leverage BIM-BEM direct integration to assess carbon emissions and enhance sustainability. Khahro et al. [112] used Revit software and Green Building Studio to improve energy efficiency and reduce carbon emissions in a hospital. In another study, Krasny et al. [113] used a BIM-based energy assessment approach to compare bio-based houses (i.e., straw walls, wooden structures, and green roofs) with traditional concrete houses (i.e., concrete, brick walls, and styrofoam insulation). It was found that bio-based houses have lower construction and lifecycle energy costs, energy use, and carbon emissions.

LCA can be combined with BIM-BEM to evaluate environmental impacts throughout a building's lifecycle. Najjar et al. [114] applied LCA practices within Revit, Green Building Studio, and OpenLCA software to estimate operational energy performance and evaluate impacts on human health, ecosystem quality, and resource depletion, highlighting the potential of BIM-BEM in promoting sustainable building design while reducing the environmental footprint from construction activities.

BIM-BEM direct integration can also be used with Multi-Criteria Decision-Making (MCDM) methodologies to enhance energy performance, reduce carbon emissions, and maximize economic benefits. Marzouk et al. [115] proposed a framework using Revit software and Green Building Studio to estimate energy consumption and carbon emissions of air-conditioning and lighting systems in an educational building. They applied the Superiority and Inferiority Ranking (SIR) method to rank these systems' energy performance, determining the most effective configuration for minimizing energy use and emissions while maximizing economic benefits. Similarly, Mahmoud et al. [116] developed a sustainable framework for existing buildings, addressing regional variations. Using BIM for detailed building representation, energy simulations for consumption analysis, and MCDM for ranking

sustainability attributes and managing uncertainties, the study offered an approach to evaluate sustainability performance, considering factors such as energy performance, water use, material management, indoor environmental quality, and building management.

BIM-BEM direct integration has proven to be a valuable complement to the energy performance assessment and optimization of buildings. Typically, BIM-authoring tools can be integrated with energy analysis tools such as Green Building Studio [117], Insight [108,111], and Sefaira [118] to assess a building's energy performance. Additionally, semantic data can be acquired directly from BIM software, and further analysis, such as cost estimation, can be automated using Excel macros [118]. This approach has been increasingly adopted, with studies demonstrating its potential to conduct energy performance assessments and optimizations through seamless data integration and analysis.

Despite its merits, BIM-BEM direct integration faces criticism for its perceived limitations in performing detailed energy simulations, primarily due to software constraints. Some reports suggest that this approach is best suited for early-stage design, yielding generic results mostly due to a lack of customization for simulation data input and advanced features for energy simulation [119,120]. However, not all studies support these limitations. Ferreira et al. [121] revealed that this approach can yield accurate results, depending on the complexity of the building systems and the availability and accuracy of data. Another relevant aspect was highlighted by Danial et al. [122], who found that results from DesignBuilder and the Insight plug-in were approximate. Inaccuracies may occur due to limited available data and estimated values derived from field surveys and occupant behavior [108], although BIM-BEM direct integration is generally faster than the traditional BEM process [122]. Additionally, the use of BIM-BEM direct integration, which heavily relies on authoring tools, may pose a financial hurdle for small firms and challenge integration with other tools.

BIM-BEM direct integration is evolving, notably with Autodesk's introduction of Systems Analysis in Revit software. This feature enhances energy simulations by integrating Revit with OpenStudio and EnergyPlus. Systems Analysis enables the creation of a virtual model of the HVAC system from the conceptual to the detailed design phase, facilitating automated and customized energy simulations using OpenStudio Measures [42,43]. The workflow starts with modeling in Revit, which

produces an energy analytical model. This model is then converted to a gbXML file, which is subsequently transformed into an OpenStudio Model (OSM) file and finally into an Input Data File (IDF) for simulation in EnergyPlus, with results returned to Revit. Users can access and modify these files, providing flexibility to adapt and adjust models according to specific needs. This process addresses a key limitation of direct integration by enabling advanced simulation capabilities. Therefore, while Systems Analysis primarily focuses on the design phase, it also facilitates more accurate operational simulations when calibrated with real usage data, which can be quickly obtained through advanced systems (e.g., IoT sensors).

In the study by Albdour et al. [123], Systems Analysis was applied to residential buildings, evaluating their energy performance against established standards and validating the simulations with actual consumption data. The models were calibrated, and the results demonstrated acceptable levels of deviation, in accordance with the recommendations outlined in ASHRAE Guideline 14 [124]. This underscores its potential for accurately predicting building energy use and informing strategies for enhanced efficiency. Furthermore, the Systems Analysis workflow can handle some unconventional geometric profiles by breaking down those surfaces into straight sub-surfaces for EnergyPlus, while still maintaining accurate energy simulations [125]. This example demonstrates how BIM-BEM can support operational-phase evaluations through calibration. However, further research is required to validate its capabilities in more complex building scenarios.

BIM-BEM direct integration offers significant opportunities for enhancing energy efficiency in buildings. Most research utilizing this integration focuses on simulating envelope options, with common outputs being annual energy consumption and the energy use intensity indicator. However, a notable limitation is the lack of consideration for occupant behavior, as most studies adopt default values rather than explicitly addressing this factor. Consequently, while design-stage modifications can be simulated, actual operational outcomes may deviate unless real-world usage data is integrated. The challenge of accurately capturing factors such as user behavior, occupancy patterns, appliance usage, and comfort preferences appears to be one of the primary hurdles in achieving reliable simulations. Table 4 outlines the benefits and limitations of each topic covered in this section, providing an overview of the current state of research in each area. Table 5 presents the main topics covered by the studies

in this section, including the BIM and BEM tools used, tested variables, and evaluated outputs, correlating these metrics with the references in this section.

Despite these limitations, ongoing efforts and technological advancements continue to enhance this methodology. The key lies in leveraging these tools judiciously, understanding their strengths and limitations, to achieve optimal results in creating energy-efficient buildings. Case studies demonstrate the potential of BIM-BEM integration to optimize energy performance and reduce carbon emissions. While challenges persist, advancements in tools and methods showcase a commitment to overcoming these obstacles. The studies discussed in this section suggest that BIM-BEM direct integration may face challenges when applied to complex systems and innovative renewable technologies. Existing tools and plugins may present limitations in capturing the intricacies of these systems with the level of detail needed for accurate energy assessments. Furthermore, achieving reliable real-world performance could depend on the calibration of models that incorporate factors such as occupant behavior and maintenance practices, which may not always align with initial design assumptions. As a result, while direct integration may be well-suited for conventional or moderately complex projects, more advanced methodologies might be necessary to enhance its applicability to highly innovative building scenarios. Future efforts could focus on improving simulation capabilities, increasing flexibility in parameter inputs, and refining calibration approaches to better bridge the gap between predicted and actual performance.

Table 4 Benefits and limitations of BIM-BEM direct integration.

| Main topic | Benefit | Limitation | Reference |
|---|---|---|---|
| Energy performance evaluation | -Facilitates evaluation of multiple design scenarios and alternatives to identify energy-efficient solutions.<br>-Streamlines energy analysis process, saving time.<br>-Assists in compliance with thermal code regulations and standards (e.g., ASHRAE 90.1, CBECS). | -Software limitations restrict input variables.<br>-Difficulty in interpreting results due to browser-based display.<br>-Default operation profiles may impact accuracy.<br>-Energy audits and detailed BIM model creation can be time-consuming. | [108–110,121] |
| Energy performance optimization | -Offers advanced simulation capabilities (e.g., OpenStudio and EnergyPlus integration).<br>-Supports detailed analysis of energy models.<br>-Simplifies energy modeling workflow.<br>-Automates quantity and data provision (e.g., U-values, R-values).<br>-Facilitates compliance with energy performance certification schemes (e.g., EUI output). | -Accuracy depends on data availability and model quality.<br>Requires adjustments for accurate simulation outputs and customization of inputs.<br>-Limitations in HVAC system configurations and operational parameters.<br>-May lack flexibility in modifying outputs and limitations in BIM-BEM workflows. | [42,43,101,111–113,119,122,123,125] |
| LCA & Sustainability Assessment | -Automates material quantities and selection of eco-friendly options.<br>-Can reduce environmental footprint through sustainable material choices.<br>-Provides comprehensive building and interior space information for sustainability assessments. | -Requires substantial effort and robust database integration.<br>-Default parameters may result in inaccuracies.<br>-Effectiveness varies with data accuracy, completeness, and software expertise. | [114,116,117] |

Table 5 Correlation of BIM-BEM direct integration main topics, BIM and BEM software, tested variables, and evaluated outputs.

| | Main topic | | | | BIM tool | | BEM tool | | | | | | | Tested variable | | | | | | | | | | | | Evaluated output | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| References | Energy performance evaluation | Energy performance optimization | Lifecycle assessment | Sustainability assessment | ArchiCAD | Revit | DesignBuilder | Energy performance evaluation | Green Building Studio | Insight | IESVE | Sefaira | Systems Analysis | Location | Orientation | Typology | Geometry | Envelope | Structure | HVAC system | Control system | Lighting system | Equipment | Renewable system | Energy use intensity | Energy consumption | Energy cost | Financial analysis | $CO_2$ emission | Envelope thermal properties | Cooling/heating loads | LEED requirements |
| [108] | ✓ | | | | | ✓ | | | | ✓ | | | | | ✓ | | | ✓ | | | | | | | ✓ | ✓ | ✓ | | ✓ | | | |
| [121] | ✓ | | | | | ✓ | | | | ✓ | | | | | | | | ✓ | | | | | | | ✓ | ✓ | ✓ | ✓ | | ✓ | | |
| [111] | | ✓ | | | | ✓ | | | | ✓ | | | | | ✓ | | | ✓ | | | | | | | ✓ | | ✓ | | | | | |
| [122] | | ✓ | | | | ✓ | | | | ✓ | | | | | | | | ✓ | | ✓ | ✓ | ✓ | | ✓ | ✓ | | | | | | | |
| [43] | | ✓ | | | | ✓ | | | | | | | ✓ | ✓ | | | | ✓ | | ✓ | | | | | | ✓ | | ✓ | | | ✓ | |
| [125] | | ✓ | | | | ✓ | | | | | | | ✓ | ✓ | | | ✓ | ✓ | | | | | | | ✓ | ✓ | ✓ | | | | | |
| [108] | ✓ | | | | ✓ | | | ✓ | | | | | | | | | | ✓ | | | | | | | | ✓ | ✓ | | ✓ | | | |
| [123] | | ✓ | | | | ✓ | | | | | | | ✓ | | ✓ | | ✓ | ✓ | | | | | | | ✓ | ✓ | | | | | | |
| [112] | | ✓ | | | | ✓ | | | ✓ | | | | | | ✓ | | | ✓ | | ✓ | ✓ | | | | ✓ | ✓ | ✓ | | ✓ | | | |
| [42] | | ✓ | | | | ✓ | | | | | | | ✓ | | | | | ✓ | | ✓ | | | | ✓ | | ✓ | | ✓ | ✓ | | | |
| [101] | | ✓ | | | | ✓ | ✓ | | | | | | | | | | ✓ | ✓ | | | | | | | | ✓ | | ✓ | | | | |
| [119] | | ✓ | | | | ✓ | | | | ✓ | | | | | | | | ✓ | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | | | | | | ✓ |
| [110] | ✓ | | | | | ✓ | | | ✓ | | | | | ✓ | ✓ | | | ✓ | | ✓ | | | | | ✓ | ✓ | ✓ | ✓ | | | | |
| [114] | | | ✓ | | | ✓ | | | ✓ | | | | | | | | | ✓ | ✓ | | | | | | | ✓ | | | | | ✓ | |
| [116] | | | | ✓ | | ✓ | | | | | ✓ | | | ✓ | | ✓ | | | | | | | | | | ✓ | | | | | | |
| [113] | | ✓ | | | | ✓ | | | ✓ | | | | | | | | | ✓ | ✓ | | | | | | | | | | | | | |
| [118] | | ✓ | | | | ✓ | | | | | | ✓ | | | | | | ✓ | | | | | | | ✓ | | | ✓ | | ✓ | | ✓ |
| [117] | | | ✓ | | | ✓ | | | ✓ | | | | | ✓ | | | | | | ✓ | | | | | ✓ | ✓ | ✓ | ✓ | | | | |

## 7 BIM-BEM open data standards

Despite the benefits of BIM-BEM direct integration in assessing and optimizing building energy performance, challenges arise primarily due to software limitations, hindering the delivery of accurate results. Current tools often lack the advanced features necessary for detailed simulations, leading to generic outputs that may not accurately reflect the building's energy performance. Additionally, issues such as data loss and simplifications during model exchanges can compromise the reliability of energy assessments. These challenges directly impact the ability of BIM-BEM to support energy labeling schemes effectively.

Furthermore, integrating BIM with advanced energy simulation tools, such as EnergyPlus, is hindered by interoperability issues. Such issues are evident in both the design phase, where translating detailed geometry, material properties, and system configurations is critical, and the operational phase, which requires capturing real-world conditions such as occupancy and operation schedules. Without addressing these limitations, BIM-BEM integration may fail to provide reliable and actionable insights into building performance, which are essential for ensuring credible and effective energy labeling schemes [14,49].

Adopting open data standards such as Industry Foundation Classes (IFC) and Green Building XML (gbXML) offers a promising solution. These standards act as a bridge, enabling the exchange of detailed information between BIM models and advanced energy simulation tools, thereby enhancing the precision and reliability of energy performance assessments. By facilitating data transfer between different software platforms, these open data standards allow for the detailed representation of building elements, including geometry, materials, thermal zones, and air-conditioning systems. As a result, they can address design-stage specifics while also offering frameworks for operational data when models are updated over time. This dual applicability enhances the value of open data standards by potentially reducing the performance gap in energy labeling.

IFC is a widely adopted standard that supports the development of BIM-BEM methods for energy performance assessments. It enables data transfer from BIM to BEM and comprehensively analyzes a building's energy performance [126]. The Model View Definition (MVD), a subset of IFC, has been used to manage and simplify data transfer, ensuring that only necessary data is passed to energy simulation tools [39].

Some research has focused on developing IFC-based workflows to streamline the data exchange process and enhance the integration of BIM and BEM. Andriamamonjy et al. [127] proposed an IFC2Modelica workflow based on MVD that enabled accurate and efficient transfer of building data, improving the reliability of energy performance assessment. IFC-based frameworks can also streamline renewable energy simulation. For example, Gupta et al. [128] proposed a conceptual framework for developing IFC-compliant renewable energy simulation tools. This framework aimed to list the input data requirements of a solar photovoltaic simulation model, analyze the IFC data model, and extract relevant input data to run the simulation. The study demonstrated the potential of using IFC as a central data model linked to simulation models and information repositories to enhance the interoperability of renewable energy analysis tools. These examples demonstrate how open data standards can enhance energy simulations by reducing manual input errors and improving data consistency, both critical for reliable energy labeling.

Studies have demonstrated the integration of BIM-BEM using IFC to assess building performance. Plienaitis et al. [37] used IFC to import BIM data into IDA ICE simulation software, facilitating detailed studies of indoor comfort and energy consumption. This integration allowed for parametric scenario analysis, such as evaluating the impact of installing thermostatic valves on energy consumption and comfort levels. Besides the interoperability capabilities, open data standards for integrating BIM-BEM can generate reliable simulation results and streamline the energy performance assessment of buildings [129].

IFC allows for accurate mapping of a building's design parameters, which can then be enhanced with user behavior profiles in the energy simulation environment [18]. This integration elevates the potential of BIM beyond static design and energy calculations to model the complex interactions between occupants and their built environments. Incorporating behavioral dynamics with architectural data enables a comprehensive understanding of how daily activities influence energy usage and thermal comfort. Additionally, IFC facilitates BIM integration with other tools to assess heating and cooling loads, solar analysis, wind loads, and energy usage, allowing for precise energy performance analysis and optimization [130].

The gbXML standard is another open data format designed specifically for the energy simulation domain, enabling data transfer from BIM models to BEM software [38]. Although not as comprehensive as IFC, gbXML focuses on handling energy

simulation data, making it valuable for the energy performance assessment of buildings [57]. For example, Guo et al. [131] introduces a BIM-based evaluation system aimed at assessing and optimizing green building performance. This method highlights the integration of BIM with Ecotect and DesignBuilder to manage energy-related data and facilitate energy simulations. In this context, gbXML was used to streamline data between BIM and BEM tools. Similarly, other studies have demonstrated the integration capabilities of gbXML for combining BIM and BEM to perform energy simulations [98,122,132]. This approach facilitates evaluating a building's energy performance and aligns with energy labeling requirements [133].

The gbXML schema is proficient in capturing design parameters, and it is important to recognize that it evolves over time. Each new version and release of gbXML introduces additional classes and objects, thereby improving its capability to capture necessary information more effectively. For example, the most recent version, 7.03, released in August 2023, introduced new classes and objects, particularly related to HVAC systems [134], to further enhance this ability. However, while these continuous developments provide more detailed and precise data structures, gbXML may not fully address all issues, and the accuracy ultimately depends on the quality of the input data.

While open data standards facilitate BIM-BEM processes and enable the use of more sophisticated BEM tools compared to direct BIM-BEM integration, several challenges persist, including semantic data loss, translation errors of geometry, and the need for manual intervention [58,103,135]. These standards are still evolving and currently cannot represent all necessary details for building performance simulation due to a lack of standardized property sets [39]. Semantic divergences lead to inconsistencies when transferring data between BIM and BEM tools, as the same term might be interpreted differently depending on the context, resulting in incorrect or incomplete data being used in energy simulations and inaccuracies in energy predictions [94]. Furthermore, fully achieving bidirectional information exchange between BIM and BEM models remains challenging [120]. Additionally, inconsistent processes for adding attribute information during BIM modeling lead to inaccuracies and inefficiencies in creating BEM models [129].

Efforts are ongoing to improve middleware solutions, develop tools, and advance intelligent algorithm-based systems for automating BIM to BEM conversions. Continued promotion and development of IFC [39,136] and gbXML [137,138] are

crucial for advancing BIM-BEM interoperability and supporting automated workflows. Research utilizing Semantic Web technologies has shown that BIM data enrichment results in more precise energy consumption predictions [139], establishing a solid foundation for reliable energy labels. Developing corrective tools to automatically identify inaccuracies in open data standards is a promising solution to avoid manual corrections. For example, Kamel and Memari [40] developed a tool capable of correcting gbXML files for the BIM-BEM process. Additionally, an automated system that utilizes BIM data in IFCXML format and semantic name matching has been developed to improve the efficiency and accuracy of material property data input for BEM [94]. The development of intelligent algorithm-based systems holds promise for improving the efficiency and accuracy of energy simulations [140], with one notable algorithm achieving over 97.5% accuracy in converting IFC-based air-conditioning objects into IDF files [141]. Such automation could expedite the energy performance assessment and labeling process while reducing costs and potential human error. Fig. 3 visually represents the integration process between BIM and BEM using open data standards. It highlights the roles of BIM and BEM in providing detailed building information and energy performance simulations, respectively, while also outlining the benefits, issues, and improvement strategies associated with this integration.

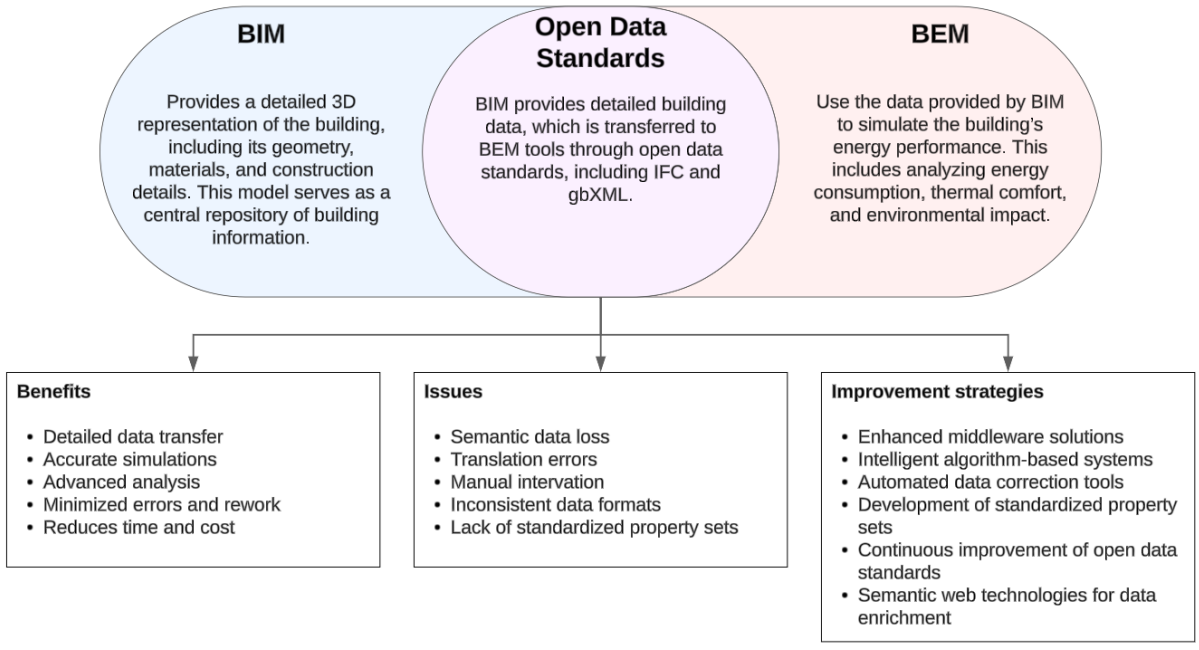



Fig. 3. Overview of BIM-BEM Integration Using Open Data Standards. Source: The authors (2025).

The BIM-BEM approach holds great potential for bridging the performance gap by enabling advanced energy consumption simulations during a building's operational

phase. Ensuring accurate data from BIM and addressing interoperability issues during the translation to BEM is imperative for fully leveraging BIM-BEM benefits. With well-defined and universally accepted open data standards, the industry can achieve seamless communication between BIM and BEM, facilitating straightforward and automated workflows to meet building energy efficiency objectives. Although open data standards significantly advance data exchange, further refinement is needed for specialized buildings and cutting-edge systems [39,58]. Semantic mismatches and incomplete data mappings still arise when attempting to model specific or nonstandard components [88]. Moreover, the pace of innovation seems to frequently outstrips updates to these standards, leaving practitioners reliant on manual workarounds or third-party extensions. These considerations suggest the importance of ongoing improvements to open data standards and the development of more robust middleware solutions. Enhancing these aspects could help streamline complex projects and support the continued relevance and adaptability of BIM-BEM to the evolving demands of sustainable construction.

## 8 BIM-based multi-objective optimization

Despite the widespread adoption of energy labeling schemes, especially in Europe, few buildings achieve high energy efficiency ratings [14]. This discrepancy suggests that while energy labeling policies are important, they often result in buildings merely meeting the minimum required standards rather than striving for higher efficiency. One goal of energy labeling is to encourage the development of highly energy-efficient buildings, thereby reducing greenhouse gas emissions and overall energy consumption. However, designing or retrofitting buildings to achieve high energy performance is a complex task, influenced by many factors and parameters, often with conflicting objectives. These include balancing thermal comfort and energy consumption within budget limitations and integrating renewable energy sources with existing systems. By evaluating multiple performance criteria simultaneously, this approach may help stakeholders identify cost-effective design solutions that improve building efficiency while maintaining financial feasibility.

A multi-objective optimization is an approach that aims to balance conflicting objectives by considering multiple criteria simultaneously [47]. This approach addresses the inherent complexity of design decision-making, enabling the development of more integrated and effective solutions for energy-efficient buildings.

Designers can identify options that best balance energy efficiency, initial cost, and occupant comfort, leading to more economical buildings that provide a comfortable and sustainable indoor environment [48]. In the context of energy labeling, this approach may offer an opportunity to refine design strategies by considering long-term performance and occupant needs, supporting a more adaptive and performance-driven labeling framework.

However, several limitations can affect its applicability and effectiveness. Multi-objective optimization evaluates multiple criteria simultaneously, requiring considerable computational resources and increasing the time needed to analyze and evaluate design options [142]. Additionally, multi-objective optimization may be sensitive to uncertainties and variations in input data, leading to significant variations in results, making it difficult to interpret and compare the solutions found [142]. Ensuring the accuracy and reliability of input data is therefore essential, yet it remains a considerable challenge in practical applications. These challenges are particularly relevant in the context of energy labeling schemes, where precise assessments of building performance are critical for generating meaningful energy labels. Addressing these issues is fundamental to improving the reliability and applicability of optimization-based approaches in real-world scenarios.

BIM can support multi-objective optimization by providing a detailed digital model of the building, serving as the basis for energy performance analysis and simulations. This enables designers to evaluate the building's performance against various criteria and identify improvement opportunities [45]. Additionally, BIM facilitates the integration of data from different sources and disciplines, which is essential for multi-objective optimization [143]. It provides a centralized platform for storing and sharing information, allowing designers to access and analyze relevant data efficiently. This ensures consistency and accuracy in performance analyses critical for informed decision-making [46].

In general, the application of BIM-based multi-objective optimization approaches begins with developing a BIM model containing the necessary data for energy simulation [144]. Machine learning algorithms can be used for result predictions, but the core of multi-objective optimization lies in genetic algorithms, applied to identify optimal solutions on the Pareto front [145]. The solutions are then evaluated against a reference case to measure improvements about the desired objectives such as energy consumption, thermal comfort, and cost-effectiveness [46].

Machine learning-based predictive models could offer a significant advantage for energy labeling by quickly estimating key performance metrics, automating simulations, and identifying optimal design solutions tailored to energy performance objectives.

Uncertainty and sensitivity analyses can be conducted to enhance the accuracy and robustness of predictive models [146]. Parametric and visual programming tools, such as Dynamo and Grasshopper, can be employed to automate processes and data exchange in the BIM-based multi-objective optimization workflow [45]. These tools streamline workflows, reducing the manual effort required for energy labeling processes, directly addressing challenges related to labor intensity and time consumption. Table 6 summarizes the software, machine learning techniques, genetic algorithms, optimization objectives, and tested variables used in the studies discussed in this section.

Table 6 Summary of BIM-based multi-objective optimization approaches in building energy performance.

| Reference | Software | Machine Learning | Genetic Algorithm | Objectives | Tested Variables |
|---|---|---|---|---|---|
| [145] | Revit<br>DesignBuilder | Least Squares Support Vector Machines | NSGA-II | -Minimize energy consumption.<br>-Maximize thermal comfort. | -Wall, roof, and glass U-value.<br>-Wall and roof solar absorptance.<br>-WWR. |
| [46] | Revit<br>Dynamo<br>Green Building Studio | Self-Organizing Map | NSGA-II | -Maximize daylight autonomy.<br>-Maximize useful daylight illuminance.<br>-Minimize energy use intensity. | -Building height and width.<br>-Window width. |
| [45] | Revit<br>Rhinoceros<br>Grasshopper<br>Ladybug tools | - | SPEA-2 | -Maximize indoor environmental quality.<br>-Minimize life cycle cost. | -External and internal walls, roof, floor and window system. |
| [47] | Revit<br>Dynamo | - | NSGA-II | -Minimize overall thermal transfer value.<br>-Minimize retrofit cost. | -Wall and glass U-value.<br>-Wall cost per m².<br>-WWR.<br>-Shading angles.<br>-Window cost. |

| | | | | | |
|---|---|---|---|---|---|
| [144] | Revit DesignBuilder | Random Forest | NSGA-III | -Minimize energy consumption.<br>-Minimize life cycle cost.<br>-Minimize carbon emissions.<br>-Maximize thermal comfort. | -WWR.<br>-Wall, roof, and glass U-value.<br>-Wall and roof solar absorptance.<br>-Window airtightness.<br>-Setpoint (heating and cooling). |
| [147] | Revit Dynamo Insight | - | NSGA-II | -Maximize LEED points.<br>-Minimize life cycle cost. | -43 variables. |
| [148] | Revit DesignBuilder | Grey Wolf Optimization-Random Forest | NSGA-II | -Minimize carbon emissions.<br>-Minimize costs.<br>-Maximize thermal comfort. | -Wall, roof, and glass U-value.<br>-Roof solar absorptance.<br>-WWR.<br>-Setpoint (heating and cooling). |
| [146] | Revit DesignBuilder | Bayesian Optimization-Light Gradient Boosting Machine | AGE-MOEA | -Minimize energy consumption.<br>-Minimize carbon emissions.<br>-Maximize thermal comfort. | -Wall, floor, and glass U-value.<br>-Infiltration rate.<br>-Window solar factor.<br>-WWR.<br>-COP (heating and cooling).<br>-Setpoint (heating and cooling).<br>-Setpoint (window operation). |
| [48] | Revit DesignBuilder | Particle Swarm Optimization-Random Forest | NSGA-III | -Minimize energy consumption.<br>-Minimize carbon emissions.<br>-Maximize thermal comfort. | -WWR.<br>-Wall and roof U-value.<br>-Airtightness.<br>-Wall and roof solar absorptance.<br>-Setpoint (heating and cooling). |

During the design process, it is essential to consider a range of goals and recognize that a uniform approach may not address the complex challenges of energy-efficient construction [147]. In this context, BIM-based multi-objective optimization, particularly through the application of genetic algorithms, has been highlighted [45,144,145]. The most common optimization objectives include reducing energy consumption and carbon emissions while maximizing thermal comfort.

Integrating energy simulation with BIM-based multi-objective optimization offers a comprehensive approach to sustainable building design [148]. However, this approach requires substantial input data and time, which can lead to increased costs and complexity. Recent studies have investigated the potential of machine learning to mitigate those challenges. By leveraging Random Forest algorithms and detailed BIM data, these predictive models can rapidly generate accurate estimates of energy consumption and thermal comfort [48,144]. This approach streamlines the resource-intensive process of traditional energy simulations, enabling more efficient decision-making in building design. While primarily applied during the design phase, these approaches could also support retrofit projects by incorporating data on existing building conditions, thereby enhancing the accuracy of energy labeling.

Another approach that has been utilized is a hybrid method, which combines genetic algorithms and machine learning techniques [48,146,148]. This combination aims to address the individual limitations of each algorithm and provide a more robust solution for optimization problems using the BIM model's database. The flexibility and adaptability of these methods are emphasized when dealing with complexities and uncertainties, highlighting the feasibility and effectiveness of hybrid approaches in achieving optimal solutions for building projects. Accordingly, such methods can address both initial design decisions (e.g., envelope) and operational-phase refinements (e.g., system scheduling).

BIM-based multi-objective optimization also helps with compliance with energy performance regulations and environmental goals. A retrofit method has been introduced to optimize building envelope thermal performance [144]. This method utilizes BIM, visual programming language, and multi-objective optimization to identify cost-effective retrofits that improve energy efficiency. This approach assists in selecting the best building components to reduce Overall Thermal Transfer Value (OTTV) and retrofitting costs, thus aiding in meeting regulatory OTTV values and other thermal performance standards.

By considering different combinations of variables related to lifecycle costs and sustainability, studies seek solutions that balance energy performance requirements with associated costs, leveraging the capabilities of BIM for integration and collaboration [147]. The importance of approaches that consider not only technical aspects, but also economic and regulatory factors involved in the design and construction of sustainable buildings is emphasized, using BIM as a tool for data

analysis and simulation. These studies offer insights for industry professionals interested in achieving energy labels and optimizing costs simultaneously, leveraging the capabilities of BIM for data analysis and modeling. This dual focus on technical and economic factors may support energy labeling by helping designs align with performance standards while maintaining financial feasibility for stakeholders.

While energy consumption, carbon emissions, and thermal comfort are commonly considered, a more integrated approach should address indoor environmental quality and lifecycle costs. These aspects are essential for the widespread adoption of energy labels, as a lack of well-being indicators hinders its usage [14]. It is worth noting that although most research does not explicitly mention problems with data interoperability, it is implied by the absence of direct BIM-to-BEM workflows and the prevalent use of middleware [45]. In a study by Jalilzadehazhari et al. [143], gbXML was used to transfer building data from Revit software to DesignBuilder; however, manual adjustments were required later in EnergyPlus, highlighting interoperability limitations.

The proposed approaches in this section were created to develop energetically efficient and sustainable buildings, offering several benefits such as identifying cost-effective solutions and automating energy-related certification requirements [47,147]. However, the case studies were mostly limited to controlled experiments, lacking real-world applications in design processes, which may raise doubts about the feasibility of the proposed optimization methods. While multi-objective optimization can lead to longer design process time and requires significant computational resources and trained professionals [46], it also provides a robust approach to achieving optimal energy performance in buildings. Balancing these advantages with the associated challenges is essential for successfully implementing these approaches in practical settings.

The potential of a BIM-based multi-objective optimization approach is highlighted in developing highly energy-efficient buildings. Energy performance labeling evaluates a building's energy performance based on operational energy consumption; however, it's equally important to consider broader environmental impacts such as greenhouse gas emissions and resource depletion. Energy-saving measures may not always proportionally reduce these impacts, underscoring the necessity for balanced solutions in building renovations [26]. Integrating BIM-based multi-objective approaches into the energy labeling process could address both energy

performance and environmental impacts, ensuring that energy-efficient measures lead to cost savings and overall environmental sustainability. Ultimately, successful implementations should account for decisions made early in the design phase as well as adjustments and performance assessments in the operational phase.

## 9 Digital twin for efficient operation

Integrating BIM with BEM tools and optimization techniques alone cannot guarantee a building's energy performance. Most research has yet to account for crucial factors impacting energy consumption, such as occupant behavior and poor maintenance practices. Occupant behavior significantly influences energy usage during the operational stage, while poor maintenance can lead to equipment and systems degradation, reducing energy efficiency. Therefore, maintaining good energy performance and indoor environmental quality is essential to avoid the performance gap. Energy labeling schemes could benefit from addressing these operational challenges through advanced monitoring and predictive strategies. Some research has explored the fusion of BIM with IoT-based systems to support both the design process, in cases of retrofits or expansions. and the operational management of buildings.

BIM-based IoT systems generally rely on real-time data streams to generate interactive digital replicas of physical buildings [50]. These systems can include digital meters, sensors, actuators, microcontrollers, and other IoT devices throughout buildings to capture real-time data on desired parameters [51]. Data storage and processing typically occur on cloud-based platforms, allowing for real-time monitoring and analytics [51]. BIM serves as a digital replica that can consolidate architectural, structural, and systems data into a cohesive model [54]. Continuous data integration connects physical assets with the BIM model by updating it with current building performance metrics [149]. This integration enables dynamic visualization, analysis, and predictive insights [54], empowering stakeholders in managing and optimizing the building's operational efficiency [52].

Recent studies have highlighted the significant benefits of BIM-based real-time monitoring and management across various domains. Spūdys et al. [51] proposed a framework for operational building assessment using a digital twin approach to address operational efficiency. This method controls and incorporates real-time data collection through IoT sensors into the BIM model. The authors proposed a set of Key Performance Indicators (KPIs) to evaluate operational building performance more

accurately. These KPIs, integrated into the digital twin platform, provide a more realistic and dynamic assessment of a building's energy performance.

Using actual data from IoT sensors instead of simplified and default data is an important step to bridge the performance gap [51], but several other aspects must also be addressed. Maintaining optimal performance of a building's systems throughout the operational stage can be challenging. Factors such as wear and tear, aging equipment, changing environmental conditions, and occupant behavior can all impact system performance, making it difficult to maintain optimal operation consistently. Proactive maintenance, monitoring, and management strategies are essential for addressing these challenges. In this regard, digital twins have been used to visualize, monitor, and predict faults and degradation in physical assets.

A study by Li et al. [150] presented a foundation model for building digital twins, focusing on a case study of a chiller system to demonstrate its practical application. The digital twin provided a high-fidelity virtual replica of the physical chiller system, allowing for detailed representation and monitoring of its real-time working status. The research also employed intelligent algorithms to adjust and optimize the set values of the chiller, improving its coefficient of performance. Digital twins can also be employed for anomaly detection, as demonstrated by Lu et al. [151]. In their study, a digital twin-enabled anomaly detection system that leverages BIM and integrates data from various sources, including real-time sensor data, to identify anomalies was proposed. The authors demonstrated the system's effectiveness through a case study of centrifugal pumps in an air-conditioning system, where it successfully identified an anomaly indicative of a pump shutdown.

Occupant behavior is one of the main reasons for the performance gap, along with operational and maintenance issues. Therefore, it is crucial to develop approaches that can raise occupants' awareness of energy usage in buildings. In this sense, BIM can be fused with IoT technology, providing a user-friendly digital platform capable of demonstrating real-time data related to the building's energy performance, including energy patterns.

Some studies have developed digital platforms that provide real-time feedback on energy usage to building occupants, making them more aware of their energy consumption patterns [54]. BIM serves as a virtual representation of the physical assets, containing energy-related data and providing a visual representation of the building and its systems, enabling occupants to visualize the impact of their behavior.

By making energy use more visible and understandable to occupants, the platform aims to motivate behavior change towards more energy-efficient practices. Lee et al. [54] have demonstrated that effective energy feedback can influence energy-saving behavior among building occupants. Mataloto et al. [149] implemented a user-friendly 3D IoT system for monitoring indoor environmental conditions and energy consumption within an office building. The aim was to make energy consumption data more accessible and understandable for occupants without technical expertise, ultimately promoting sustainable behaviors. The BIM model visually represents the data collected from sensors in a colored, intuitive way.

Despite the benefits, Lee et al. [54] and Mataloto et al. [149] argue that changing long-standing behavioral habits related to energy use can be challenging, even with access to real-time energy data. Occupants may revert to old habits over time, reducing the initial impact of the BIM-based IoT platforms. Some occupants may not actively engage with the digital platform or fully understand how to interpret the energy data provided, hindering behavior change efforts. Furthermore, not all occupants may have a strong awareness of sustainability issues or may prioritize other factors over energy conservation. This lack of awareness or differing priorities can influence occupants' willingness to participate in energy-saving initiatives actively. To mitigate these challenges, certain solutions, such as intuitive controls and easy-to-understand interfaces, can support post-occupancy engagement. To address these issues, some research has gone beyond visualization and monitoring approaches, developing BIM-based IoT systems capable of monitoring energy usage and environmental data, analyzing it, and optimizing the building's operation with automated systems.

Tan et al. [51] introduced a digital twin approach integrating BIM with real-time occupancy and ambient light data. The proposed system offers an automated solution for intelligent lighting control and energy management in buildings, enabling smart lighting control, dynamically adjusting or turning off lights in unoccupied or naturally well-lit areas to avoid unnecessary energy use. The system optimizes energy savings, leading to a reduction in electricity costs by approximately 79%, as demonstrated in a case study.

Beyond energy management, BIM-based IoT systems can enhance occupant thermal comfort, which is crucial for building energy efficiency. Optimizing indoor temperatures within comfortable ranges can reduce HVAC energy consumption,

leading to cost savings and a lower environmental impact [56]. Sensors deployed indoors can acquire real-time data on parameters like temperature, humidity, and air quality [152]. This data can be stored in microcontrollers and linked to the BIM model through visual programming approaches, such as using Dynamo to acquire data from Arduino microcontrollers [152]. This data can then be interpolated, used to determine thermal comfort (e.g., PMV index), and visualize thermal comfort conditions within the BIM model [56]. Integrating these insights into energy labeling schemes allows for a more comprehensive assessment by considering both energy performance and occupant satisfaction, ultimately promoting wider adoption.

IoT devices integrated within BIM facilitate real-time analysis and feedback on indoor environmental conditions. These devices monitor and collect data, feeding it into BIM-driven analyses for a nuanced understanding of thermal comfort. Advanced predictive modeling, refined by real-time data from smart devices, informs machine learning models to predict thermal comfort levels accurately [55]. These models can also control HVAC systems based on data collected by IoT sensors, ensuring optimal thermal conditions and enhanced energy efficiency [56]. Besides, BIM-based IoT approaches could be used to predict and enhance indoor conditions and energy usage based on environmental outdoor parameters collected by IoT sensors on the facade of the building [50].

The integration of BIM with IoT for optimizing individual building performance is widely explored in the literature, but these technologies have broader implications. For instance, Qian and Leng [97] proposed a City Intelligent Model (CIM) framework for maintaining and managing Chinese rural traditional dwellings by integrating BIM, IoT, GIS, AI, and other technologies for comprehensive district-level management analysis. The study aimed to modernize traditional dwellings with minimal intervention by collecting influencing factors, providing design guidance, and enabling early warning and prediction through CFD-ANN simulations on a digital platform. The CIM framework facilitated proactive risk mitigation and guided residents in preventive actions, such as during strong plum rain. Besides, real-time data gathered through IoT devices is analyzed using AI, specifically a CFD-based ANN, to simulate and predict energy performance. This integration enables a proactive and predictive approach, allowing for informed interventions and optimized energy use. This initiative could be used to leverage a district-level energy labeling framework, enabling aggregated data insights that foster regional sustainability improvements.

As exemplified by Qian and Leng [97], smart management at a district level could leverage the energy performance of buildings by aggregating and analyzing data from multiple buildings within the district collectively. This data set could provide insights into the overall district's energy consumption patterns, identify trends, and highlight areas for improvement across the district. The district-level approach also allows for benchmarking and comparing energy performance among buildings within the district, supporting the development of energy efficiency policies and planning initiatives on a broader scale.

The adoption of BIM-based IoT systems spans various focuses and offers numerous benefits for enhancing the energy performance of buildings and addressing challenges associated with energy labeling. However, this approach also encounters significant hurdles, as highlighted in Table 7. Implementing BIM-based IoT systems can be resource-intensive, involving high costs, time commitments, and potential disruptions, which necessitate meticulous planning and stakeholder engagement. Beyond the initial complexity, ongoing maintenance expenses, computational complexities, challenges in managing large datasets, and costs associated with cloud services further contribute to the overall investment. Moreover, widespread adoption is hindered by the absence of digital BIM representations in many buildings, complicating interoperability between different systems. Additionally, the operation of IoT devices may require consistent power sources, posing a constraint in existing buildings where such infrastructure may not be readily available.

Table 7 Benefits and limitations of BIM-based IoT systems for building energy performance.

| Focus | Benefit | Limitation | Reference |
|---|---|---|---|
| Asset Monitoring | -Real-time monitoring enhances decision-making and energy efficiency.<br>-High-fidelity mapping provides detailed representation and monitoring of physical assets.<br>-Efficient anomaly detection improves maintenance practices. | -System complexity and integration issues can hinder implementation.<br>-Interoperability and data quality are ongoing concerns.<br>-Security, privacy, and skill gaps must be addressed. | [150,151] |
| Energy Management | -Real-time monitoring and user interaction promote sustainable behaviors.<br>-Energy consumption reduction and improved efficiency through data analysis and pattern identification. | -Hardware compatibility and data security challenges.<br>-Scalability and power consumption issues.<br>-Integration complexity and initial investment costs. | [54,149] |

| | | | |
|---|---|---|---|
| Operational Optimization | -Automated solutions for intelligent lighting control and energy management.<br>-Real-time analysis and enhanced monitoring for operational efficiency.<br>-Improved energy assessment and decision-making. | -Pedestrian follower mechanism accuracy and data integration challenges.<br>-Technical feasibility, system scalability, and cost constraints.<br>-Lack of standardization and data quality issues. | [49,51] |
| Outdoor Environment Monitoring | -Real-time monitoring provides a framework for digital twin development.<br>-Potential for future expansions and improved environmental monitoring. | -Connectivity disruptions and signal attenuation can impact reliability.<br>-Balancing system affordability with benefits remains a challenge. | [50] |
| Smart Management | -Holistic analysis and improved sustainability for smart campus and district management.<br>-Low intervention, high-efficiency management for traditional dwellings.<br>-Enhanced decision-making and sustainable technology implementation. | -Hardware integration and interoperability issues.<br>-Complexity in comfort measurements and interdisciplinary collaboration.<br>-Data prediction accuracy and technological challenges. | [52,53,97] |
| Thermal Comfort | -Real-time monitoring and optimization of thermal comfort levels.<br>-Enhanced decision-making through automated integration and visualization.<br>-Improved energy efficiency and reduced HVAC consumption. | -Interoperability and data collection accuracy challenges.<br>-BIM model availability and technical expertise requirements.<br>-User acceptance and training for optimal use. | [56,152] |

Despite these hurdles, the benefits of such systems are substantial, enhancing data reliability and transparency. Real-time data generated by these systems contribute to a comprehensive database with accurate information about the building, which could be crucial for energy labeling and future retrofitting initiatives. Moreover, this approach enhances users' perception of energy usage relevance in the built environment and leverages the maintenance of the building’s systems, critical aspects for the performance gap. Effectively, digital twins and BIM-based IoT networks effectively support both the design phase, by providing insights for improved system specifications and layouts, and the operational phase, by enabling data-driven optimizations that foster sustained energy efficiency throughout the building’s lifecycle.

BIM-based real-time monitoring systems offer an approach to managing building performance and promoting energy efficiency. By integrating digital modeling with live data streams, these systems provide insights into energy consumption, environmental conditions, and occupant behavior, driving informed decision-making and sustainable practices. By leveraging real-time data from BIM-based IoT systems,

stakeholders may have the opportunity to refine energy labeling by incorporating actual system performance, occupant interactions, and maintenance needs, rather than relying solely on static or simplified inputs. This operational feedback could also contribute to informing future design decisions, fostering a continuous loop between initial modeling and real-world performance. As a result, energy labels have the potential to become more accurate, reflecting occupant satisfaction alongside energy metrics and encouraging broader adoption of sustainable practices. Additionally, the digital twin approach could help maintain the adaptability and transparency of labeling processes, supporting their alignment with operational performance, an aspect that remains a key challenge in building energy management.

However, while digital twins hold considerable promise to align modeled and real-world performance, practical deployments frequently encounter issues with data quality, uncertain occupancy patterns, and system wear over time [49,51,54]. Managing these variables demands ongoing calibration processes, that may involve advanced analytics or machine learning [145,146]. Moreover, the implementation of advanced and innovative systems introduces additional layers of complexity that may need to be thoughtfully addressed to achieve a more accurate representation within the digital environment. These challenges underscore the need for consistent IoT infrastructure, refined modeling protocols, and intelligent algorithms capable of adapting to dynamic conditions [55]. By addressing these factors, digital twin applications can move beyond proof-of-concept scenarios and drive substantial gains in operational energy efficiency and occupant well-being.

## 10 Discussions

This research investigates the potential issues and challenges facing energy labeling and reviews the potential of BIM-based approaches to leverage energy performance assessment. Initially, through the literature review, it was noted that the implementation of energy labeling is hampered by several issues [13,14,16,20], leading to its limited adoption. Fundamental problems revolve around data availability, acquisition, and accuracy. Manual processes also pose a significant obstacle, being labor-intensive, time-consuming, and prone to errors. Energy labeling schemes may resort to simplifications to circumvent these challenges, yet they often result in a performance gap. This gap is compounded by other factors such as user behavior and inadequate maintenance practices, which undermine the credibility and reliability of

energy labeling. For instance, governmental reliance on energy label data for developing new energy policies is hindered if the accuracy of the data is questionable. Investors also face uncertainty, as it becomes challenging to gauge the return on investment when confronted with a performance gap. Furthermore, there is a consensus that the current energy label schemes lack useful indicators for building occupants, such as well-being metrics, thereby diminishing their role as decision-making tools in property acquisition.

In light of these challenges, the BIM-based approaches identified in this review offer several strategic advantages that can be effectively leveraged to address these issues:

- BIM as a data repository plays a significant role in improving data management and addressing the performance gap in energy labeling. By centralizing detailed building information, such as geometry, materials, mechanical systems, and occupancy patterns, BIM offers a more structured and consistent data management framework for energy performance assessments. This centralization can potentially reduce discrepancies caused by fragmented data sources and manual processes, thereby enhancing data consistency. Additionally, the dynamic nature of BIM enables it to accommodate updates reflecting changes throughout the building lifecycle, supporting better alignment between design intentions and actual performance. However, the effectiveness of BIM as a data repository depends on accurate data input and regular updates by users, as well as proper integration with other tools. While it establishes a more reliable foundation for energy assessments, further efforts in data validation, user training, and management are crucial to fully realizing its benefits in energy labeling. Furthermore, when buildings integrate innovative HVAC systems, on-site renewable energy sources, or energy storage solutions, additional data fields and modeling guidelines may be necessary to accurately represent these unique elements within BIM models. Ensuring such adaptability is particularly crucial for capturing the operational complexities associated with advanced, low-carbon developments, enabling more precise energy performance assessments and informed decision-making throughout the building lifecycle.
- Enhanced BIM model generation techniques provide detailed digital models that accurately represent as-built conditions through methods such as 3D laser

scanning, thermography, and point cloud processing. These techniques help capture geometric details, material properties, and thermal characteristics, which are essential for precise energy assessments. Automated model generation reduces the reliance on manual data entry, minimizing errors and potentially improving the accuracy of energy labels. This approach particularly benefits older buildings with non-standardized practices and inconsistent data. However, while it accelerates data acquisition and improves model accuracy, its success depends on factors like equipment quality, user expertise, and integrating generated models into the energy labeling process. Proper training and investment in scanning technologies are necessary to ensure meaningful contributions to energy performance evaluations. At the same time, high-tech or unconventional buildings with atypical geometries or cutting-edge systems may still require additional calibration efforts, since capturing visual data alone does not solve interoperability challenges or operational-related uncertainties.

- BIM-BEM direct integration aims to streamline workflows by connecting BIM software directly to BEM tools through built-in plug-ins or add-ons. This approach allows users to conduct energy simulations within the BIM environment, minimizing manual data transfer and file conversions. By keeping users within the BIM domain, this integration reduces interoperability challenges and improves workflow efficiency, enabling faster iterations of design and analysis. However, despite these benefits, BIM-BEM direct integration often relies on default data and simplified models, limiting the accuracy of energy predictions. This approach can lead to less precise simulations than more robust methods like BIM-BEM open data standards. While it enhances user convenience and speeds up the modeling process, its effectiveness in achieving accurate energy assessments is contingent on the quality of input data and the capabilities of integrated simulation engines. The results are generally more suitable for early-stage design evaluations, rather than detailed operational assessments, given the potential inaccuracies that arise from data transposition limitations. Moreover, many existing plug-ins are not yet fully equipped to handle specialized or emerging clean-energy technologies, highlighting a gap in current toolsets that can limit their applicability in advanced projects.

- BIM-BEM open data standards focus on facilitating interoperability between different software tools by using standardized formats like IFC and gbXML. Unlike direct integration, which is confined to proprietary workflows within BIM tools, open data standards promote broader compatibility, enabling comprehensive data exchange between BIM models and advanced energy simulation tools. This approach supports more detailed and accurate simulations by allowing for a broader transfer of building information, including geometry, material properties, and HVAC system details. As a result, it offers more precise energy predictions and reduces the reliance on default values. However, achieving these benefits depends on consistent protocol adherence, user training, and software compatibility. Although open standards can provide a more robust framework for energy assessments, challenges like semantic data loss, translation errors, and the need for manual adjustments persist, affecting the overall reliability of energy labeling outcomes. Furthermore, specialized or emerging technologies may not be fully represented within existing IFC or gbXML schemas, requiring either interim middleware solutions or customized extensions. As these advanced systems evolve, continuous revisions to open data standards become essential to accommodate new materials, components, and performance metrics.
- BIM-based multi-objective optimization provides a comprehensive approach to building design by simultaneously considering multiple criteria, such as energy efficiency, thermal comfort, and cost-effectiveness. It enables stakeholders to evaluate various design scenarios, identify optimal retrofit strategies, and balance conflicting objectives. The use of optimization algorithms within BIM workflows helps maximize energy savings while maintaining economic viability. This approach is particularly useful in identifying cost-effective measures that go beyond compliance with minimum standards, supporting the development of high-performance buildings. However, its effectiveness relies on the availability of accurate input data, computational resources, and user expertise. These practical constraints still limit the adoption of multi-objective optimization in real-world applications, but when implemented effectively, it encourages stakeholders to pursue designs that prioritize both energy performance and economic feasibility. Additionally, projects incorporating near-zero carbon systems or experimental energy technologies could benefit

from multi-objective optimization to explore trade-offs between emerging solutions. However, achieving meaningful results requires comprehensive calibration processes to better align simulations with real-world operational performance.

- Digital Twin for Efficient Operation extends BIM's capabilities by integrating it with IoT technologies, creating a real-time digital replica of the physical building. This approach allows for continuous system performance monitoring, occupant behavior, and environmental conditions, facilitating dynamic adjustments to maintain optimal energy performance. Digital twins can address the performance gap more effectively by providing insights into real-world building operations and enabling proactive maintenance strategies. By visualizing energy consumption patterns and detecting deviations from expected performance, digital twins promote better energy management and user awareness. However, their implementation requires significant investment in IoT infrastructure, data processing capabilities, and skilled personnel. While digital twins offer substantial potential for improving energy labeling accuracy, their impact depends on data quality, system maintenance, and user engagement to translate insights into actionable measures. In specialized buildings featuring complex HVAC or renewable systems, digital twin platforms could be enhanced through model calibration and the integration of sensor data, which may support more effective implementation and validation of operational strategies. Without such refinements, evolving occupant behavior and system degradation could continue to contribute to discrepancies between simulated and actual energy performance.

While each of these BIM-based approaches offers distinct advantages and addresses specific shortcomings in the traditional energy labeling process, they can be even more effective when strategically combined. Table 8 presents a conceptual overview that illustrates how each approach can be applied at different phases of a building's life cycle. In doing so, it highlights the complementary nature of these methods: for instance, direct BIM-BEM integration and multi-objective optimization may be most valuable during design, whereas enhanced model generation and digital twin technologies play critical roles in post-construction monitoring and retrofit scenarios. By viewing these strategies as components of an integrated map rather than

isolated tools, stakeholders can more systematically reduce the performance gap, streamline workflows, and improve the overall reliability of energy labeling.

Table 8 BIM-based approaches for energy labeling across design, retrofit, and operation phases.

| Lifecycle phase | Recommended approaches | Key considerations | Expected outcomes |
|---|---|---|---|
| Design (new buildings) | -BIM-BEM direct integration: Supports early-stage simulations, potentially guiding energy-efficient design and compliance assessment.<br>-BIM-BEM open data standards: May improve interoperability and facilitate collaboration by reducing manual errors.<br>-BIM-based multi-objective optimization: Helps explore trade-offs between energy efficiency, costs, and occupant comfort. | -Advantages: May facilitate iterative design processes and support compliance validation.<br>-Challenges: Reliance on assumptions and generic data, difficulties in capturing real operational conditions. | More informed design decisions; potentially improved workflows; better alignment with regulatory requirements; enhanced data coordination among stakeholders. |
| Operation (in-use) | -BIM-BEM open data standards: May support continuous energy performance assessments by facilitating data integration.<br>-Digital Twin: Can provide real-time monitoring, performance analysis, and occupant engagement opportunities. | -Advantages: May assist in ongoing performance tracking and proactive maintenance planning.<br>-Challenges: Issues related to data accuracy, sensor integration, and the unpredictability of occupant behavior. | Potential reduction of the performance gap; improved operational insights; proactive strategies for maintenance; possible enhancements in occupant comfort. |

| | | | |
|---|---|---|---|
| Retrofits (existing buildings) | -Enhanced BIM model generation techniques: Aims to provide more reliable as-built models to support retrofit planning and simulations.<br>-BIM-BEM open data standards: Can contribute to data consistency between legacy and new systems.<br>-BIM-based multi-objective optimization: Supports the identification of potential retrofit strategies that balance cost and energy efficiency. | -Advantages: Could provide useful baseline data for retrofitting efforts.<br>-Challenges: Potential inconsistencies in documentation, variations in building usage, and difficulties in integrating with older systems. | More effective energy retrofitting approaches; potentially cost-effective retrofit planning; improved data centralization for long-term building management. |

The complementary nature of BIM-based methods across different stages of energy labeling demonstrates their potential to enhance accuracy, efficiency, and transparency. BIM-BEM open data standards play a crucial role throughout the building lifecycle by supporting interoperability, minimizing reliance on proprietary software, and facilitating continuous model calibration as buildings evolve. However, to fully leverage these advantages, ongoing advancements in existing tools are required, particularly to address the complexities of high-tech and non-standard building systems.

Utilizing BIM's capabilities presents a viable approach to overcoming key challenges in energy assessments and labeling, contributing to more accurate energy labels, promoting sustainable building practices, and improving operational efficiency. Nevertheless, the integration of specialized technologies may introduce additional challenges, emphasizing the need for continuous refinement of both proprietary and open-source tools to effectively support next-generation building systems. Despite advancements, certain areas remain underexplored, highlighting opportunities for further research to optimize the role of BIM in energy performance labeling.

Current BIM-based approaches primarily target performance gaps by enhancing data accuracy and process automation. However, these methods face limitations when applied to real-world scenarios, especially in the context of energy labeling. This underscores the need to explore new research directions to make the labeling process more effective and aligned with building performance realities.

One promising research direction can be the integration of BIM with artificial intelligence (AI) and machine learning for estimating energy use intensity [35], thermal comfort [153], and user behavior [154]. Although the broader field of AI encompasses a wide range of methods, such as advanced deep learning and large language models, this paper uses the term “AI-based approaches” primarily to refer to data-driven machine learning and meta-modeling techniques [61,155], aimed at energy performance forecasting and occupant behavior analysis. Such methods can potentially enhance the energy labeling process by offering more refined building performance predictions, reducing the reliance on default values, and capturing dynamic factors such as occupant behavior. Additionally, AI-based energy evaluation approaches demand less effort than traditional methods based on BEM, and the results obtained through this strategy closely align with those produced by advanced BEM tools [155].

It's worth noting that energy performance assessments based on machine learning approaches are already being used for building energy labeling. For example, Brazil introduced a Normative Instruction in 2022 allowing the use of an ANN-based simplified method for cooling load estimation [155]. However, there is a gap in the integration of BIM into this approach and its potential impact on enhancing the accuracy and efficiency of energy labeling [156]. Few studies have delved into integrating BIM with AI-based methods for energy labeling purposes [61], revealing the need for further research and exploration in this area.

Another critical area of exploration is the integration of BIM with natural ventilation strategies in energy assessments [157,158]. Incorporating natural ventilation can provide a more accurate picture of a building’s energy performance, particularly in climates or scenarios where natural airflow plays a significant role in energy dynamics. Enhancing energy labels with metrics that account for natural ventilation could help differentiate buildings that employ passive design solutions, potentially improving label accuracy and reflecting the building's true energy-saving potential. This approach also has social implications, offering more cost-effective solutions for economically disadvantaged communities and addressing energy poverty by reducing the dependency on HVAC systems.

A significant limitation of energy labeling schemes is the lack of consideration for embodied energy. While most of the energy consumption occurs during the operational stage of the building [159], embodied energy should be treated more

carefully, particularly in countries with cleaner energy matrices, where the impact of operational energy use is less pronounced [117]. As presented in this paper, BIM can be utilized to calculate a building's embodied energy, streamlining the evaluation of operational energy associated with materials and construction processes [160,161]. While some countries have specific policies to leverage reductions in a building's embodied energy [14], incorporating embodied energy aspects into energy labeling schemes could further benefit climate change mitigation efforts.

Moreover, considering climate change is becoming increasingly essential in energy performance simulations, as shifting climate patterns alter building energy demands over time. Integrating climate change scenarios into BIM-based energy assessments could refine the accuracy of labels, making them more resilient to future conditions. For example, accounting for projected temperature increases or changing weather patterns could help predict a building’s long-term energy performance more reliably. Such considerations would enhance the credibility of energy labels by aligning them with adaptive strategies that ensure long-term building efficiency, ultimately making labels more relevant and actionable in policymaking and investment decisions.

The explored strategies pinpointed in this review hold promise for facilitating the implementation of energy performance labeling, specifically by reducing time and costs, enhancing accuracy, and influencing societal perceptions of energy label usefulness. However, it's crucial to acknowledge that certain challenges persist beyond the scope of BIM-based approaches.

Barriers to widespread investment in energy-efficient buildings, such as financial constraints and limited awareness, continue to pose significant hurdles, particularly in developing nations [126]. Addressing these challenges requires a multifaceted approach that encompasses regulatory frameworks, financial incentives, and technology policies to foster energy-efficiency developments. Moreover, this underscores the importance of education and technology adoption within the construction industry, with specific emphasis on BIM technology and energy efficiency in buildings. While the development of innovative methods and technologies holds promise, their impact may be limited without adequate regulations and policies to incentivize the creation of energy-efficient buildings. For instance, energy efficiency labeling schemes in some countries have faced challenges with low adherence due to a lack of supportive policies [14].

The adoption of BIM-based approaches in energy performance labeling processes raises important ethical and social considerations. One key aspect is the potential impact on job roles and responsibilities, particularly for professionals involved in energy assessment and labeling. As BIM-based approaches automate certain tasks, there may be concerns about job displacement or the need for upskilling and reskilling to adapt to new technologies. Equitable access to BIM tools and training opportunities is essential to ensure that all stakeholders, including smaller firms and individuals from diverse backgrounds, can participate in the transition to BIM-enabled practices. The ethical use of data collected through BIM for energy performance assessment must be carefully considered to protect privacy rights and prevent misuse or unauthorized access. Transparency and accountability in data management practices are crucial to maintain trust and integrity within the industry. Lastly, there are social implications related to the broader goals of sustainability and environmental stewardship. By promoting energy efficiency and reducing carbon emissions, BIM-enabled energy performance labeling processes contribute to creating healthier and more sustainable built environments, benefiting communities and future generations. Therefore, ethical considerations should be integrated into decision-making processes to ensure that BIM-based approaches align with societal values and aspirations for a more sustainable future.

Overall, while BIM-based approaches offer significant potential, real-world applications involving atypical building designs, advanced equipment, or uncertain occupant behavior suggest the need for ongoing improvements. The continuous advancement of standards, calibration procedures, and AI-based analytics could contribute to maintaining the relevance and accuracy of energy labeling, while also adapting to the rapid innovations shaping the built environment.

## 11 Conclusion

This study explored how BIM can contribute to enhancing the accuracy, reliability, and efficiency of energy performance labeling. A comprehensive literature review has identified key limitations in existing labeling schemes, such as fragmented data collection, labor-intensive manual processes, inconsistent methodologies, and limited policy support. These factors collectively affect the credibility and utility of energy labels. Additionally, challenges related to user behavior and inadequate maintenance practices contribute to the performance gap between predicted and

actual energy use, potentially impacting stakeholder confidence and the adoption of energy-efficient solutions.

BIM-based approaches present several opportunities to address these challenges and offer notable advantages. As a centralized data repository, BIM provides a structured framework for collecting and managing critical information required for robust energy assessments. Advanced modeling techniques, including 3D laser scanning and thermography, can capture as-built conditions with greater accuracy, helping to minimize reliance on default values and reduce errors. The integration of BIM with BEM tools, whether through direct plug-ins or open data standards such as IFC and gbXML, enhances interoperability and expands analytical capabilities, supporting more precise simulations. Furthermore, multi-objective optimization offers a systematic approach to balancing multiple performance criteria, such as energy use, occupant comfort, and financial constraints, which can support the development of high-performance buildings that exceed regulatory minimums. The use of digital twins further strengthens energy labeling by leveraging real-time operational data to bridge the gap between design assumptions and actual performance, facilitating proactive maintenance strategies and improving occupant engagement.

The study highlights that existing labeling schemes often face challenges related to inconsistent and unreliable data, which can undermine stakeholder trust. In contrast, BIM's coordinated data environment offers a way to address many of these documentation and modeling challenges while also enabling the incorporation of occupant-related information, such as behavioral patterns. Despite the benefits provided by standards such as gbXML and IFC, as well as tools like Systems Analysis, OpenStudio, Dynamo, and Ladybug, interoperability issues may persist, especially in unique or specialized buildings that incorporate innovative technologies. The operational phase also presents additional challenges, including model calibration, uncertainties related to occupant behavior, and evolving maintenance requirements, which may require more sophisticated workflows and data-driven feedback mechanisms. Therefore, the successful implementation of BIM-based approaches depends not only on technological adoption but also on the development of supportive policies, financial incentives, training programs, and broader access to technology to facilitate widespread industry adoption.

Despite these ongoing challenges, this review provided insights by synthesizing various BIM-based approaches for energy labeling, identifying where each approach can be most effectively applied, and clarifying how digital transformation can address persistent issues within labeling schemes. These findings emphasize the need for continuous refinement of open data standards, robust simulation platforms, and AI-driven predictive models capable of capturing dynamic, real-world conditions. Further research into integrating BIM with natural ventilation strategies, embodied energy assessments, and evolving climate scenarios could contribute to enhancing energy labels to better reflect future conditions. Advancements in these areas have the potential to enhance energy labeling as an essential tool for policymaking, investment decisions, and occupant well-being. Recognizing the interconnected roles of technology, policy, and ethical considerations, stakeholders may leverage BIM's capabilities to achieve more accurate energy labels while fostering healthier and more sustainable built environments for current and future generations.

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# APÊNDICE C

ARTIGO 3

Design Misdirection: How BIM Modeling Granularity Compromises Energy Performance Assessment in Integrated BIM-to-BEM Workflows

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**Contrato de Autoria Compartilhada**

Esse documento atesta que todos os coautores do artigo intitulado *Design misdirection: how BIM modeling granularity compromises energy performance assessment in integrated BIM-to-BEM workflows*, publicado na *Energy & Buildings*, **CONCORDAM** com o seu uso como parte da tese de doutorado de Luís Filipe Muta, orientado pela professora Ana Paula Melo do Programa de Pós-Graduação em Engenharia Civil (PPGEC) da Universidade Federal de Santa Catarina (UFSC) e coorientado pela professora Annamaria Buonomano do Departamento de Engenharia Industrial da Università degli Studi di Napoli Federico II.

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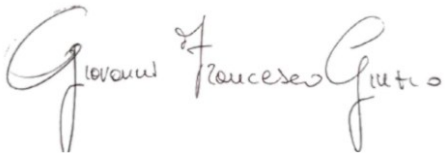

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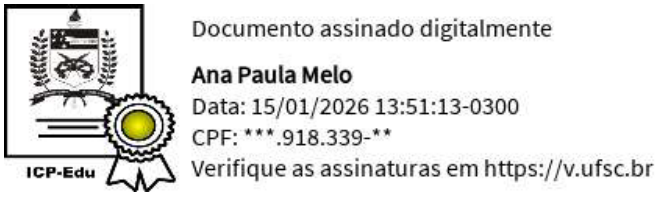


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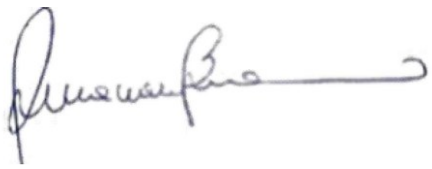

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Florianópolis, 15 de janeiro de 2026.

**Design Misdirection: How BIM Modeling Granularity Compromises Energy Performance Assessment in Integrated BIM-to-BEM Workflows**

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## Abstract

Building Information Modeling (BIM) to Building Energy Modeling (BEM) integration offers a promising pathway to enhance energy performance assessment, yet the variability in BIM modeling granularity remains a significant source of uncertainty, contributing to the performance gap. This study systematically investigates how different facets of modeling granularity impact BEM outcomes. Using a university building archetype, a parametric matrix of 62 scenarios was generated by varying four domains of modeling granularity: spatial configuration, construction assemblies, thermal zoning, and internal conditions. An automated BIM-BEM workflow was employed to process and simulate each scenario. The analysis reveals a significant performance spread across the scenarios, with the predicted Energy Use Intensity (EUI) varying by up to 68%. The results identify internal conditions, a form of semantic granularity, as the dominant factor driving this variability, organizing outcomes into distinct, non-overlapping performance clusters that far outweigh the influence of spatial or construction detail. Furthermore, the study demonstrates that simplified semantic models can significantly distort the building's energy balance, in some cases overestimating total cooling energy use by 18%. This distortion, in turn, can lead to design misdirection by masking localized load peaks and altering the identification of critical spaces for system sizing. Based on these findings, the study articulates a conceptual model that distinguishes between spatial and semantic granularity. This model serves as a heuristic guide to facilitate the shift from a paradigm of "as detailed as possible" to a more resilient strategy of "as detailed as useful", thereby promoting a more conscious and purpose-driven approach to modeling granularity.

**Keywords**: Building Information Modeling, Building Energy Modeling, Energy Performance Assessment, Modeling Granularity, Data Uncertainty.

## 1 Introduction

Energy performance assessment has become a pivotal policy tool for promoting energy efficiency in buildings, shaping design decisions and regulatory frameworks worldwide [1]. The European Union promotes national schemes under the Energy Performance of Buildings Directive (EPBD) to encourage transparency and market transformation [2]. The United States implements programs, to certify building energy performance, such as Energy Star [3]. In Brazil, the Brazilian Building Labeling Program (PBE Edifica) uses an alphabetic scale to indicate efficiency levels for different building types and systems [4]. Similar initiatives also happen in Australia [5], Canada [6], India [7], and Argentina [8], each one adapting performance assessment to local contexts and policy objectives.

However, a persistent challenge in this domain is the performance gap – the recurring discrepancy between predicted and actual building energy consumption [9]. This gap has been widely documented and is often attributed to a complex interplay of factors, including oversimplified assumptions, incomplete data, and misalignment between design intent and operational realities [10]. One major driver of the performance gap lies in the variability and uncertainty introduced during the modeling process itself. This is particularly true for the BIM modeling granularity, which is the degree of specificity in the model's spatial and semantic information that is represented and transferred into energy simulations [11–14].

Most regulatory frameworks employ two primary pathways for energy performance assessment: (i) simplified methods, relying on manual entry of key parameters into calculation tools, and (ii) simulation-based approaches (Building Energy Modeling – BEM), which promise deeper insights through dynamic modeling [12]. Although BEM is theoretically capable of capturing nuanced interactions and enabling more accurate predictions, its impact is often constrained by the complexity of configuring numerous parameters that may be fragmented across project documentation or inconsistently represented between software platforms [10].

In this context, Building Information Modeling (BIM) has emerged as a promising solution for integrating energy analysis into the design process,

especially by reducing the effort required to develop BEM models [15]. By considering architectural information, construction properties, and relevant mechanical and electrical system data into a unified digital environment, BIM enables more seamless transfer of information to energy simulation tools [16]. Open data standards, such as Green Building XML (gbXML) and Industry Foundation Classes (IFC), have further advanced this integration by allowing energy modeling tools to directly extract geometric and semantic data from BIM models, minimizing redundant inputs [17].

Yet, simply adopting digital workflows and open data standards does not resolve the core issue – the quality and specificity of information embedded in BIM models can vary substantially, depending mostly on the stage of design, available documentation, and modeling practices of each team [18,19]. For instance, early-phase BIM models may provide only schematic spatial data, while later-stage models may include detailed zoning, material properties, and detailed internal conditions [20,21]. These differences in BIM modeling granularity directly influence the output from BEM tools and can significantly affect the predicted energy performance and the assessment of simulation outcomes.

Understanding the impact of BIM modeling granularity on building energy simulation results is essential, not only to enhance the robustness of energy assessments but also to minimize the performance gap that continues to challenge both practitioners and policymakers. As digitalization reshapes building design and compliance workflows, clarifying the relationship between BIM modeling granularity and BEM variability becomes fundamental for setting realistic expectations, developing effective regulations, and supporting the transition to high-performance buildings.

## 2 Context

Accurately predicting building energy performance during the design phase is subject to a range of challenges. Discrepancies between predicted and measured energy use may arise due to factors such as divergences in occupant behavior [22], climatic uncertainties [23], limitations inherent to simulation software [24], and incomplete or imprecise project information [25]. Regarding the latter, the building information transferred from BIM to BEM models appears to play a relevant role in shaping the variability of results, and investigating this

relationship may contribute to advance digital workflows and support more consistent approaches in regulatory and practical contexts for building energy performance assessment.

The integration of BIM to BEM is often recognized for its potential to streamline modeling workflows and reduce manual effort [26,27]. However, uncertainty remains regarding the modeling granularity required within BIM models to produce meaningful distinctions in energy simulation outputs. This situation is further complicated by the fact that building energy simulation tools often impose their own limitations on input data [28]. Consequently, even when more detailed BIM models are available, their impact on BEM results may be diminished if software interoperability is limited or if certain attributes are not fully transferred [29,30]. In response, open data standards have been increasingly adopted to support more flexible and accurate data exchange between BIM and BEM platforms [31,32].

Several studies have considered the relationship between BIM modeling granularity and BEM results. Early research [33] observed that highly schematic BIM models, common in initial design phases, might yield substantial variability in simulation outputs due to simplified geometry and generic internal loads. Other studies within the BIM-BEM context have highlighted the sensitivity of simulation results to design parameters like building form and technical characteristics; however, the specific roles of internal conditions and detailed zoning are not always explicitly addressed as dimensions of BIM modeling granularity [34,35]. More recent investigations indicate that increasing BIM modeling granularity may affect BEM results, particularly when operational data are available for calibration; however, the impact of these effects during the design phase, when short-term data and assumptions predominate, remains uncertain [36].

Additional contributions, such as the proposal of metrics like LOD2ES, a specific Level of Detail (LOD) model tailored for energy simulation, suggest that lower modeling granularity in BIM may lead to considerable differences in simulation outcomes and potentially to systematic underestimation or oversimplification of building performance [37]. While advances in parametric analyses have explored the effects of geometry, envelope composition, and air-conditioning specifications [38–40], relatively few studies have examined how incremental changes in BIM modeling granularity influence the variability and

robustness of BEM outputs during the design phase, when information is still evolving and modeling trade-offs are most evident.

This issue may be particularly relevant for regulatory frameworks that rely on simulation results from the design-phase BIM models. There appears to be little consensus regarding the relationship between the degree of BIM modeling granularity and the reliability of BEM outputs, or how incremental changes in specificity affect performance-based metrics. This uncertainty raises practical questions for BIM-BEM workflows, where modeling choices can significantly influence outcomes.

Mostly design decisions affecting building energy performance are typically made during early design stages, such as envelope specification, window-to-wall ratio, and spatial zoning [10]. Early performance assessment may offer opportunities for optimization and help to minimize costly modifications at later stages, although the amount of information available related to BIM modeling granularity tend to vary throughout the process [41]. Conversely, delaying analysis until later phases may reduce the range of viable interventions due to project or budgetary constraints [42]. In this context, BIM-BEM workflows may offer ways to support performance evaluation as project information develops [43,44], but questions remain regarding the most appropriate balance between workflow efficiency, data availability, and the reliability of simulation outputs [44,45].

Despite ongoing progress, there is still a lack of clear guidance on how to define or manage modeling granularity for energy performance assessment. Without standardized protocols or established practices, inconsistencies and uncertainties in model preparation may persist, limiting the practical and regulatory value of simulation-based energy performance evaluation.

## 3 Approach and objectives

This study examines how the modeling granularity in BIM environments may affect the variability of BEM results, using an automated and scenario-based BIM-to-BEM workflow. The analysis is based on a university building archetype [45]. This typology offers a context characterized by a variety of space functions and internal loads, which tend to increase the uncertainty of simulation results to modeling assumptions. Employing an archetype also standardizes parameters

across scenarios, facilitating direct comparisons and isolating the influence of variations in modeling granularity on simulation variability.

The choice to frame the analysis around “BIM modeling granularity”, rather than Level of Development (LOD) or Level of Information Need (LOIN), reflects specific considerations related to energy performance assessment. Although LOD and LOIN are widely recognized in design and construction practice, their definitions are typically oriented toward geometric representation or general documentation requirements [46,47], whereas key aspects for BEM, particularly the semantic and operational attributes that influence simulation, are often not addressed explicitly. By adopting the term BIM modeling granularity, this study aims to focus on domains that are especially relevant to BEM but are not always explicitly covered in established BIM standards.

To systematically explore these effects, the research adopts an automated BIM-to-BEM workflow that generates, processes, and simulates multiple model variants. This workflow is underpinned by a series of custom Python scripts developed by the authors to handle tasks ranging from data processing and simulation execution to the final quantitative analysis. This automation reduces manual intervention, limits user-dependent variability, and enables a broader exploration of modeling configurations. The workflow employs gbXML for data exchange, given its widespread support among BIM authoring tools and its ability to encode both spatial and semantic information to BEM [10,43,48].

The methodological contribution of this research lies in its systematic and automated analysis of how different aspects of BIM modeling granularity, including spatial configuration, construction assembly, thermal zoning, and internal conditions, may interact to affect the variability of BEM outputs in the design phase. This scenario matrix enables the exploration of combined effects that would be challenging to assess through isolated or manually generated cases.

The central research question addressed is:

- To what extent does BIM modeling granularity influence the variability of energy performance assessment outcomes during the design phase?

Additional questions considered in this study include:

- What trade-offs may be observed between modeling effort and the consistency of BEM results as BIM modeling granularity changes?
- Which aspects of building information appear to have the greatest influence on BEM results within an automated workflow?
- How does modeling complexity appear to affect the sensitivity of key performance metrics to incremental changes in BIM modeling granularity?

Ultimately, the results aim to inform modeling strategies and digital workflows by clarifying how both geometric and semantic modeling choices influence simulation variability, supporting more robust and consistent energy performance assessments in building design.

## 4 Method

The methodological approach adopted in this study seeks to clarify how variations in BIM modeling granularity influence the variability of BEM outcomes within a controlled and reproducible environment. The research is structured as a multi-stage process designed to systematically generate, simulate, and analyze a wide range of modeling scenarios. This is accomplished by first establishing a representative building archetype, then defining a parametric matrix based on four distinct domains of modeling granularity, and finally employing an automated workflow to ensure consistency across all simulations. The entire methodological structure, from model definition to final analysis, is summarized in the conceptual framework illustrated in Figure 1.

The process begins with the definition of a building archetype, which serves as a standardized baseline for all scenarios. Next, a parametric scenario matrix is developed by systematically varying four key domains of modeling granularity, encompassing both the building's geometric configuration and its non-geometric, semantic attributes. Each of these model variations is then processed through a custom automated BIM-to-BEM workflow, which handles the conversion from BIM to energy models, data enrichment, and execution of simulations, thereby minimizing user-dependent variability. Finally, the simulation outputs are subjected to a structured five-stage data analysis, moving from a high-level characterization of results to detailed statistical tests and granular, zone-level investigations. The following subsections detail each of these stages.

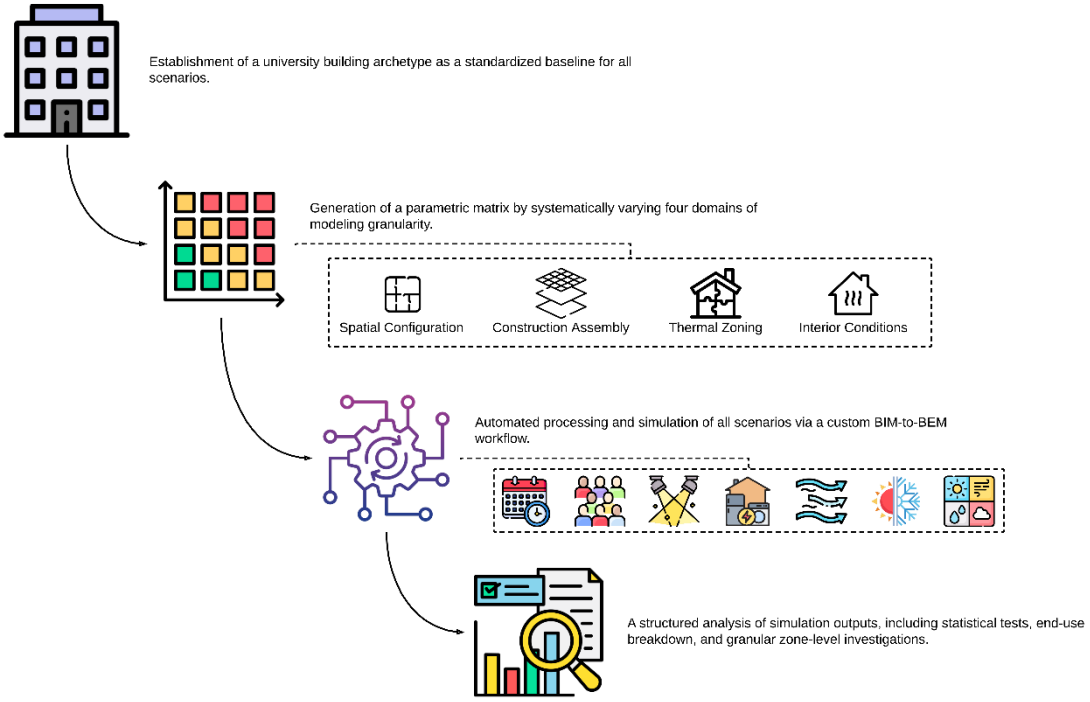


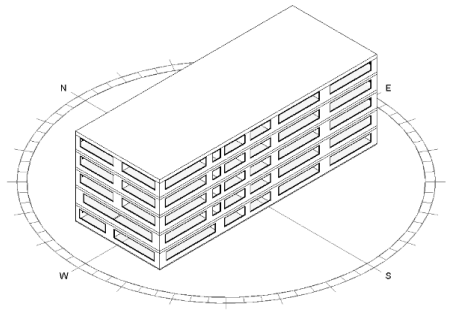

Figure 1 – Schematic representation of the methodological workflow

## 4.1 Archetype definition

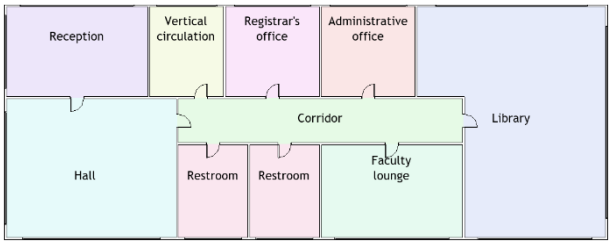
This study adopts a university building archetype designed to reflect the spatial and functional characteristics of higher education facilities in Brazil. The archetype's parameters are based on the Operational Energy Performance in Buildings (DEO) Project [49] and considered the baseline conditions of Brazilian regulatory guidelines (Ordinance No. 309/2022) [50].

The archetype features a five-story configuration, oriented along the east-west axis, with its longest facades facing north and south. The total gross floor area is approximately 3,400 m², with each floor spanning roughly 680 m² and a uniform floor-to-floor height of 3.0 m. The ground floor primarily accommodates support and administrative functions, including the main entrance hall, reception, restrooms, a faculty lounge, administrative and registrar's offices, the library, and vertical circulation. The first floor is dedicated to academic and collective activities, comprising a canteen, auditorium, classroom, laboratories, restrooms, storage area, and vertical circulation. The upper floors (second, third, and fourth) feature a standardized layout that prioritizes teaching spaces, with multiple classrooms located throughout each floor. These levels also include supporting areas such as storage rooms, restrooms, and vertical circulation

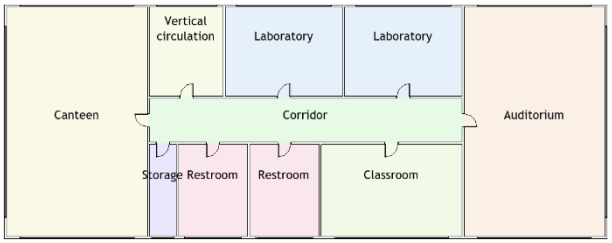
cores, organized to serve the instructional functions of the building. The base archetype and its floor plans are shown in Figure 2.



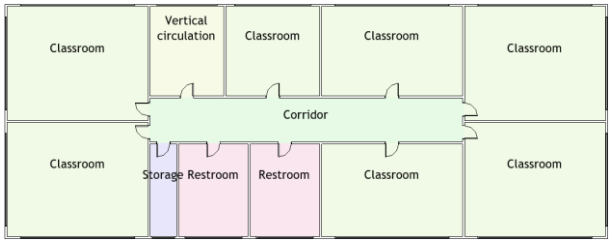

(a) Isometric 3D view




(b) Ground floor




(c) First floor




(d) Second, third, and fourth floors (typical)

Figure 2 – Archetype: (a) isometric 3D view; (b) ground floor; (c) first floor; (d) second, third, and fourth floors (typical)

The archetype includes 57 distinct spaces. Transitory spaces comprise a hall, circulation areas, restrooms, storage rooms, a canteen, and vertical circulation zones, which are generally occupied for short periods. Spaces characterized by prolonged occupancy include administrative offices, faculty offices, a library, laboratories, an auditorium, and classrooms, where occupants remain for extended periods.

The building envelope is specified according to the baseline requirements of Brazilian regulatory guidelines for academic buildings [50,51]. Its opaque elements consist of masonry walls (solar absorptance 0.5), concrete floors, and a roof composed of a concrete slab and fiber-cement tiles (solar absorptance 0.8). The glazing system features single-pane (6 mm) windows with a U-value of 5.7 W/m²·K, a solar heat gain coefficient of 0.82, and an overall window-to-wall ratio of 40%. Internally, the 25 cm spaces between the ceilings

and the concrete floor slabs are represented in two distinct ways to test the impact of this modeling choice. Depending on the scenario (section 4.2), these spaces are either modeled as simplified static air layers, which only contribute a fixed thermal resistance, or as fully dynamic thermal zones (plenums), which allows for the simulation of the air volume's own temperature changes.. Complete properties for all construction assemblies are detailed in Table 1.

Table 1 – Layered composition and thermophysical properties of envelope and partition constructions

| **Construction** | **Description** | **Material layer** | **Thickness (cm)** | **Thermal conductivity (W/m.K)** | **Density (kg/m³)** | **Specific heat (kJ/kg.K)** |
|---|---|---|---|---|---|---|
| Internal/External wall | Internal plaster (2.5 cm), ceramic block masonry (9.0 × 14.0 × 24.0 cm), mortar joints, external plaster (2.5 cm), external paint finish | Exterior cement plaster | 2.50 | 1.15 | 2,000 | 1.00 |
| | | Ceramic brick | 1.34 | 0.90 | 1,600 | 0.92 |
| | | Air chamber | 6.32 | 0.36 | | |
| | | Ceramic brick | 1.34 | 0.90 | 1,600 | 0.92 |
| | | Interior cement plaster | 2.50 | 1.15 | 2,000 | 1.00 |
| Floor | Concrete slab (10 cm), mortar bed (1 cm), ceramic tile finish (1 cm) | Ceramic tile | 1.00 | 1.05 | 1,800 | 0.92 |
| | | Mortar | 1.00 | 1.15 | 2,000 | 1.00 |
| | | Concrete slab | 10.00 | 1.75 | 2,200 | 1.00 |
| Ceiling | Gypsum plasterboard (1.25 cm) | Gypsum | 1.25 | 0.35 | 1,000 | 0.84 |
| Roof | Concrete slab (10 cm), fiber-cement roofing sheet (0.8 cm) | Fiber-cement roofing sheet | 0.8 | 0.95 | 1,900 | 0.84 |
| | | Air chamber | 25.00 | 1.19 | | |
| | | Concrete slab | 10.00 | 1.75 | 2,200 | 1.00 |

Internal gains for the entire building were specified using global values (for all thermal zones), in accordance with Brazilian regulatory guidelines for university buildings [50]. Occupant density is set at 1.5 m² per person, with an internal gain of 120 W per person. Lighting power density is 15.5 W/m², and

equipment power density is 15 W/m². The operational schedule assumes 200 days of use per year, with daily occupancy concentrated in an 8-hour period, with adjustments to account for seasonal recess periods (January and July) [45].

The air-conditioning system is represented using an Ideal Load Air System, assuming full conditioning during occupied hours. Heating and cooling setpoints are set at 21°C and 24°C, respectively, with an infiltration rate of 0.5 air changes per hour, reflecting typical airtightness conditions in Brazilian buildings [45]. Outdoor air exchange rates are specified at 0.0075 m³/s per person, consistent with national health and ventilation guidelines [52].

This study uses a future weather dataset for Florianópolis (2050s, RCP 8.5) generated with the MPI-ESM-RegCM model chain [23]. While climate change is not directly analyzed, the approach reflects buildings' long lifespans by accounting for projected conditions rather than relying solely on historical data, which could underestimate future thermal demands. This aligns with academic best practices for evaluating energy performance under increasingly severe climatic conditions [10,23].

The archetype establishes a base reference. The following section introduces modeling scenarios that systematically vary four domains of BIM modeling granularity.

### 4.2 Parametric study

This study organizes model variations across four fundamental domains of modeling granularity – Spatial Configuration (SPA), Construction Assembly (CON), Thermal Zoning (ZON), and Internal Conditions (INT) – to assess the impact of specific modeling choices on BEM outcomes. These domains were selected as they encompass key informational inputs for energy simulation that are defined with varying levels of specificity within the BIM environment [19,53,54]. To ensure a controlled analysis, all other simulation parameters were fixed.

The SPA domain was defined to capture the specification of internal partitions, room boundaries, functional uses, and the modeling approach adopted within the BIM environment. Model variations were structured as follows: In SPA-1, only the external envelope was represented, with all internal partitions, doors, technical spaces, and plenums omitted; unoccupied voids were modeled as static

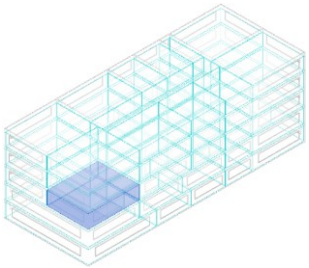
air layers, which contribute only a fixed thermal resistance value to the overall construction assembly. In SPA-2, internal partitions and doors were included, allowing for basic differentiation of spaces by function, and windows were modeled as grouped or continuous strips. In SPA-3, all internal partitions, windows, and doors were individually positioned according to the base archetype layout, with room functions assigned to reflect the intended use. In these cases, plenums were absent; in such instances, air layers continued to be represented as static elements within the construction. In SPA-4, plenums were explicitly modeled as separate, unoccupied thermal zones, requiring the subdivision of constructions and the explicit assignment of boundary conditions for these spaces.

The CON domain compares two approaches to construction assembly representation in BIM. In CON-1, construction elements are modeled as generic objects without explicit material layers, and thermal properties are assigned automatically during export using schematic templates. In CON-2, each assembly is explicitly detailed in BIM, with all material layers defined by thickness, thermal conductivity, density, and specific heat. Both approaches yield identical simulation inputs, thereby isolating any effects associated solely with the organization and transfer of construction assembly information from BIM to BEM.

The INT domain defines internal gains and their corresponding ventilation rates. This study considers three levels of granularity for this domain. The first two approaches, INT-1 and INT-2, are methodologically identical in their application, as both treat internal gains globally by applying a single, uniform set of values across the entire building model, regardless of individual space function. The difference between them lies in the source of the data. INT-1 represents a conceptual stage, using generic values from Brazilian regulatory guidelines [50] (as defined in section 4.1); these guidelines are adapted from the international ASHRAE standards, such as Standard 90.1 [55] that also serve as the basis for INT-3. INT-2 is a methodological scenario that uses weighted-average values calculated from the detailed INT-3 dataset to assess if averaged values can approximate the results of a more customized assignment. In contrast, INT-3 employs a detailed and granular approach, where tailored internal conditions and ventilation rates are assigned to each room based on its specific function and classification, following the international ASHRAE standards 62.1 and 90.1

[55,56]. Consequently, while the global parameters of INT-1 and INT-2 can be applied even when internal layout or zoning is limited, the granular approach of INT-3 is contingent upon the defined use and typology of each room. Table 2 illustrates these distinctions by presenting a representative example, detailing the assignment of internal conditions for a single classroom.

Table 2 – Illustration of internal condition parameters across INT levels for a single classroom

| Visualization | Parameter | INT-1 | INT-2 | INT-3 |
|---|---|---|---|---|
|  | Area per person [m²] | 1.50 | 1.96 | 1.54 |
| | Sensible heat gain per person [W] | 80.0 | 72.7 | 73.3 |
| | Latent heat gain per person [W] | 40.0 | 56.1 | 58.6 |
| | Lighting load density [W/m²] | 15.5 | 10.1 | 15.1 |
| | Equipment load density [W/m²] | 15.0 | 7.5 | 10.8 |
| | Design outdoor air method | Person | Person and area (sum) | Person and area (sum) |
| | Design outdoor air per person [m³/s] | 0.0075 | 0.00306 | 0.00354 |
| | Design outdoor air per area [m³/(s.m²)] | 0 | 0.00027 | 0.00030 |

A summary of each domain and its corresponding modeling granularity is presented in Table 3. To visually illustrate the differences between these levels, a supplementary set of diagrams is provided in Appendix A.

Table 3 – Summary of domains and levels of modeling granularity

| Domain | Level | Description |
|---|---|---|
| Spatial Configuration | SPA-1 | Simplified envelope; no internal partitions, doors, or technical/plenum spaces; single glazing opening per façade per floor. |
| | SPA-2 | Envelope with initial internal partitions and doors, enabling functional zoning; windows defined as continuous strips or grouped; no plenum spaces. |
| | SPA-3 | Definitive layout with all internal partitions, individually placed windows and doors; accurate room functions; no plenum spaces. |
| | SPA-4 | Same as SPA-3, with addition of plenum spaces for dynamic thermal modeling. |
| Construction Assembly | CON-1 | No explicit material layers in BIM; generic constructions without thermal properties; thermal data are assigned schematically via external templates. |
| | CON-2 | All constructions modeled explicitly in BIM, with defined layers, thickness, conductivity, density, and specific heat for each material. |
| Thermal Zoning | ZON-1 | Entire floor modeled as a single thermal zone. |
| | ZON-2 | Core and perimeter zones differentiated for each floor. |

| | | |
|---|---|---|
| | ZON-3 | Each floor subdivided into functional zones, reflecting typical use diversity. |
| | ZON-4 | Each room modeled as an individual thermal zone, allowing maximum detail for loads and ventilation. |
| Internal Conditions | INT-1 | Uniform internal loads and ventilation rates based on the Brazilian regulatory guidelines [50]. |
| | INT-2 | Weighted-average internal loads and ventilation rates, methodologically mimicking INT-1 but using INT-3 dataset. |
| | INT-3 | Internal loads and ventilation rates differentiated by room type, based on ASHRAE standards [55,56] |

The scenario matrix adopted in this study is visually summarized in Figure 3. The horizontal axis represents the progression of SPA, from models with minimal modeling granularity on the left to highly detailed configurations on the right. The vertical axis illustrates increasing granularity in ZON, ranging from simplified zoning at the bottom to fully individualized room zoning at the top. Each colored model in the matrix exemplifies a unique combination of SPA and ZON. This visual representation clarifies the structure of the parametric study and highlights dependencies between domains, such as the need for sufficient spatial resolution to enable more granular zoning or space-specific internal conditions.

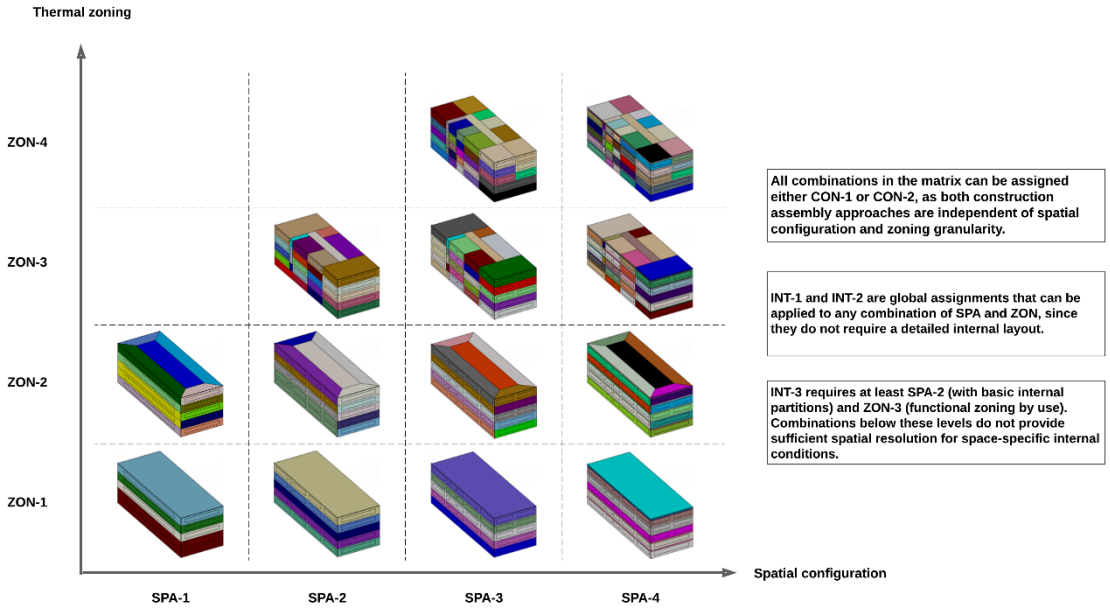



Figure 3 – Parametric scenario matrix

The figure also highlights that not all possible combinations are viable. Certain assignments require a minimum spatial or zoning resolution to maintain internal consistency. To keep the main text concise, the complete table of all 62 scenario combinations is provided in the Appendix B. With this scenario matrix

established and the archetype parameters defined, the next section details the automated BIM-to-BEM workflow used to generate, process, and simulate each scenario in the study.

### 4.3 BIM-to-BEM workflow

A custom automated BIM-to-BEM workflow was developed to systematically process each scenario, minimizing manual intervention and ensuring consistency across all simulations. This multi-stage process, illustrated in Figure 4, defines a structured pipeline that begins with the creation of the source BIM model and concludes with the extraction of analyzable simulation outputs.

A custom BIM-to-BEM workflow (illustrated by Figure 4) was developed to automate the transition from BIM to BEM, minimizing manual intervention. BIM models are initially created in Revit 2025, following the base structure described in section 4.1. These models are then adapted to reflect the different gradations of BIM modeling granularity outlined in section 4.2. After modeling, the files are converted into gbXML format (v. 7.03), which serves as the input for the workflow.

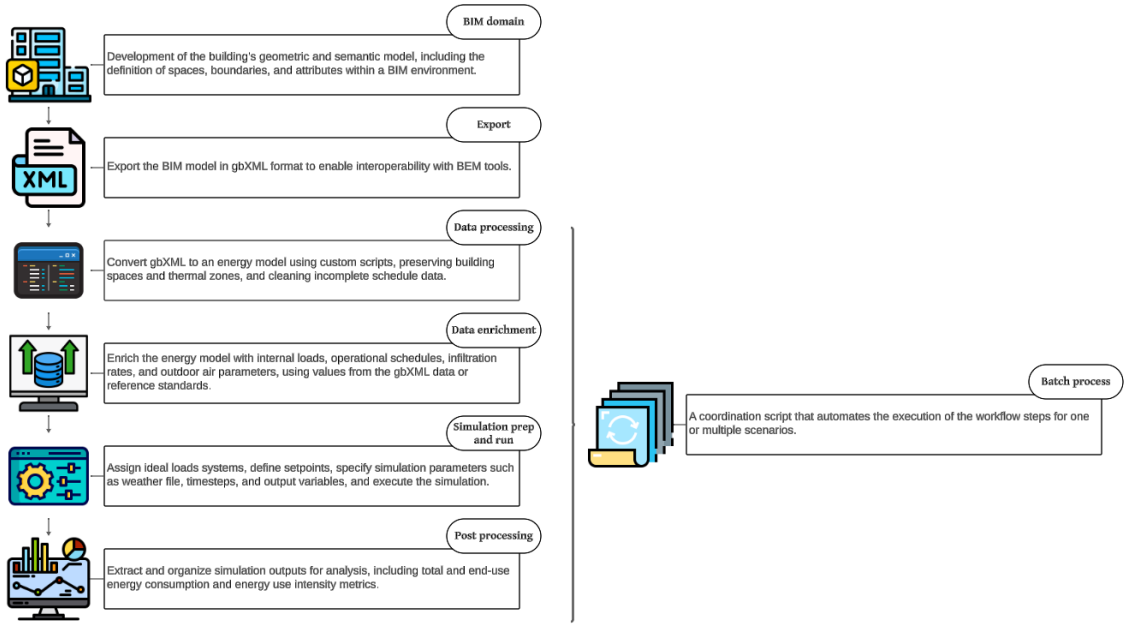



Figure 4 – Schematic representation of the BIM-BEM workflow

The process originates in the BIM domain, where models for each scenario are created in Revit 2025, following the base structure described in Section 4.1 and adapted to reflect the different gradations of modeling granularity

outlined in Section 4.2. Following this, each model undergoes the Export stage, where it is converted into the gbXML format (v. 7.03), which serves as the standardized input for the automated sequence.

The next step is the Data processing, which involves the conversion of gbXML files into OpenStudio Model (OSM) files using custom Python scripts and the OpenStudio SDK (v. 1.9.0). This step preserves the geometric and spatial structure of the building, including spaces, constructions, and thermal zones. To address attributes, especially operational schedules, that may not transfer directly or completely, the workflow incorporates a parsing and data cleaning step. These routine extracts schedule data from the gbXML, restructures it to comply with the schema, and then rebuilds the schedules in the energy model to ensure the accurate representation of temporal profiles for occupancy, lighting, equipment, and air-conditioning operation.

Following the conversion, the model undergoes Data enrichment. This subsequent step involves assigning internal load parameters such as occupant density, lighting power density, and equipment power density, primarily based on values extracted from the original gbXML file or supplemented with predefined inputs. Additional model attributes are also assigned, including infiltration rates (fixed at 0.5 ACH [45]), outdoor air design rates (based on either gbXML data or programmatic assignment by space use type [52,56]), and solar absorptance for opaque surfaces [50], which is set programmatically to maintain consistency.

The next stage consists of Simulation prep and run. Ideal Load Air Systems and temperature setpoints are then assigned to each thermal zone [45]. To prevent distortion of density-based performance metrics like Energy Use Intensity (EUI), plenum spaces are excluded from total floor area calculations. All preprocessing routines can be orchestrated sequentially by a master script, enabling the batch processing of multiple gbXML files so that uniform modeling logic is applied across all scenarios. This setup routine specifies the weather file [23], simulation timesteps, and output variables before executing the simulations in EnergyPlus (v. 24.2.0).

After simulations are complete, the final stage is Post-processing, where scripts extract and organize the results. The calculation of the final performance metric follows a detailed procedure: thermal loads for heating and cooling are converted to electricity consumption in kWh by applying a Coefficient of

Performance (COP) of 3.54 [50]; subsequently, all end-use consumptions are converted to primary energy using a factor of 1.6 [50]. The final EUI for each scenario is then calculated as the sum of these primary energy consumptions, divided by the building's total floor area.

### 4.4 Data analysis

The quantitative analysis of the simulation data is performed through a computational routine implemented in Python, which supports the consistency and reproducibility of the procedures. The analytical methodology is structured as a sequence of five stages, moving from a general characterization of the results to more granular investigations, as illustrated in Figure 5.

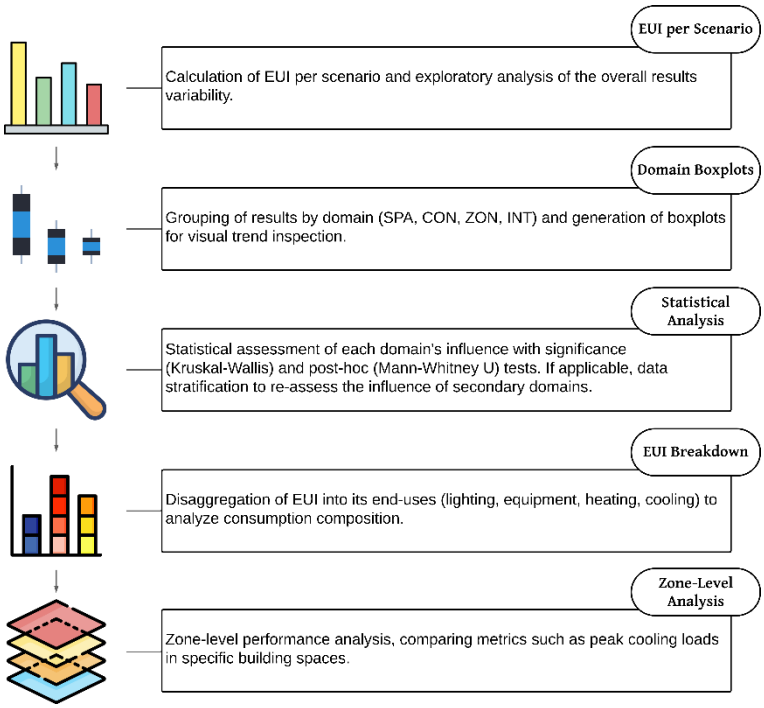



Figure 5 – Data analysis workflow

The first stage, EUI per Scenario, begins with the preparation of the energy performance metric. The EUI from each simulation is organized to conduct an exploration analysis of the complete dataset. The importance of this step lies in establishing the overall scope of the problem by characterizing the total range of EUI variation and determining whether modeling choices result in distinct performance clusters. This initial overview determines if the impact of granularity is substantial enough to warrant further, more detailed investigation.

The second stage, Domain Boxplots, involves a visual analysis of the influence of the four granularity domains (SPA, CON, ZON, INT). By generating comparative boxplots, this step allows for a high-level visual inspection to identify which, if any, of the domains appears to be the primary driver of the variability observed in the first stage. Its purpose is to form an initial hypothesis and guide the focus of the subsequent statistical procedures.

The third stage, Statistical Analysis, is designed to formally test and quantify the trends observed visually. The importance of this stage is to move from visual inference to statistically robust conclusions. The test applied are:

- The Kruskal-Wallis test is first employed to formally assess whether the observed differences between the levels of a domain are statistically significant; if an effect is found to be significant, Eta-squared ($\eta^2$) is used to quantify its magnitude by estimating the proportion of total EUI variability that can be attributed to that specific factor [57].
- A post-hoc analysis using the Mann-Whitney U test with Bonferroni correction then allows for precise pairwise comparisons, pinpointing exactly which levels within a domain differ from one another (e.g., INT-1 vs. INT-2) while controlling the error rate across these multiple comparisons [57,58].
- A conditional stratification of data is performed. If a primary driver is confirmed, the dataset is split by its levels to re-assess the influence of the secondary domains. This is crucial for understanding more subtle, secondary effects and potential interactions between the different facets of modeling granularity.

The fourth stage, EUI Breakdown, extends the analysis beyond total energy consumption to investigate its end-uses. The EUI of each scenario is disaggregated into its end-uses (lighting, equipment, heating, and cooling). This step is important because it helps explain the underlying physical reasons for the EUI differences between scenarios, revealing how modeling choices can alter the building's fundamental energy balance rather than just the final consumption value.

Finally, the fifth stage, Zone-Level Analysis, assesses performance impacts on a more granular scale. By comparing metrics such as peak cooling loads in specific building spaces across representative scenarios, this step

demonstrates the practical consequences of different modeling choices. Its importance lies in highlighting how decisions about granularity can influence key engineering outcomes, such as HVAC system sizing, and potentially lead to design misdirection.

## 5 Results

The scenario matrix produced a significant variation in EUI results. Figure 6, which organizes the 62 scenarios in descending order, illustrates this spread. A visual analysis reveals that the EUI values are not continuously distributed but are instead grouped into three distinct clusters with EUI ranges of 348.9 to 357.5 kWh/m², 233.9 to 241.9 kWh/m², and 212.5 to 218.3 kWh/m². The overall range, from 212.5 to 357.5 kWh/m², underscores the substantial impact of modeling granularity choices on BEM outcomes. However, while the establishment of these clusters is clear, Figure 6 by itself does not allow for the identification of the specific BIM granularity domains that cause this grouping.

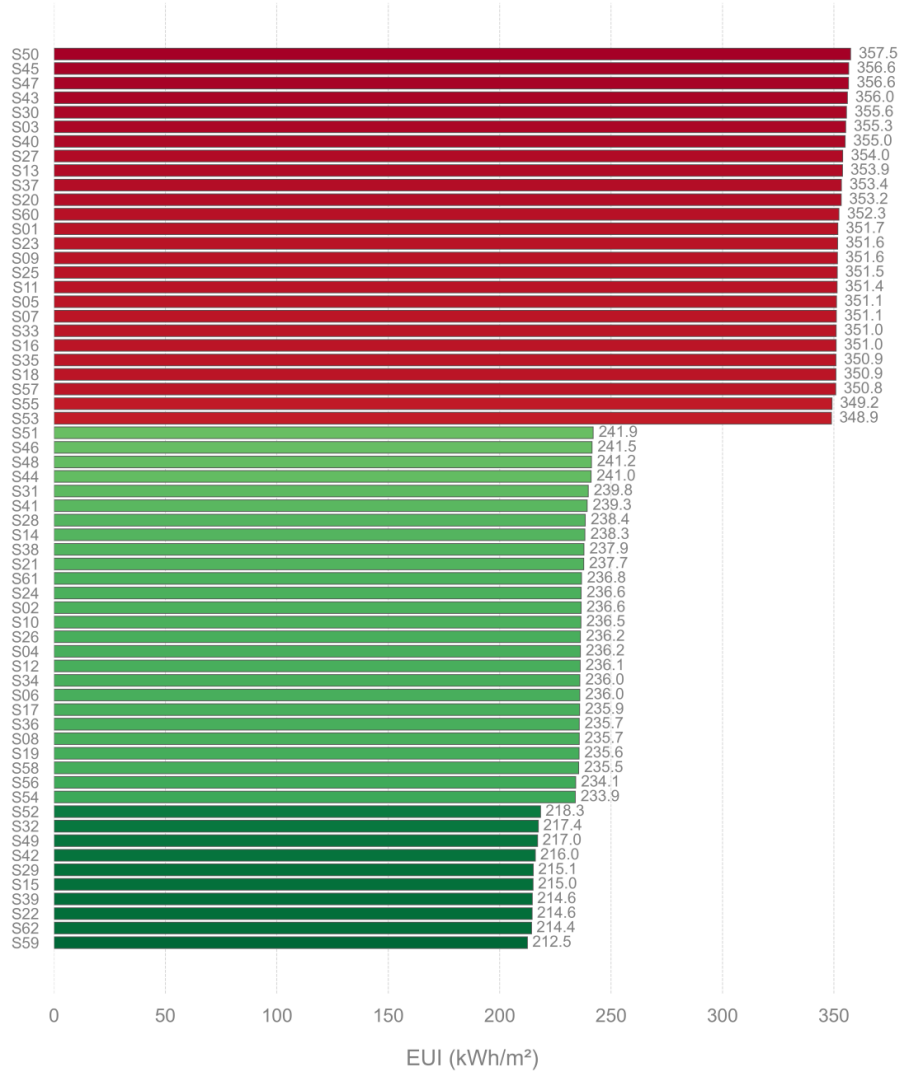



Figure 6 – Distribution of EUI across all simulation scenarios

To further examine the influence of BIM modeling granularity on EUI, the results were grouped by each domain and analyzed using boxplots. This approach enables a direct comparison of the EUI distributions associated with each level within the four domains, as illustrated in Figure 7.

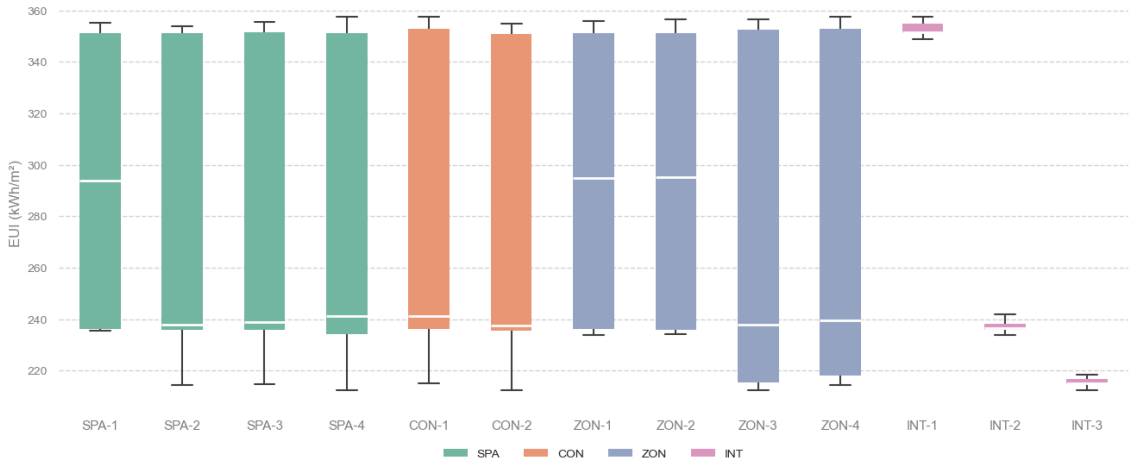



Figure 7 – Effect of BIM modeling granularity on EUI across all domain combinations

A Analysis of the SPA, CON, and ZON domains reveals no consistent trend in EUI, as their respective levels show wide and overlapping value ranges. This indicates a minor overall influence on the results, despite some median shifts at specific levels of granularity. In sharp contrast, the INT domain is the dominant factor, with its levels producing distinct, non-overlapping EUI clusters; INT-1 consistently yields higher values, whereas INT-2 and INT-3 are associated with lower, more tightly grouped results. The analysis thus demonstrates that the specification of internal conditions has a far more pronounced impact on EUI variability than the other domains. Given that the INT domain is the clear driver of this variability, the subsequent analysis is disaggregated to examine the results within each INT level individually. The detailed results of this stratified statistical analysis are provided in the following paragraphs and are presented in Appendix C.

For INT-1 scenarios (Figure 8), the boxplots reveal a pattern where higher levels of granularity are associated with changes in EUI distribution. Notably, increased granularity in the SPA domain corresponds with greater EUI dispersion; this visual trend is statistically confirmed by a significant difference in variance among its subgroups (Levene's test, $p = 0.007$). Conversely, while higher levels of the ZON domain, such as ZON-2 and ZON-4, appear to have a wider spread, this observation is not statistically supported, as the groups maintain equal variance (Levene's test, $p = 0.94$).

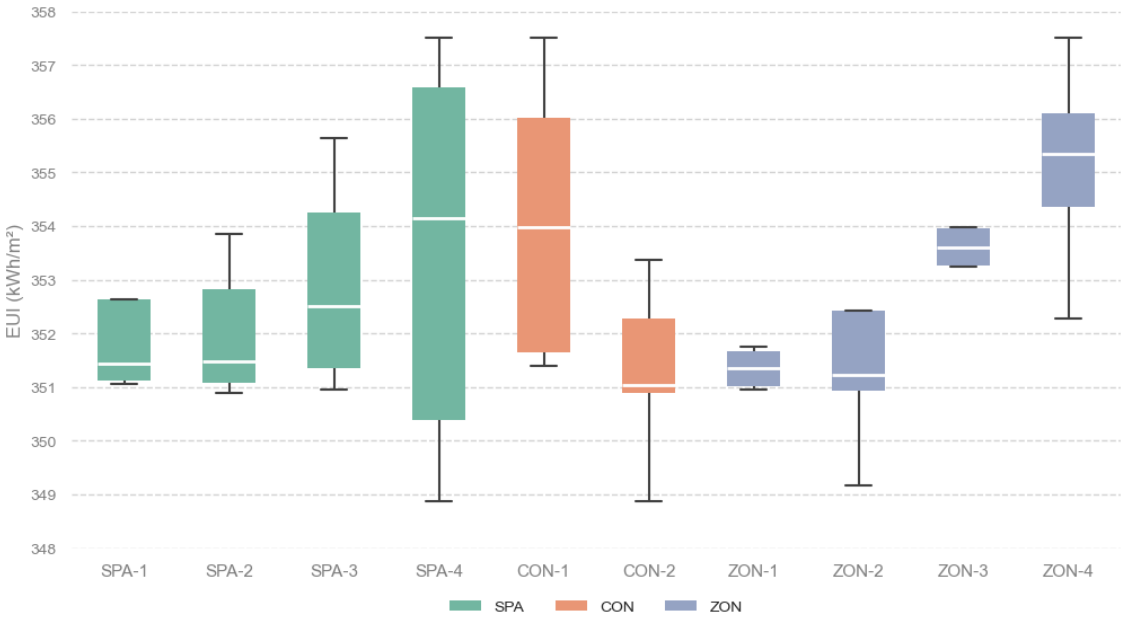



Figure 8 – Influence of SPA, CON, and ZON granularity on EUI variability under INT-1

Analysis of scenarios within the INT-1 group, where EUI values are confined to a narrow 2.5% range (348.7-357.3 kWh/m²), reveals that only the CON domain has a statistically significant impact on EUI ($p = 0.001$). This factor alone accounts for a considerable portion of the variance in the results ($\eta^2 = 0.333$), with the CON-1 approach yielding higher EUI values than the CON-2 approach. In contrast, the SPA ($p = 0.803$) and ZON ($p = 0.090$) domains lack statistical significance. For ZON, a noticeable contrast between its extreme levels (ZON-1 and ZON-4) is present but was not consistent enough to be conclusive in post-hoc tests. This demonstrates that within a highly standardized internal load configuration, CON is the only tested factor that produces a clear, statistically robust, and quantitatively substantial impact on EUI.

For INT-2 scenarios (Figure 9), the boxplots visually suggest that increased modeling granularity correlates with a wider EUI distribution across the tested domains. For SPA, there is a gradual widening of the data spread from SPA-1 to SPA-4, with SPA-4 displaying a notably higher median and a much broader range. A similar tendency appears for ZON, where the ZON-4 level shows the highest upper quartile. The contrast for CON is particularly clear: CON-1 results are consistently higher and more scattered, whereas CON-2 values are clustered in a much narrower and lower band.

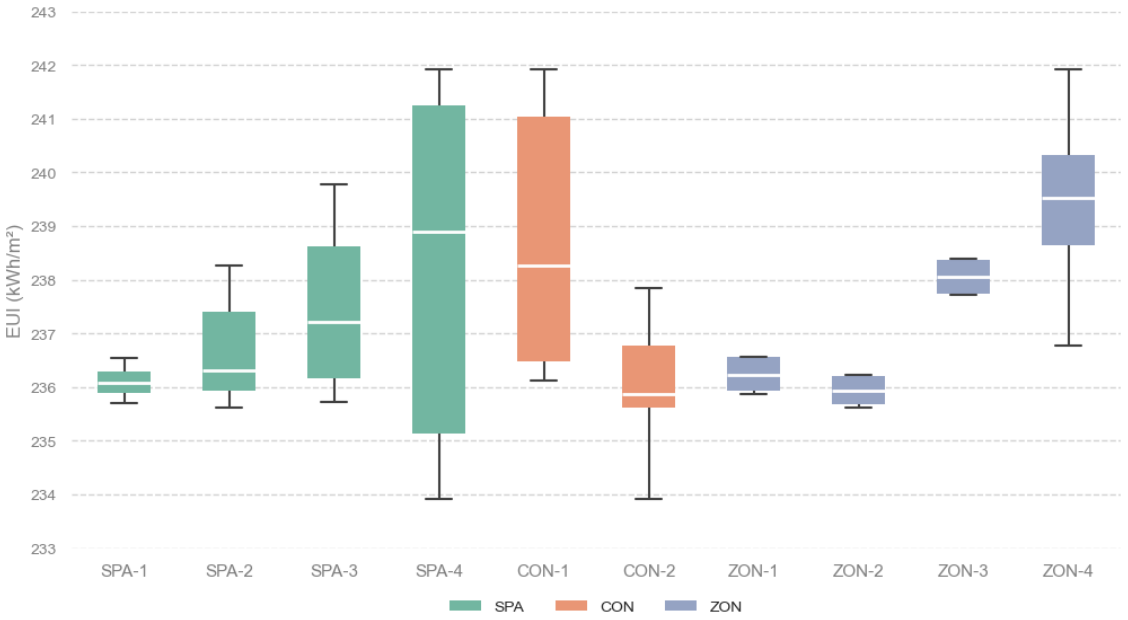



Figure 9 – Influence of SPA, CON, and ZON granularity on EUI variability under INT-2

A detailed analysis, however, qualifies these visual trends within the context of a relatively narrow overall EUI interval of 234 to 242 kWh/m² (a ~3.4% difference). The effect of the CON domain is decisive and statistically significant ($p = 0.003$). The ZON domain also shows a significant overall difference ($p = 0.041$); however, post-hoc tests do not pinpoint this difference between any specific pair of levels. This suggests the effect, while statistically present, is not as robust or consistently attributable to a single change in granularity as the impact seen in the CON domain. In contrast, the visual spread in the SPA domain is not statistically significant ($p = 0.527$). This indicates that while the most granular zoning level can introduce a subtle overall effect, only CON provides a consistent and statistically robust impact between specific modeling choices within this set of scenarios.

For INT-3 scenarios (Figure 10), the boxplots reveal several visual trends despite the narrow absolute range of EUI values. For the SPA domain, distributions are compact at lower granularities and become noticeably broader at higher levels; this visual observation of increased dispersion is statistically significant (Levene's test, $p = 0.047$). In contrast, while the CON and ZON domains also appear to show some visual differences in spread, these are not statistically supported.

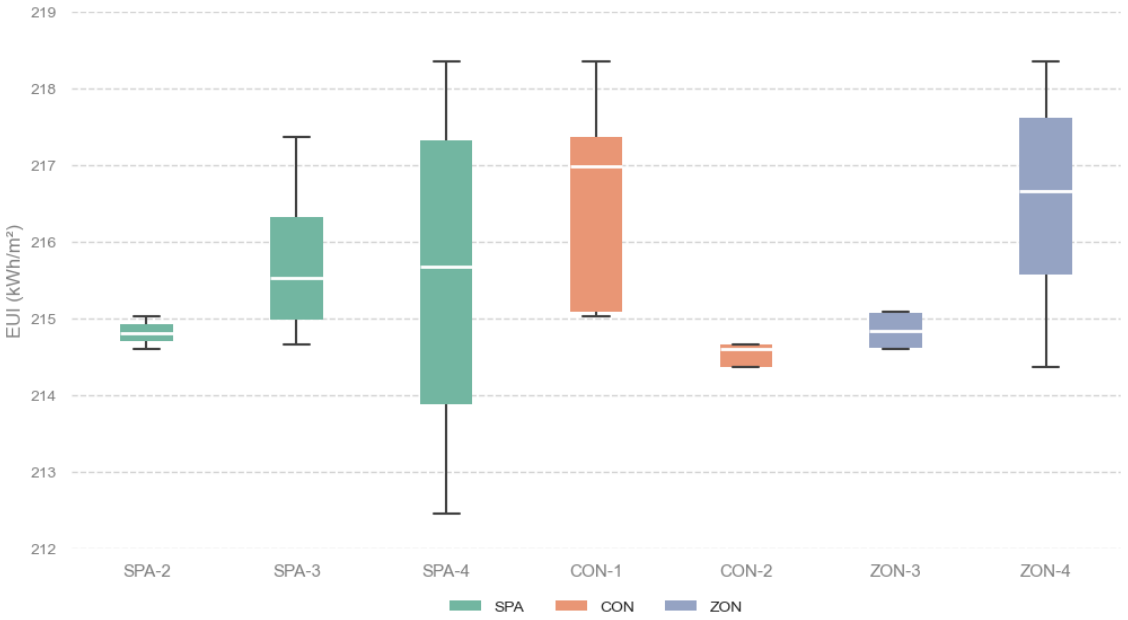



Figure 10 – Influence of SPA, CON, and ZON granularity on EUI variability under INT-3

Despite these visual trends, the analysis occurs within a very narrow overall EUI range of 212.3 to 218.2 kWh/m² (a ~2.8% difference). Within this stable context, the only statistically significant difference arises from the CON domain ($p = 0.028$). Although increased granularity in SPA does contribute to a more unpredictable range of EUI values, neither SPA nor ZON has a significant effect on the central EUI value itself. This demonstrates that even when space-specific internal loads stabilize EUI predictions, the representation of construction assemblies remains the most impactful and statistically robust factor on performance variability.

In addition to the overall trends in EUI, a closer inspection of the disaggregated end uses (lighting, equipment, heating, and cooling) provides further insight into how INT drives EUI. The stacked bar chart in Figure 11 demonstrates that the composition of EUI is strongly dominated by the cooling component across nearly all scenarios, while lighting and equipment maintain a relatively stable share and heating remains marginal.

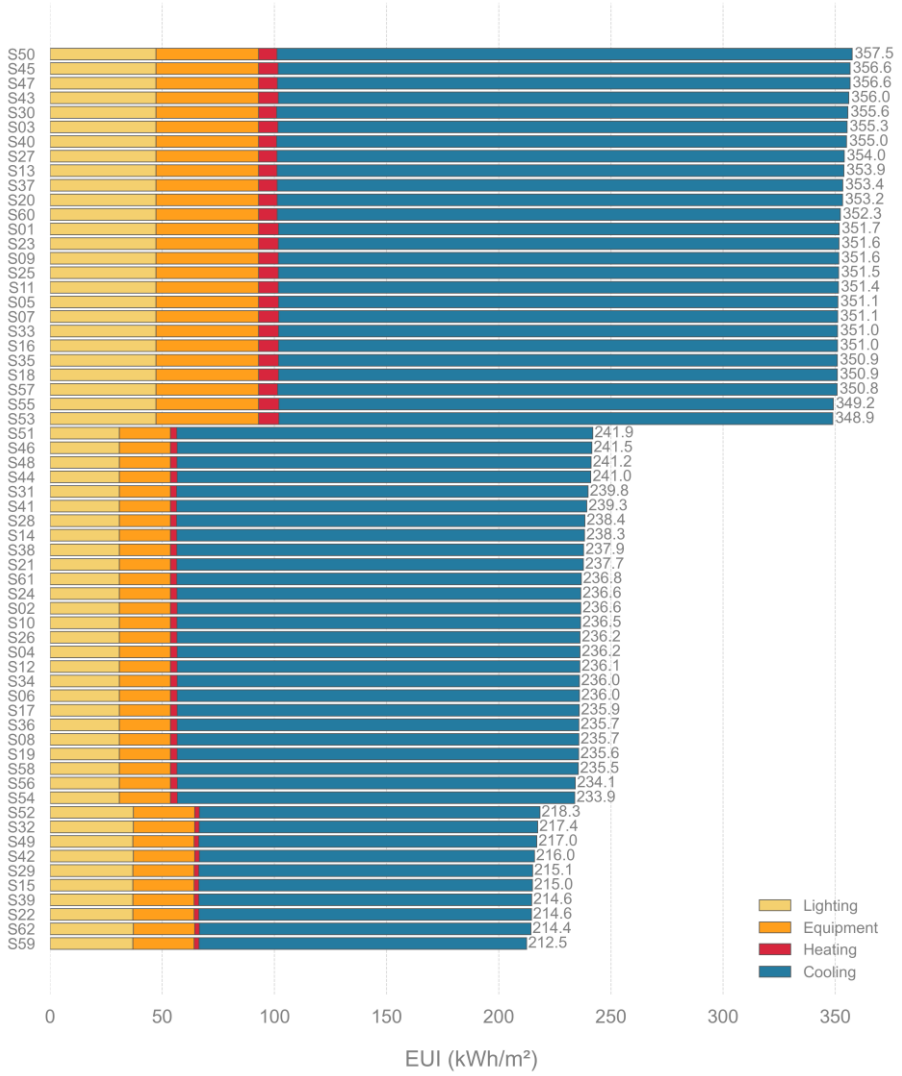



Figure 11 – EUI breakdown by scenario

Within the highest EUI group (INT-1), cooling accounts for roughly 68–71% of total energy use, while lighting and equipment each contribute about 13–15%, and heating represents only 2–3%. In the groups with lower EUI values (INT-2 and INT-3), the cooling representative is reduced to around 63–67%, while the proportions of lighting and equipment increase slightly – lighting rises to 16–17%, and equipment stabilizes between 13–14%. Heating remains a minor component in all cases.

The three levels of INT produce a clear EUI order. Scenarios using INT-1 yield the highest EUI values, which are on average 48% higher than INT-2 and 64% higher than INT-3. Although the total EUI for INT-2 scenarios is approximately 10% higher than for INT-3, their end-use breakdown differs. The INT-3 scenarios show higher loads from lighting (37.0 kWh/m²) and equipment

(27.4 kWh/m²) compared to the INT-2 scenarios (30.9 kWh/m² and 22.8 kWh/m², respectively). This increase is offset by lower heating loads and an 18% reduction in the average cooling EUI, which drops from 180.7 kWh/m² in INT-2 to 148.9 kWh/m² in INT-3. This shows that averaging internal loads at the building level versus assigning them to specific spaces fundamentally modifies the energy balance, primarily by overestimating cooling demand.

To exemplify the influence of INT on cooling loads, Figure 12 compares annual thermal cooling energy use and peak cooling loads for two representative zones – the library and a single classroom – across three illustrative scenarios (S40, S41, and S42). In these examples, all parameters related to SPA, CON, and ZON granularity are held constant, with only INT varying from INT-1 to INT-3. This approach is representative of the broader trends observed throughout the scenario matrix.

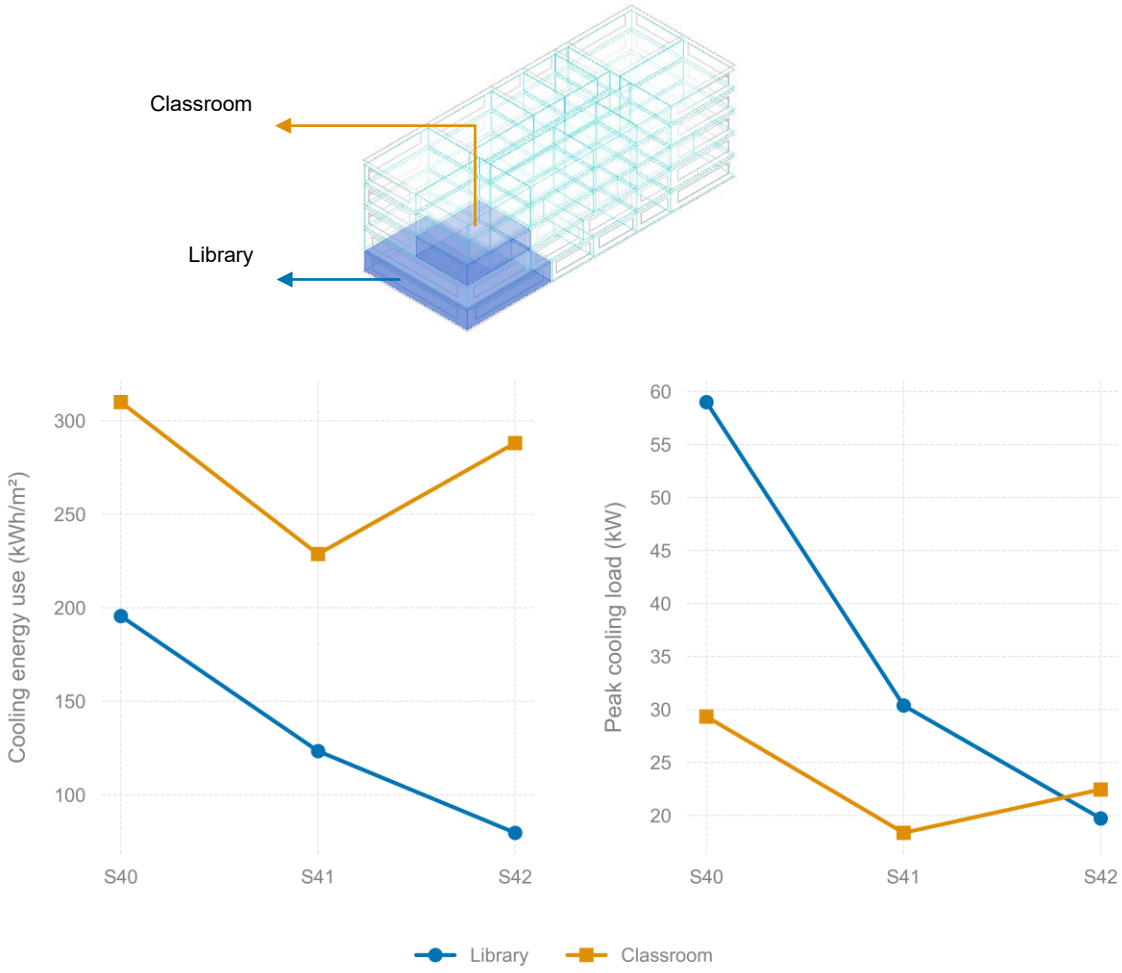



Figure 12 – Impact of INT granularity on annual and peak cooling loads in selected spaces

The library and classroom respond differently to changes in how internal loads are assigned. For the library, both annual cooling energy use and peak cooling demands decrease progressively as the assignment becomes more space-specific, with its peak load reducing from 59.0 kW under the uniform assignment (INT-1) to 19.7 kW when space-level information is used (INT-3). The classroom, in contrast, shows a more complex response. This is best understood by clarifying the averaged approach (INT-2), which calculates a single, building-wide internal load profile by creating a weighted average of all the detailed, space-specific loads from the INT-3 model, typically weighted by floor area. This process, intended as a realistic simplification, results in the classroom exhibiting its minimum annual and peak loads. Both the generic uniform assignment (INT-1) and the detailed space-specific assignment (INT-3) yield higher values, as the averaging process dilutes the classroom's high-density loads with the lower loads of common areas like corridors and storage rooms. This non-linear behavior leads to a critical shift in which space drives the peak cooling demand: under the uniform or averaged assignments, the library is predominant, but with space-specific assignments, the classroom becomes the primary driver.

These patterns reflect the spatial and operational characteristics of each environment. The library's large area and variable occupancy tend to dilute internal gains, lowering annual loads per square meter, but it can generate higher instantaneous peaks when using uniform or average assignments. Classrooms, with more concentrated and consistent usage profiles, generally show higher annual demand per square meter and less pronounced peaks, except when space-level assignments reveal concentrated load periods. The fact that there is only one library in the building means that approaches based on weighted averages are less effective in representing its unique load profile, while space-specific inputs provide a closer match to its actual operational pattern.

These results indicate that simplified internal load assignments may overlook significant diversity in space-by-space demand and influence which spaces are identified as critical for system sizing. Increasing the spatial granularity of internal gain assignments tends to change both the overall magnitude and the distribution of energy use and peak loads, which may affect the robustness and clarity of BEM outputs.

## 6 Discussion

The results of this study confirm the pronounced influence of the internal conditions, which were clearly identified as the dominant factor driving the variability of simulation outcomes and organizing them into three distinct performance clusters. While this finding reinforces the established sensitivity of BEM to operational assumptions [13,59], the core contribution of this research lies not in simply quantifying this effect, but in examining its practical implications for automated BIM-to-BEM workflows and informed design decision-making. In traditional BEM practice, internal conditions are often assigned manually based on normative references or a modeler's judgment [54]. By contrast, modern BIM-BEM integration facilitates the automated transfer of such semantic data – as demonstrated in this study – fundamentally altering how modeling choices impact the results.

Therefore, the dominance of the INT domain should not be viewed as an analytical artifact, but rather as an authentic feature that reflects the diverse and dynamic nature of building operations. This study suggests that the effectiveness of BIM- BEM automation is fundamentally dependent on the quality and specificity of this semantic data, not just on geometric and spatial accuracy. For researchers and practitioners, this means that the structure, attribution, and transfer of data regarding internal gains are at least as important as material or spatial detail in shaping the credibility of performance-based assessments. This focus aligns with the recent shift in energy efficiency research [60], which now incorporates building management and occupant behavior alongside traditional technological updates.

Perhaps the most critical challenge revealed by this study is the potential for design misdirection stemming from simplified internal load models. The analysis revealed a significant inversion in which space drives peak cooling demand. While the library is predominant under uniform and average assignments, the classroom becomes the primary driver under the detailed, space-specific model. This occurs even though the total EUI difference between the average model and the space-specific model is relatively 10%. The underlying cause is that the averaging process, while seemingly a reasonable simplification, masks localized load variations and fundamentally alters the building's energy

balance, primarily by overestimating cooling demand by a substantial 18% compared to the more granular approach.

This inversion represents a qualitative failure in design guidance, not just a quantitative error. It also serves as a clear example of the mechanisms that contribute to the well-documented performance gap [22], a challenge for which many numerical results are hard to validate in real projects. The pragmatic risk is that an engineering team relying on a simplified or average model could incorrectly identify the library as the critical space for system sizing and focus optimization efforts there. Such a misinterpretation could lead to improperly sized air-conditioning systems, either through oversizing based on the overestimated peak in one area or undersizing relative to the true peak in another, resulting in increased capital costs, reduced operational efficiency, and potential risks to occupant comfort.

It is important to clarify that while an Ideal Load Air System does not model specific equipment dynamics, its calculated peak load represents the raw thermal demand required to meet setpoints. This metric is therefore a solid indicator for this analysis's specific goal: comparing the relative thermal criticality of different spaces and identifying which zone imposes the greatest demand on a potential system. The observed design misdirection is thus a failure at the demand assessment level, which precedes and misinforms the subsequent system sizing. Before addressing this question, it is important to acknowledge that this study focused on the building model granularity itself, rather than the granularity of mechanical systems. The modeling of HVAC systems is, of course, another critical dimension of granularity that significantly affects energy outcomes. The methodological choice to use an Ideal Load Air System was intended to isolate the impact of BIM data on thermal demands, separating the building's intrinsic performance from the efficiencies and dynamics of a specific system.

This focus on demand, however, leads back to the question: why do simplified modeling approaches persist in practice? The answer seems to lie in the inherent tension between analytical rigor and the practical constraints of the BIM-BEM workflow. Implementing a detailed, space-by-space model is often perceived as a laborious and error-prone process that requires significant manual effort to map semantic data, making homogeneous models an appealing shortcut

under tight deadlines. This preference for simpler, lower-effort approaches reflects a broader industry challenge where the cost-effectiveness of interventions is a primary concern. This study, however, reveals that these workflow challenges extend beyond time and effort into subtle procedural nuances that can introduce unintended variability. The findings for the CON domain serve as a powerful case in point. Despite being based on identical material properties, the schematic (CON-1) and explicit (CON-2) modeling techniques produced statistically different results, a discrepancy that can be traced back to the calculation method itself, specifically whether the U-value was supplied by an external template or calculated by Revit's internal engine. This procedural artifact, invisible to most users, demonstrates that even the choice of modeling technique, not just the input data, is a source of uncertainty.

This practical dilemma – balancing accuracy against workflow complexity – suggests that pursuing maximum granularity across all domains is not an optimal strategy in the BIM-BEM field. Instead, the findings advocate for a more strategic approach, which can be conceptualized through a conceptual model of spatial and semantic granularity (Figure 13). This model distinguishes between spatial granularity, which pertains to the detail of the explicit geometric and spatial representation, and semantic granularity, the richness of the underlying, non-geometric information that gives meaning to that geometry. This model reveals three key operational states for a project:

- The "Spatial Plateau" describes a state of diminishing returns where the geometric model is more detailed than its assigned data. Further spatial resolution yields negligible impact on the results because the semantic attributes are too coarse to differentiate the new components.
- The "Semantic Saturation" is the opposite state, where the insertion of rich semantic detail is impeded because the geometric framework is too coarse to host it, lacking the necessary components for data assignment.
- The "Growth Stair" represents the balanced and productive path, where increasing either spatial or semantic granularity continues to produce meaningful changes in simulation outputs.

The goal of a strategic modeling approach is therefore to navigate this "Growth Stair" while avoiding the unproductive plateaus.

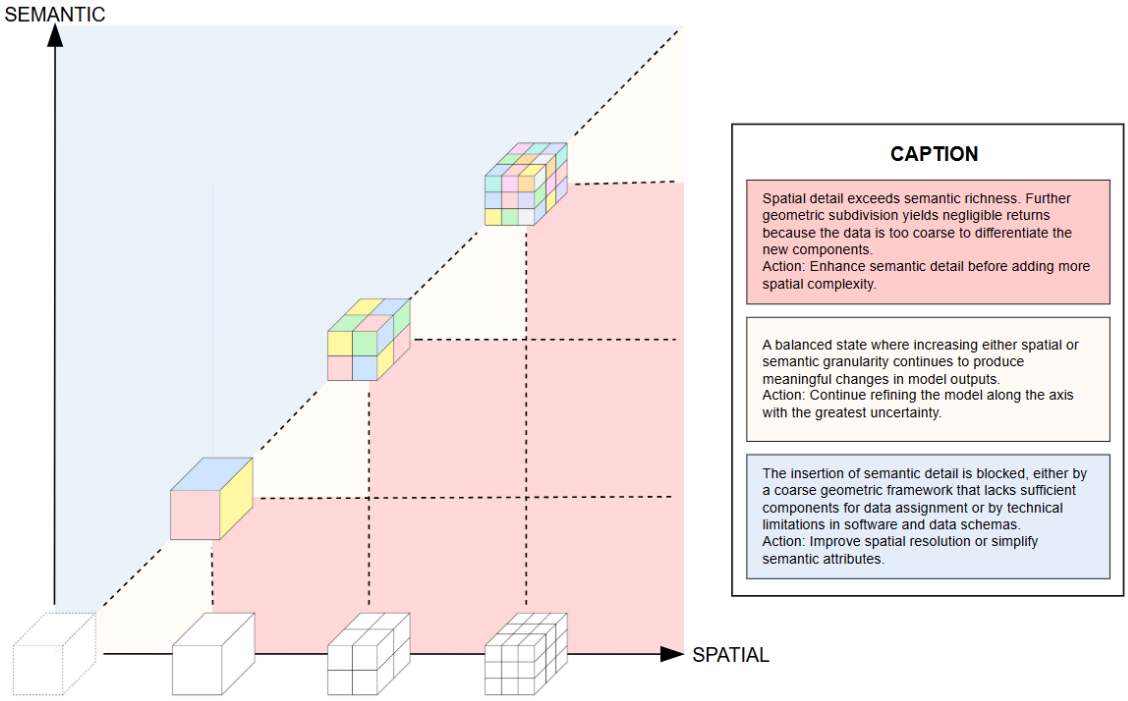



Figure 13 – Conceptual model of spatial and semantic granularity

It is critical to interpret this model not as a literal map but as a heuristic guide. The “Growth Stair” is a conceptual ideal; the actual relationship between spatial and semantic development is decidedly non-linear and occurs in discrete, often disproportional, leaps. For instance, a significant increase in spatial complexity, such as modeling plenums, may only require a minor semantic adjustment. In contrast, the transition to space-specific load profiles represents a massive semantic leap over an already established geometry. Furthermore, the “Semantic Saturation” is not only a consequence of a coarse geometric framework. It can also be imposed by technical constraints inherent in the modeling ecosystem, where the BIM authoring tools, BEM engines, or data exchange schemas (e.g., gbXML, IFC) may lack the capability to represent or transfer the required non-geometric attributes, creating a ceiling for semantic richness regardless of the modeler’s intent. This understanding, that the path is non-linear and constrained by both geometric and technical bottlenecks, reinforces the shift from a paradigm of “as detailed as possible” to a more resilient strategy of “as detailed as useful”, where modeling effort is consciously directed toward the most impactful dimension for a given design question.

This trade-off is not limited to modeling effort; it also includes computational cost. While not formally quantified in this study, models with higher

spatial and zoning granularity (e.g., ZON-4) inherently require longer simulation times. The magnitude of this effect, however, strongly depends on the project's scale. While this impact was minor in the relatively small building used in this case study, computational costs can rise significantly in larger projects featuring numerous analytical objects. A truly useful approach must therefore balance the need for sufficient semantic detail to avoid design misdirection against the manual effort of data input and the computational cost of simulation, especially during early design phases where rapid iteration is essential

The findings from this study have direct implications for regulatory practice and suggest a path toward more effective, context-aware energy assessment protocols. The clear dominance of internal conditions in driving simulation outcomes indicates that regulatory frameworks, which often focus heavily on geometric and envelope requirements, would benefit from placing greater emphasis on the quality and specificity of semantic data. By establishing minimum requirements for the attribution of internal gains, operational schedules, and space use types, regulations could help reduce the systematic deviations and risks of design misdirection identified in this research. This does not necessarily imply a universal mandate for maximum detail. Instead, the results advocate a more flexible and adaptive approach, where regulatory requirements could be tiered to match the project’s complexity and the intended use of the simulation. For routine compliance assessments, a streamlined model with validated semantic data might be sufficient, while for high-risk or complex projects, more stringent granularity could be required. Such a context-sensitive framework would embody the principle of “adaptive granularity”, ensuring that the required modeling effort is proportional to the decision-making stakes, thereby balancing analytical rigor with practical efficiency in both design and compliance workflows.

## 7 Conclusion

This study demonstrates that BIM modeling granularity exerts a profound and multifaceted influence on the outcomes of energy performance assessment. The extent of this impact is substantial, with modeling choices leading to a significant variation in the EUI. The internal conditions domain was unequivocally identified as the primary driver of variability, far surpassing the influence of spatial

configuration, construction assemblies, and thermal zoning. The research also reveals that the trade-off between modeling effort and the consistency of results is not linear; an increase in complexity does not guarantee a proportional improvement in reliability.

The synthesis of the main findings reveals a complex interplay between the domains of granularity. First, the internal conditions not only dominate the overall variability but also organize the results into distinct, non-overlapping performance clusters. Within these clusters, secondary factors introduce statistically significant variations. Perhaps the most critical finding is the risk of design misdirection: models with simplified semantic data mask localized load peaks, which can alter the identification of which spaces drive the building's peak demand and become critical for system sizing. Furthermore, the study demonstrates that the modeling technique itself – the way information is structured in BIM and interpreted during the BIM-to-BEM transfer – can introduce significant uncertainty, even when the underlying physical properties remain identical.

The original contribution of this work is twofold. First, it systematically quantifies the risks associated with using simplified models in automated workflows, proving that the simplification of semantic data can lead to qualitative failures in design guidance, not just quantitative errors. Second, and more importantly, the research proposes a new conceptual model for managing this complexity, based on the distinction between spatial and semantic granularity. This model challenges the conventional mindset of "more detail is better" for a strategic approach where modeling effort is aligned with the analytical purpose.

The implications of these findings are direct for both professional practice and academia. For practitioners, the research serves as a caution to prioritize the richness and accuracy of semantic data, as these have a more significant impact on simulation reliability than the pursuit of maximum geometric accuracy. For the academic field and regulatory bodies, the study highlights that normative frameworks, often focused on geometric and envelope requirements, would benefit from incorporating minimum requirements for the quality of semantic information, thereby mitigating the systematic deviations identified.

It is important to acknowledge the limitations of this study. The conclusions are derived from the analysis of a single building archetype, a

university facility, in a specific climate. The dominance of cooling loads and the relevance of certain factors may vary in other climates or building typologies. Furthermore, the methodological scope was focused on thermal demands using an ideal load system, meaning the interaction with specific HVAC system modeling granularity was not addressed. Similarly, the assessment focused primarily on energy use and peak loads, while other holistic performance metrics, such as indoor environmental quality and occupant comfort, were not part of the research scope. Additionally, the proposed conceptual model is a qualitative abstraction intended to guide strategic thinking; it is far from a finalized version and requires significant future work to be refined into a practical tool.

Based on the findings and limitations, future research should focus on validating and expanding this work. It would be valuable to apply the same methodology to different building archetypes and in diverse climatic contexts. Another promising avenue is to investigate how spatial and semantic granularity affect other performance metrics, such as lifecycle cost, as well as the previously mentioned indicators of occupant comfort and indoor air quality. Quantifying the trade-offs between modeling granularity, computational cost, and result accuracy also remains a key area for investigation, particularly to support the “as detailed as useful” strategy. Finally, there is an opportunity to develop and test standardized protocols that operationalize the “adaptive granularity” approach in practice, helping professionals make more informed and efficient modeling decisions.

## Acknowledgments

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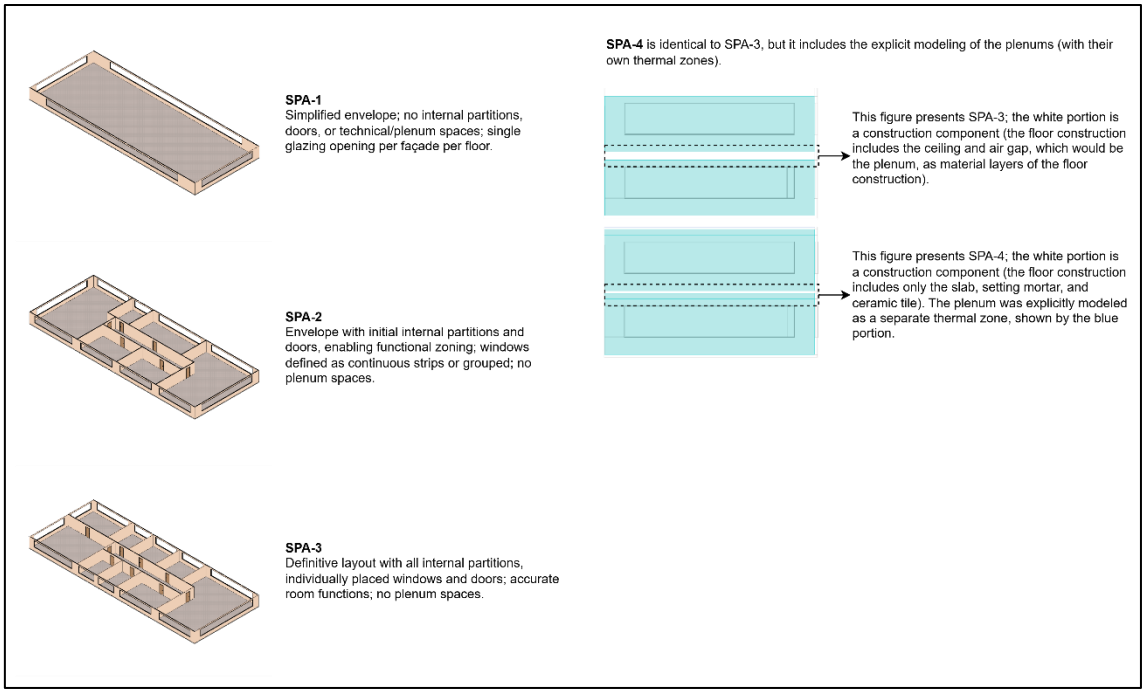
# Appendix A

## Explanation of each domain and its corresponding modeling granularity



**SPA-1**
Simplified envelope; no internal partitions, doors, or technical/plenum spaces; single glazing opening per façade per floor.

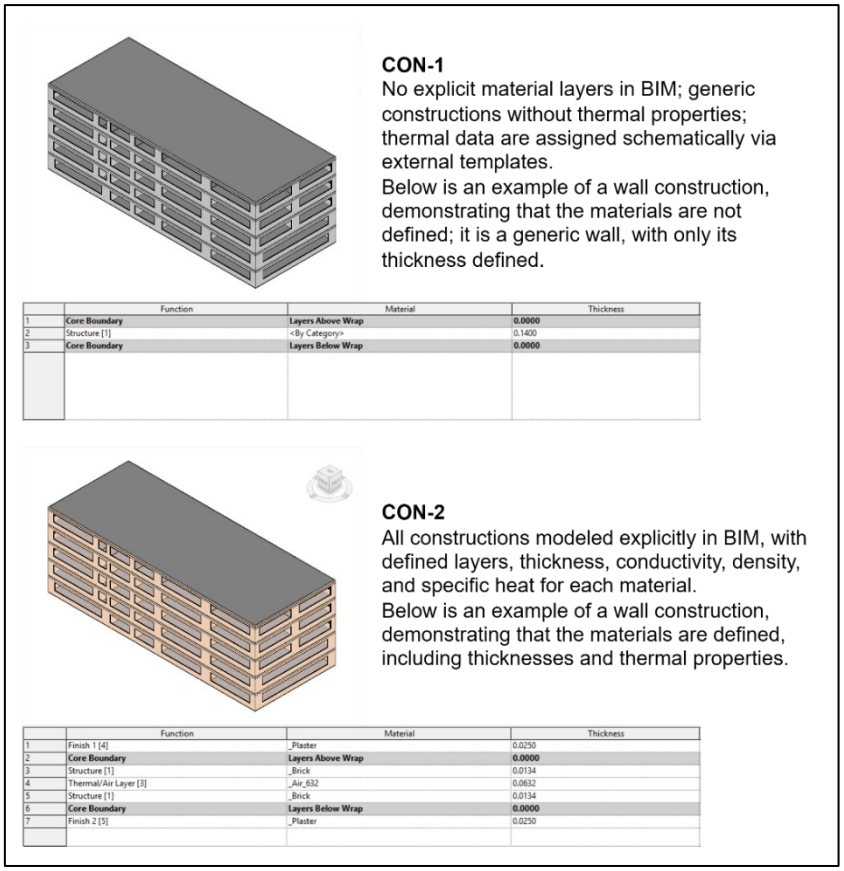
**SPA-2**
Envelope with initial internal partitions and doors, enabling functional zoning; windows defined as continuous strips or grouped; no plenum spaces.

**SPA-3**
Definitive layout with all internal partitions, individually placed windows and doors; accurate room functions; no plenum spaces.

**SPA-4** is identical to SPA-3, but it includes the explicit modeling of the plenums (with their own thermal zones).

This figure presents SPA-3; the white portion is a construction component (the floor construction includes the ceiling and air gap, which would be the plenum, as material layers of the floor construction).

This figure presents SPA-4; the white portion is a construction component (the floor construction includes only the slab, setting mortar, and ceramic tile). The plenum was explicitly modeled as a separate thermal zone, shown by the blue portion.

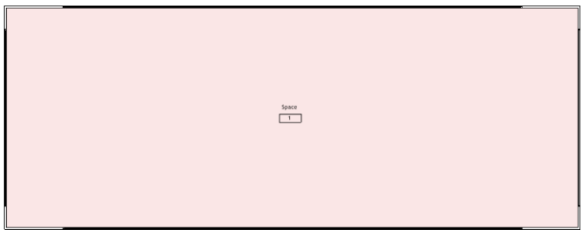


**CON-1**
No explicit material layers in BIM; generic constructions without thermal properties; thermal data are assigned schematically via external templates.
Below is an example of a wall construction, demonstrating that the materials are not defined; it is a generic wall, with only its thickness defined.

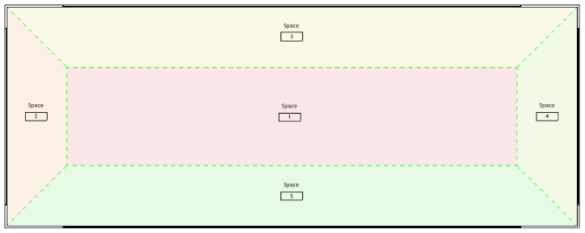
| | Function | Material | Thickness |
|---|---|---|---|
| 1 | **Core Boundary** | **Layers Above Wrap** | **0.0000** |
| 2 | Structure [1] | <By Category> | 0.1400 |
| 3 | **Core Boundary** | **Layers Below Wrap** | **0.0000** |

**CON-2**
All constructions modeled explicitly in BIM, with defined layers, thickness, conductivity, density, and specific heat for each material.
Below is an example of a wall construction, demonstrating that the materials are defined, including thicknesses and thermal properties.

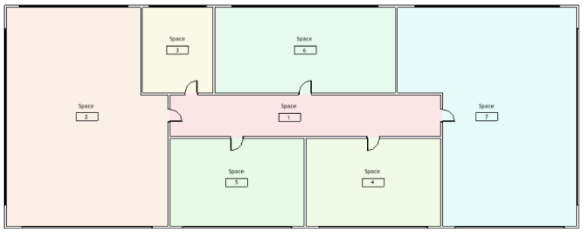
| | Function | Material | Thickness |
|---|---|---|---|
| 1 | Finish 1 [4] | _Plaster | 0.0250 |
| 2 | **Core Boundary** | **Layers Above Wrap** | **0.0000** |
| 3 | Structure [1] | _Brick | 0.0134 |
| 4 | Thermal/Air Layer [3] | _Air_632 | 0.0632 |
| 5 | Structure [1] | _Brick | 0.0134 |
| 6 | **Core Boundary** | **Layers Below Wrap** | **0.0000** |
| 7 | Finish 2 [5] | _Plaster | 0.0250 |



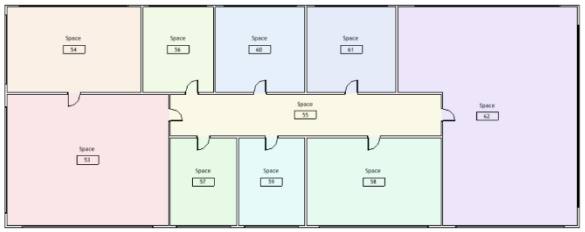
**ZON-1**
Entire floor modeled as a single thermal zone.



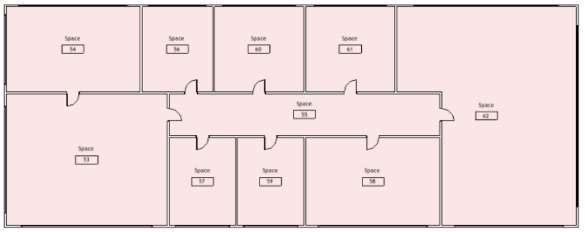
**ZON-2**
Core and perimeter zones differentiated for each floor.



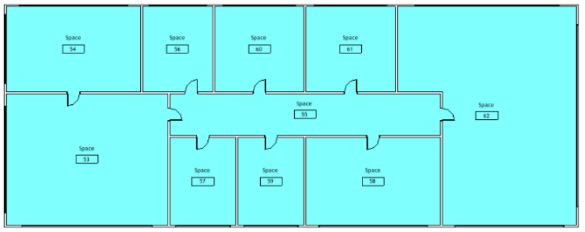
**ZON-3**
Each floor subdivided into functional zones, reflecting typical use diversity.



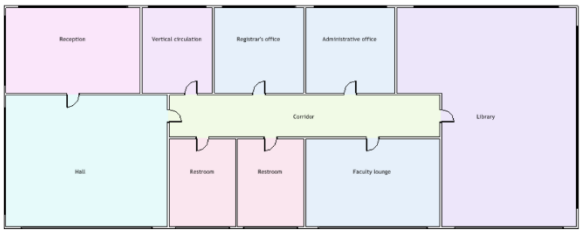
**ZON-4**
Each room modeled as an individual thermal zone, allowing maximum detail for loads and ventilation.



**INT-1**
Uniform internal loads and ventilation rates based on the Brazilian regulatory guidelines [50].



**INT-2**
Weighted-average internal loads and ventilation rates, methodologically mimicking INT-1 but using INT-3 dataset.




**INT-3**
Internal loads and ventilation rates differentiated by room type, based on ASHRAE standards [55,56].

# Appendix B

## Matrix of 62 scenarios

| Scenario ID | Spatial Configuration | Thermal Zoning | Construction Assembly | Internal Conditions |
|---|---|---|---|---|
| S01 | SPA-1 | ZON-1 | CON-1 | INT-1 |
| S02 | SPA-1 | ZON-1 | CON-1 | INT-2 |
| S03 | SPA-1 | ZON-2 | CON-1 | INT-1 |
| S04 | SPA-1 | ZON-2 | CON-1 | INT-2 |
| S05 | SPA-1 | ZON-1 | CON-2 | INT-1 |
| S06 | SPA-1 | ZON-1 | CON-2 | INT-2 |
| S07 | SPA-1 | ZON-2 | CON-2 | INT-1 |
| S08 | SPA-1 | ZON-2 | CON-2 | INT-2 |
| S09 | SPA-2 | ZON-1 | CON-1 | INT-1 |
| S10 | SPA-2 | ZON-1 | CON-1 | INT-2 |
| S11 | SPA-2 | ZON-2 | CON-1 | INT-1 |
| S12 | SPA-2 | ZON-2 | CON-1 | INT-2 |
| S13 | SPA-2 | ZON-3 | CON-1 | INT-1 |
| S14 | SPA-2 | ZON-3 | CON-1 | INT-2 |
| S15 | SPA-2 | ZON-3 | CON-1 | INT-3 |
| S16 | SPA-2 | ZON-1 | CON-2 | INT-1 |
| S17 | SPA-2 | ZON-1 | CON-2 | INT-2 |
| S18 | SPA-2 | ZON-2 | CON-2 | INT-1 |
| S19 | SPA-2 | ZON-2 | CON-2 | INT-2 |
| S20 | SPA-2 | ZON-3 | CON-2 | INT-1 |
| S21 | SPA-2 | ZON-3 | CON-2 | INT-2 |
| S22 | SPA-2 | ZON-3 | CON-2 | INT-3 |
| S23 | SPA-3 | ZON-1 | CON-1 | INT-1 |
| S24 | SPA-3 | ZON-1 | CON-1 | INT-2 |
| S25 | SPA-3 | ZON-2 | CON-1 | INT-1 |
| S26 | SPA-3 | ZON-2 | CON-1 | INT-2 |
| S27 | SPA-3 | ZON-3 | CON-1 | INT-1 |
| S28 | SPA-3 | ZON-3 | CON-1 | INT-2 |
| S29 | SPA-3 | ZON-3 | CON-1 | INT-3 |
| S30 | SPA-3 | ZON-4 | CON-1 | INT-1 |
| S31 | SPA-3 | ZON-4 | CON-1 | INT-2 |
| S32 | SPA-3 | ZON-4 | CON-1 | INT-3 |
| S33 | SPA-3 | ZON-1 | CON-2 | INT-1 |
| S34 | SPA-3 | ZON-1 | CON-2 | INT-2 |
| S35 | SPA-3 | ZON-2 | CON-2 | INT-1 |
| S36 | SPA-3 | ZON-2 | CON-2 | INT-2 |
| S37 | SPA-3 | ZON-3 | CON-2 | INT-1 |
| S38 | SPA-3 | ZON-3 | CON-2 | INT-2 |
| S39 | SPA-3 | ZON-3 | CON-2 | INT-3 |

| | | | | |
|---|---|---|---|---|
| S40 | SPA-3 | ZON-4 | CON-2 | INT-1 |
| S41 | SPA-3 | ZON-4 | CON-2 | INT-2 |
| S42 | SPA-3 | ZON-4 | CON-2 | INT-3 |
| S43 | SPA-4 | ZON-1 | CON-1 | INT-1 |
| S44 | SPA-4 | ZON-1 | CON-1 | INT-2 |
| S45 | SPA-4 | ZON-2 | CON-1 | INT-1 |
| S46 | SPA-4 | ZON-2 | CON-1 | INT-2 |
| S47 | SPA-4 | ZON-3 | CON-1 | INT-1 |
| S48 | SPA-4 | ZON-3 | CON-1 | INT-2 |
| S49 | SPA-4 | ZON-3 | CON-1 | INT-3 |
| S50 | SPA-4 | ZON-4 | CON-1 | INT-1 |
| S51 | SPA-4 | ZON-4 | CON-1 | INT-2 |
| S52 | SPA-4 | ZON-4 | CON-1 | INT-3 |
| S53 | SPA-4 | ZON-1 | CON-2 | INT-1 |
| S54 | SPA-4 | ZON-1 | CON-2 | INT-2 |
| S55 | SPA-4 | ZON-2 | CON-2 | INT-1 |
| S56 | SPA-4 | ZON-2 | CON-2 | INT-2 |
| S57 | SPA-4 | ZON-3 | CON-2 | INT-1 |
| S58 | SPA-4 | ZON-3 | CON-2 | INT-2 |
| S59 | SPA-4 | ZON-3 | CON-2 | INT-3 |
| S60 | SPA-4 | ZON-4 | CON-2 | INT-1 |
| S61 | SPA-4 | ZON-4 | CON-2 | INT-2 |
| S62 | SPA-4 | ZON-4 | CON-2 | INT-3 |

## Appendix C

## Stratified statistical test results (Kruskal-Wallis)

| INT group | Domain | H-Statistic | p-value | Effect size ($\eta^2$) | Sample size (n) | Line interpretation | Group summary |
|---|---|---|---|---|---|---|---|
| INT-1 | SPA | 0.994 | 0.803 | 0.171 | 26 | Not significant. SPA does not show a statistical effect. | This group (INT-1) has a clear statistical signal. Only CON (p=0.001) is a significant driver. Both SPA (p=0.803) and ZON (p=0.090) are not. |
| | CON | 10.273 | 0.001 | 0.333 | 26 | Significant. CON is a key driver of variability. | |
| | ZON | 6.488 | 0.090 | 0.362 | 26 | Not significant. ZON (p=0.090) does not meet the 0.05 threshold. | |
| INT-2 | SPA | 2.227 | 0.527 | 0.216 | 26 | Not significant. SPA does not show a statistical effect. | This group (INT-2) shows a mixed signal. CON (p=0.003) remains a strong driver, and ZON (p=0.041) also becomes significant. SPA remains non-significant. |
| | CON | 9.000 | 0.003 | 0.295 | 26 | Significant. CON is a key driver of variability. | |
| | ZON | 8.266 | 0.041 | 0.360 | 26 | Significant. ZON is a driver of variability in this group. | |
| INT-3 | SPA | 0.955 | 0.620 | 1.000* | 10 | Not significant. The p-value indicates no effect. | Small sample (n=10) limits statistical power. The $\eta^2$ values are statistical artifacts. Despite the limitation, CON (p=0.028) still shows a significant effect. |
| | CON | 4.811 | 0.028 | n.a.** | 10 | Significant. CON remains a factor, even with n=10. | |
| | ZON | 1.636 | 0.201 | 1.000* | 10 | Not significant. The p-value indicates no effect. | |

* In small samples (n=10), $\eta^2$ effect size calculations can be unstable, as seen here. The more reliable indicator is the p-value ($p > 0.20$), which confirms that no statistically significant effect was found.
** The $\eta^2$ calculation is not applicable (n.a.) due to low variance in the small sample. This does not impact the validity of the p-value, which remains robustly significant (p=0.028).

# APÊNDICE D

Artigo 4

Enabling Scalable Dynamic Simulation for Building Energy Performance Certification: An Automated BIM-to-BEM Workflow

**Contrato de Autoria Compartilhada**

Esse documento atesta que todos os coautores do manuscrito intitulado *Enabling Scalable Dynamic Simulation for Building Energy Performance Certification: An Automated BIM-to-BEM Workflow* **CONCORDAM** com o seu uso como parte da tese de doutorado de Luís Filipe Muta, orientado pela professora Ana Paula Melo do Programa de Pós-Graduação em Engenharia Civil (PPGEC) da Universidade Federal de Santa Catarina (UFSC) e coorientado pela professora Annamaria Buonomano do Departamento de Engenharia Industrial da Università degli Studi di Napoli Federico II.

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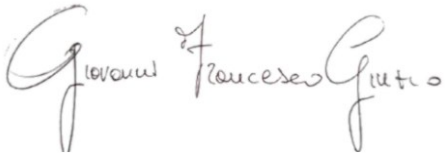

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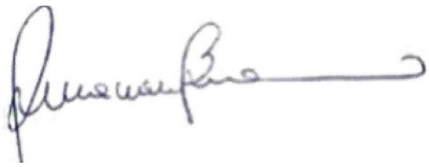

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Annamaria Buonomano
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Florianópolis, 15 de janeiro de 2026.

# Enabling Scalable Dynamic Simulation for Building Energy Performance Certification: An Automated BIM-to-BEM Workflow

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## Abstract

Mandatory energy performance certification demands scalable and transparent processes. Currently, BIM-to-BEM interoperability gaps hinder the automation of dynamic simulations required for compliance. This research proposes a multi-stage workflow integrating modeling guidelines with an automated Python pipeline. This pipeline rectifies interoperability errors and enriches the model with regulatory data, programmatically generating “real” and “reference” models for comparative labeling. Validated on an 8,100 m² university building, the workflow corrected persistent interoperability issues and automated the configuration of thousands of components. The complete certification assessment took approximately 15 minutes. The findings demonstrate that post-export automated verification is essential for consistency. By streamlining the generation of high-fidelity compliance models, this work contributes a replicable framework for objective and auditable energy certification, proving that rigorous dynamic simulation is viable for large-scale regulatory implementation.

**Keywords**: BIM, BEM, Energy Performance Certification, Workflow, Automation.

## 1 Introduction

Addressing global climate change and achieving sustainable development goals demands a fundamental shift in how societies consume energy [1]. The built environment accounts for a substantial portion of energy demand and is the largest source of greenhouse gas emissions [2]. Consequently, the assessment of energy performance in buildings has become a global imperative, progressively integrated into policy and industry agendas worldwide [3]. This reflects a growing perception of the built environment's significant energy consumption and environmental impact [4]. Numerous legislative frameworks and voluntary initiatives have emerged across continents, establishing common approaches for energy performance certification (EPC) schemes [3]. While their specific requirements and implementation tools may vary, these programs consistently emphasize transparency, comparability, and the adoption of standardized procedures to assess building energy use at scale [5].

In the context of EPC, energy performance assessment is fundamentally structured to ensure compliance with predefined standards or criteria [6]. Unlike detailed operational consumption modeling, regulatory methodologies often rely on prescriptive values, standardized parameter sets, and fixed assumptions, which are clearly outlined in codes or technical manuals [7]. The selection of these methods is typically driven by considerations of reproducibility and broad applicability across diverse building types [3]. By prioritizing the consistent application of rules over individualized precision, these frameworks aim to facilitate benchmarking, enforcement, and market transformation, thereby supporting a predictable compliance process for various projects [4].

Regulatory schemes commonly employ two primary assessment methods: simplified calculation and dynamic simulations. The former approach involves the explicit entry of prescribed characteristics, such as envelope properties, system efficiencies, and usage patterns, into standardized forms or software [8]. These methods are typically structured to facilitate straightforward verification and ensure direct alignment with specific policy targets. Alternatively, simulation-based approaches use digital models to represent building geometry, material properties, internal loads, occupancy profiles, and technical systems,

enabling the calculation of energy indicators through simulation engines [5]. Within this domain, Building Energy Modeling (BEM) has emerged for creating detailed virtual representations of buildings to predict energy consumption and other performance metrics [9]. These simulation-based approaches represent a shift towards capturing complex thermal dynamics and high-resolution temporal profiles, offering superior accuracy compared to quasi-static methods. However, despite their capacity for greater complexity and flexibility, the effective application of simulation-based BEM for compliance purposes can be hindered by challenges in data preparation, consistency of interpretation, and the substantial effort required to align project documentation with model inputs [10]. These difficulties are often exacerbated under conditions of scale, where manual data handling and the diversity of project documentation introduce further complexity for compliance [11].

Recent advancements in Building Information Modeling (BIM) offer promising avenues for organizing and integrating the vast amount of information required for energy performance assessment. BIM tools consolidate geometric, spatial, material, and system data within a single coordinated digital environment, accessible and processable throughout different stages of design and construction [12]. The adoption of open data standards, such as Green Building XML (gbXML) and Industry Foundation Classes (IFC), can facilitate the transfer of information from BIM to BEM, potentially reducing redundancies, minimizing manual intervention, and supporting more consistent data interpretation [13]. Nevertheless, in practical applications, the structure, completeness, and granularity of BIM data can vary significantly depending on project stage, discipline conventions, and the specific requirements of regulatory frameworks [14]. Consequently, reliance on manual workflows often persists, which limits opportunities for automation and diminishes the reproducibility of regulatory assessments.

Given these challenges, particularly in achieving scalable and transparent energy performance assessments within regulatory contexts, this research aims to develop and test an automated BIM-to-BEM workflow tailored for mandatory energy performance assessment. By integrating structured information requirements, modeling guidelines, and a simulation protocol into a cohesive automated pipeline, this study seeks to streamline data flow from BIM

models to BEM simulations, thereby enhancing the scalability, consistency, and transparency of the certification process.

## 2 Background

Following the demand for automated assessments, assessing building energy performance integrates technical modeling, policy, and digital information management to meet sustainability objectives [15]. Often guided by codes and regulations, these assessments support energy efficiency targets, mitigate environmental impacts, and promote market transparency and occupant well-being [16]. Regulatory frameworks often specify how to structure, document, and analyze building data [17]. Standardized inputs and procedures promote scalability and consistency in application [18].

This structured approach, used for compulsory and voluntary evaluation and certification, ensures practical implementation and effective verification of energy standards across various building types [19].

Globally and regionally, several frameworks share a focus on energy efficiency. In the United States, ASHRAE Standard 90.1 defines minimum requirements [20], complemented by benchmarking programs like ENERGY STAR [21]. In Brazil, the PBE Edifica constitutes a labeling initiative [22] with phased minimum performance standards [23], while Australia's NABERS evaluates buildings based on measured operational energy and contractual obligations [24]. In the European Union, the Energy Performance of Buildings Directive (EPBD) mandates Energy Performance Certificates to promote transparency [25]. Notably, the recent recast of the EPBD has expanded this scope, triggering discussions on requirements such as demand-side flexibility and grid-interactive performance. These developments are shifting performance assessment tools beyond static, asset-based ratings toward capturing temporal profiles and interactions with the electricity system, reflecting a broader shared goal of utilizing energy metrics for regulatory compliance and market-driven improvements [26].

Despite broad adoption, current energy assessment practices face challenges hindering efficiency and scalability. Manual, document-based workflows often require repetitive data entry across platforms, increasing risks of transcription errors and inconsistencies between design and evaluations [3].

Reliance on simplified, static reporting methods fails to capture the complex temporal dynamics of modern buildings and often causes information loss, as detailed data is aggregated for predefined templates [5]. Verification is also limited to specific project stages, reducing early issue identification and increasing reliance on specialized consultants for complex requirements [27]. These inefficiencies worsen as project volumes grow and regulations evolve [28]. This highlights the need for innovative approaches to maintain data integrity, support continuous validation, and minimize manual intervention. These challenges are significant for contexts requiring rapid, reproducible assessments, like regulatory compliance [29]. To overcome these challenges, adopting systematic data management across the entire building lifecycle is necessary to achieve consistency and robust traceability.

In this context, BIM is a promising solution, addressing limitations in compliance-driven evaluations while benefiting wider design and operational contexts [30]. BIM's parametric nature allows automated data extraction for energy analysis, streamlining the conversion of design specifications into actionable insights [31]. BIM also supports integration between architectural design tools and energy simulation software, improving data flow consistency [32]. Studies suggest these capabilities improve the accuracy and efficiency of energy assessments, enhancing traceability and reducing rework [33]. As projects become increasingly complex and expectations become stricter – driven by regulation or market demands – BIM provides a structured method for organizing, validating, and communicating technical data for energy verification, thereby aiding digital transformation in construction [34].

For energy assessment, a key concept is connecting BIM with BEM. While BIM is a central data repository, BEM includes tools to simulate and analyze a building's energy performance [35]. BIM and BEM integration links these domains, using BIM data in BEM simulations to evaluate performance with greater coherence and reduced manual effort [36]. This connection often relies on standardized formats like IFC and gbXML for compatibility between diverse software used by architects, engineers, and energy consultants [37,38]. To systematize this integration, BIM-to-BEM workflows were developed, offering structured approaches to transfer and adapt building data across systems, supporting informed decision-making [39].

BIM-to-BEM workflow development is shaped by clearly defined objectives, which determine their structure and application for both design and simulation purposes. Some workflows are broad, integrating BIM with BEM across design phases to enhance overall energy simulation [40]. Others focus on defined challenges, tailoring processes to specific requirements. For example, Andriamamonjya et al. [41] present a specialized workflow automating BEM model generation, emphasizing Modelica to improve simulation accuracy. More recently, Garlet et al. [19] focused on enhancing workflows for natural ventilation simulations through the integration of AirflowNetwork in EnergyPlus. This diversity shows how workflows adapt to varying specificity and complexity in achieving energy goals.

Although BIM-to-BEM have the potential to improve building energy performance assessment, these workflows still face complex challenges that impact how effectively they can be implemented and scaled. Individually, human issues hinder progress, as limited modeling skills or data provision oversight disrupt BIM-to-BEM interoperability, with errors amplified by lacking clear information requirements and guidelines [42]. Industrially, software limitations are obstacles, as tools often lack essential features and data transformation algorithms, resulting in data loss and generic outputs [43]. Also, while open schemas like IFC and gbXML aid integration, current versions are not comprehensive enough. Even updated schemas are constrained by ecosystem limitations, where BIM or BEM tools may not support specific attributes defined in the open schemas [5]. These multifaceted challenges highlight the need for continued improvements in BIM-to-BEM workflows to support energy and sustainability goals.

Addressing BIM-to-BEM integration barriers often start with well-defined information requirements and modeling guidelines to standardize data for energy assessment. Information requirements outline critical BIM data (e.g., geometry, thermal properties) supporting BEM integration, as noted by Sanhudo et al. [44], stressing the need to specify information needed at each project stage. Modeling guidelines instruct BIM development, reducing errors and promoting uniformity. O'Donnell et al. [45] and Bracht et al. [11] highlight this, showing how BIM tool differences, like Revit modeling walls by centerline versus others using wall faces, affect gbXML geometry for simulations. Reeves et al. [46] also emphasize

broader interoperability, advocating for standardized practices to align inputs and outputs across building lifecycle phases. Lacking such practices causes interoperability issues, as key attributes may be omitted without guidance.

Even with proper requirements and guidelines, a key interoperability challenge is semantic discrepancies, where data's meaning is lost or misinterpreted during transfer [47]. These issues emerge when attributes (e.g., material properties, boundary conditions) are inconsistently defined or mistranslated during export to gbXML or IFC, resulting in inaccurate energy simulations [43]. For example, a BIM element with a specific function might be misclassified in BEM tools due to differing algorithm interpretations or schema limitations [13]. To address these gaps, recent approaches explore automated correction and semantic enrichment, using methods such as data mapping via dictionaries or ontologies to standardize terms and infer correct attributes for energy assessment [48,49]. These solutions – from ontology-based standardization [48] to similarity matching [49] and data transformation [50] – aim to enhance data consistency and reduce manual adjustments by aligning information understanding across software.

Simulation protocols complement these foundational elements, addressing the need for consistent BEM model configuration, especially for regulation compliance for automated contexts. These protocols define procedures for setting up energy models [9], applying prescriptive values from energy codes to balance standardization with flexibility for different building types [30]. This is relevant because varying objectives, like compliance verification [31] or retrofit planning [51,52], require distinct model adjustments for appropriate assumptions. In automation, protocols further delineate BEM configurations aligning with predefined BIM data [53], showing opportunities to reduce manual intervention while maintaining regulatory alignment.

Figure 1 presents a simplified BIM-to-BEM workflow, illustrating how these foundational elements integrate. It outlines key steps from model development to simulation, incorporating information requirements, modeling guidelines, and simulation protocols, and highlights critical decision points and adjustments needed for consistency. This depiction helps understand the structured data flow and practical integration challenges, setting the stage to examine specific workflow implementations and their limitations.

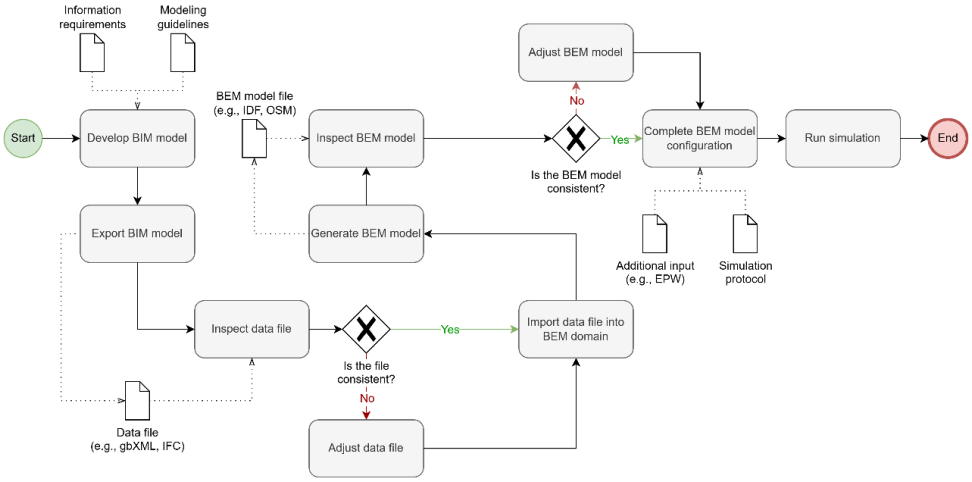



Figure 1 – Simplified BIM-to-BEM workflow

Several studies developed semi-automated workflows using common data formats and validation to address interoperability issues. For instance, Barone et al. [54,55] use gbXML to transfer Revit data to OpenStudio, demonstrating how this pipeline facilitates parameter extraction but requires corrections for export discrepancies to enable practical energy assessments. Similarly, Pinheiro et al. [56] apply IFC-based Model View Definitions (MVD) to connect BIM data with tools such as EnergyPlus, adding collaborative checks to limit setup errors. Alexandrou et al. [52] also presents semi-automatic BIM-to-BEM workflows using gbXML and IFC in heritage buildings, highlighting the importance of interdisciplinary coordination and tailored modeling practices to handle complex geometries. These efforts show a shared focus on format-driven exchange and automated input, providing insights to minimize data inconsistencies for energy assessments.

Recent research also presents adaptable, open-source solutions tackling data imperfections and supporting diverse project needs, though technical limitations persist. Jansen et al. [57] and Garlet et al. [19] illustrate this shift adjustingusing tools like bim2sim and Python-based add-ons in Blender, which process IFC models through data enrichment or semantic frameworks to create BEM-compatible outputs for EnergyPlus. This approach accommodates varied goals, such as natural ventilation studies, and adjusts to different data granularity levels. These initiatives reduce manual tasks through systematic validation and modular designs; however, they also highlight unresolved issues in geometry and

format conversion, indicating a need for further improvement. These workflows indicate potential advancements in automating BIM-to-BEM processes.

Despite these advancements, applying automated and semi-automated approaches within regulatory frameworks that mandate energy assessments remains challenging. Here, strict adherence to legislative parameters and consistent certification outcomes places elevated demands on interoperability and automation. Carvalho et al. [58], explored a BIM-based framework to streamline energy analysis for buildings under Portuguese standards, using native interoperability between Revit and Cype software to reduce manual input and meet national requirements. Similarly, Bracht et al. [11] investigated integrating BIM with a thermal load prediction metamodel for the Brazilian energy code, using gbXML to automate early-stage calculations from BIM tools for regulatory compliance. However, both studies revealed limitations, including manual adjustments for export inconsistencies and insufficient scope for comprehensive simulations, highlighting a critical gap in achieving standardized, scalable solutions for mandatory certification.

Given the challenges in applying BIM-to-BEM workflows in regulatory frameworks, a notable opportunity exists to develop pipelines that automate key processes tailored to meet energy performance requirements. In regulatory contexts, the urgent need for rapid, scalable assessments reinforces this, as certification delays can hinder compliance and project timelines. Integrating foundational elements (e.g., information requirements, modeling guidelines) into cohesive automated systems can address current limitations, improving efficiency and alignment with broader sustainability goals. Addressing these gaps with novel approaches is vital to advance digitalization in construction, especially where scalable EPC issuances is paramount, reflecting global trends shifting from static compliance checks to digital, performance-based assessments.

## 3 Approach and objectives

This research develops and validates a BIM-to-BEM workflow for mandatory energy performance assessment and certification, tackling challenges in scalability, consistency, and transparency. By integrating key elements – information requirements, modeling guidelines, simulation protocol, and an automated pipeline – the method streamlines data flow from BIM to BEM, aligning

with requirements for transparent and reproducible certification. This approach addresses gaps in interoperability and automation, enabling rapid assessments across diverse building types and project volumes. It comprises two phases: preparing the BIM model for data sufficiency and compatibility, followed by automated translation and configuration for BEM execution. These phases work together to reduce errors and ensure compliance with standards, with a case study providing practical validation. This research thus contributes to digital transformation in construction by showcasing how automation enhances regulatory processes.

A key benefit of BIM-to-BEM workflows is leveraging a BIM model's geometric and semantic richness to accelerate the BEM process. First, the BIM model must have sufficient data, necessitating clear information requirements. Second, since varied modeling methods and BIM tools have unique specifications impacting interoperability and data structure, defining how to build the model is crucial. Thus, modeling guidelines are vital, offering a prescriptive method for constructing the model and embedding information requirements.

These steps finalize the BIM phase, but the model still needs translation for simulation. As BEM tools cannot directly read native BIM formats, an open data schema is required for interoperability. However, this doesn't fully resolve the data gap, as limitations in BIM ad BEM software inputs and outputs leave the exported file unprepared for simulation, typically requiring manual configuration in the BEM tool. The automated pipeline in this research bridges this gap by handling configurations automatically. To develop such a pipeline, simulation rules must be defined first. For code compliance, assumptions, parameters, and calculation rules must be considered. Hence, a simulation protocol is essential, providing explicit rules for BEM configuration and analysis before detailing the pipeline.

The method's design choices, including selecting gbXML for data exchange, stem from its compatibility with common BIM and BEM tools, reducing reliance on proprietary formats and aiding broader adoption in regulatory contexts. Additionally, this choice leverages the relative scarcity of gbXML solutions [5,59] compared to more developed IFC options [60–64], offering a chance to address a field gap and boost compatibility in underrepresented areas. The focus on pipeline automation meets the need for efficient large-scale

assessments, minimizing inconsistencies and delays from manual interventions. This approach operates the workflow and enables testing via a case study, confirming research alignment. While adaptable across regulatory frameworks, the workflow is exemplified in the Brazilian context, offering a concrete setting for development and validation with potential for wider application. The implementation uses Revit 2025 for BIM authoring, OpenStudio SDK (version 1.9.0) and EnergyPlus (version 24.2.0) for simulation, gbXML (version 7.03) for data exchange, and Python scripts for pipeline automation. The case study uses a university building as proof of concept to assess feasibility and effectiveness in a real-world scenario.

To guide this workflow's development and validation, the research is framed by a central question and supporting sub-questions addressing specific aspects. These questions aim to uncover the challenges and opportunities of automating regulatory energy assessments, ensuring a comprehensive exploration of the workflow's components and practical implications.

Main research question:

- What challenges and opportunities arise from automating BIM-to-BEM workflows for energy performance certification?

Sub-questions:

- To what extent can the definition of information requirements and modeling guidelines address the challenges of establishing an interoperable BIM model for regulatory energy performance certification?
- What is the role of an automated pipeline in transforming a raw data export into a regulatory-compliant BEM model?
- What are the implications of integrating information requirements, modeling guidelines, simulation protocol, and automated pipeline for the scalability, consistency, and transparency of regulatory energy performance certification?

By addressing these questions, this research contributes to both society and academia by advancing methodologies for energy-efficient building design and compliance, supporting broader sustainability goals via streamlined regulatory processes. For the construction industry, it offers a practical workflow to reduce the time and cost of energy performance certification, enhancing

productivity and improving adherence to local standards. This work aligns with the global context of digital transformation in construction by addressing identified gaps in BIM-to-BEM automation and interoperability. It provides a replicable, and adaptable model for other regulatory environments, fostering innovation in policy implementation and building performance evaluation. The following sections detail the method's components and implementation, exploring these questions through development and validation.

## 4 Method

This research addresses scalability, reproducibility, and transparency challenges in energy performance certification by proposing and evaluating a BIM-to-BEM workflow for compliance purposes. The method integrates information requirements, modeling practices, simulation standards, and automation in a structured approach, validated by a case study. Figure 2 illustrates the method's overall structure, detailing its key components and their interconnections. This overview outlines these components and their roles in meeting research objectives, which are elaborated below.

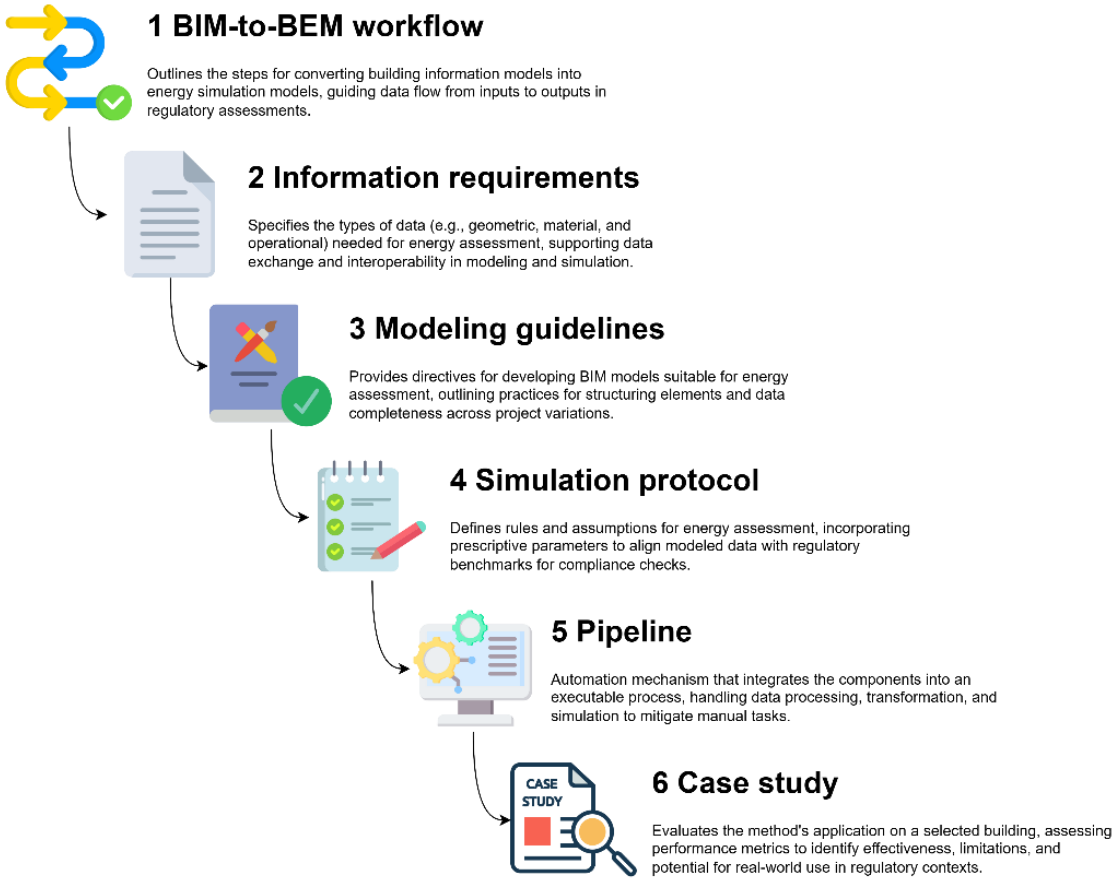



Figure 2 – Schematic representation of the method

## 4.1 BIM-to-BEM workflow

The proposed BIM-to-BEM workflow targets mandatory energy performance certification, integrating foundational components into a cohesive, compliant process. It outlines sequential tasks transforming raw data into verifiable certification metrics, minimizing errors and supporting standards. Figure 3 shows this workflow, illustrating its key tasks, inputs, outputs, and interconnections.

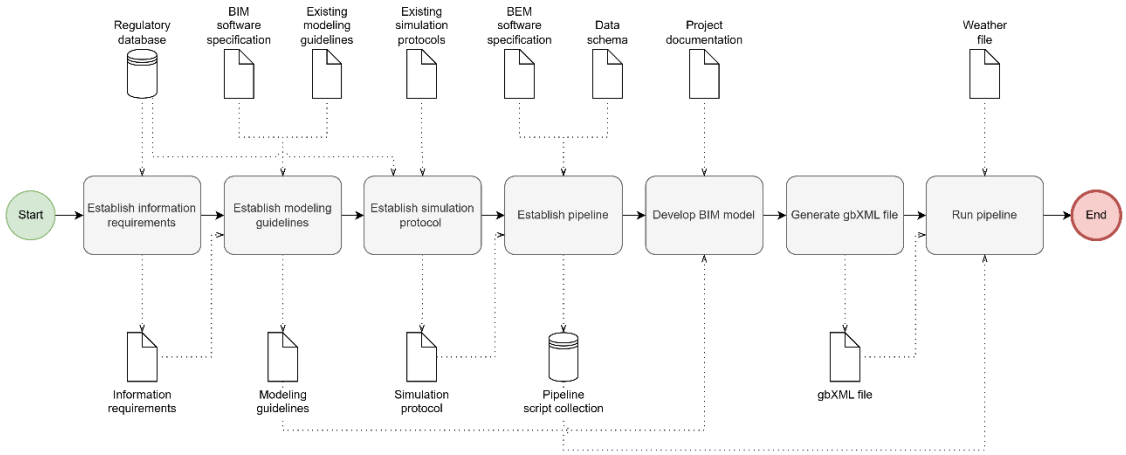



Figure 3 – BIM-to-BEM workflow for energy performance assessment and certification

The workflow begins with establishing information requirements, defining data needed for compliant certification. This task uses a regulatory database of codes, standards, and laws shaping the required data categories. The output, information requirements, forms the workflow's foundational data specification layer.

Next, establishing modeling guidelines prescribes how to build the BIM model and embed the information requirements. It considers BIM software specifications, as practices and interoperability vary by tool, impacting the BEM transition. It also uses existing literature for established modeling practices. The information requirements are critical inputs, clarifying what data the model needs before detailing how to structure it. These guidelines standardize model development.

Establishing the simulation protocol defines the rules and assumptions for BEM configuration and energy calculations. It uses the regulatory database as a primary input, as standards and legislation often provide guidelines for simulation parameters. It also integrates existing simulation protocols when permitted by regulatory frameworks. The resulting protocol guides the configuration and execution of compliance-based energy simulations.

Establishing the pipeline involves creating an automation mechanism that operationalizes the BIM-to-BEM transition, converting BIM data into BEM outputs. It accounts for BEM software specifications, as different simulation tools have unique requirements influencing the automation process. It also considers the data exchange format, which directly impacts pipeline capabilities. The

resulting script collection automates data interpretation, BEM model construction, simulation, and metric generation, minimizing manual intervention.

After these preparatory tasks, the workflow enters the implementation phase, beginning with BIM model development. This step relies on the modeling guidelines (which incorporate the information requirements) to produce a fully developed BIM model. Next, generating the gbXML file exports the BIM model into a BEM-compatible format. Finally, running the pipeline integrates the gbXML file, the pipeline script collection, and a weather file for the certification process. This automates BEM model creation, runs the simulation, and generates performance metrics that can be directly used for building energy certification. In doing so, the proposed workflow operates as a generic framework for certification-oriented energy assessment, capable of accommodating increasingly detailed requirements and metrics.

### 4.2 Information requirements

Information requirements constitute the data specification layer of the workflow. While the definition of these requirements is a universal step in the proposed method, their specific content is inherently dependent on the applicable regulatory framework, local energy codes, or certification scheme. In this study, the requirements were established to comply with the Brazilian energy code [22]. Table 1 overviews the specific dataset mandated by the chosen regulatory framework, which includes the data needed for the certification assessment. Each category from the table is detailed in the following paragraphs.

Table 1 – Summary of information requirements

| **Category** | **Information requirement** | **Description** |
|---|---|---|
| Location | Latitude and longitude | Precise location coordinates. |
| Orientation | Solar orientation | The building's orientation to True North. |
| Building geometry | Geometric elements | Dimensions and positioning of walls, floors, roofs, openings, and shading elements. |
| Opaque envelope materials | Material layers and thermal properties | Values for thickness, thermal conductivity, density, specific heat capacity, and solar absorptance (R-value, U-value, thermal mass). |
| Glazing elements | Thermal-optical properties | Values for SHGC and U-value. |
| Internal gains | Occupants, LPD, and EPD | Occupancy density, LPD, and EPD. |

| | | |
|---|---|---|
| Air exchange | Infiltration and outdoor air for ventilation | Characterization of uncontrolled air infiltration and specification of outdoor air. |
| Air-conditioning system | Performance parameters | System's COP, EER, or SEER along with cooling and heating setpoint temperatures. |
| Schedules | Daily, weekly, and annual operating hours | Schedules for occupancy, lighting, equipment, and air-conditioning operation. |

The first category is global settings, including location and orientation. Latitude and longitude are required for selecting the appropriate weather file, enabling the simulation to account for local climatic conditions. The building's true north orientation also affects solar incidence on its envelope and thermal zones.

The next category is building geometry. Geometric elements defining the building's form are required in the BIM model, forming the basis for non-geometric data. Geometry includes the dimensions and positioning of walls, floors, roofs, and openings. This representation defines the building's volume, bounded by heat transfer surfaces. Shading elements must also be included.

Opaque envelope materials require specific thermal properties. These include exterior surface solar absorptance, plus each layer's thickness, thermal conductivity, density, and specific heat capacity. These data characterize the envelope's thermal resistance (R-value), thermal transmittance (U-value), and thermal mass, which is critical for capturing thermal lag effects in dynamic simulations. Glazing elements also require thermal-optical properties, including SHGC and U-value.

Internal gains within each thermal zone are another requirement. This category includes occupancy density, lighting power density (LPD), and equipment power density (EPD). These values are needed to calculate internal heat contributions.

Air exchange information is also required. This includes characterizing envelope infiltration and specifying outdoor air volumes for ventilation to maintain zonal air quality.

The air-conditioning system requires specific performance parameters. These include the Coefficient of Performance (COP), Energy Efficiency Ratio (EER), and Seasonal Energy Efficiency Ratio (SEER), each of which characterizes the system's efficiency. Cooling and heating setpoint temperatures are also required.

The final category is operational schedules. These data define daily, weekly, and annual operating hours for key loads and systems (occupancy, lighting, equipment, and air-conditioning). These schedules provide the temporal resolution needed to calculate the building's hourly energy profile, distinguishing this approach from static assessment methods.

### 4.3 Modeling guidelines

The modeling guidelines specify how to develop the model's geometry and semantic data so that BIM representations become suitable for the proposed BIM-to-BEM workflow oriented to energy performance certification. The guidelines are formulated in a software-agnostic manner, focusing on the information that must be explicitly represented and structured. The concrete implementation of these guidelines may vary across platforms, but the underlying requirements for geometry, physical properties and semantic attributes remain the same and are compatible with the information needs of compliance-based performance tools [65].

Table 2 summarizes the modeling guidelines. The table outlines each step, its objective, related information requirements, and the corresponding modeling guidelines. Each step is detailed in the following paragraphs, emphasizing generic modeling capabilities that can later be instantiated under different regulatory frameworks and assessment schemes.

Table 2 – Summary of modeling guidelines

| **Step** | **Objective** | **Related information requirement** | **Modeling guideline** |
|---|---|---|---|
| Global settings | Define the project's climatic and solar context. | Location<br>Orientation | Assign geographic coordinates (latitude/longitude) and align Project North to True North. |
| Geometric modeling | Create the building's physical envelope. | Building geometry | Model continuous envelope elements (walls, roofs, slabs) ensuring proper bounding of interior volumes. |
| Physical properties | Assign thermal properties to the envelope components. | Opaque envelope materials<br>Glazing elements | Create multi-layer material assemblies with defined thermal properties. |
| Analytical space definition | Translate the physical geometry into analytical surfaces and volumes. | N/A (process step) | Place space/zone objects in all occupiable areas to capture volume boundaries for energy analysis. |

| | | | |
|---|---|---|---|
| Semantic data assignment | Populate the analytical zones with usage and operational data. | Internal gains<br>Air exchange<br>Air-conditioning system<br>Schedules | Assign occupancy, lighting, and equipment attributes to space/zone objects based on function. |
| Analytical model generation and export | Generate the final energy model and export it as a gbXML file. | N/A (process step) | Generate the energy analytical model abstracting physical geometry and export to open standard (gbXML). |

The first step comprises global settings. The project must be linked to a geographic location, either by specifying coordinates and a reference city or by associating the model with a representative weather station. This linkage anchors the BIM model to a climatic and solar context and supports the later selection of an appropriate weather file. In addition, the building orientation must be defined consistently with the site, ensuring that the model reflects the actual relationship between façades and cardinal directions.

With the global context established, the next step is geometric modeling of the building envelope. The physical boundary between conditioned spaces and the exterior (or unconditioned spaces) must be clearly represented through walls, floors, roofs and openings. From a BIM-to-BEM perspective, a key requirement is that this envelope forms a continuous and coherent thermal boundary [11,45], without unintended gaps, overlaps or ambiguous intersections that could lead to errors when deriving surfaces for simulation [65]. Complex geometries should be rationalized where possible, for example by approximating highly curved elements with planar segments or by subdividing zones with significant level changes into separate volumes, in order to reduce interoperability risks [33]. Roofs with pitched configurations can be represented by equivalent assemblies that capture the overall thermal effect, for instance by including a layer with a prescribed thermal resistance to account for attic spaces [66,67]. Shading devices, such as overhangs and canopies, should be modeled explicitly so that they can be recognized as distinct shading elements in the BEM.

An additional aspect concerns the intended function of construction elements, which affects how surfaces are interpreted in the energy model. Building components should carry explicit classification attributes indicating whether they are external or internal, in contact with the ground or another zone, or separating conditioned and unconditioned spaces. Even when such attributes exist, misclassifications and loss of detail can occur during data exchange. For

this reason, the guidelines recommend consistent naming conventions that encode functional roles in element or construction identifiers, for example by distinguishing ground-contact slabs from intermediate floors. This practice enables the downstream pipeline to perform semantic checks, using a data dictionary to verify, adjust or enrich surface types based on inherited naming patterns and associated metadata.

The following step is the assignment of physical properties. Opaque envelope components are modeled as multi-layered assemblies, with each layer characterized by its thickness and thermo-physical properties such as thermal conductivity, density and specific heat. Exterior surfaces are further defined by optical properties, including solar absorptance. Transparent elements are described by their optical and thermal performance, typically through parameters such as solar heat gain coefficient and thermal transmittance. In some BIM environments, direct representation of air gaps or explicit R-values is limited. Where native tools lack specific thermal parameter inputs, the guideline recommends matching the total thermal resistance of the assembly indirectly; for example, by defining a material layer with adjusted conductivity so that the resulting construction reproduces the desired overall resistance. The essential requirement is that the ensemble of layers in the BIM model can be reliably mapped to constructions in the BEM with equivalent thermal performance.

Once the envelope and its properties are defined, the internal volume is structured into zones compatible with energy simulation. For performance assessment, these zones represent aggregations of spaces with similar use, internal loads and conditioning strategies, rather than purely architectural rooms. The BIM model must therefore support the explicit identification of such simulation zones, either by assigning zone identifiers to spaces or by grouping spaces into higher-level entities. Elements that do not correspond to thermal boundaries, such as low partitions or internal dividers between areas with the same conditions, should not fragment the zoning structure. The objective is to obtain a set of volumes that accurately reflect the analytical zoning adopted in the BEM, avoiding unnecessary segmentation while preserving differences that are relevant for energy performance [47].

The next step involves assigning semantic data related to usage and operation. For each simulation zone, the BIM model should expose information

on internal gains, air exchange and conditioning conditions in a structured manner. Typical data categories include lighting and equipment power densities, occupant densities, infiltration and ventilation rates, and temperature setpoints, represented either as explicit values or through references to predefined usage types. The specific parameters and numerical values adopted in each application depend on the underlying energy code or certification scheme, but the workflow assumes that this family of attributes can be accessed and processed consistently in subsequent stages.

Schedules for occupancy, lighting and equipment can be defined either within the BIM environment or downstream in the BIM-to-BEM pipeline. The guidelines accommodate both approaches, as the preferred location for schedule definition depends on the assessment procedure and on the degree of standardization prescribed by the target energy code or certification system. This arrangement allows the framework to support contexts in which schedules are fully prescribed, as well as those in which project-specific time profiles are required, provided that the chosen approach is applied consistently to both the real and reference models.

The final step in the modeling guidelines is the generation of an export model suitable for energy simulation. The BIM environment must be able to produce a representation in an interoperable format, such as gbXML, that captures the defined geometry, constructions, zones and semantic attributes. Before export, a review of this representation is recommended, verifying that surfaces form closed volumes, that the segmentation of elements is reasonable, and that attributes such as constructions, zone identifiers and internal loads are assigned as intended [11,12]. Export options must be configured so that the representation of spaces and boundaries in the file corresponds to the simulation zoning strategy [11,68].

### 4.4 Simulation protocol

The simulation protocol defines how BEM models are configured, simulated and compared within the proposed BIM-to-BEM workflow. It specifies the rules that the pipeline follows when transforming BIM-based information into performance indicators suitable for energy performance certification. While the existence of a clearly defined protocol is a prerequisite for any automated

workflow, its specific configuration – including baselines, schedules, and efficiency targets – is inherently tied to the regulatory framework of the region. Therefore, the protocol must be adapted to the premises, standards, and regulations adopted in each specific application.

At a conceptual level, the protocol adopts the widely used logic of comparing two computational models under consistent boundary conditions: a real-condition model and a reference-condition model. In this automated workflow, both models are derived from the same BIM representation, processed through the same BIM-to-BEM pipeline, and simulated with the same engine, version, and climate file. This programmatic consistency ensures that differences in results are attributable to the input data and regulatory rules assigned to each model, rather than to modeler bias or variations in the calculation environment.

Figure 4 summarizes the simulation protocol adopted in this research. The diagram organizes the process into three main tasks: BEM generation, simulation setup and execution, and performance certification. The following paragraphs describe these tasks. To demonstrate the workflow's applicability, the protocol described below is instantiated using the procedures established by the Brazilian energy code [22]. This serves as an illustrative case of how the framework accommodates specific regulatory constraints.

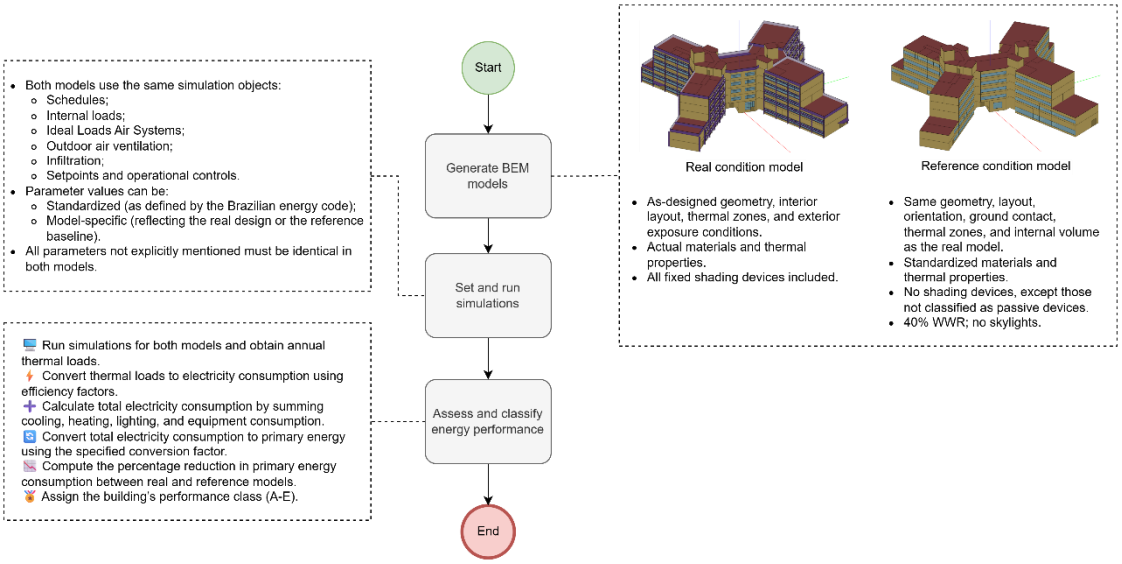



Figure 4 – Summary of simulation protocol

The first task concerns the generation of the BEM models. The entire building is represented, including permanently and transiently occupied areas

(POA and TOA, respectively). All building surfaces are assigned boundary conditions that reflect their actual exposure, accounting for solar gains, ground contact and adjacency to unconditioned spaces. Two models are then defined. The real-condition model represents the building as designed, preserving volumetric characteristics, thermal zoning, external exposure, constructions and thermal properties of opaque and transparent elements, internal loads and fixed external façade shading that is part of the design strategy. The reference-condition model maintains the same geometry, zoning, exposure, internal volume, floor area, ground contact, location, and orientation, but replaces selected parameters with typology-dependent baseline values defined by the applicable regulation (e.g., standardizing window-to-wall ratios or envelope thermal properties), while keeping other parameters identical to those of the real model. Shading elements that result from non-strategic features, such as external circulation, remain present in both models.

The second task involves simulation setup and execution. Internal loads for occupants, lighting and equipment are defined for all relevant occupancy areas in both models, and schedules are assigned following the adopted assessment procedure. In regulatory contexts where schedules are standardized, identical hourly profiles are applied to the real and reference models; in contexts that allow project-specific operation, distinct schedules may be used. By utilizing dynamic simulation engines, the protocol captures the temporal resolution of these schedules, allowing for a more accurate assessment of thermal mass and peak loads compared to static methods. Thermal conditioning is represented by an idealized load system or equivalent formulation capable of reporting zone heating and cooling demands without distribution losses. Setpoints, control strategies, minimum outdoor airflows and other ventilation requirements follow the rules of the chosen code or certification scheme. Parameters such as internal load densities, system efficiencies, infiltration and ventilation rates are typically fixed at prescribed baseline values in the reference model, while the real model either adopts the same assumptions or uses project-specific values when allowed by the procedure and supported by design documentation or measurements. In all cases, both models are simulated over the same period using the same climate file.

The third task encompasses energy performance classification. Annual heating and cooling loads obtained from the simulations are converted into energy use by applying appropriate efficiency factors, which in the reference model reflect baseline performance levels defined by the regulation and in the real model reflect the characteristics of the specified systems. Electricity consumption for lighting and equipment is calculated consistently for both models, based on the corresponding loads and schedules. The total final energy use for each model results from aggregating these contributions and any additional end uses required by the assessment scheme. Total energy use is then converted into primary energy through suitable primary energy factors that account for generation, transmission and distribution losses in the energy supply. The key indicator is expressed as the relative difference between the primary energy consumption of the real- and reference-condition models, typically as a percentage reduction. This relative performance metric is then mapped onto the rating scales defined by the certification system (i.e., classes A through E). In the specific instantiation for this research, the Brazilian energy code provides the specific parameter sets and class limits used to instantiate the assessment structure; these details are discussed in the pipeline and case study sections.

### 4.5 Pipeline

The pipeline automates the preparation, standardization, simulation execution, and post-processing of BEM models from gbXML files. Developed in Python, it leverages the open-source OpenStudio SDK (v1.9.0), using EnergyPlus (v24.2.0) as its simulation engine. OpenStudio was chosen for its openness and community support [5], supporting replicability and adaptability, as well as providing an object-oriented architecture that supports a programmatic modeling approach through the Python API libraries. The pipeline systematically applies the simulation protocol’s rules and parameters, transforming the generic BEM generation process into a targeted compliance check that addresses common BIM-to-BEM interoperability challenges.

Figure 5 overviews the pipeline, summarizing sequential tasks converting gbXML metadata into verifiable energy performance results. The diagram illustrates the key stages: importing and parsing the gbXML file, generating and enriching the real condition BEM model, and producing the reference model for

regulatory comparison. The final steps include simulation execution and automated performance certification.

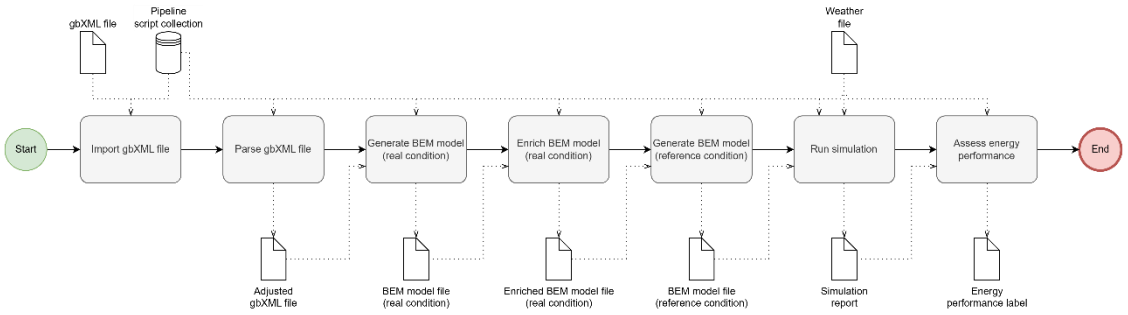



Figure 5 – Pipeline for energy performance assessment and certification

The following subsections reflect the pipeline's main stages. A detailed technical reference for this workflow, mapping each task to its governing script and the specific OpenStudio classes and methods used, is provided in Appendix A. Section 4.5.1 details the automated routine for configuring the real condition model, from initial data processing to applying relevant simulation parameters. Section 4.5.2 describes how the pipeline modifies this model to generate the reference condition model, detailing the applied adjustments and standardizations. Finally, section 4.5.3 outlines simulation execution, result extraction, and the building's energy performance classification based on computed metrics.

### 4.5.1 Real condition model routine

The pipeline starts by processing the gbXML file, the primary data source from the BIM environment. It translates gbXML data, creating the BEM model's geometry, spaces, zones, constructions, and materials. A validation step then corrects known data inconsistencies from the BIM export, like verifying and adjusting opaque surface absorptance for solar radiation, aligning the data with simulation requirements.

After translation, the pipeline determines each space's semantic classification using the gbXML spaceType attribute and a semantic matching routine. For each Space, the script reads the spaceType value (per the gbXML taxonomy) and compares it to entries in a data dictionary acting as a translation layer. Dependent on the assignment of attributes during the BIM modeling phase, the dictionary maps gbXML categories to the simulation protocol's required

occupancy classes, indicating if the space is a POA or TOA. Figure 6 shows this matching process, with actual examples of gbXML spaceType values and their occupancy classifications.

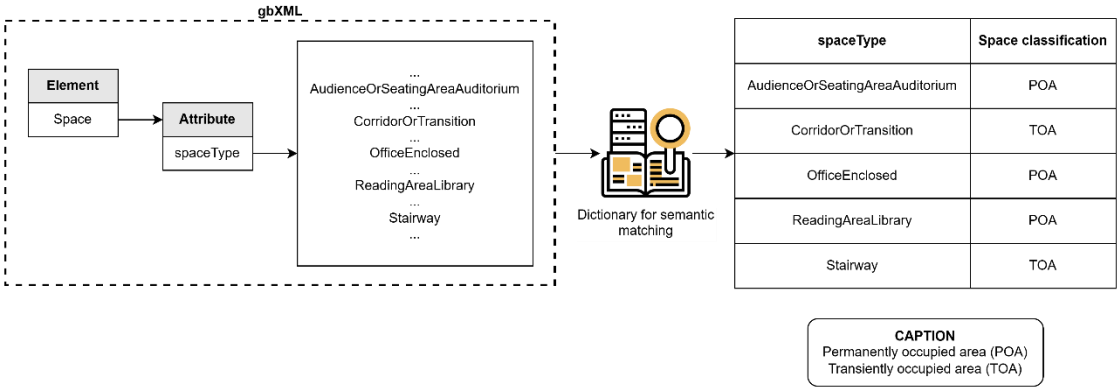



Figure 6 – Semantic matching dictionary for space classification

Once classified as POA or TOA, the pipeline performs BEM enrichment by applying standardized loads, airflow parameters, and thermal zone conditions. Table 3 summarizes parameters of the pipeline automatically assigns based on semantic mapping rules and simulation protocol values. It shows the main inputs for internal loads, airflow, and thermal control settings for each space type used in the BEM model.

Table 3 – Simulation protocol parameters applied through the BEM enrichment step

| **Parameter** | **POA** | **TOA** | **Schedule** |
|---|---|---|---|
| Occupancy | 1.5 m²/person | N/A | Weekdays: 9AM to 5PM<br>Weekend: closed |
| EPD | 15 W/m² | 15 W/m² | |
| LPD | Same as gbXML file | 15.5 W/m² | |
| Ideal loads air system | Heating and cooling setpoints of 21 °C and 24 °C | N/A | |
| Outdoor airflow | 0.0075 m³/person | N/A | |
| Infiltration | 0.5 ACH | 0.5 ACH | Always on |

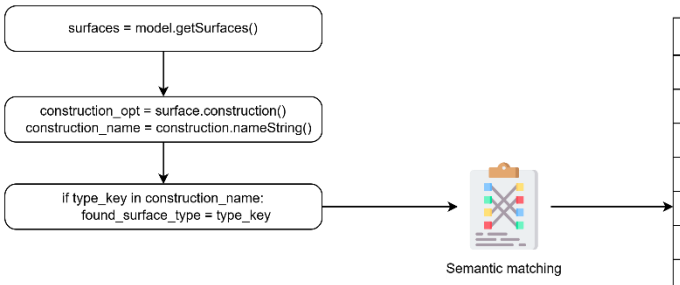
In the context of the Brazilian regulations applied here, POA spaces are assigned 1.5 m²/person occupancy, 15.0 W/m² EPD, and gbXML-imported LPD values, while TOA spaces receive 15.5 W/m² lighting loads. Operation schedules are set to full activity weekdays (9 AM-5 PM), no weekend activity, and a 120 W/person activity level. Airflow parameters are applied uniformly: all spaces get 0.5 Air Changes per Hour (ACH) infiltration [19], and POA spaces also get 0.0075 m³/s of outdoor air per person [69]. POA-associated thermal zones include ideal loads air systems operating continuously according to the occupancy schedule,

with heating/cooling setpoints at 21 °C and 24 °C, respectively; TOA zones remain unconditioned.

The pipeline then adjusts floor area calculations by disabling all plenum spaces from the total floor area computation (setting their “part of total floor area” property to false). This avoids distorted downstream results, such as Energy Use Intensity (EUI), that would arise if plenums were included in the building’s reported floor area.

Next, the pipeline standardizes construction and material names while verifying surface type assignments that may be incorrect post-BIM-to-gbXML conversion. This export often generates generic identifiers or misassigns surface types, hindering audits of whether each surface has the intended construction and boundary condition. To address this, display names are normalized into human-readable identifiers, and a display-name-based map infers the intended surface function. Relying on the modeling guidelines, semantic matching against a mapping dictionary detects inconsistencies between exported surface types and inferred functions, applying correction rules as needed. For instance, if adjacent zones lack a physical partition, “Air” constructions (surfaceType = Air) are identified as air membranes. An Air Boundary Construction is then assigned and configured for interzonal airflow (via SimpleMixing), enabling direct air/heat exchange between spaces.

Figure 7 illustrates the semantic matching process for verifying and correcting surface type assignments during BEM enrichment. The flowchart outlines the logic for inferring intended surface functions based on construction display names and a semantic mapping dictionary. The table shows standardized associations between surface types, boundary conditions, and exposure attributes used for this correction.




| Surface type | Outside boundary condition | Sun exposure | Wind exposure |
|---|---|---|---|
| InteriorWall | Surface | NoSun | NoWind |
| ExteriorWall | Outdoors | SunExposed | WindExposed |
| Roof | Outdoors | SunExposed | WindExposed |
| InteriorFloor | Surface | NoSun | NoWind |
| UndergroundWall | Ground | NoSun | NoWind |
| UndergroundSlab | Ground | NoSun | NoWind |
| Ceiling | Surface | NoSun | NoWind |
| Air | Surface | NoSun | NoWind |
| SlabOnGrade | Ground | NoSun | NoWind |
| RaisedFloor | Outdoors | NoSun | WindExposed |

Figure 7 – Semantic matching and correction of surface type assignments

### 4.5.2 Reference condition model routine

With the real condition model configured, the pipeline proceeds to generate the reference model. This process serves as the automated baseline creation, ensuring the comparison model strictly adheres to the certification rules. The process begins by identifying surfaces classified as floors, walls, or roofs, based on their surface type attribute (e.g., Floor, InteriorWall, ExteriorWall, Roof). The script programmatically replaces the original constructions with standardized assemblies. Table 4 details the specific thermal properties mandated by the Brazilian energy code used in this instantiation, describing the opaque envelope materials applied to the reference model. Each construction type is assigned directly to the corresponding surfaces in the energy model, modifying only the envelope elements targeted by the protocol.

Table 4 – Thermal properties of opaque envelope materials in the reference model

| **Construction** | **Solar absorptance** | **Material** | **Thickness [cm]** | **Conductivity [W/m·K]** | **Density [kg/m³]** | **Specific Heat [J/kg·K]** | **R-value [m²·K/W]** |
|---|---|---|---|---|---|---|---|
| Floor | Same as real condition model | Concrete | 10 | 1.75 | 2,200 | 1,000 | |
| Wall | 0.5 | External render | 2.5 | 1.15 | 2,000 | 1,000 | |
| | | Ceramic brick | 1.34 | 0.90 | 1,600 | 920 | |
| | | Air layer | 6.32 | | | | 0.175 |
| | | Ceramic brick | 1.34 | 0.90 | 1,600 | 920 | |
| | | Internal render | 2.5 | 1.15 | 2,000 | 1,000 | |
| Roof | 0.8 | Fiber cement roof tile | 0.8 | 0.95 | 1,900 | 840 | |
| | | Air layer | 25 | | | | 0.21 |
| | | Concrete | 10 | 1.75 | 2,200 | 1,000 | |

Following this step, the pipeline enforces the baseline fenestration ratio defined in the protocol (set to 40%) applied exclusively to exterior wall surfaces that originally included glazing. For each applicable surface, all existing windows are removed, and new windows are generated. These new windows are assigned the baseline glazing properties specified in the Brazilian energy code, specifically a U-value of 5.7 W/m²·K and a SHGC of 0.82.

In the next stage, the LPD is normalized to the regulatory baseline of 15.5 W/m² in all spaces that originally contained lighting objects. This modification is applied only to zones where lighting systems were present in the real-condition model; other spaces remain unchanged.

The pipeline then removes all external shading surfaces modeled as separate geometry, including any resulting empty shading surface groups. This step applies uniformly across the model and excludes user-defined or auxiliary shading elements from the reference configuration.

Finally, all skylights are removed from the building envelope. Each skylight object is identified and excluded from the simulation model, resulting in a configuration without skylight area, as specified by the simulation protocol.

To consolidate the parameters applied beyond the opaque envelope, Table 5 summarizes the standardized values for fenestration, internal loads, and system operations enforced by the pipeline for the reference model.

Table 5 – Baseline specifications for glazing, internal loads, and air-conditioning in the reference mode

| Parameter | Value | Unit |
|---|---|---|
| Window-to-Wall Ratio | 40 | % |
| Skylight-to-Roof Ratio | 0 | % |
| Glazing – U-value | 5.7 | W/m².K |
| Glazing – SHGC | 0.82 | Dimensionless |
| Lighting Power Density | 15.50 | W/m² |
| Equipment Power Density | 15.00 | W/m² |
| Occupant Density | 1.50 | m²/person |
| Coefficient of Performance | 3.24 | W/W |
| Cooling Setpoint | 24.00 | ºC |
| Heating Setpoint | 21.00 | ºC |

All other aspects of the BEM model are preserved from the real-condition model without modification. It is important to reiterate that the modifications described above represent a specific instantiation of the workflow's generic structure. While the automated pipeline architecture supports broader logic, including the application of differentiated information requirements, the strict standardization applied in this routine reflects the specific compliance rules of the adopted certification scheme.

### 4.5.3 Energy simulation and assessment routine

Once the real and reference models are fully configured, the pipeline executes the energy simulations. Prior to execution, the pipeline assigns a standard set of output variables selected to meet the specific reporting requirements of the regulatory framework. To capture the thermal demand of the building envelope independent of HVAC system inefficiencies, the pipeline requests Zone Ideal Loads Supply Air Total Heating Energy and Zone Ideal Loads Supply Air Total Cooling Energy. These variables measure the amount of thermal energy needed to maintain comfort temperatures, representing the building's thermal load as if conditioned by a theoretically perfect system with no energy losses. Simultaneously, Zone Lights Electricity Energy and Zone Electric Equipment Electricity Energy are tracked to quantify the direct electricity consumption of lighting fixtures and plug loads. The simulation timestep is set to

four intervals per hour, and the weather file corresponding to the project's location is specified. The pipeline then runs both simulations using the EnergyPlus engine.

After the simulations are complete, the pipeline initiates the post-processing routine to transform raw simulation outputs into the final regulatory performance indicators. The pipeline first aggregates and converts the raw energy data through a structured sequence.

First, the pipeline processes the eplusout.csv reports (the CSV output from EnergyPlus) for both the real and reference models to determine the total electrical consumption. It sums the annual values for lighting, equipment, ideal loads heating, and ideal loads cooling. The transformation of these thermal loads into electrical consumption follows specific regulatory logic:

- Heating Energy check: The pipeline checks the project's Bioclimatic Zone [70]; annual heating loads are only factored into the total consumption if the building is located in a zone with rigorous winter conditions.
- System Efficiency conversion: The thermal energy for cooling (and heating, if applicable) is converted to electrical energy through a post-processing step. For the reference model, a fixed COP of 3.24 is programmatically applied to represent the baseline efficiency. For the real model, the user-defined performance factors are applied to reflect the actual design.

All energy values are then converted from Joules to kWh and summed to obtain the Total Electrical Consumption. Next, the pipeline calculates the Primary Energy Consumption (PEC) for each model by applying a primary energy factor of 1.6 to the electrical total. This factor serves as a proxy for the generation, transmission, and distribution losses of the national grid.

Only after establishing the PEC for both models does the pipeline calculate the Percentage Reduction in Primary Energy Consumption (PRPEC). This metric represents the relative efficiency gain of the design compared to the baseline, calculated as shown in Equation 1:

$$PRPEC = \frac{(PEC_{reference} - PEC_{real})}{PEC_{reference}} \times 100 \qquad \text{(Equation 1)}$$

Where:

PRPEC is the Percent Reduction of Primary Energy Consumption;

PECreference is the Primary Energy Consumption of the reference model (kWh/year);

and PECreal is the Primary Energy Consumption of the real model (kWh/year).

Parallel to the energy calculations, the pipeline determines the geometric normalization parameter, known as Coefficient i. In this regulatory framework, the efficiency targets scale based on the building's geometry. To derive this metric, the pipeline parses the eplustbl.htm report (the HTML output from EnergyPlus) to extract two key geometric properties: the total building volume (read from the "Zone Summary" table) and the total envelope area (calculated by summing the "Gross Area" of all surfaces identified as exterior wall, roof, or raised floor in the "Opaque Exterior" table).

From the total building volume and total envelope area values, the pipeline calculates the form factor (ratio of envelope area to volume). Using this form factor and the project's Bioclimatic Zone, the pipeline looks up the corresponding Primary Energy Consumption Reduction Coefficient for Classifications D to A (PECRCD-A) value. This value is sourced from a standardized table originating from the Brazilian energy code [22] and embedded in the script. Finally, the classification coefficient (i) is computed using Equation 2:

$$i = \frac{(PECRC_{D-A} \times 100)}{3} \qquad \text{(Equation 2)}$$

Where:

i is Coefficient i;

and PECRCD-A is Primary Energy Consumption Reduction Coefficient for Classifications D to A.

In the final stage, the pipeline combines these two key metrics – PRPEC and Coefficient i – to determine the building's final energy performance classification. The Coefficient i serves to dynamically define the stringency of the rating thresholds (Classes A, B, C, D), adapting the requirement to the building's

shape. The calculated PRPEC is compared against those dynamic intervals (Table 6). A PRPEC value below the “D” threshold results in a class “E”. This final classification provides the definitive energy performance certification rating, completing the automated compliance check.

Table 6 – Limits of the intervals for overall building energy efficiency classifications

| Energy efficiency class | Rationale |
|---|---|
| A | $\mathrm{PRPEC} > 3\mathrm{i}\%$ |
| B | $3\mathrm{i}\% \geq \mathrm{PRPEC} > 2\mathrm{i}\%$ |
| C | $2\mathrm{i}\% \geq \mathrm{PRPEC} > \mathrm{i}\%$ |
| D | $\mathrm{i}\% \geq \mathrm{PRPEC} > 0\%$ |
| E | $0\% < \mathrm{PRPEC}$ |

## 4.6 Case study

The case study focuses on a publicly university building located in southern Brazil. This building was selected as an appropriate testing ground for the proposed methodology due to its functional diversity architectural complexity. Beyond typical test cases, this selection serves as a reliability and stress test for the proposed workflow, challenging the automated pipeline with a data-rich model that mimics the rigorous demands of real-world certification. Moreover, the selection aligns with the regulatory focus of this research, as federal public buildings are required to undergo mandatory energy performance certification under the national legislation [23,71]. An additional advantage of this case is the public availability of its architectural documentation, since the design and construction processes of federally funded projects are tied to public procurement and therefore open to access. These attributes provide a suitable and transparent context for operationalizing the proposed workflow.

The building analyzed in the case study encompasses a total gross floor area of approximately 8,100 m², distributed across five stories. Its layout follows a distinctive X-shaped configuration, formed by two main wings connected through a central block. This connecting block functions as a circulation hub linking the two wings. On the ground level, the two main wings are positioned at slightly different elevations – one at +1.70 m and the other at 0.00 m – creating a split-level condition within the base floor. Above this level, four additional floors extend across the two wings and the connecting block, maintaining continuity between the building sections and forming a five-story composition. This

architectural arrangement is depicted in Figure 8, which presents the main façade (a) to illustrate the five-story composition, alongside the site plan (b) detailing the characteristic X-shaped layout.

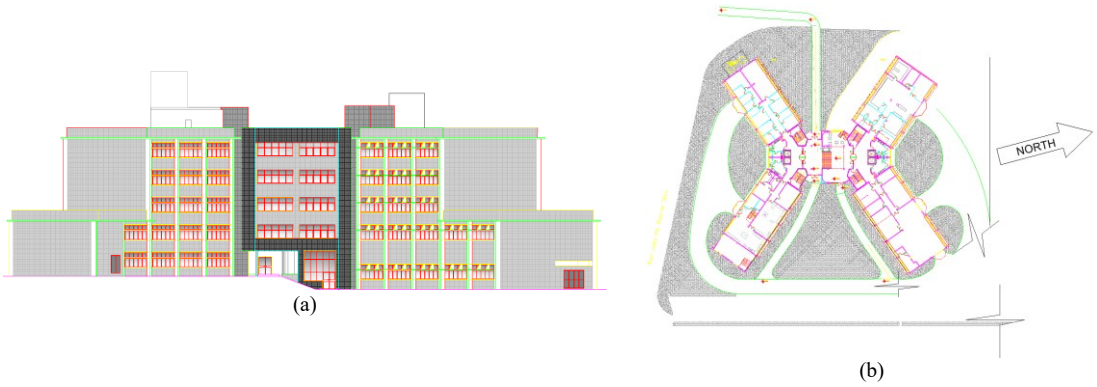



Figure 8 – Case study building (a) main façade (East); and (b) site plan

The building accommodates a wide range of functional spaces distributed across its five levels, reflecting the multifaceted nature of a higher education facility. The programmatic composition spans educational, research, administrative, technical, and support functions, resulting in an operational profile with varying occupancy patterns and thermal demands. To illustrate this functional diversity and spatial distribution, detailed floor plans for all levels are provided in Appendix B, where different space types are color-coded according to their primary use.

Based on the project's documentation, the building's internal load values are a LPD of 10.73 W/m² and an EPD of 6.55 W/m². It is important to note, however, that the regulation applied in this study requires the use of a standardized EPD value of 15 W/m² for the real condition model simulation, which overrides the as-designed value. According to Brazilian legislation [71], federal public buildings are obliged to use class A (high-efficiency) energy-rated air-conditioning equipment. Therefore, a COP of 5.5 W/W – the threshold for class A – was adopted in the real condition model to comply with this regulatory requirement.

To characterize the thermal behavior of the building envelope, Table 7 summarizes the construction details of the opaque components, including material layers, thicknesses, and relevant physical properties such as thermal conductivity, density, specific heat, and solar absorptance. These parameters are crucial for energy performance simulations, as they significantly influence heat

transfer and storage within the building fabric. The data, extracted from the available architectural documentation, provides a foundation for modeling the envelope in the BIM-to-BEM workflow and evaluating its response under the simulated conditions.

Table 7 – Thermal properties of opaque envelope materials in the real model

| **Construction** | **Solar absorptance** | **Material** | **Thickness [cm]** | **Conductivity [W/m·K]** | **Density [kg/m³]** | **Specific Heat [J/kg·K]** | **R-value [m²·K/W]** |
|---|---|---|---|---|---|---|---|
| Floor | 0.5 | Ceramic tile | 1.0 | 1.05 | 2,000 | 920 | |
| | | Mortar | 4.0 | 1.15 | 2,000 | 1,000 | |
| | | Concrete slab | 10.0 | 1.75 | 2,200 | 1,000 | |
| Ceramic wall | 0.2 (white) and 0.7 (blue) | External render | 1.5 | 1.15 | 2,000 | 1,000 | |
| | | Ceramic brick | 1.3 | 0.90 | 1,600 | 920 | |
| | | Air layer | 9.4 | | | | 0.175 |
| | | Ceramic brick | 1.3 | 0.90 | 1,600 | 920 | |
| | | Internal render | 1.5 | 1.15 | 2,000 | 1,000 | |
| Gypsum wall | 0.7 | Gypsum wallboard | 1.25 | 0.35 | 900 | 870 | |
| | | Air layer | 4.5 | | | | 0.16 |
| | | Gypsum wallboard | 1.25 | 0.35 | 900 | 870 | |
| Insulated roof | 0.5 | EPS-cored sandwich panel | 4.2 | 0.042 | 154 | 1,420 | |
| | | Air layer | | | | | 0.21 |
| | | Concrete slab | 10.0 | 1.75 | 2,200 | 1,000 | |
| Technical roof | 0.5 | Ceramic tile | 0.8 | 0.95 | 1,900 | 840 | |
| | | Air layer | 25.0 | | | | 0.21 |
| | | Concrete slab | 10.0 | 1.75 | 2,200 | 1,000 | |

The building documentation indicates the project is located in Florianopolis, situated in the South region of Brazil. Accordingly, the simulations adopt the projected mid-century weather file for Florianopolis (2050s, RCP8.5) produced by the MPI-ESM-RegCM model chain [72]. Although the study does not set out to perform a climate-change impact assessment, the use of future weather datasets is imperative given the long operational lifecycle of buildings. Relying on

historical records fails to capture established climatic trends, leading to an inaccurate representation of the thermal stress the building will endure. Consequently, adopting projected meteorological conditions is established as a best practice for energy performance assessment [5,72].

## 5 Results

The results presented in this section demonstrate the complete implementation of the proposed BIM-to-BEM workflow. The outcomes are organized to reflect each transformation step, highlighting the interoperability between BIM modeling and BEM simulation environments, and the automated routines that connect them. Figure 9 provides an overview of this process, illustrating the visual and data progression through five stages: the BIM model created in Revit, the energy analytical model generated within the same platform, an excerpt of the exported gbXML file, and the two BEM models generated by the pipeline – the real condition model and the reference condition model used for regulatory assessment. This overview establishes the structure for the detailed results that follow.

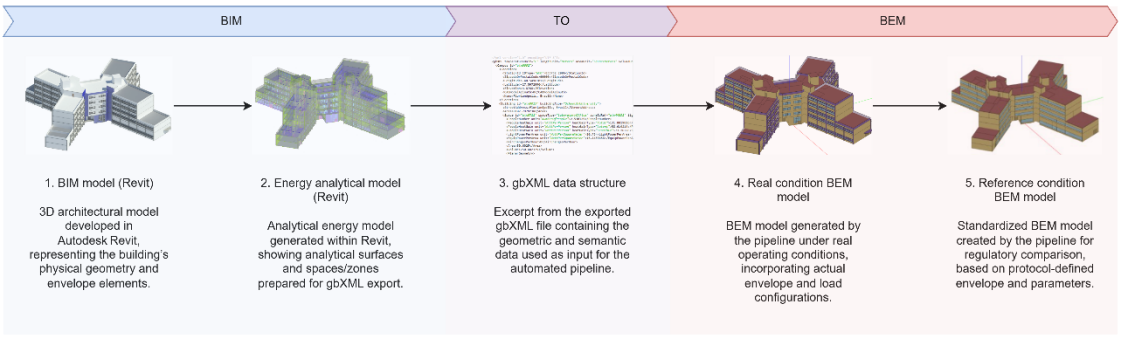



Figure 9 – Representation of the implemented BIM-to-BEM workflow

The BIM model of the case study building was developed according to the modeling guidelines defined in the method. It represents the complete architectural geometry of the facility, including all envelope components, volumetric organization, and external projections. Figure 10 illustrates the model's key aspects: an overall 3D view (a) showcasing its X-shaped configuration and the connection between the two main wings through the central block; a top view (b) presenting the model positioned under the project compass, which defines the true north (this orientation corresponds to the actual site

conditions and confirms the proper alignment of the model); and the building's main façade (c), highlighting its external composition and opening distribution in the BIM environment. These views collectively demonstrate the contextual configuration of the BIM model used as the basis for the subsequent analytical and simulation stages.

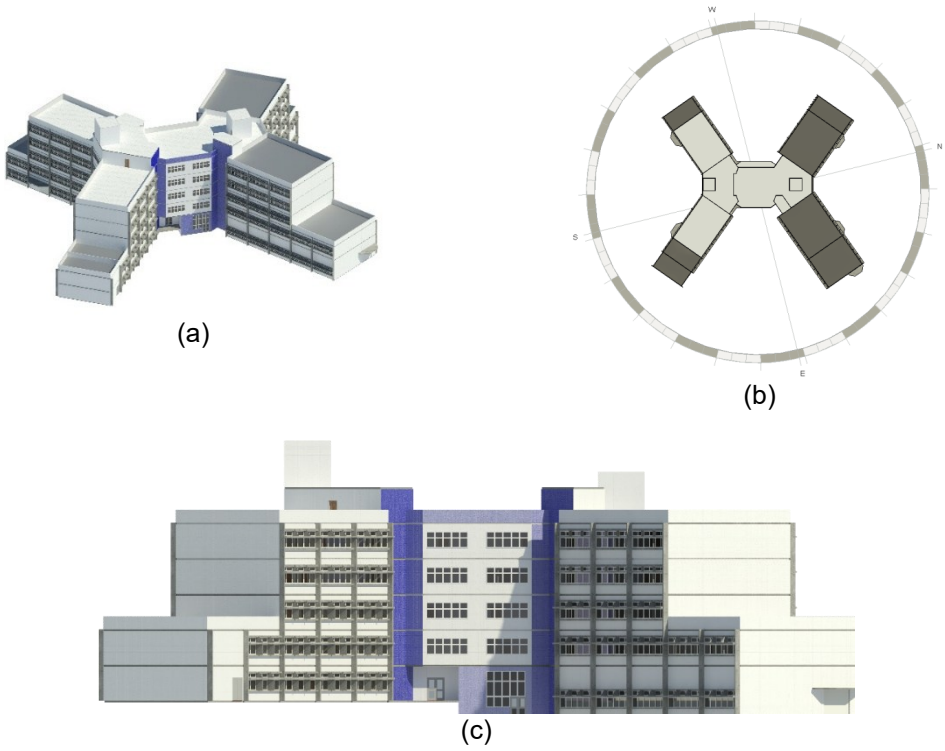



Figure 10 – Visual representation of the BIM model illustrating (a) overall geometry, (b) model orientation relative to true north, and (c) main façade (East).

The BIM model's internal spatial organization comprised 139 spaces distributed across five levels. These spaces represented the functional diversity of a higher education facility, encompassing educational, research, administrative, technical, and support functions. This programmatic composition (Appendix B) resulted in an operational profile with varying occupancy patterns and thermal demands.

The BIM and energy analytical models were developed in alignment with the defined modeling guidelines and information requirements. All data required for the energy assessment – including geometry, orientation, material properties, internal gains, ventilation, and operational parameters – were successfully integrated into the model. The energy analytical model reproduced the overall building geometry and space boundaries as expected. However, discrepancies were observed in the automatic classification of certain surface types: all floor

surfaces at the +1.70 m elevation were tagged as “RaisedFloor” instead of “SlabOnGrade”. Figure 11 shows an example of this condition in the energy analytical model.

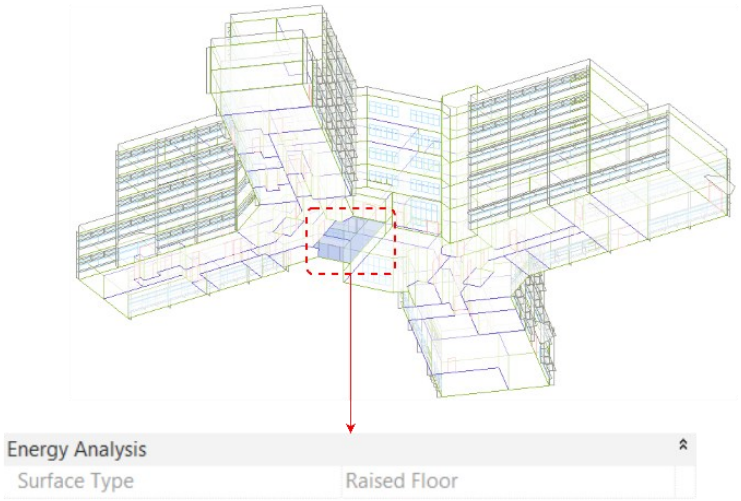



Figure 11 – Example of surface type misclassification

The gbXML file exported from the energy analytical model contained the geometric and semantic data defined in the BIM model. The file comprised 139 space and thermal zone objects, 1,669 surfaces, 1,089 openings, 64 construction assemblies, 46 material definitions, and 29 operational schedules. Each space included geometric definitions, internal load specifications, and airflow parameters. Visual inspection revealed overall geometric continuity, though the surface type misclassification identified in the analytical model (e.g., “RaisedFloor” instead of “SlabOnGrade”) was present in the exported file. This gbXML file served as the input dataset for the subsequent automated processing stages.

Prior to generating the real condition model, the pipeline’s automated parsing of the gbXML file identified that the absorptance field for opaque constructions was defined as infrared absorptance (ExtIR) rather than solar absorptance (ExtSolar). This discrepancy affected 22 constructions and was corrected before model generation. Figure 12 illustrates this correction in the gbXML file, showing an excerpt of a construction element before and after the automatic replacement of the ExtIR enumeration with ExtSolar.

```
<Construction id="aim14698" constructionIsSchematic="false">
  <U-value unit="WPerSquareMeterK">1.7270537</U-value>
  <Absorptance unit="Fraction" type="ExtIR">0.2</Absorptance>
```

```
<Construction id="aim14698" constructionIsSchematic="false">
  <U-value unit="WPerSquareMeterK">1.7270537</U-value>
  <Absorptance unit="Fraction" type="ExtSolar">0.2</Absorptance>
```

Figure 12 – Automatic replacement of the ExtIR enumeration with ExtSolar for external opaque constructions

The pipeline generated the initial BEM model (Figure 13) by converting the parsed gbXML file into the OpenStudio input structure. The geometric translation occurred without inconsistencies or missing elements, successfully reproducing the building's form and volume. In addition to geometry, spaces, and thermal zones, the constructions and materials defined in the gbXML file were successfully imported and assigned to their respective surfaces.

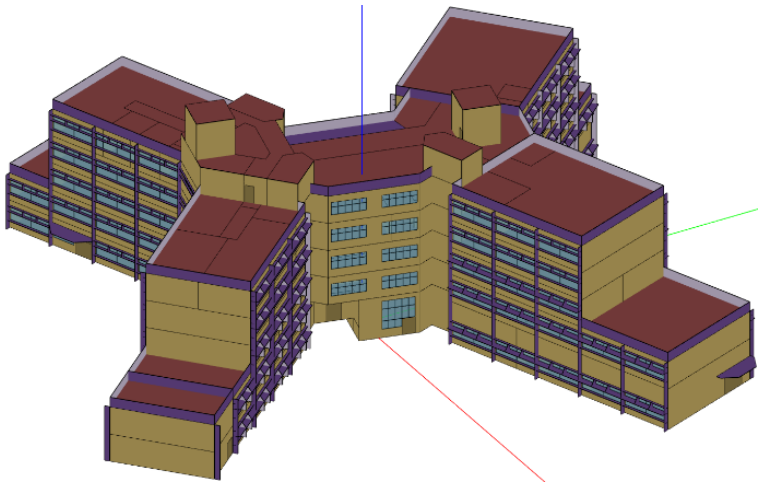


Figure 13 – 3D view of the real condition BEM model

The real condition model comprised 76 POA spaces and 63 TOA spaces, containing complete definitions of internal loads, operational schedules, and airflow parameters. The POA spaces exhibited integrated people, lighting, and equipment loads with their corresponding operational schedules. The TOA spaces included only lighting loads and schedules. Additionally, the model contained 139 infiltration objects applied to all spaces and 76 outdoor air objects associated exclusively with POA spaces. Ideal loads air system objects were successfully assigned to the 76 POA thermal zones, applying heating and cooling setpoints of 21 ºC and 24 ºC, respectively, and linked to the corresponding operational schedules. Figure 14 illustrates the enrichment structure for a

representative POA space, showing the hierarchical organization and automated object assignments across the OpenStudio interface panels.

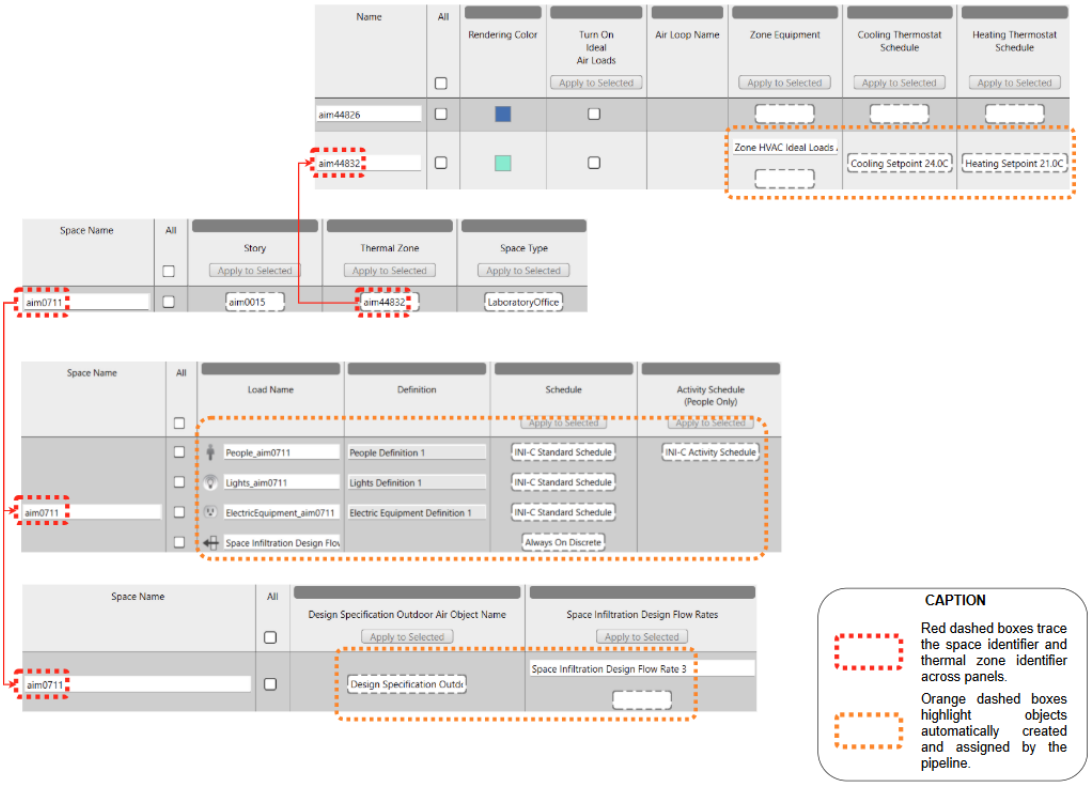



Figure 14 – Enriched POA space structure in the real condition BEM model

The final standardization and verification stages resulted in the renaming of 35 construction objects and 23 material objects to conform to the adopted naming convention. The consistency check identified attribute discrepancies in 24 surfaces across three construction types: two surfaces classified as “RaisedFloor”, three as “UndergroundWall”, and 19 as “SlabOnGrade”. These surfaces presented incorrect outside boundary condition assignments and incorrect sun and wind exposures attributes. All 24 surfaces were corrected accordingly. Furthermore, 11 internal air surfaces were identified and converted to air boundary constructions. New air boundary construction objects – using the simple mixing method – were successfully created and assigned to these surfaces. Figure 15 and Figure 16 exemplify the automated corrections, demonstrating the boundary condition adjustments for ground-contact surfaces and the air boundary construction assignments for internal air surfaces, respectively.

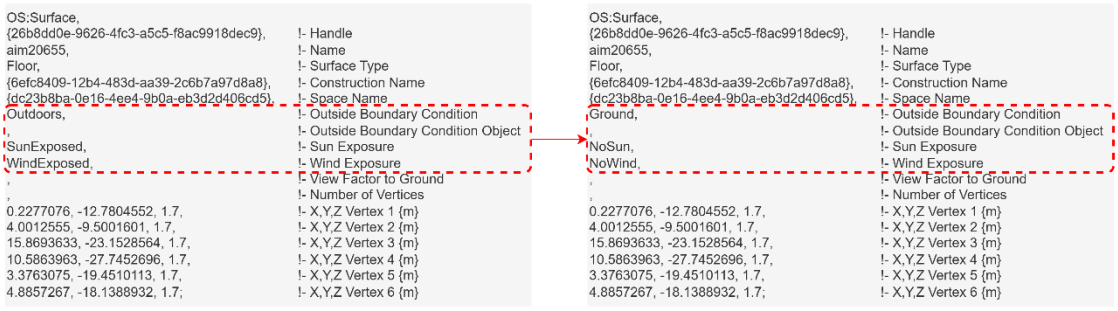



Figure 15 – Automated correction of outside boundary condition for ground-contact surface

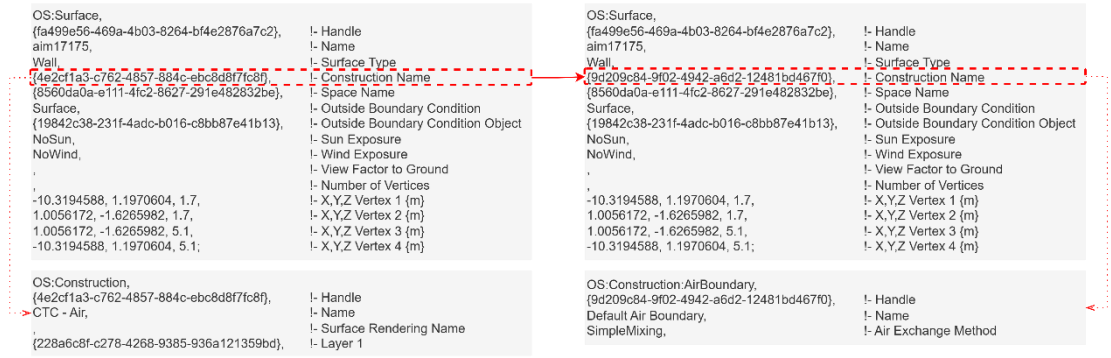



Figure 16 – Automated creation and assignment of air boundary construction for air surface

The reference condition model (Figure 17) successfully incorporated standardized envelope and lighting parameters as specified by the simulation protocol. A total of 383 floor surfaces and 40 roof surfaces were assigned standardized constructions defined by the pipeline. In addition, 1,335 wall surfaces were replaced, establishing the reference envelope while preserving the underlying geometry of the real condition model. WWR adjustment across all exterior walls with glazing resulted in the removal of the original glazing objects and their replacement with 118 new glazing objects with uniform properties specified in the simulation protocol. The automated process achieved a WWR of 40%, as expected. LPD was set to a fixed value of 15.5 W/m² in all 139 spaces originally containing lighting systems. External shading geometry was excluded from the reference model to reflect the simplified boundary conditions, resulting in the removal of 618 shading surfaces.

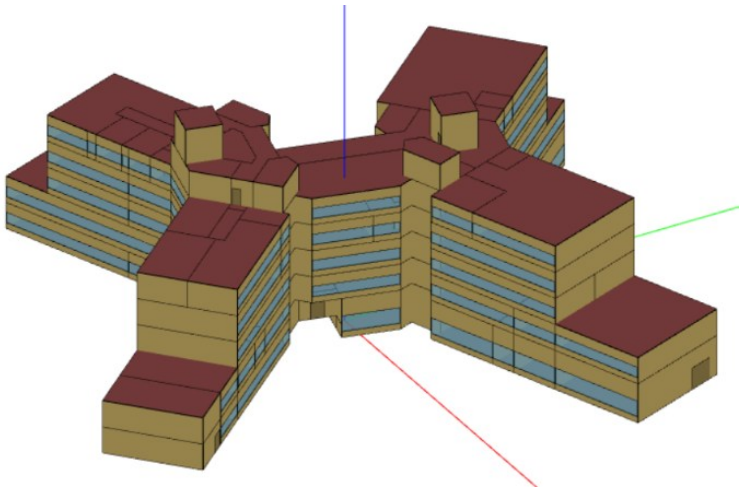


Figure 17 – Visual representation of the reference condition BEM model

All other properties – including geometry, zoning, internal loads, and thermal zone definitions – remained identical to the real condition model. The successful implementation of these modifications, encompassing detailed material properties and definitions for standardized constructions, the reference glazing properties, and standardized LPD value, is visually confirmed by the detailed fields and values presented in Figure 18, which originates directly from the reference BEM model after pipeline execution.

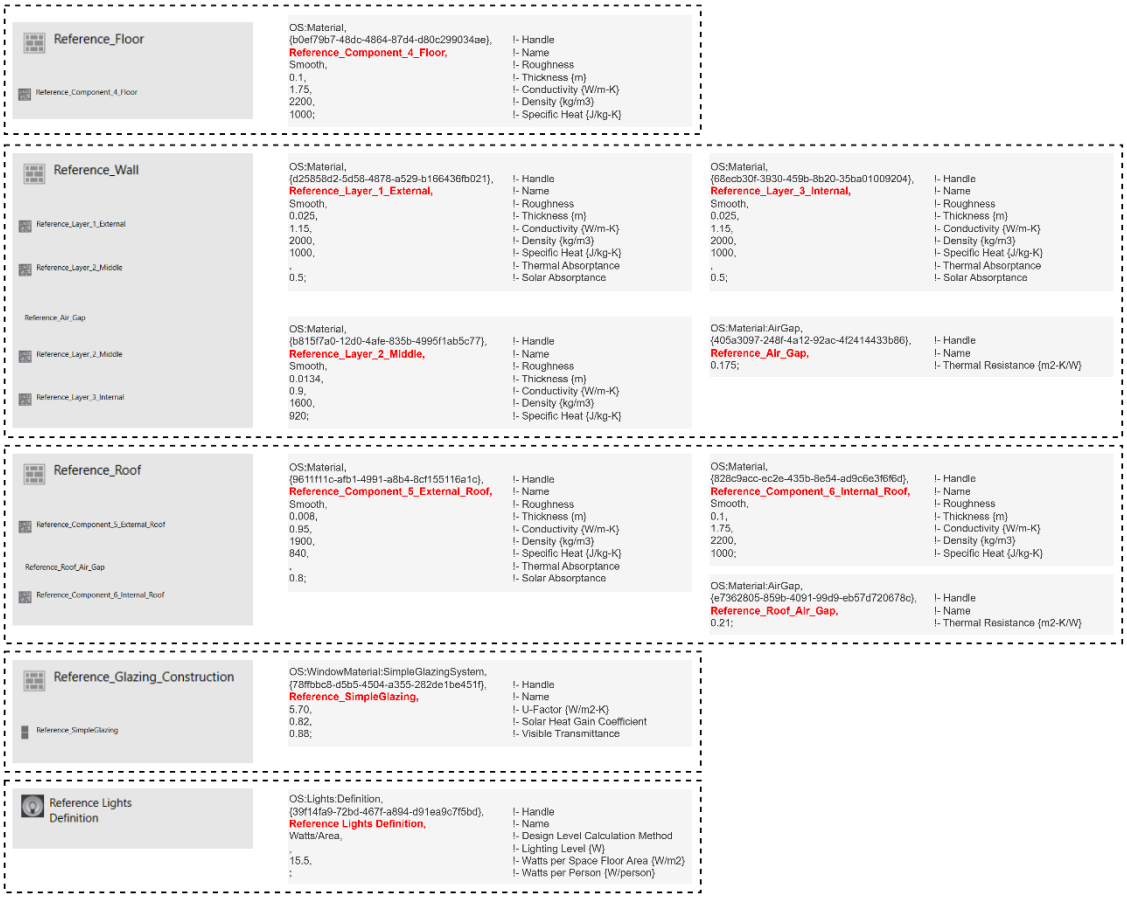
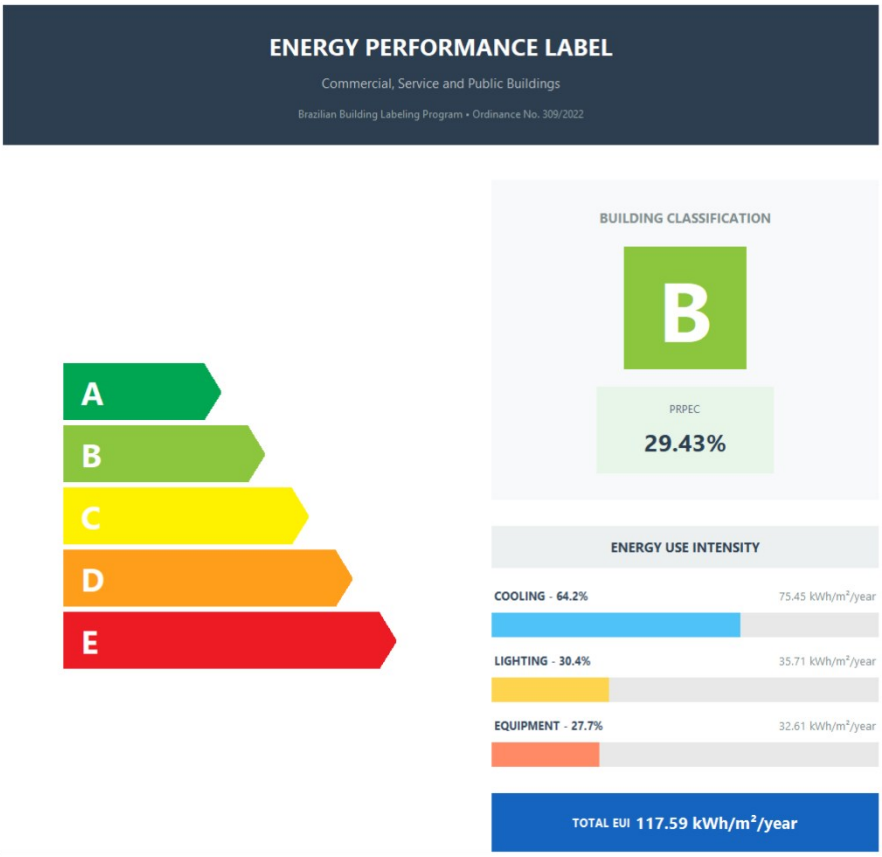



Figure 18 – Verification of implemented reference constructions, materials, and LPD definitions

Following the successful generation and verification of the real and reference condition BEM models, the final simulation outputs were configured by the pipeline according to the protocol. The weather file required for simulation was provided by the user and integrated by the pipeline as defined in the method. The entire simulation process, from model setup to result generation, was autonomously executed by the pipeline, and both simulations ran without interference. Energy simulations were then performed to assess the building's performance. The real condition model achieved an energy performance classification of B (PRPEC of 29.43%). Its total primary EUI was 117.59 kWh/m²/year, with cooling being the predominant energy end-use (64.2% or 75.45 kWh/m²/year), followed by lighting (30.4% or 35.71 kWh/m²/year), and equipment (27.7% or 32.61 kWh/m²/year). It should be noted that heating energy end-use is not computed here, since Florianopolis is not located in a Bioclimatic Zone with rigorous winter.

A detailed comparative analysis between the real and reference models further explained the building's energy performance. The reference model

exhibited a higher total primary EUI of 166.64 kWh/m²/year. Consequently, the real condition model demonstrated a substantial energy performance improvement, consuming 49.04 kWh/m²/year than the reference. This translates to a PRPEC of 29.43%, indicating that the real building is significantly more efficient than its baseline counterpart. Analyzing the primary EUI components, the real model's cooling consumption was notably lower than the reference, with a difference of 50.78 kWh/m²/year (-40.2%). Lighting also showed a significant reduction of 15.88 kWh/m²/year (-30.8%) in the real model. Conversely, the primary EUI of the equipments remained identical between both models at 32.61 kWh/m²/year, as mandated by the Brazilian energy code, which requires the EPD to be the same for both real and reference models. The pipeline results, including the building classification, detailed primary EUI breakdown for the real model, and the comparative EUI analysis between the real and reference models, are fully presented in Figure 19.




| Component | Reference Model | Real Model | Difference |
|---|---|---|---|
| Cooling (EUI) | 126.23 kWh/m²/year | 75.45 kWh/m²/year | ↓ 50.78 kWh/m²/year (-40.2%) |
| Lighting (EUI) | 51.58 kWh/m²/year | 35.71 kWh/m²/year | ↓ 15.88 kWh/m²/year (-30.8%) |
| Equipment (EUI) | 32.61 kWh/m²/year | 32.61 kWh/m²/year | = 0.00 kWh/m²/year (+0.0%) |
| **TOTAL (EUI)** | 166.64 kWh/m²/year | 117.59 kWh/m²/year | ↓ 49.04 kWh/m²/year (-29.4%) |
| **PRPEC** | 0.00% (baseline) | 29.43% | ↓ 29.43% more efficient |

**How to interpret the results:**

- PRPEC (Primary Reduction of Primary Energy Consumption): Overall efficiency metric
- Positive PRPEC (+): Your building consumes LESS energy than reference (more efficient)
- Negative PRPEC (-): Your building consumes MORE energy than reference (less efficient)
- EUI (Energy Use Intensity): Energy consumption per square meter per year
- Cooling EUI uses conditioned area, Lighting & Equipment use total building area
- TOTAL EUI uses total building area for standardized comparison
- Values with ↓: Reduction in consumption compared to reference (positive)
- Values with ↑: Increase in consumption compared to reference (negative)

Figure 19 – Energy performance label and comparative primary EUI analysis

Beyond the implementation and performance assessment, the overall processing time demonstrates the efficiency gain provided by the pipeline. The total time required to execute the full end-to-end process – from the input of the validated gbXML file to the generation of the final energy performance metrics –

was 15 minutes and 22 seconds. This time is broken down as follows: the real condition model routine took 1 minute and 35 seconds to parse the data and generate the BEM model; the subsequent simulation required 6 minutes and 37 seconds. The reference condition model routine was completed quickly in 55 seconds, followed by its simulation, which took 5 minutes and 11 seconds. Finally, the assessment routine (calculating the PRPEC and generating the final label) took 1 minute and 4 seconds. This fast turnaround highlights significant time savings not only in execution but in process: by leveraging the architectural BIM directly, the workflow avoids the redundant creation of a separate energy model parallel to the design process. This confirms the automated pipeline as a viable, high-speed alternative to traditionally time-intensive manual workflows for energy performance assessment and certification.

## 6 Discussion

This section explores the findings of the implemented BIM-to-BEM workflow, shifting the primary focus from the specific energy performance of the case study building to the overarching aspects of automation, informatics, and interoperability within mandatory energy performance certification. The discussion is structured around the central research question and its sub-questions, aiming to critically evaluate the challenges encountered, the opportunities realized, and the broader implications of automating such complex workflows in a compliance context. By integrating information requirements, modeling guidelines, a simulation protocol, and an automated pipeline tested through a case study, this research presents a holistic workflow for addressing the BIM-to-BEM challenge.

The findings first and foremost demonstrate the practical viability of the proposed modeling guidelines in preparing a real-world building for energy simulation. The case study building, with its X-shaped configuration, five stories, and 139 functionally diverse spaces, represents a significant modeling challenge that extends beyond the simpler geometries often used to test interoperability [68,72,73]. The successful integration of all required geometric and semantic data into a compliant BIM model, as shown in the results, challenges the perception that BIM-to-BEM workflows are too incipient or unreliable. This suggests that many documented interoperability failures may not stem from an inherent flaw in

the BIM-to-BEM concept itself, but rather from the lack of a structured methodology. By defining clear rules for model creation, the guidelines serve as the essential first line of defense, aiming to ensure that the data entering the translation process is as clean and well-structured as possible, thereby minimizing ambiguities that often lead to export errors. This approach embodies the principle of inputting data that is useful, not merely possible, deliberately leaving tasks that are prone to human error or better handled systematically to the automated pipeline.

However, the successful creation of a compliant BIM model does not guarantee flawless data translation, a reality that underscores the inherent limitations of current software. This vulnerability was evident in the results, which revealed two distinct classes of interoperability issues that persisted despite adherence to modeling guidelines. The misclassification of surfaces represents a semantic interpretation error, where the software's internal logic for generating the energy analytical model incorrectly assigned surface types, an issue previously identified and still persistent in the literature [11,45,65]. In contrast, the issue of solar absorptance highlights a data mapping limitation stemming from semantic ambiguity. Revit's generic "Absorptance" property is automatically mapped to the "ExtIR" (infrared) enumeration during gbXML export, without offering a user-configurable option for the "ExtSolar" value required by the simulation engine. This reflects a broader limitation in BIM tools, a challenge also noted in the literature [5,46], where users often cannot specify crucial simulation-specific attributes directly within the modeling environment. As widely acknowledged, these semantic gaps in the export process often necessitate workarounds [59,61,63]. This distinction is critical, as it demonstrates that even a BIM model compliant with established modeling guidelines remains vulnerable to data misclassification or loss during the translation stages. This finding, therefore, reinforces a widely recognized conclusion in the BIM-to-BEM literature: that including a dedicated stage for post-export data verification and correction is an essential component of automated and semi-automated BIM-to-BEM workflows. A successful workflow requires a pipeline capable of automating tasks, as well as diagnosing and correcting these multi-faceted data discrepancies that arise during translation. This is critical because the initial BEM translation directly inherits any inaccuracies from the open data schema file (in this study, the gbXML

schema), underscoring that such a pipeline is not just an efficient tool, but a fundamental requirement for improving the integrity of the final model's data.

Beyond the initial, successful geometric translation from gbXML to the OpenStudio format, the results demonstrate the pipeline's significant capability for the semantic enrichment of the BEM model. The workflow did not merely transfer data; it interpreted the programmatic use of each space, differentiating between space typologies as defined by the simulation protocol, and programmatically applied the corresponding set of standardized internal loads, operational schedules, ventilation parameters, and air-conditioning definitions. This automated assignment of simulation-specific objects represents a critical step beyond simple data conversion. It helps transform a geometrically accurate model into a simulation-ready asset where semantic data are consistently applied according to the regulatory framework. This feature is designed to enhance efficiency and consistency in how these standardized rules are applied across hundreds of spaces, which is a fundamental requirement for a scalable and equitable certification process. This programmatic assignment aims to ensure that the high-resolution temporal profiles required for dynamic simulation are correctly instantiated. This contrasts with static or quasi-static compliance methods that often aggregate data, demonstrating that automation can sustain the fidelity of hourly resolutions without the manual overhead typically associated with advanced modeling.

Furthermore, the findings highlight the pipeline's important role as an automated tool capable of diagnosing and correcting latent errors that persist even after the initial data translation. The identification and correction of incorrect outside boundary conditions for 24 ground-contact and underground surfaces, along with their sun and wind exposure attributes, are particularly significant. These are not superficial geometric errors but physical misrepresentations that would have potentially impacted the simulation outcome. Similarly, the automated conversion of 11 internal surfaces into proper air boundaries demonstrates an understanding of building physics that goes beyond simple data validation. This capability suggests that a comprehensive workflow should not end at data translation but should also incorporate a verification and correction stage. This final automated correction stage contributes to a higher level of model fidelity than

is often achievable through manual inspection, thereby building confidence in the final simulation inputs.

A particularly impactful demonstration of the workflow's utility in a regulatory context is its ability to systematically generate the standardized reference condition model. This process involved the programmatic replacement and reassignment of thousands of building components, including 1,335 wall surfaces, 383 floor surfaces, and 40 roof surfaces to apply the prescriptive envelope requirements of the simulation protocol. The pipeline's capacity to precisely adjust the WWR to the target of 40% across all façades, standardize LPD in all 139 spaces, and remove all 618 external shading elements addresses a primary bottleneck of regulatory assessments. By creating a reference model that is a well-controlled derivative of the real condition model, identical in all aspects except for the standardized parameters, the pipeline reduces the potential for subjective interpretation and manual errors. This supports an objective, transparent, and more reproducible performance comparison.

The successful execution of the energy simulations and the subsequent generation of the final performance classification serve as validation for the workflow. The pipeline's ability to autonomously manage the simulation process for both the real and reference models, from setup to result extraction, demonstrates its practical applicability. The achievement of a specific, code-compliant output, in this case a class B rating with a 29.43% PRPEC, indicates that the workflow can produce the final deliverable required by the simulation protocol. This end-to-end automation addresses the full scope of the compliance task, moving beyond the intermediate step of model creation to encompass the final analytical and reporting stages. This approach reduces the need for manual intervention, thereby minimizing the potential for procedural errors during the simulation phase.

The detailed comparative analysis between the models highlights a key benefit of the automated approach, which is its contribution to the integrity and transparency of the certification process itself. By programmatically generating the reference model as a controlled modification of the real condition model, the pipeline establishes a clear and auditable link between the two. This auditability is paramount for EPC schemes, where the final classification must be defensible against regulatory scrutiny. The value of this method is not in predicting absolute,

real-world energy consumption, but in supporting a consistent and equitable comparison against the regulatory baseline. The quantifiable differences in energy use between the two models are the direct result of the pipeline systematically applying the standardized parameters defined in the simulation protocol. This programmatic control provides a high degree of traceability, as any performance gap can be directly linked to the application of the protocol's specific rules rather than to undocumented manual adjustments. Consequently, automation supports a more objective and reproducible assessment, which is fundamental for scalable energy code compliance.

The analysis of the workflow's processing time quantitatively validates the efficiency of the automation, though it is important to contextualize these results. The total time to perform the complete compliance assessment for the case study, from processing the gbXML file to delivering the final performance label, was approximately 15 minutes. This duration is a direct function of the input model's complexity and the specific requirements of the simulation protocol. A substantial portion of this time was allocated to the core simulation engine. The EnergyPlus run for the real condition model accounted for approximately 6.5 minutes of the total simulation time, while the reference model simulation required over 5 minutes. The remaining time was spent on the pipeline's automated tasks of data parsing, correction, model generation, and results processing. This breakdown highlights that the automation's overhead is minimal compared to the computational demands of the simulation itself. Even so, this result contrasts significantly with traditional manual workflows, where the preparatory tasks of BEM creation and verification alone can require several hours or days of specialized labor [19,57]. This efficiency gain marks a significant shift in regulatory compliance, demonstrating that dynamic energy simulation no longer needs to be a bottleneck for certification. By eliminating the redundant step of creating separate energy models alongside the design process, the workflow enables advanced, hourly performance assessments to be completed with speeds comparable to those of simplified calculation methods, while delivering greater analytical depth and accuracy.

It is important to acknowledge the limitations and dependencies of the current workflow. A primary dependency is the strict adherence to the modeling guidelines previously established, particularly the textual conventions for naming

BIM objects. The pipeline's semantic matching mechanisms are designed to interpret these specific display names; consequently, any deviation from the guidelines, such as a typo or an alternative naming scheme, can lead to misclassification and would necessitate manual intervention. The workflow also has procedural constraints rooted in the underlying software libraries. For instance, the automated WWR adjustment relies on the .setWindowToWallRatio() method within the OpenStudio API. A limitation of this method is that it can cause geometric overlaps between the new windows and existing doors, which necessitates that surfaces be free of other openings for the adjustment to be applied correctly. Furthermore, the specific implementation is inherently tied to the chosen software ecosystem and data standards, as the pipeline's data parsing relies on an API developed specifically for the gbXML format. While the underlying logic and methodology are transferable, adapting the workflow to different tools or input formats would require several adjustments.

Another consideration relates to the scope of this research. The current work focused strictly on BIM-to-BEM automation and the energy assessment within a regulatory compliance framework, meaning the precision and predictive accuracy of the energy models – often addressed through calibration techniques – were outside the scope of the present work. While the workflow successfully generates a functional BEM from BIM for regulatory compliance, future research could evolve this work by applying model calibration techniques to the resulting BEM, validating its predictive capabilities against real-world data, and addressing the complex trade-off between the speed of automation and the precision required for operational performance analysis. The workflow was developed and tested for a higher education facility, and while it is designed to be adaptable to other typologies under the Brazilian energy code with minor modifications, further studies would be needed to validate its performance across a broader range of buildings.

Looking forward, this research opens several avenues for future work. By establishing a reproducible and automated process for dynamic simulation, the proposed workflow provides a structural foundation for multi-domain analyses beyond energy performance certification. Future research can extend this methodological structure to assess occupant thermal comfort, evaluate demand-side flexibility, and simulate grid-interactive efficient buildings, using the hourly

temporal resolution inherent to the process. A key opportunity involves expanding the pipeline's capabilities to include natural ventilation strategies, which is particularly relevant for addressing energy poverty [5] and promote sustainable building design in tropical and developing countries, where mechanical systems are not always feasible [19,73]. Another significant research direction involves integrating more sophisticated models of user behavior. The forthcoming gbXML schema (v. 8.01), with its focus on occupant-centric data [74], presents an opportunity to develop workflows that can better predict the performance gap between design intent and actual operation, not only in regulatory contexts but across other building performance simulations.

In summary, this discussion has examined the challenges and opportunities of automating regulatory BIM-to-BEM workflows. The findings confirm that significant interoperability gaps persist. In response to this well-documented challenge, the proposed workflow offers a structured methodology to bridge these gaps, combining clear modeling guidelines at the start with an automated pipeline to correct and enrich data after export. It is crucial to recognize that the goal of this process is to produce a standardized and simplified model suitable for regulatory comparison, not a complex simulation calibrated to real-world conditions. Ultimately, such methodological approaches remain necessary because seamless interoperability has not yet been achieved at the software industry level.

## 7 Conclusion

This research developed and validated a BIM-to-BEM workflow tailored for mandatory energy performance certification. The central research question explored the challenges and opportunities in automating this process. The study concludes that while significant challenges persist due to interoperability limitations, such as semantic interpretation errors and data mapping issues during export, the primary opportunity lies in a structured, multi-stage methodology. This approach combines modeling guidelines for data preparation with an automated pipeline for post-export correction and enrichment, establishing a practical method for conducting scalable regulatory compliance.

Addressing the first sub-question, this study showed that well-defined information requirements and modeling guidelines serve as a foundational step

in creating an interoperable BIM model. For a real-world building with an X-shaped configuration, five stories, and 139 diverse spaces, these guidelines facilitated the integration of all necessary geometric and semantic data into a compliant BIM model. This outcome suggests that many documented interoperability failures may stem from a lack of structured methodology rather than from fundamental flaws in the BIM-to-BEM concept. However, the research also confirmed that even with adherence to these guidelines, specific interoperability issues – such as the misclassification of surfaces and the incorrect mapping of metadata – persisted during gbXML export, highlighting the limitations of current software and the need for subsequent automated correction.

Regarding the second sub-question, the automated pipeline has a multi-faceted role in transforming raw data exports into certification-ready BEM models. First, it functions as a correction mechanism, rectifying interoperability errors that persist in post-export, such as the misclassification of surfaces and the incorrect mapping of solar absorptance. It also converts internal surfaces designated as air type into air boundaries. Second, the pipeline performs semantic enrichment by interpreting the use of each space and programmatically applying the corresponding standardized internal loads, operational schedules, ventilation parameters, and air-conditioning definitions. Third, in the context of mandatory certification, it acts as a regulatory engine by systematically generating the standardized reference model. This involves programmatically replacing and reassigning thousands of components (e.g., 1,335 wall surfaces, 383 floor surfaces), adjusting the WWR to 40% across all façades, standardizing LPD to 15.5 W/m² in all spaces, and removing external shading elements. Finally, the pipeline manages the simulation process for both real and reference models, from setup to result extraction, and delivered the final energy performance classification.

Addressing the third sub-question, this study concludes that the integration of information requirements, modeling guidelines, a simulation protocol, and the automated pipeline affect the scalability, consistency, and transparency of energy performance certification. Scalability is improved by reducing the assessment time from potentially hours or days of manual labor to approximately 15 minutes of automated processing. This efficiency demonstrates that rigorous, dynamic simulation need not be a bottleneck for certification,

enabling high-resolution hourly analysis at speeds comparable to simplified calculation methods. Consistency is improved through the programmatic application of the simulation protocol's rules across all spaces, which reduces subjective interpretation and the potential for human error in model setup. Transparency is improved by establishing a clear, auditable, and reproducible link between the real and reference models. As a result, the performance gap and final classification are direct, traceable consequences of the regulatory rules rather than of undocumented manual adjustments, which supports a more objective assessment.

The main contribution of this research is the demonstration of a methodological framework that addresses the persistent BIM-to-BEM data gap within a regulatory context. This approach, which prioritizes standardized and simplified models for compliance checks, provides a practical and replicable model for automating energy code compliance. While acknowledging its limitations, such as the dependency on specific modeling guidelines, procedural constraints of underlying software libraries, and its initial validation on a higher education facility, the workflow provides a methodological foundation. Future research could focus on expanding the pipeline's capabilities to include natural ventilation strategies or to integrate more sophisticated models of user behavior. Ultimately, this research indicates that structured methodological approaches, like the one proposed, remain necessary to bridge the gap between BIM and BEM, transforming the certification process from a static administrative hurdle into a dynamic, data-driven assessment.

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# Appendix A

| Real condition model routine | | | |
|---|---|---|---|
| **Task** | **Class** | **Method** | **Description** |
| Pre-process and correct gbXML data | ElementTree | .findall()<br>.set() | This class parses the raw gbXML file, finds all <Absorptance> elements with the type ExtIR, and uses .set() to change their type attribute to ExtSolar. |
| Translate source data to OpenStudio model | GbXMLReverseTranslator | .loadModel() | This class reads a source gbXML file and uses the .loadModel() method to translate its contents into a complete OpenStudio model object. |
| Apply internal loads based on occupancy type | Space<br>PeopleDefinition<br>People<br>LightsDefinition<br>Lights<br>ElectricEquipmentDefinition<br>ElectricEquipment | .setNumberofPeople()<br>.setWattsperSpaceFloorArea()<br>.setSpace() | This class creates and assigns People, Lights, and ElectricEquipment loads to spaces in the model, using load values that differ based on the space's occupancy classification (POA/TOA). |
| Apply operational schedules to internal loads | ScheduleRuleset<br>People<br>Lights<br>ElectricEquipment | .setSchedule()<br>.setNumberofPeopleSchedule()<br>.setActivityLevelSchedule() | This class creates complex, protocol-compliant ScheduleRuleset objects and then assigns them to all People, Lights, and ElectricEquipment loads in the model. |
| Apply airflow based on occupancy type | Space<br>DesignSpecificationOutdoorAir<br>SpaceInfiltrationDesignFlowRate | .setDesignSpecificationOutdoorAir()<br>.setOutdoorAirFlowperPerson()<br>.setAirChangesperHour() | This class assigns SpaceInfiltrationDesignFlowRate and DesignSpecificationOutdoorAir objects to spaces based on their occupancy classification (POA/TOA). |
| Apply HVAC system and thermostats | ThermalZone<br>ZoneHVACIdealLoadsAirSystem<br>ThermostatSetpointDualSetpoint | .addToThermalZone()<br>.setThermostatSetpointDualSetpoint() | This class creates a ZoneHVACIdealLoadsAirSystem and a ThermostatSetpointDualSetpoint and assigns them only to ThermalZones classified as POA. |

| | | | |
|---|---|---|---|
| Exclude specific space types from floor area calculation | Space<br>SpaceType | .setPartofTotalFloorArea() | This class identifies spaces associated with a Plenum SpaceType and sets their partofTotalFloorArea property to False. |
| Standardize object names | Construction<br>Material<br>AdditionalProperties | .setName()<br>.getFeatureAsString() | This class reads the displayName from AdditionalProperties and applies it as the primary name for Construction and Material objects to improve model readability. |
| Correct surface boundary conditions | Surface | .setOutsideBoundaryCondition()<br>.setSunExposure()<br>.setWindExposure() | This class corrects the OutsideBoundaryCondition and exposure properties of surfaces based on a mapping between the construction name and the required property. |
| Apply standard air boundary constructions | Surface<br>ConstructionAirBoundary | .setConstruction()<br>.setAirExchangeMethod() | This class creates a ConstructionAirBoundary object and assigns it to all surfaces whose original construction name contains “Air”. |

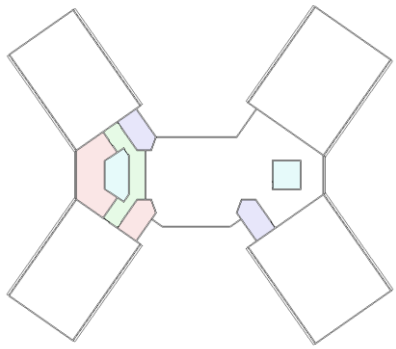
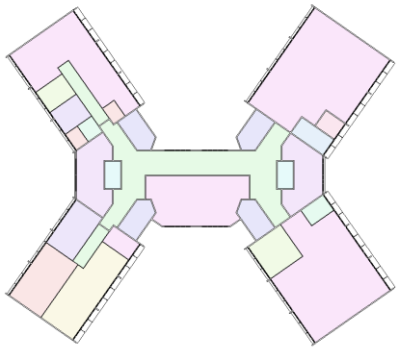
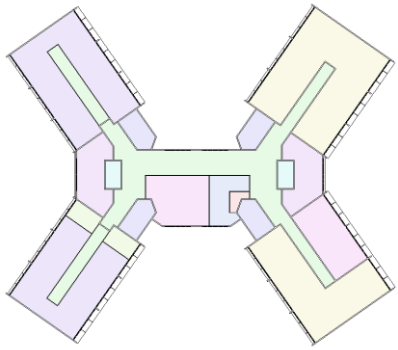
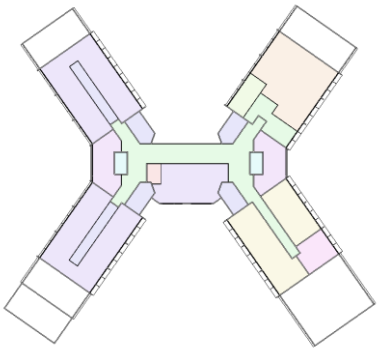
| **Reference condition model routine** | | | |
|---|---|---|---|
| **Task** | **Class** | **Method** | **Description** |
| Replace floor constructions with a standard assembly | Surface<br>Construction<br>StandardOpaqueMaterial | .setConstruction() | This class creates a new protocol-compliant floor Construction and Material, then assigns it to all surfaces whose original construction is identified as a floor type. |
| Replace wall constructions with a standard assembly | Surface<br>Construction<br>StandardOpaqueMaterial<br>AirGap | .setConstruction() | This class creates a new protocol-compliant, multi-layer wall Construction (including materials and an air layer) and assigns it to all surfaces whose original construction is identified as a wall type. |

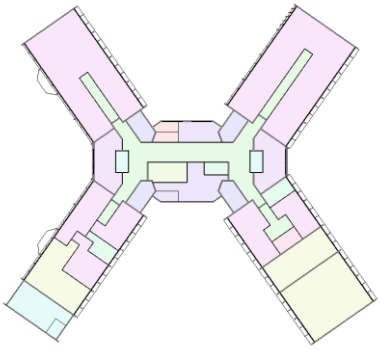
| | | | |
|---|---|---|---|
| Replace roof constructions with a standard assembly | Surface<br>Construction<br>StandardOpaqueMaterial<br>AirGap | .setConstruction() | This class creates a new protocol-compliant, multi-layer roof Construction (including materials and an air layer) and assigns it to all surfaces whose original construction is identified as a roof type. |
| Remove external shading geometry | ShadingSurface<br>ShadingSurfaceGroup | .remove() | This class finds all ShadingSurface objects and their associated ShadingSurfaceGroup objects in the model and removes them. |
| Remove skylight sub-surfaces | Surface<br>SubSurface | .remove() | This class iterates through all Surface objects in the model, finds any SubSurface with the type Skylight, and removes it. |
| Standardize WWR and glazing properties | Surface<br>SubSurface<br>SimpleGlazing<br>Construction | .setWindowToWallRatio()<br>.setConstruction() | This class removes existing windows from exterior walls, applies a standard WWR using .setWindowToWallRatio(), and assigns a new protocol-compliant glazing Construction. |
| Standardize lighting power density | Lights<br>LightsDefinition | .setLightsDefinition()<br>.setWattsperSpaceFloorArea() | This class finds all existing Lights objects and assigns them a new or existing LightsDefinition object that has been set to a protocol-compliant W/m² value. |

| **Energy simulation and assessment routine** | | | |
|---|---|---|---|
| **Task** | **Class** | **Method** | **Description** |
| Define simulation outputs and timestep | Timestep<br>OutputVariable | .setNumberOfTimestepsPerHour()<br>.remove() (on existing variables) | This task prepares the model for simulation by setting the global Timestep and replacing all existing OutputVariable objects with a specific list required for post-processing. |

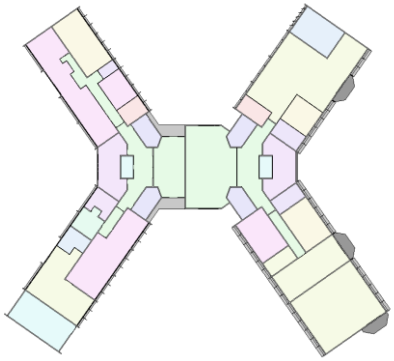
| | | | |
|---|---|---|---|
| Run the energy simulation | subprocess (Python stdlib) | subprocess.run() | This task executes the OpenStudio simulation by making an external command-line call to openstudio run -w using Python's subprocess module. |
| Read simulation energy results | pandas | read_csv() | This class reads the eplusout.csv file into a data structure (DataFrame) to sum the energy consumption (in Joules) for lighting, equipment, cooling, and heating. |
| Read simulation building area | bs4.BeautifulSoup | .find_all() | This class parses the eplustbl.htm report, using .find_all() to navigate its tables and extract the building area values required for the EUI calculation. |
| Read simulation building geometry | bs4.BeautifulSoup | .find_all()<br>.find_next_sibling() | This class parses the eplustbl.htm report, navigating its tables to find and extract the total building volume (from Zone Summary) and the envelope areas (from Opaque Exterior). |
| Calculate final energy performance class | tkinter.Tk<br>tkinter.Toplevel | calculate_energy_class() (local function) | This class takes the final metrics (PRPEC and Coefficient i) from user input and applies the protocol's thresholds to determine the final A-E classification. |

## Appendix B

| Floor plan | Description |
|---|---|
|  | The building's uppermost levels are shown in this plan, comprising 8 spaces with a total area of 210 m². These levels are dedicated to building services and technical areas, consisting primarily of active storage (71 m²) and electrical/mechanical rooms (59 m²). |
|  | This plan details the Fourth Floor, which includes 26 spaces totaling 1,379 m². The floor is heavily characterized by open-plan offices, which comprise the largest functional area (674 m²). This is followed by corridors (208 m²) and various academic and support spaces, including classrooms (83 m²) and enclosed Offices (59 m²). |
|  | The Third Floor consists of 19 spaces, summing to a total area of 1,325 m². This level is primarily defined by its academic functions, containing the largest share of classroom and lecture space (379 m²) and a significant number of offices (332 m²). These areas are connected by the central corridor and atrium (272 m²). |
|  | The Second Floor is detailed in this plan, encompassing 19 spaces with a total area of 1,386 m². This level is primarily dedicated to offices (460 m²), corridors (246 m²), and classrooms (182 m²). A notable feature of this floor is a 171 m² Auditorium. |



The First Floor contains 30 distinct spaces, summing to a total area of 1,864 m². Its layout is functionally dominated by offices (814 m²), followed by workshops (344 m²) and the central corridors (264 m²). This floor houses several research groups and administrative departments.



This plan shows the Ground Floor, which is divided into two main levels to accommodate the site's topography (0.00m and +1.70m). This floor contains 37 distinct spaces, summing to a total area of 1,853 m². The layout is functionally dominated by large-area workshops (562 m²), extensive circulation corridors (388 m²), and offices (309 m²). This floor houses five key research groups and contains a substation.

**Caption**

| | | | |
|---|---|---|---|
| Active Storage<br>RGB 250-230-230 | Audience Seating Area<br>RGB 250-240-230 | Conference Meeting<br>RGB 241-250-230 | Corridor Transition<br>RGB 230-250-230 |
| Dining Area<br>RGB 230-250-240 | Electrical Mechanical<br>RGB 230-250-250 | Lounge Recreation<br>RGB 230-235-250 | Office Enclosed<br>RGB 237-250-250 |
| Office Open Plan<br>RGB 250-230-250 | Office Common Activity<br>RGB 250-230-239 | Stairway<br>RGB 231-230-250 | Workshop<br>RGB 246-250-230 |