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Doctoral Thesis

BIM-based Building Energy Modelling for holistic simulation-based assessment and optimisation of operating industrial production facilities

submitted in fulfilment of the requirements for the degree of
Doctor of Science in Civil Engineering
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Dissertation

BIM-basiertes Building Energy Modelling zur ganzheitlichen simulationsbasierten Bewertung und Optimierung von industriellen Produktionsanlagen im Betrieb

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Dipl.-Ing. Dipl.-Ing. Georgios Gourlis
Matrikelnummer 01225611

Supervisor:	Univ.-Prof.in Dipl.-Ing. Dr.in techn. Iva Kovacic Institute of Building- and Industrial Construction, TU Wien
Reviewer:	Univ.-Prof. Dipl.-Ing. Dr. techn. Wolfgang Kastner Institute of Computer Engineering, TU Wien
Reviewer:	Associate Prof. Dipl.-Ing. Dipl.-Ing.(FH) Dr. techn. Schuß Matthias Wilhelm Institute of Architectural Sciences, TU Wien

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Abstract

Enhancement of energy and resource efficiency in industrial production facilities is a core objective in the era of the fourth industrial revolution – Industry 4.0. There are substantial opportunities for achieving such targets in existing operating facilities by engaging measures towards retrofitting and digitalisation, to avoid energy demand in the first place. Significant benefits can be gained by utilising computational modelling and simulations for predicting and optimising the energy demand in both of the above directions. This requires an interdisciplinary approach, extending over production and logistic processes as well as the building and technical building services, consolidated through integrated modeling and simulation-based optimization. From this viewpoint, this doctoral thesis addresses an interdisciplinary research domain, extending over production engineering, energy systems, computer aided automation and building technology, while focusing on the topic of the industrial building, as the physical space in which everything else is occurring.

The doctoral thesis is cumulative, based on five peer-reviewed scientific papers. The conducted work attempts to close the research gap of the utilisation of building energy modelling (BEM) in the holistic assessment of industrial production facilities in operation. It does so by a thorough investigation focusing, on the one hand, on energy retrofitting concerning the optimisation potentials of industrial construction, and on the other, on the digital representation of the building in a holistic digital twin simulation framework for highly digitalised facilities. The interconnection of building information modelling (BIM) with industrial building energy models is therefore examined, given the fact that BIM is established as modelling technology in the architecture, engineering and construction industry to process and analyse building models, while also forming a joint digital knowledge domain with geometrical and/or non-geometrical information.

The main research question is how and to which extent can BIM-based building energy modelling be utilised in holistic simulation-based assessment of operating industrial production facilities towards energy-efficient optimisation. Thus, BIM-to-BEM processes and BEM assessment are analysed for the first time on the case studies of existing industrial buildings. State-of-the-art implementation of BEM tools and methods, with active consideration and integration of production process loads is conducted and thoroughly presented in exploration of refurbishment strategies for the building energy retrofitting on a case study. Additionally, a BIM-based semi-automated workflow for acquiring data directly from already developed BIM models is proposed, in order to create a BEM representation for a holistic hybrid simulation within a digital twin ecosystem, enabling the integration of energy-related planning into the actual plant operation. A proof-of-concept implementation of the workflow is then presented.

The contribution of the conducted work is assessed on two levels, those of energy retrofitting and industrial digitalization. On the level of energy retrofitting, it demonstrates the way to utilise BEM for optimising the building performance of industrial productions facilities, supporting the argument for the creation of a BIM model, where the facility can be well documented, providing a knowledge database for energy retrofit measures assessment with higher cost and time efficiency next to the basis for life-cycle operational management. However, this does not entail a de facto faster modelling of the necessary BEM simulation model, due to the required simplification and filtering of BIM-provided data as well as interoperability issues of the different discipline-oriented software applications. On the level of industrial digitalisation, this work contributes the necessary abstraction level for BEM in holistic applications for optimising energy and resource efficiency of operating facilities, helping future research in the field of hybrid industrial simulations to prioritise the essential building-related information in the creation of the building digital twin models. This enables reaching the desired complexity of a holistic digital representation of a facility, while omitting unnecessary domain-specific information and thus increasing the error rates and computational time of such models. The proposed semi-automated workflow for a BIM-based creation of the abstracted BEM model could also be utilised in a hybrid cyber-physical system simulation, not employing typical BEM tools but a discrete event system specification formalism.

Keywords

building information modelling; energy retrofitting; building performance simulation; hybrid simulation; industrial building; holistic industrial modelling

Kurzfassung

Die Steigerung der Energie- und Ressourceneffizienz in industriellen Produktionsanlagen ist ein Kernziel im Zeitalter der vierten industriellen Revolution – Industrie 4.0. Es gibt beträchtliche Möglichkeiten, solche Ziele in bestehenden Betriebsanlagen zu erreichen, indem Maßnahmen zur Nachrüstung und Digitalisierung ergriffen werden, um den Energiebedarf von vornherein zu vermeiden. Durch den Einsatz von Computermodellen und -simulationen zur Vorhersage und Optimierung des Energiebedarfs in beiden oben genannten Richtungen können erhebliche Vorteile erzielt werden. Dies erfordert einen interdisziplinären Ansatz, der sich sowohl auf die Produktions- und Logistikprozesse als auch auf das Gebäude und die technische Gebäudeausrüstung erstreckt und durch integrierte Modellierung und simulationsgestützte Optimierung konsolidiert wird. Die vorliegende Dissertation widmet sich daher einem interdisziplinären Forschungsfeld, das sich über Produktionstechnik, Energiesysteme, computergestützte Automation und Gebäudetechnik erstreckt und sich auf das Thema Industriegebäude als den physischen Raum konzentriert, in dem sich alles andere abspielt.

Die Dissertation ist kumulativ und basiert auf fünf begutachteten wissenschaftlichen Artikeln. Die durchgeführte Arbeit versucht, die Forschungslücke des Einsatzes von Gebäudeenergiemodellierung (BEM) bei der ganzheitlichen Bewertung von industriellen Produktionsanlagen im Betrieb zu schließen. Dies geschieht zum einen durch eine eingehende Untersuchung der energetischen Nachrüstung bzw. Sanierung im Hinblick auf die Optimierungspotenziale des Industriebaus und zum anderen durch die digitale Abbildung des Gebäudes in einem ganzheitlichen digitalen Zwillingssimulationsrahmen für hochdigitalisierte Anlagen. Untersucht wird daher die Verbindung von Building Information Modelling (BIM) mit industriellen Gebäudeenergiemodellen – BEM, da BIM als Modellierungstechnologie in der Architektur-, Ingenieur- und Bauindustrie etabliert ist, um Gebäudemodelle zu verarbeiten und zu analysieren und gleichzeitig eine gemeinsame digitale Wissensdomäne mit geometrischen und/oder nicht-geometrischen Informationen zu bilden.

Die zentrale Forschungsfrage ist, wie und inwieweit die BIM-basierte Gebäudeenergiemodellierung für eine ganzheitliche simulationsgestützte Bewertung des Betriebs industrieller Produktionsanlagen im Sinne einer energieeffizienten Optimierung genutzt werden kann. Dazu werden erstmals BIM-zu-BEM-Prozesse und die BEM-Bewertung an Fallbeispielen von bestehenden Industriegebäuden analysiert. Eine moderne Implementierung von BEM-Werkzeugen und -Methoden unter aktiver Berücksichtigung und Integration von Produktionsprozesslasten wird durchgeführt und in der Untersuchung von Sanierungsstrategien für die energetische Gebäudesanierung an einer Fallstudie ausführlich dargestellt. Zusätzlich wird ein BIM-basierter, halbautomatischer Arbeitsablauf für die Erfassung von Daten direkt aus bereits entwickelten BIM-Modellen vorgeschlagen, um eine BEM-Darstellung für eine ganzheitliche hybride Simulation innerhalb eines digitalen Zwillingsökosystems zu erstellen, die die Integration der energiebezogenen Planung in den tatsächlichen Anlagenbetrieb ermöglicht. Anschließend wird eine Proof-of-Concept-Implementierung des Workflows vorgestellt.

Der Beitrag der durchgeführten Arbeit wird auf zwei Ebenen bewertet, die der energetischen Sanierung und die der industriellen Digitalisierung. Auf der Ebene der energetischen Sanierung zeigt sie den Weg zur Nutzung von BEM für die Optimierung der Gebäudeleistung industrieller Produktionsanlagen und unterstützt das Argument für die Erstellung eines BIM-Modells, in dem die industrielle Anlage gut dokumentiert werden kann. Mittels des BIM-Modells wird sowohl eine Grundlage für das Lebenszyklus Facility Management als auch eine Wissensdatenbank für die Bewertung von energetischen Sanierungsmaßnahmen mit höherer Kosten- und Zeiteffizienz geschafft. Dies führt jedoch nicht zu einer de facto schnelleren Modellierung des jeweils notwendigen BEM-Simulationsmodells. Die entsprechenden Schwierigkeiten sind auf die erforderliche Vereinfachung und Filterung der vom BIM-Modell bereitgestellten Daten sowie auf Interoperabilitätsprobleme der verschiedenen disziplinorientierten Softwareanwendungen zurückzuführen ist. Auf der Ebene der industriellen Digitalisierung trägt diese Arbeit mit der Bestimmung der notwendigen Vereinfachung von BEM in ganzheitlichen Anwendungen zur Optimierung der Energie- und Ressourceneffizienz von Betriebsanlagen bei. Darüber hinaus wird der zukünftigen Forschung im Bereich hybrider industrieller Simulationen die wesentlichen gebäudebezogenen Informationen bei der Erstellung der digitalen Zwillingsmodelle von Gebäuden zu priorisieren geholfen. Dies ermöglicht die gewünschte Komplexität einer ganzheitlichen digitalen Repräsentation einer industriellen Anlage zu erreichen, während unnötige domänenspezifische Informationen weggelassen werden, was die Fehlerraten und die Rechenzeit solcher Modelle erhöht. Der vorgeschlagene halbautomatische Arbeitsablauf für eine BIM-basierte Erstellung des abstrahierten BEM-Modells könnte auch in einer hybriden cyber-physischen Systemsimulation verwendet werden, bei der keine typischen BEM-Tools, sondern ein Formalismus zur Spezifikation diskreter Ereignisse zum Einsatz kommen.

Contents

List of publications

Related publications to this work are listed below in chronological order. Those constituting this cumulative doctoral thesis are highlighted in bold.

Journal Articles

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Abbreviations

AEC	Architecture, Engineering and Construction
AI	Artificial Intelligence
BaMa	Balanced Manufacturing (research project)
BEM	Building Energy Modelling
BIM	Building Information Modelling
BIM-to-BEM	Building Information Modelling to Building Energy Modelling
BMS	Building Management System
CAD	Computer-aided Design
DEVS	Discrete Event System Specification
DT	Digital Twin
ERP	Enterprise Resource Planning
EU	European Union
FVM	Finite Volume Model
gbXML	Green Building Extensible Markup Language
GIS	Geographic Information Systems
IFC	Industry Foundation Classes
IPF	Industrial Production Facility
IoT	Internet of Things
HVAC	Heating, Ventilation and Air Conditioning
MPS	Manufacturing Process Simulation
MVD	Model View Definition
s-o-t-a	state-of-the-art
TABS	Thermally Activated Building Systems
TBS	Technical Building Services

Glossary

BEM

A technology as well as software tools for physics-based simulation of building performance assessment regarding energy use and indoor climate conditions.

BEM model calibration

The process through which a BEM model is adjusted based on monitoring data, to reduce uncertainties and deliver reliable simulation results.

BIM

A joint digital knowledge domain supporting activities of all stakeholders in AEC; based on various data models with geometrical and/or non-geometrical information; allowing data generation, exchange and processing within the lifecycle of built structures (Sibenik 2022).

BIM-based

Utilising BIM models to automatically extract geometrical and/or non-geometrical information that is available.

black box models

Black box models are purely data-driven probabilistic models, based on statistical data. They do not require detailed knowledge of the underlying physical phenomena, focusing on the input/output parametric values and ignoring the complex interrelationships within the unknown system (Yang et al. 2017).

"classical" simulation

A simulation process which utilises one model executed by a single simulation engine (Steinbrink et al. 2018).

co-simulation

A simulation process employing different sets of models simulated by their accompanying simulation engines, results of which are interconnected and refeed the models' parameters (Steinbrink et al. 2018).

digital twin

A virtual representation of a system (and its associated environment and processes) that is updated through the exchange of information between the physical and virtual systems (VanDerHorn and Mahadevan 2021).

digital twin ecosystem

The overall condition comprising the sensor and measurement technologies; industrial Internet of Things; simulation and modelling; and machine learning and genetic algorithms.

holistic assessment of industrial production facilities

Incorporation of all elements of an industrial production facility, including the building, the technical building services, the production process and logistics.

hybrid simulation

A simulation process during which multiple different models are executed by one simulation engine (Steinbrink et al. 2018).

white box models

White box or forward modelling approach uses detailed physics-based equations, rules and theories. Such models usually require comprehensive knowledge of the target system and are usually represented by parametric formulation (Yang et al. 2017). Due to the detailed dynamic equations in white box models, they have the potential to capture the reality dynamics well, but they are time-consuming to develop and solve (Li and Wen 2014).

Structure of the thesis

This doctoral thesis is conducted and presented as a cumulative dissertation.

Part I – **Synthesis** – introduces the problematics of industrial building modelling in BIM and BEM within the context of simulation-based assessment of complex production facilities. It includes problem statement, research question and research scope. As background of this work, a thorough analysis of the main topics of energy efficiency in industrial productions facilities (IPFs), BIM for industrial production facilities, challenges in BIM-based BEM, holistic energy modelling and simulation of IPFS, building energy retrofitting on the case of IPFs, BIM-based BEM research, DTs in manufacturing and AEC industries and the holistic DT simulation framework proposed in the BaMa research project are presented. Subsequently, the objectives of the thesis are described, followed by the research design together with the methodology used in each step of the research. The research papers are then summarised, followed finally by the contributions of this work and a future outlook in the conclusion.

Part II – Scientific peer-reviewed papers – presents the five scientific peer-reviewed research papers, as published in complete editions.

Part I

Synthesis

1 Introduction

1.1 Problem statement

Enhancement of energy efficiency in industrial production facilities (IPFs) is a core objective in the era of the fourth industrial revolution – Industry 4.0 (Mohamed et al. 2019); where the aim is a highly digitalised, networked and automated production, equipped with sensors and smart data collection processes (Oesterreich and Teuteberg 2016). The industrial sector thus holds a massive potential in developing a sustainable future and keeping the door open to the 1.5 °C goal of the Paris Agreement. Compared to most other sectors, there are substantial opportunities for energy and resource efficiency, as well as improving low emissions technologies by engaging measures such as retrofitting and digitalisation to avoid energy demand in the first place (International Energy Agency 2021). While digitalisation is pretty straight-forward in the light of Industry 4.0, retrofitting in the case of IPFs is distinguished in two types. On one hand that of “smart retrofitting”, by adding new functionalities and technological solutions in the manufacturing process and transforming legacy equipment into smart connected assets, able of interaction on the digital level (Jaspert et al. 2021). And on the other hand, the “energy retrofitting” of the so-called auxiliary components of the factory, non-value adding to the production process, namely the technical building services (TBS) and the industrial building itself. The latter expands over another large research field, where building information modelling (BIM) holds a key role in enhancing energy retrofitting by gathering, analysing and providing structured data for the energy performance assessments (Sanhudo et al. 2018). However, building energy performance optimisation of IPFs has seldom been in the focus of research, due to the large energy-consumption of industrial production processes (Heravi et al. 2015).

Significant benefits can be gained by utilising computational modelling and simulations for predicting and optimising the energy and resources efficiency of operating IPFs in both of the above-described directions of retrofitting and digitalisation. In order though to grasp full potential, two conditions must be met. First, the mathematical modelling of the relevant components consisting the system under investigation, based on physics equations, as of the so called “white box” modelling method (Li and Wen 2014). Second, an interdisciplinary approach, extending over production and logistic processes as well as the building and TBS, consolidated through integrated modelling and enabling a holistic assessment (Thiede et al. 2013). Especially within the context of digitalised IPFs and high system complexity, such a holistic simulation-based assessment can reveal synergies and optimisation potential on multiple levels, from machine to production line and up to the whole facility. Whereas, in cases of retrofitting, special attention concerning appropriate simulation tools must be given for assessing building energy and smart equipment performance respectively.

Building Energy Modelling (BEM) and Manufacturing Process Simulation (MPS) are mature simulation analysis techniques which find application in the industrial sector, for continuous time-driven and discrete aspect assessments, respectively. BEM has been mainly adopted for the analysis of building thermal performance in the residential and commercial sector, and its application in IPFs is still relatively young (Katunsky et al. 2013; Mastrapostoli et al. 2014; Bac et al. 2021). MPS is traditionally used for optimising manufacturing process lines, analysing machinery utilisation and throughput (Garwood et al. 2018a). Regarding energy assessment, commercially available BEM software tools limit their scope to a certain area, that of the building and HVAC systems (Trčka and Hensen 2010). MPS on the other hand is unable to assess interactions between manufacturing equipment and the production processes with TBS or the building (Haapala et al. 2013). For a holistic examination, as described above, capabilities of BEM and MPS must be thus combined, requiring modelling of both continuous – e.g., energy flows – and discrete aspects – e.g., production events – within complex systems. Previous research on such kind of integrated modelling and holistic simulation-based assessment of IPFs has focused on the planning of new energy-efficient facilities (Herrmann et al. 2011; Bleicher et al. 2014), on the energy savings of operating manufacturing processes (Despeissie et al. 2013), or on the optimisation of manufacturing processes operation in relation to the TBS (Hesselbach et al. 2008; Sun et al. 2016; Thiede et al. 2016). The combination of BEM and MPS in the conducted research is performed by interdisciplinary co-simulation of the separate state-of-the-art simulation tools or by MPS integration in BEM. Making one step further, the research project Balanced Manufacturing (BaMa) at the TU Wien proposed a holistic framework and an accompanying prototypical toolchain for hybrid simulation and optimisation of operating IPFs (Bleicher et al. 2018). It aims to achieve the optimum balance between reducing energy demand and greenhouse gas emissions, and economic factors, such as production time, meeting delivery deadlines and cost. The hybrid nature of the simulation lies in the fact that both continuous and discrete aspects are addressed in a single environment of interconnected digital twin (DT) components of all subsystems, forming a holistic DT ecosystem of the whole facility.

Both in the case of utilisation of state-of-the-art simulation tools and in the case of the BaMa hybrid DT-based simulation, the creation of the "white box" simulation sub-models for the holistic representation of the IPF system proves challenging. Bringing the industrial building as part of the IPF model in the spotlight, it is observed that in all conducted research the industrial building is regarded as the indoor environment where TBS (e.g., mechanical ventilation, heating) and production (e.g., waste heat, exhaust air) interact, which is particularly important when certain production conditions are crucial. However, this relatively simple functionality of the building model requires quite detailed information and involves a certain effort and knowledge for its creation, which may pose an obstacle in further industrial application. To mitigate such obstacles, the building model should be as detailed as necessary and not as detailed as possible.

Examining under this lens, with a special focus on the industrial building part, the two directions of digitisation and retrofitting for achieving energy and resource efficiency in IPFs, a research gap is identified. This gag pertains to the characteristics and qualities of the building energy model in each occasion. Given the fact that BIM is established as modelling technology in the AEC industry to process and analyse building models (Sacks et al. 2018); forming also a joint digital knowledge domain with geometrical and/or non-geometrical information of the building

(Sibenik 2022); the interconnection of BIM with industrial building energy models should be thoroughly investigated. Both in cases of simulation-based energy retrofitting of IPFs and in the case of IPFs with high level of digitisation, where implementation of holistic simulation-based frameworks as that of BaMa can take full advantage of the digital infrastructure of the facility.

1.2 Research question

This work investigates the research area of BIM-based building energy models in the field of energy-efficient industrial production facilities (IPFs) in operation and addresses the research gap of the utilisation of building energy modelling (BEM) in the holistic assessment of operating IPFs. It focuses on the role of building modelling for holistic simulation-based assessment of manufacturing facilities as complex systems with interdependencies, interactions and synergies.

The main research question (RQ) of this doctoral thesis is:

RQ: How and to which extent can BIM-based building energy modelling (BEM) be utilised in holistic simulation-based assessment of operating industrial production facilities (IPFs) towards energy-efficient optimisation?

In order to answer the main research question, the following sub-questions are investigated:

- SQ1: Which are the potentials, challenges and limitations in industrial building BIM and industrial BIM-based BEM?
- SQ2: How and to which extent can a state-of-the-art BIM-based BEM workflow be implemented within the industrial building context?
- SQ3: Which are the important BEM design parameters for simulation-based performance assessment in energy retrofitting of operating IPFs?
- SQ4: How can state-of-the-art BEM be implemented in energy retrofitting of operating IPFs for building performance optimisation, under a holistic consideration of building, building systems and production processes?
- SQ5: Which are the challenges and processes of BIM-based BEM within the novel holistic DT simulation framework for highly digitalised IPFs, integrating the building, TBS, production processes and logistics, as proposed in the BaMa research project?
- SQ6: How efficiently can the novel holistic DT simulation framework of BaMa be implemented in highly digitalised IPFs regarding BIM-based parametrisation of the DTs for the BEM representation?
- SQ7: How capable is the novel holistic DT simulation compared to the state-of-the-art BIM-based BEM workflows and tools and what is the role of the building energy model in each simulation-based approach?

1.3 Research scope

Achieving energy and resource efficiency in industrial production facilities (IPFs) is a multi-faceted problematic spreading over many engineering disciplines. Model-based simulation is a state-of-the-art methodology for assessing possibilities and reaching optimisation targets, and especially within the context of IPFs, it requires a holistic approach instead of insular optimisation of singular domains. Many challenges arise when there is a necessity to combine available technologies, such as BIM, BEM, MPS and DEVS; with process workflows, such as BIM-to-BEM, BEM with MPS and DEVS via co-simulation or hybrid simulation; among different disciplines and discipline-related peoples' views and understandings. The scope of this doctoral thesis lies in the modelling of industrial buildings within such an interdisciplinary context, setting the research boundary on what is happening inside the manufacturing facility, namely from gate-to gate. It focuses first on the occasion of building energy retrofitting of operating IPFs utilising BIM and BEM technologies and state-of-the-art processes. Second, on the occasion of highly digitalised IPFs, with facilitating the creation of the BEM representation in the holistic DT simulation framework, as proposed by the BaMa research project, by utilising BIM as a digital knowledge-database. Out of the scope of this research lie production process related modelling or assessment of the supply chain and scheduled orders, which can also extend outside the building's gates; as well as production process related retrofitting, the so-called smart retrofitting.

2 Background and State of the Art

This research is closely related to the topics of BIM for industrial production facilities (IPFs), challenges in BIM-based BEM, energy modelling and simulation of IPFs, energy retrofitting of IPFs and digital twins in the context of IPFs. In the following, the relevant topics are presented and the state of the art in the literature is discussed. Furthermore, a brief overview of the BaMa holistic DT simulation framework is provided.

2.1 BIM for industrial production facilities

Adoption of BIM is particularly beneficial for design, planning, optimisation and management of IPFs. Industrial facilities as building typology are particularly demanding in terms of design, due to the diverging interior climate requirements of various functional units (office, production, storage), regulations of vertical and horizontal circulation and accessibility (e.g., employees vs. customers) and finally interactions of various systems such as building and structural components, HVAC and machine floor layout and infrastructure. The design process requires sound validation and design review (e.g., in terms of collisions), which is enhanced through a BIM modelling approach combined with automated model checking and analysis tools (Hjelseth 2015).

Use of BIM for design and life-cycle management of industrial facilities is increasing in the practice, however due to the confidentiality and data protection there are still a very few published studies identifying the potentials and limits of BIM in industrial construction. Huang et al. (2012) identify the BIM potential for life-cycle management of industrial parks in Taiwan, underlining the advantages of combining BIM-based visualisation, GIS and IoT solutions, for successful management of industrial parks. Zhang et al. (2013) explore the possibilities of BIM in the design of IPFs from the pre-design (workshop design) till construction using Autodesk Revit Software, and .dxf interface towards a workflow-software for optimisation of production-workflows. On the concrete case study of a semiconductor facility the information between the equipment supplier and facility- and equipment-layout designer was exchanged using BIM (Chasey and Pindukuri 2012). A so-called Tool Information Model was imported in Revit MEP application (facility supply model) testing the Industrial Foundation Classes (IFC) interface; however, it was found that the IFC standard does not match the SEMI Standard (semiconductor industry standard) thus allowing the data exchange only in one way. Other researches examine the possibility of BIM for integrated factory planning of manufacturing and construction systems, revealing poor realisation in factory planning projects due to lack of maturity specifications and data management standard (Burggräf et al. 2019). Researchers at TU Dortmund develop an automated BIM-based decision support method and focus on the technical transformability of the factory building using BIM (Haymaker et al. 2018). Utilisation of BIM for optimising the energy performance of industrial buildings is hardly found in published studies, and when it is, it refers to the planning of new IPFs (Kovacic et al. 2013).

2.2 Challenges in BIM-based Building Energy Modelling

The use of BIM data for facilitating the creation of BEM models to assess building thermal and energy performance has been a topic of thorough research, both academic and industrial, barring a huge potential for building design process optimisation. BIM models, considered as knowledge databases, can contain more than 70% of the information required for a BEM analysis (Choi et al. 2016), however, BIM-based BEM still poses great challenges. These can be briefly sorted into two main fields, being the discipline-specific requirements between the BIM and BEM authoring sides, resulting in the necessity of BIM simplification for performing BEM simulations, and the interoperability issues between BIM and BEM software.

It is known that different software applications typically reflect different “views” of the same building and each must deal with issues unique to its discipline (Bazjanac and Kiviniemi 2007). These essential discipline-specific differences in the “view” of the building, with usually that of the architect creating the original BIM model not complying with that of the simulation expert further utilising the BIM model for BEM analysis, can be exceeded by following guidelines during the creation of the initial BIM model (Maile et al. 2013; Senave and Boeykens 2015). However, such an approach is difficult to implement in practice, especially in large industrial building projects where the shared BIM model is altered by various disciplines. The major challenge here lies in the geometrical representation of the building, as BEM requires a much simpler geometry than Computer-Aided Design (CAD) software. BEM implements a Finite Volume Model (FVM) of buildings and room envelopes to simulate the thermal performance of each thermal volume relative to each other and the surrounding environment of the building. The highly detailed and accurate modelling of the building is not required in BEM, as small discrepancies will not have a significantly detrimental effect on the overall building performance (Garwood et al. 2018b). BIM-originated geometry must therefore be simplified and reduced to be used for BEM, also contributing to shorter computational times in simulating complex models (Lagüela et al. 2014; Choi et al. 2016). The preparation or simplification can be done automatically to some extent, but also needs manual efforts (Ladenhauf et al. 2016; Pinheiro et al. 2018). Furthermore, insufficient construction or material information in BIM objects, not defined by the original BIM authoring side, poses another barrier for BIM-based BEM (Kim et al. 2016).

Concerning data interoperability, the two prevalent data exchange schemata for BIM-based BEM are IFC (Industry Foundation Classes) and gbXML (Green Building Extensible Markup Language), developed by BuildingSmart and Green Building Studio Inc., respectively. While IFC, being the only ISO-certified schema (ISO 16739 2016), has been developed with a wider scope for providing BIM interoperability among different domains and disciplines from building construction to building operation, gbXML is focused on the energy simulation domain, adopted by several BEM software vendors as a de facto standard for importing BIM data (Nugraha Bahar et al. 2013). Since the IFC version IFC4 add2 in July 2016 (BuildingSMART 2022), both exchange schemata can contain the necessary information for a BEM analysis as building geometry, thermal zones, construction types, and material properties, whereas only limited data related to HVAC systems (Kamel and Memari 2019). Differences lie in the fact that gbXML can only export rectangular geometry from BIM models, which is not the case for IFC, but it is the only one to provide information on the location of the building (Kamel and Memari 2019). Further on, geometry in gbXML is defined utilising centreline representation (Pinheiro et al. 2018), while IFC is capable of exporting 2nd-level space boundaries by employing standardised Model View Definitions (MVDs), which specify how each object or information should be represented for a particular, discipline-specific view (Venugopal et al. 2012). The first can lead gbXML-generated BEM to an increased zone volume and a potential overestimation of the resulting energy consumption (Bazhanac et al. 2016), however, 2nd-level space boundary data in IFC are often missing or incorrect, hindering the BEM creation process with manual corrections or requiring specific algorithms to produce valid data (Lilis et al. 2017).

Regardless of the selected schema, information loss during data exchange from BIM to BEM is a frequently reported problem (El Asmi et al. 2015; Sanhudo et al. 2018; Gao et al. 2019; Kamel and Memari 2019). Kamel and Memari (2019) divide the causes of interoperability issues into four categories where: a) the BIM software may not transfer all the required information in the exchange file, e.g. the IFC exporter of Revit (version 2018) is not exporting information about thermal and optical properties of construction materials, although IFC can incorporate them (Lilis et al. 2018); b) the exchange file may not be able to save all the information properly, e.g. building location, HVAC properties, building usage; c) the BEM software may not be able to read all the information in the data exchange file; d) information may not be mapped and transferred properly to the BEM and energy simulations engine's file format.

2.3 Holistic energy modelling and simulation of industrial production facilities

Assessing and optimising IPFs from an energy use perspective is more challenging than buildings in the residential and tertiary sector, as internal heat gains from manufacturing activities can have a significant impact on the indoor conditions and their scheduling can vary greatly over time, given production demand and economic cycles (Liu et al. 2013). Production-related internal gains can be assumed based on installed equipment or directly measured in the case of an operating facility, with the first potentially leading to disputable results and the second being restrictive to existing production configurations. Brinks et al. (2016) criticise the fact that only default values are considered when planning new IPFs (e.g., 40 W/m² for all production buildings in Germany) and actual level of internal gains should be examined for defining an optimum building envelope. In any case, when employing BEM software, thus "classical" simulation tools, simplistic operating schedules defining maximum loads (Moynnihan et al. 2012; Lee et al. 2014) can be considered within the software environment of BEM, as current software cannot accurately incorporate industrial processes (Wright et al. 2013).

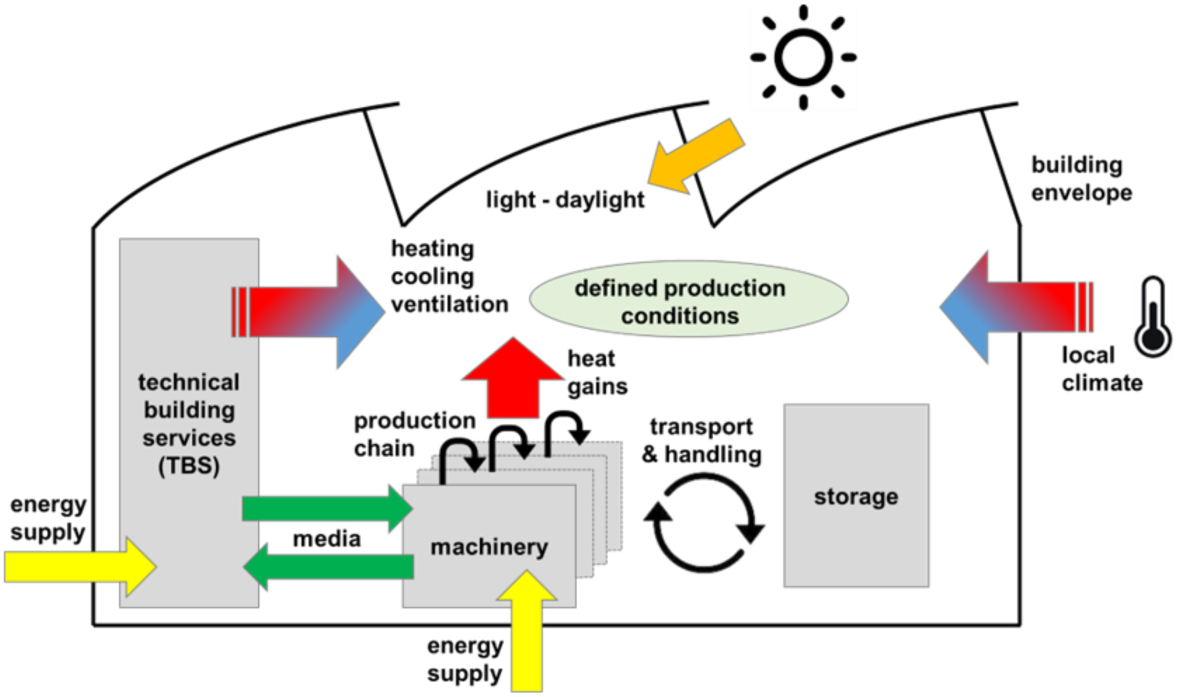

Figure 1. Energy flows and interaction of subsystems within a factory.

During the last decade, a new simulation paradigm evolved for the simulation of energy flows in manufacturing systems, aiming at the coupling of different simulation models (Herrmann et al. 2011). The goal of these so-called coupled or holistic simulation approaches is the integrated analysis of multiple systems or subsystems and their interrelations (Sweafford and Yoon 2013; Brecher et al. 2009). Hesselbach et al. (2008) were one of the first to point out that the complex and dynamic interdependencies of machines and production processes, operational management, technical building services (TBS), and the building climate could only be analysed via a holistic view of the facility. Figure 1 gives a schematic representation of the complex and dynamic interdependencies. According to Duflou et al. (2012) a holistic understanding of the different levels of manufacturing processes, from unit-processing and multi-machine levels to factory level or even further on multi-factory and supply-chain level are essential for developing the next generation of manufacturing facilities. Coupling of BEM capabilities with manufacturing process simulation (MPS), generally used for optimising manufacturing process line and plant's throughput, offers such a solution, up to the whole factory level. Garwood et al. (2018a) produced a comprehensive review of energy simulation tools and methods for the manufacturing sector, focusing on the combination of BEM with MPS. They categorise holistic approaches into two types, co-simulation and hybrid simulation solutions. Co-simulation uses a state-of-the-art software platform for each discipline and couples them to share data between simulation iterations. The hybrid simulation uses a single solver platform capable of modelling all entities, flows, and interdependencies, achieving a maximum level of interaction between various processes. This level of high interaction between systems may not be achieved by a compartmentalised co-simulation solution, as information, e.g., about internal heat gains, can be only unidirectional from one software to another (MPS to BEM) and is not modelled in a bidirectional manner among different facility subsystems, being the case in coupling Simulink/MATLAB with EnergyPlus (Brundage et al. 2014).

Literature review shows that holistic simulation solutions may not be suitable for small or medium-sized enterprises, as these usually require considerable effort in the modelling process, and in the case of simpler systems' energy metering, energy and resource flows visualisation and evaluation via static numerical calculations would be more appropriate (Thiede et al. 2013, Trianni et al. 2013). For more complex systems and large automated production lines, holistic simulations can reveal synergies and optimisation potential on multiple levels, from machine to production line and the whole factory. Furthermore, they are mostly utilised in the planning of new IPFs, where numerous data are available from all planners for the creation of for the creation of comprehensive simulation models (Kovacic et al. 2013). In operating IPFs, the collection of required data can prove quite challenging.

2.4 Building energy retrofitting: the case of industrial buildings

Conducted energy retrofit studies have mainly focused on buildings of the residential (De Boeck et al. 2015) and tertiary sector (Ruparathna et al. 2016); fields where researchers have achieved significant advancements in developing models and frameworks for identifying the most effective thermal building envelope refurbishment and systems upgrade options. Sophisticated tools have been proposed for thermal optimisation and refurbishment of office and commercial buildings. Based on standardised data for such building types, benchmarking values and pre-simulated results, a web-based toolkit enables fast calculation of retrofit alternatives and evaluation of multi-criteria parameters like energy and costs savings (Hong et al. 2015), while another software solution provides information based on a matrix of retrofit measures and economic uncertainty scenarios (Hillebrand et al. 2014). Industrial facilities, on the other hand, are seldom studied under an energy retrofit perspective (Trianni et al. 2014), with efforts focusing on thermal envelope, when structural upgrades are compulsory (Katunská et al. 2014); or on installed technical building services, when these are identified as inefficient, e.g., heating (Chinese et al. 2011), ventilation (Caputo and Pelagagge 2009); while rarely on both (Ascione et al. 2020). Industrial heritage has also been studied under an energy retrofit perspective, however mostly concerning ex-industrial facilities and their transformation to other uses as housing (Valančius et al. 2015), mixed-use developments (Becchio et al. 2016) or event locations with zero carbon emissions targets (Opher et al. 2021).

State-of-the-art approach in building refurbishment requires detailed monitoring and in-situ investigation of the pre-renovation state in order to calibrate the simulation models (Pisello et al. 2012; Ascione et al. 2020) and so enable reliable evaluation of different retrofit alternatives, related to envelope thermal properties (Aste et al. 2015). As regards industrial buildings, large-scale building monitoring and measurements necessitate special equipment, resulting in important investments (Pernetti et al. 2014). Data unavailability is also enhanced by the fact that many companies do not track their energy consumption, thus lacking awareness of their energy needs on individual systems (O'Rielly and Jeswiet 2015). Consequently, the high complexity in terms of energy supply and consumption as well as diverse building typology of industrial facilities makes it difficult to define benchmarks for energy performance comparison.

Even with calibrated building energy models, predicting energy savings with simulation tools has received critique as in many occasions fails to integrate the role of occupants' behaviour as an imponderable factor on the end energy performance (Li et al. 2015; Mahdavi et al. 2015; Jami et al. 2021). It can be presumed that in IPFs equipment and machinery are a substitute for this uncertainty factor, as according to Vaghefi (2015) industrial loads are often massive, non-stationary with random fluctuation over time, while thermally contributing to the indoor climate. A parametric simulation study about the impact of process loads and occupancy patterns on annual energy demand of a simple hypothetical industrial building observed that the optimum building envelope can differ according to manufacturing conditions, with actual heat emissions, air change rates and daylighting controls having a great influence on the energy performance (Lee et al. 2014). Furthermore, on the case of an existing industrial hall in Slovakia, analysis of thermal energy demand and saving potential via measurements, static calculations and dynamic simulations also showed that real interior gains from machinery are crucial for realistic modelling of the building (Katunsky et al. 2013).

Limited studies regarding building energy retrofitting in industrial buildings were identified during this research. A European research project, including studies on renovation strategies of existing industrial buildings using steel-based technologies, employed thermal simulations and experimental "before and after" measurements (e.g., air tightness tests, wall thermography) to derive empirical relationships for the energy demands of industrial facilities (Lawson et al. 2013). Mastrapostoli et al. (2014) also pinpointed significance of the roof as cool roof coating essentially decreased summer cooling loads by 73% with a minor heating penalty for an industrial building in the Netherlands. Chen et al. (2014) implemented in-field measurements and simulation models on a single floor factory with a hackle-shape roof in China, where daylighting control showed large energy savings in electrical lighting consumption. Wang et al. (2013) in the case of a large workshop with skylights, also in China, developed a solution for lighting control based on a sensor network, realising lighting energy savings of up to an average of 80% on cloudy days. Furthermore, for a light steel structure industrial shed in the UK, complying with local building regulations, researchers studied the influence on energy performance and space overheating when introducing skylights and proposed that unwanted summer solar gains could be remedied by the application of ridge natural ventilation (Wang et al. 2014). In case studies under hot-humid climate conditions, the potential of passive cooling strategies to improve thermal comfort conditions of workers was addressed in Colombia (Alba et al. 2013), and poor thermal performance was observed in a garment factory with low-quality building envelope in Bangladesh (Chowdhury et al. 2015). Ascione et al. (2020) investigated multiple solutions for the energy retrofit of the building envelope and the HVAC systems with a calibrated model of an existing industrial building in southern Italy, focusing mainly on the HVAC upgrade of the mechanically ventilated office areas, combined with window retrofit and solar control systems.

Finally, the potential of BIM use in building energy retrofitting has been reviewed by Gholami et al. (2013) and Sanhudo et al. (2018). Authors state that BIM should be applied from the early stages of a project and that it can assist environmental performance analysis of design alternatives; however, a solid framework about the process is lacking.

2.5 Digital twins in manufacturing and AEC industries

The original concept of a Digital Twin (DT) was introduced by Grieves in 2003 on product life-cycle management in the field of manufacturing engineering (Grieves 2014). Since then, it has grown across various industries and it has been given a variety of definitions and characterisations. A generalised and consolidated definition, avoiding industry-specific characteristics was recently provided by VanDerHorn and Mahadevan (2021), where a DT is “a virtual representation of a physical system (and its associated environment and processes) that is updated through the exchange of information between the physical and virtual systems”. This virtual representation is an idealised form of the physical reality, based on the interpretation of the data collected from the physical world, considering a certain level of abstraction imposed by the scope of the created model. The primary motivation for the use of a DT is the monitoring of the system of interest as it changes over time. The DT virtual representation describes a single instance of the physical system and is updated at frequent intervals (VanDerHorn and Mahadevan 2021).

Manufacturing-related DT research is mainly focusing on products’ design and lifecycle (Tao et al. 2018; Lo et al. 2021), production lines and machinery, (Cimino et al. 2019), predictive maintenance (Aivaliotis et al. 2019), and equipment energy consumption management (Zhang et al. 2018). Applications of DTs also considering the auxiliary components of a factory are less common, such as the study by Blume et al. (2020) on DTs for TBS operation in factories, on a case study of a cooling tower. Manufacturing-related DTs are usually high-fidelity virtual representations of systems and processes and are monitored in real-time, with DT update frequencies in the scale of seconds or less. Furthermore, they generally focus on the low field level of the automation pyramid, (Martinez et al. 2021), that of sensors and actuators for collecting production data and executing commands (ANSI/ISA-95 2018).

DTs in the AEC industry are up-to-date dynamic models of a physical asset or a facility, including all structured and unstructured information of the project used to model, simulate, understand, predict and optimise aspects of the physical asset (Alizadehsalehi and Yitmen 2021). BIM as a digital platform is directly related to the implantation of DTs in the AEC, as the latter evolve from detailed BIM models by integrating simulations, real-time monitoring, and AI. As in product design applications, DTs in the AEC can be utilised before the physical system really exists. In the design phase, they can create a solution and virtually and accurately assess its operation (Deng et al. 2021). In the build phase, DTs can provide the construction specifications to the different providers and enhance the procurement process (Shirowzhanet al. 2020). Finally, in the operation phase, when the physical asset is equipped with enough sensors, backed by AI, they provide predictive maintenance and performance optimisation by enabling the system to automatically modify its operation or indicate the need for human intervention (Boje et al. 2020).

It should be noted, that in the case of DTs referring to the built environment, the physical system of interest is usually a whole construction project, building, or even part of a city, with various aspects and interconnections to be considered. Unlike manufacturing DTs, where the model may consist of a single machine or production line (modelled in detail as a system together with its environment influences), AEC DTs are usually extensive and detailed virtual representations of the physical reality, resulting in very high levels of model fidelity. However, a DT is not destined to be an exact representation of reality, as the level of model detail directly relates to the level of abstraction of reality chosen for the virtual representation, defined by the scope and required outcomes of the particular use case (VanDerHorn and Mahadevan 2021). Considering this position, a building DT can also be outlined by a greater abstraction level, if this complies with the intended use of the model.

BIM-based DTs in an industrial context have been studied principally in terms of a detailed geometric representation of existing facilities, linked with a navigation framework supporting human and robot movements (Delbrügger et al. 2017), or real geometric configuration of the DT regarding complicated shapes (Agapaki and Brilakis 2022). No research regarding BEM as well as energy and thermal performance of an industrial building assessed via BIM-based DTs is known to the authors.

2.6 Research project BaMa – Balanced Manufacturing

The research presented within this cumulative dissertation was conducted and builds upon the flagship research project "Balanced Manufacturing" – BaMa, funded by the Austrian Climate and Energy Funds – program e!MISSION.at – through the Austrian Research Promotion Agency (FFG, grant number: 840746). The research project was conducted together with other 5 scientific project partners from TU Wien (Institute of Production Engineering and Laser Technology - IFT, Institute for Energy Systems and Thermodynamics - IET, Institute for Computer Aided Automation - ASG, Institute for Management Science – IMW, research Tub GmbH), 6 industrial project partners (GW St. Pölten Integrative GmbH, Berndorf band GmbH, Infineon Technologies Austria AG, Franz Hass Waffel- und Keksanlagen-Industrie GmbH, Metall- und Kunststoffwaren Erzeugungs-gesellschaft mbH, MPREIS Warenvertiebs GmbH) and also 6 development partners (AutomationX GmbH, Siemens AG Österreich, ATP Sustain GmbH, Daubner Consulting GmbH, dwh GmbH, Wien Energie GmbH).

Within BaMa a DT framework for a software architecture and also a prototypical toolchain were proposed, enabling large IPFs to integrate energy-related planning into the actual plant operation. A holistic approach addressing all subsystems of a facility (production process, logistics, TBS, and the building itself) was chosen, considering both ecological and economic aspects as optimisation targets. The DT simulation-based framework enables monitoring, predicting, and optimising energy demand and the associated carbon emissions as well as costs, to be linked to the existing industrial automation systems of the facility. BaMa, therefore, does not just assess the optimisation potential of designed or existing production but introduces energy efficiency as a steering value into a factory's operational planning and can be utilised iteratively, like an advanced planning and scheduling system would support a cost and/or time efficient production process (Chryssolouris 1992). The novelty of the BaMa framework lies in the fact that it addresses existing operation facilities and utilises a holistic hybrid simulation approach with discrete and continuous models solved simultaneously in a single solver platform. These form a holistic DT ecosystem of all factory subsystems, which are continually updated by monitoring data for a simulation-based optimisation.

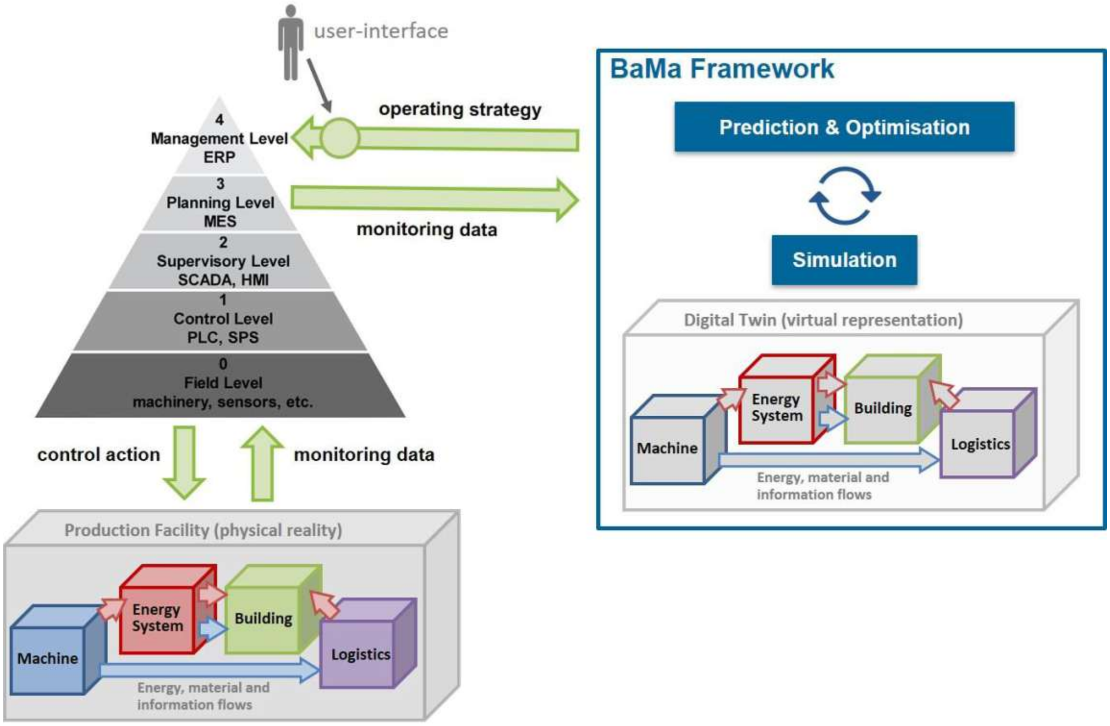

Figure 2. Schematic representation of the BaMa framework's components and interconnectivity (adapted from Bleicher et al. 2018)

The BaMa holistic DT ecosystem consists of three main parts: constant monitoring, simulation-based predictions, and multicriteria genetic algorithmic (GA) optimisation. Figure 2 shows a schematic representation of the system's components and interconnectivity. BaMa acquires real-time data from various sensors attached to the production process and the building technical systems, referring to the logistic flows and storage, as well as monitoring the space's indoor conditions or outdoor weather data. It reports back on the planning and management levels. However, offline data collection is also relevant, including physical inspections and changes regarding the physical relations of the modelled subsystems (e.g., machinery is removed from a certain space or a big hall is structurally and thermally divided into smaller ones). Prediction of the energy and resources demand, performed by the hybrid simulation, is based on the real-time monitoring data from the four subsystems comprising a factory-production equipment and processes, logistics, TBS, and the building-extended by day-ahead production plans and forecasting data (e.g., weather information).

The optimisation of the plant operation via a GA regards the targets of energy, time, and costs as well as restrictions resulting from given degrees of freedom, resource availability, and product quality. The GA aims especially in minimising energy demand with the utilisation of synergies, peak load management, and efficient use of available equipment (Sobottka et al. 2017). Its prototypical deployment in an operating industrial baking facility indicated a reduction of the overall energy consumption by up to 30% (Sihn et al. 2018).

BaMa implements a generic modular approach to create a facility's DT and models a unified virtual representation of all four factory subsystems in a single solver platform, aiming for the flexibility and reusability of the modular models for a variety of industrial facility types. The core modular element of BaMa DT is the *cube*. Cubes are the components of the DT, represent physical parts of the facility, and are mapped into mathematically formulated virtual counterparts in the DT. They decompose the overall physical system into manageable elements with well-defined interfaces at a chosen level of abstraction and are assembled each time in virtual constellations representing a unique plant, enabling the analysis of complex and heterogeneous processes. From a top-down view, cubes can be considered as black box models of e.g., a machine, a room, or a piping grid, arranged hierarchically, meaning that a cube can be contained in another cube, without the first being aware of the modelling processes and calculations of the second "inside" him. The level of abstraction of each cube must correspond to the intended use of the resulting model. The data abstraction process requires thus a detailed observation and understating of the reality and a further interpretation process of the data which will consist of the idealised virtual representation, providing the relevant evidence about the reality. The resulting cube models have interfaces consisting of three distinct types of data exchange: energy flow, material flow, and information flow. Energy flows are described by continuous values that require a time-driven modelling approach, whereas material and product flows are discrete entities demanding event-driven modelling. Both carry related carbon emissions and cost weights for assessing the ecological and economic performance of the production. Lastly, information flows can exchange various information needed for the internal calculations of a cube. The process of determining the modular parts from which the whole facility consists, as well as their interrelationships, is defined inside BaMa as *cubing*. For example, cubing is performed to analyse a production line in all its stages as well as for defining the thermal view of the building envelope. Data of the relevant physical system, parameters outside the selected physical system that affect it, and also its interconnections to other physical systems, are collected, interpreted, and stored in the virtual representation. A detailed description of the BaMa methodology is available in Leobner et al. (2015) and Leobner (2016).

BaMa cubes are divided into four classes, namely, "machines and production process", "building", "energy system and TBS" and "logistics", which include different generic cube types aiming to be able to model all the functions within the factory. Detailed descriptions of all cube models are available in Raich et al. (2016), Smolek et al. (2017), Smolek et al. (2018) and Bleicher et al. (2018).

3 Objectives

The objective of this doctoral thesis is to investigate the creation and utilisation of building energy models for operating industrial production facilities (IPFs); employing BIM as a knowledge-database and under the lens of a holistic assessment of the whole facility. The general goal is to assist existing IPFs achieve energy and resource efficiency, in both directions of energy retrofitting and digitalisation. Focusing on the role of the industrial building within the whole system of an IPF, the main objective can be broken down into the following four sub-objectives:

1. State-of-the-art analysis of available technology and processes for BIM-based BEM and attempt of a novel application in the field of IPFs.
2. Regarding energy retrofitting: Novel BIM-based BEM implementation for energy retrofitting of operating IPFs and definition of design parameters for BEM; with state-of-the-art tools and methods for building performance assessment and optimisation; and under a holistic consideration of the production process along the TBS and the building.
3. Concerning digitalisation: Facilitation of a BIM-based creation of the BEM representation in the novel BaMa holistic digital twin (DT) simulation framework; with definition of design parameters for BEM in the DT ecosystem as well as the BIM level of abstraction; and by proposing and testing an as automated as possible workflow.
4. Comparison of capabilities and limitations of the BEM approaches in the two directions for improving energy and resource efficiency in IPFs.

The listed objectives are addressed through the following scientific peer-reviewed papers, respectively:

1. Paper 1 – P1: “Building Information Modelling for analysis of energy efficient industrial buildings–A case study”, Renewable and Sustainable Energy Reviews, Volume 68 (2017), Georgios Gourlis and Iva Kovacic
2. Paper 2 – P2: “A study on building performance analysis for energy retrofit of existing industrial facilities”, Applied Energy, Volume 184 (2016), Georgios Gourlis and Iva Kovacic

   and

   Paper 3 – P3: “Passive measures for preventing summer overheating in industrial buildings under consideration of varying manufacturing process loads”, Energy, Volume 137 (2017), Georgios Gourlis and Iva Kovacic
3. Paper 4 – P4: “A holistic digital twin simulation framework for industrial facilities: BIM-based data acquisition for building energy modeling”, Frontiers in Built Environment, Volume 8 (2022), Georgios Gourlis and Iva Kovacic
4. Paper 5 – P5: “Energy efficient operation of industrial facilities: the role of the building in simulation-based optimisation”, IOP Conference Series: Earth and Environmental Science, Volume 410/1 (2020), Georgios Gourlis and Iva Kovacic

4 Research Design and Methodology

4.1 Research design

This doctoral thesis is conceptualised with the aim to answer the main research question (RQ):

How and to which extent can BIM-based building energy modelling (BEM) be utilised in holistic simulation-based assessment of operating industrial production facilities (IPF) towards energy-efficient optimisation?

By breaking down the main research question into the different research fields constituting it, the following areas are identified:

- BIM for IPFs
- BEM for IPFs
- BIM-based BEM
- Building energy retrofitting
- Holistic simulation-based assessment of IPFs
- Digital twins in manufacturing and AEC industries

Regarding energy-efficient optimisation of operating IPFs, this doctoral thesis focuses on the two main directions of achieving this goal, namely energy retrofitting and digitalisation. However, the interrelations of all the above research areas in the course of this work are highlighted by the sub-questions following the main research question, as of section 1.2.

The first question, SQ1, involves the areas of BIM for IPFs and BIM-based BEM:

> *Which are the potentials, challenges and limitations in industrial building BIM and industrial BIM-based BEM?* This is addressed in Paper 1 and partially in Paper 4.

The second question, SQ2, involves the areas of BIM-based BEM and BEM for IPFs:

> *How and to which extent can a state-of-the-art BIM-based BEM workflow be implemented within the industrial building context?* This is addressed in Paper 1.

The third question, SQ3, involves the areas of BEM for IPFs, building energy retrofitting and holistic simulation-based assessment of IPFs:

> *Which are the important BEM design parameters for simulation-based performance assessment in energy retrofitting of operating IPFs?* This is addressed in Paper 2.

The fourth question, SQ4, also involves the areas of BEM for IPFs, building energy retrofitting and holistic simulation-based assessment of IPFs:

> *How can state-of-the-art BEM be implemented in energy retrofitting of operating IPFs for building performance optimisation, under a holistic consideration of building, building systems and production processes?* This is addressed in Papers 2 and 3.

The fifth question, SQ5, involves the areas of DTs, BIM-based BEM and holistic simulation-based assessment of IPFs:

> *Which are the challenges and processes of BIM-based BEM within the novel holistic DT simulation framework for IPFs, integrating the building, TBS, production processes and logistics, as proposed in the BaMa research project?* This is addressed in Paper 4.

The sixth question, SQ6, also involves the areas of DTs, BIM-based BEM and holistic simulation-based assessment of IPFs:

> *How efficiently can the novel holistic DT simulation framework of BaMa be implemented in highly digitalised IPFs regarding BIM-based parametrisation of the DTs for the BEM representation?* This is addressed in Paper 4.

The last question, SQ7, involves the areas of BIM-based BEM, BEM for IPFs, building energy retrofitting and holistic simulation-based assessment of operating IPFs:

> *How capable is the novel holistic DT simulation compared to the state-of-the-art BIM-based BEM workflows and tools, and what is the role of the building energy model in each simulation-based approach?* This is addressed in Paper 5.

Figure 3 provides an overview on the structure of the conducted research, aiming to answer all the research questions, as described above. The corresponding papers to each part of the research are also marked.

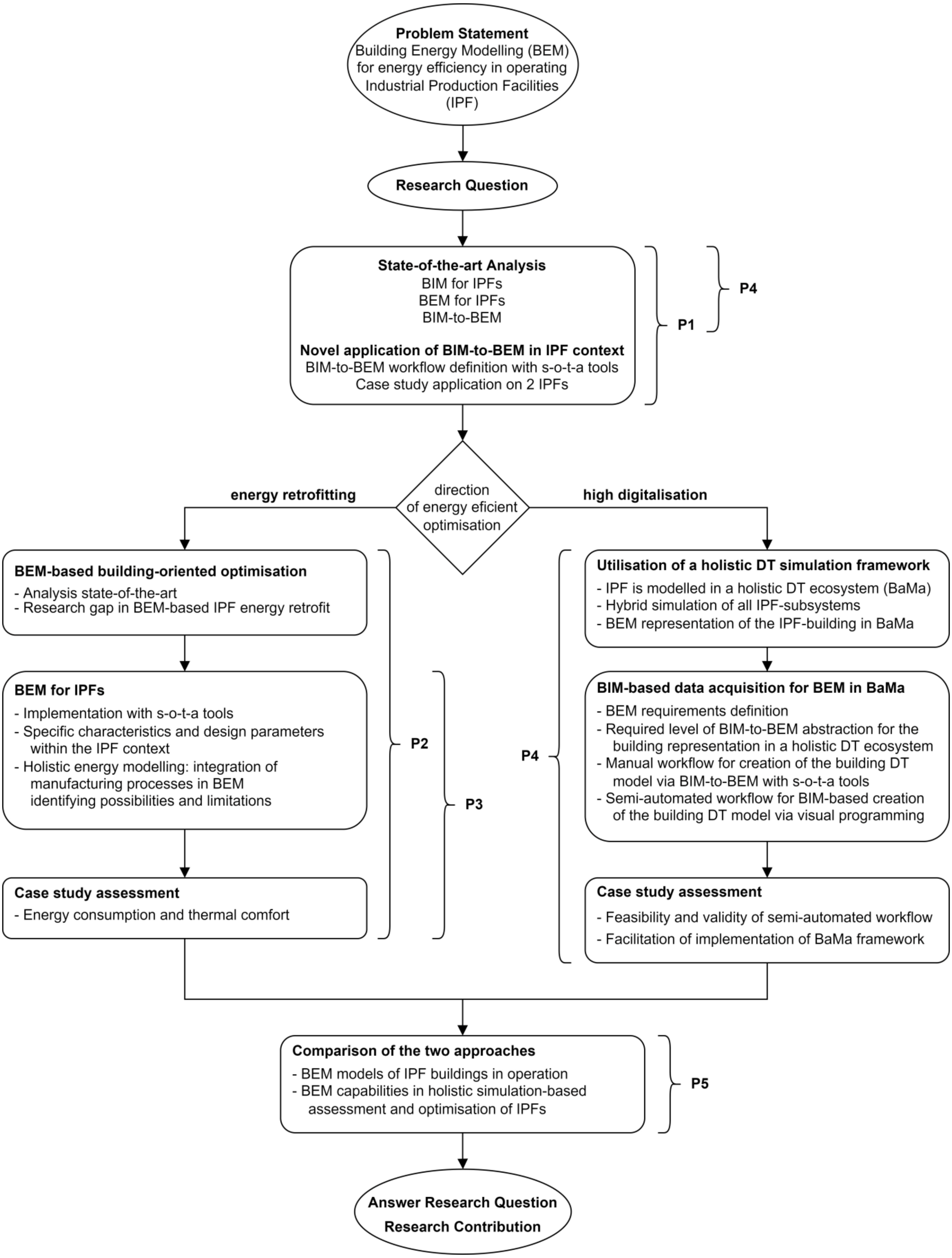

Figure 3. Research Diagram

4.2 Methodology

The developed and implemented methodological steps as well as their expected outcomes are summarised in Table 1.

Table 1. Research Methodology

Methodological Steps	Expected outcome
Analysis: BIM for IPFs, BIM-to-BEM	State of the art and limitations are identified.
Workflow definition: BIM-to-BEM for IPFs	BIM-to-BEM workflow based on available technology is defined and tested in IPFs case studies.
BEM implementation with focus on energy retrofitting: BIM-based BEM for energy retrofit of IPF with a holistic simulation-based approach	Characteristics of BEM for IPFs are defined; BEM implementation in an IPF case study with s-o-t-a tools and methods; integration of production process influence in BEM for optimum retrofit decisions.
BEM definition and workflow implementation with focus on digitalisation: BIM-based BEM for highly digitalised IPFs within a holistic DT simulation framework (BaMa)	Characteristics of BEM in the BaMa DT ecosystem are defined; BIM level of abstraction is defined and a semi-automated BIM-to-BEM for BaMa workflow is proposed; proof-of-concept for the proposed workflow in conducted on an IPF case study.
Comparison: BEM characteristics of the two simulation-based approaches	Capabilities and limitations of each BEM approach and its suitability for energy efficiency optimisation of IPFs.

All the above-described methodological steps have been successfully implemented and described in the research papers.

A detailed description of all methodological steps can be found in the corresponding papers. The overview of the methodology and methodological steps, each performed with a suitable combination of methods, are presented in the following subsections.

4.2.1 Analysis

Analysis of the BIM adoption in IPFs, BIM-to-BEM interoperability with available technologies and processes, and BEM implementation for building energy retrofitting is performed though extensive literature review as well as software theory critical reading combined with trial-and-error application tests with available software constellations. Uncertainties in building energy modelling are identified categorised as linguistic uncertainties – vagueness, ambiguity and under specify (Asxough et al. 2008), knowledge uncertainties – model inputs and parameters, model structure, model technical quality, model output (Harremoës et al. 1999), and process uncertainties – communication, available time, resources (Morgan et al. 1990).

4.2.2 BIM-to-BEM workflow definition

This research step, building upon the previous analysis, defines a workflow for BIM-to-BEM based on available state-of-the-art tools. Software utilised in the modelling process include on the BIM side Autodesk REVIT for architecture and technical building services (TBS); and EnergyPlus via SketchUp and OpenStudio Plug-in for BEM. BIM data are exported by the gbXML format. The BIM-to-BEM workflow is shown in Figure 4. A case study application on two IPFs in Austria is conducted, while observing and recording the modelling and data transfer process from BIM-to-BEM using so-called mistake trees. The case studies involve two types of IPFs. On one hand, a partially historical metal-cutting and forming production facility, with numerous additions dating from varying periods, for which an own BIM model was created based on the existing documentation and then transferred to BEM. And on the other, a new construction of a food industry consisting of two blocks, for which an already modelled BIM architectural and TBS model was obtained from an architecture and engineering company.

Figure 4. BIM-to-BEM workflow with state-of-the-art tools

4.2.3 BIM-based BEM implementation with focus on energy retrofitting

Focusing on the first case study of the old IPF, the BIM-based BEM model is employed for assessing the improvement potential on energy demand and indoor climate in case of energy retrofitting an operating IPF. Dynamic thermal simulation with EnergyPlus, a validated whole building performance simulation software developed by DoE (Crawley et al. 2008), based on a typical meteoritical year is implemented, integrating production process and TBS operation, based on energy consumption measurements on production machinery and air compressors over a period of a month. Due to the order-based manufacture procedure (production on demand – per order), production cycles and operation schedules are constantly changing, as there are also layoff periods for some machines. The goal of the measurement was to gain insight into operating patterns, serving as input for the BEM simulation, and size the amount of waste heat that is emitted into the hall. Having then a BEM model with an integrated impact of the production processes on the indoor climate of the building (in terms of a holistic assessment of the IPF), the energy consumption of the facility including heating demand, lighting, machinery and electric equipment is hourly calculated and aggregated on annual level. Thermal performance regarding summer overheating is evaluated under the adaptive comfort approach of the European standard EN 15251, as there is no active cooling in the facility. For further assessing passive cooling strategies with natural ventilation and building envelope retrofits, the BEM model is calibrated. An evidence-based iterative BEM model calibration process, through indoor air temperature monitoring in multiple control thermal zones is used to adjust the simulation outcome to the measured data (Raftery et al. 2011). Regarding thermal comfort of the employees, a significant parallel goal of the energy retrofitting, the summer overheating problematic is evaluated according to two methods. The multilevel adaptive approach of CIBSE TM52 for occupants’ expectations of a category III existing building (CIBSE TM 52 2013), as well as, the condition that mean hourly air temperature in the hall should not exceed 26 °C during work hours, derived as a relative mean value of European workplace regulations on occupational safety and health.

4.2.4 BIM-based BEM definition and workflow implementation with focus on digitalisation

Focusing on the second case study of the new IPF, where the BaMa framework for a holistic DT ecosystem (s. section 2.4) is applied, a BIM-based workflow for the BEM representation as part of the DT ecosystem is defined and implemented. The potential of utilising visual programming for extracting information from BIM models to the building-related part of the hybrid simulation to form the building DT is explored. The utilisation of a common data exchange schema for BIM-to-BEM interoperability, described in section 2.2, is not selected, as the data structure of such schemata is incompatible with the building representation of a DT with a high level of abstraction compared to that of traditional BIM-based DTs. The abstracted DT of the building maintains the spatial relations with the production and logistic processes as well as an appropriate BEM representation by extracting information from a BIM model, functioning as a knowledge database. Building-related data exchange requirements are defined and a semi-automated data acquisition workflow is proposed, building upon previous work by the author in the research project BaMa for a manual information workflow from BIM to the holistic DT ecosystem (Gourlis et al. 2017). A workflow linking BIM models with the hybrid simulation models of the BaMa DT ecosystem via visual programming is proposed and subsequently, a comparative case study is employed as a testbed for its evaluation, acting as a proof-of-concept. The proposed semi-automated BIM-based workflow for the creation of the BEM representation in the of the building in the holistic DT ecosystem is tested for its feasibility and reliability against the manual workflow. Data consistency and correlation as well as implementation times of both workflows are assessed.

4.2.5 Comparison of BEM simulation approaches for industrial production facilities

The two presented BEM simulation approaches are compared in terms of their applicability on operating IPFs; and their energy modelling capabilities and limitations in reference to the building as well as to the rest substantial parts consisting an IPF, namely the production process, the logistics and the TBS.

5 Results

The research conducted as part of the doctoral thesis is documented in five scientific peer-reviewed papers and is structured as follows:

The first paper – *Paper 1*, elaborates on the thematic of **Building Information Modelling (BIM) and Building Energy Modelling (BEM) for industrial production facilities** (IPFs) and presents a state-of-the-art review and the BIM-to-BEM workflow definition and application for the case studies of two IPFs, elaborating on potentials and challenges. The second and the third papers – *Paper 2* and *Paper 3*, present a **BEM-based simulation assessment of operating IPFs focusing on energy retrofitting**. They investigate the implementation of a BIM-based BEM in a case study of an older IPF (the first case study of Paper 1), integrating production processes and technical building services (TBS); and exploring energy savings and thermal comfort optimisation of retrofitting strategies. The fourth paper – *Paper 4*, explores the **BIM-based creation of the BEM model, as part of a holistic digital twin (DT) simulation framework for operating IPFs, focusing on digitalisation.** It defines the required level of abstraction for the BEM representation of the industrial building in the holistic DT ecosystem and proposes a semi-automated BIM-based data acquisition workflow for the BEM model creation via visual programming. A proof-of-concept application of the semi-automated workflow is conducted on a case study of a highly digitalised IPF (the second case study of Paper 1). The fifth paper – *Paper 5*, presents a **comparison of the two approaches for BEM in simulation-based assessment of operating IPFs**, in terms of energy modelling capabilities and limitations, while illustrating the role of building modelling in the two directions towards energy and resource efficiency of IPFs, energy retrofitting and digitalisation.

Paper 1 - P1	“Building Information Modelling for analysis of energy efficient industrial buildings–A case study”, *Renewable and Sustainable Energy Reviews*, Volume 68 (2), Georgios Gourlis and Iva Kovacic, 2017.
Paper 2 - P2	“A study on building performance analysis for energy retrofit of existing industrial facilities”, *Applied Energy*, Volume 184, Georgios Gourlis and Iva Kovacic, 2016.
Paper 3 - P3	“Passive measures for preventing summer overheating in industrial buildings under consideration of varying manufacturing process loads”, *Energy*, Volume 134, Georgios Gourlis and Iva Kovacic, 2017.
Paper 4 - P4	“A holistic digital twin simulation framework for industrial facilities: BIM-based data acquisition for building energy modeling”, *Frontiers in Built Environment,* Volume 8, Georgios Gourlis and Iva Kovacic, 2022.
Paper 5 - P5	“Energy efficient operation of industrial facilities: the role of the building in simulation-based optimization”, *IOP Conference Series: Earth and Environmental Science,* Volume 410, Georgios Gourlis and Iva Kovacic, 2020.

The focus areas and associated research papers of this thesis are presented in Figure 5.

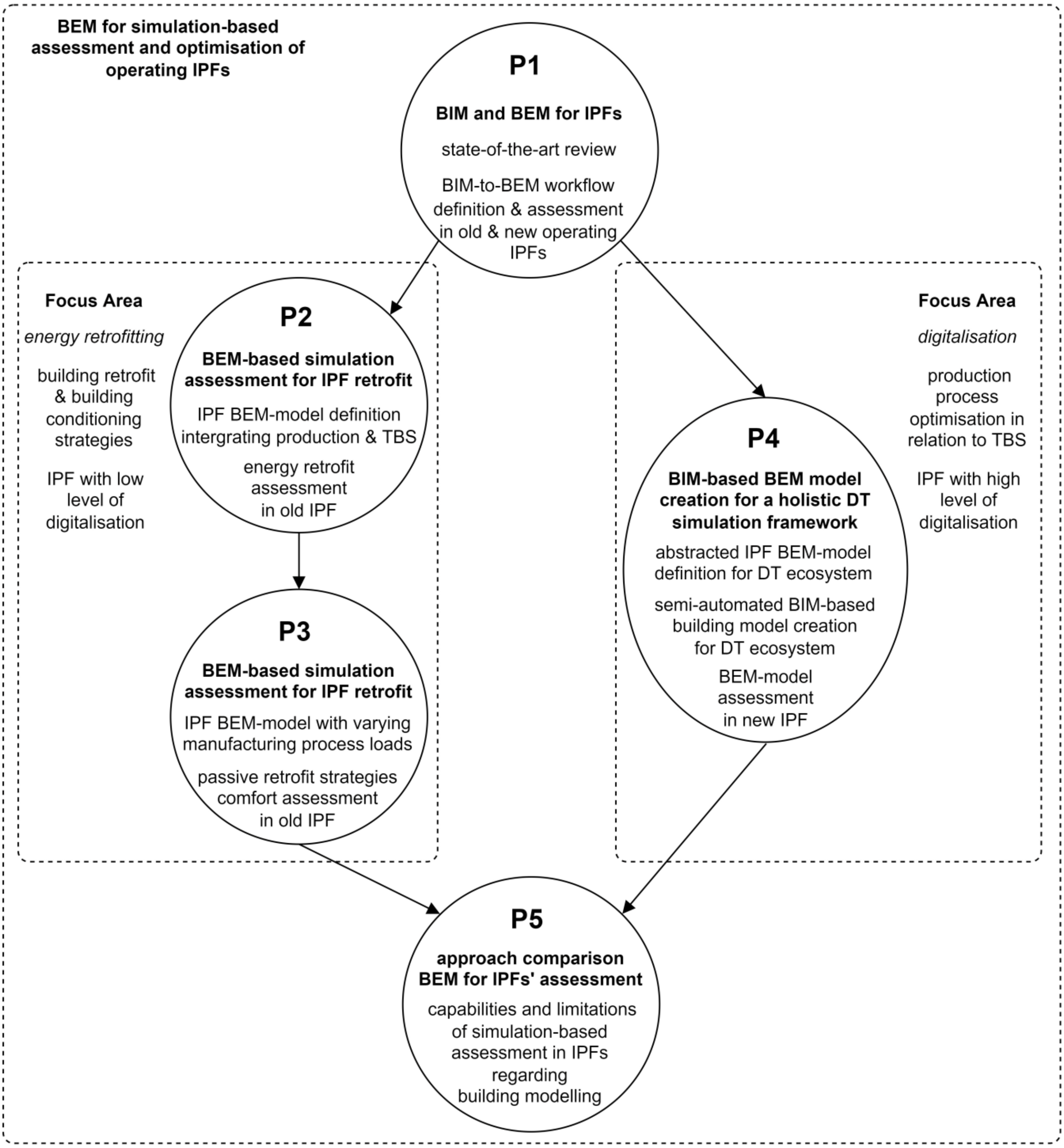

Figure 5. Research papers overview in relation to the focus areas of this thesis

5.1 Summary of research papers

5.1.1 Paper 1

Paper 1 conducts a literature review of BIM utilisation in the field of industrial facilities, in the light of enhancing energy efficiency and analyses their special characteristics in relation to other building typologies. It is shown that although BIM utilisation for design and life-cycle management of industrial facilities is increasing, very few published studies, identifying the potentials and limitations of BIM, are available, mainly due to confidentially and data protection issues. Furthermore, an extensive analysis on the state of the art of BIM-to-BEM interoperability is presented. It is revealed that a seamless interconnection of BIM and BEM tools is not possible, as there are often problems in data transferability with automated or semi-automated transfer interfaces, leading to inconsistencies and loss of information. Especially for large and complex "realistic" BIM models, particularly interesting in the case of industrial buildings, the BIM-to-BEM process may completely fail and a manual trial-and-error procedure for exporting data from the BIM model to create a functioning BEM model has to be employed, without providing a guaranteed outcome. Similar BIM-to-BEM interoperability problems are still reported in current research, especially for big and complex buildings (Pezeshki et al. 2019; Bastos Porsani et al. 2021).

A novel application of BIM-to-BEM workflow for the case of IPFs is then presented, using a case study analysis of two facilities, an older metal-cutting and forming building complex and a newly constructed, highly digitalised food industry. The greatest challenge identified is the simplification of the architectural models, and re-definition of the boundaries essential for the thermal zones-definition as needed by the BEM simulation, as well as the application/transfer of the material and construction bound data. It is demonstrated, that with the increasing number of partaking disciplines and models, the number of linguistic, knowledge and process uncertainties in the BIM-to-BEM process is increasing. However, even a low number of knowledge uncertainties can have huge impact on the analysis outcome, through oversimplification of the model. Therefore, prior to the modelling process, it is important to identify all of the uncertainties and related risks, due to the fact that a few key-parameters can have large impact on the simulation, much more than the large number of uncertainties with little impact, which still provide a valid model.

Paper 1 concludes that BIM bares great potential not only for the planning and construction of industrial facilities, but also as an industrial facility management tool. However, its success lies in the integration of several systems – building models, HVAC, equipment and infrastructure, which again call for a possibility of coupling several software-platforms, such as CAD, ERP, GIS, and equipment-CAD. Especially for improving energy efficiency, a BIM-based BEM model can enhance the follow-up energy analysis and optimisation of a newly constructed facility or support decision-making for retrofitting measures in an older facility. However, a BIM-to-BEM process is time intensive and prone to errors, and can contribute to the reluctance of both planners and investors to adopt a building performance analysis and

BEM-based simulation as a standard design-optimisation procedure. Thus, a modelling-process, where requirements for BEM are known from the beginning of the design can facilitate the BIM-to-BEM process. Whereas lack of coordination and modelling standards among different stakeholders in the planning process results in additional re-modelling of the BIM model to be used for BEM, or even a creation of a new BEM model, not based on BIM.

Paper 1 addresses and thereby answers SQ1 and SQ2, as of section 1.2. As of SQ1, it presents a state-of-the-art analysis in the relevant research areas. As of SQ2, a BIM-to-BEM workflow is defined, based on state-of-the-art technology and tools, considering the detected limitations and its application is tested on the case studies of two IPFs, assessing its capabilities.

5.1.2 Paper 2 and Paper 3

Papers 2 and 3 are addressed together as a thorough investigation on the BEM-based simulation assessment for energy retrofitting of operating IPFs. They are focusing on the first case study of the older metal-cutting and forming facility, as of Paper 1, and utilise state-of-the-art tools and methods for BEM-based energy retrofitting.

Paper 2, as the first part of this investigation, explains the creation and parametrisation of the BEM model and performs an initial building retrofit scenario analysis. It reviews conducted energy retrofit studies, mostly concerning the residential and the tertiary sector, and some limited industrial case studies, mainly in the context of transformation-process of industrial heritage to other. Predicting energy savings with simulation tools has received critique as in many occasions it fails to integrate the role of occupants' behaviour as an imponderable factor on the end energy performance (Li et al. 2015). It thus claimed that in IPFs equipment and machinery are a substitute for this uncertainty factor, as according to Vaghefi (2015) industrial process loads are often massive, non-stationary with random fluctuation over time, while thermally contributing to the indoor climate. Although there are some benchmark values available for industrial production process energy consumption according to industry type, sizing actual heat gains from machinery are crucial for realistic modelling of the building. It is thereby illustrated that thermal simulation of IPFs is highly case oriented. Therefore, a novel BEM-based exploration of energy retrofitting strategies for operating IPFs with actual production process loads is performed and reported in detail. It utilises the BIM-based BEM model of the IPF created in Paper 1 and provides detailed information on its parametrisation. Defining infiltration as well as natural ventilation air change rates are marked to be the greatest challenges next to the definition of internal heat gains from machinery. Energy consumption measurements on the production process machinery helped to gain insight into operating patterns. Collected data analysis showed lots of fluctuations, which led to a variants' analysis for selecting the appropriate method for parametrising the waste heat from machinery in the BEM model. This led to input schedules of machinery waste heat gains on daily basis. A retrofit analysis was finally carried out for two scenarios, compared with the initial state of the building. Energy savings from annual heating demand and thermal performance against summer overheating were evaluated. A comparison with the few available similar studies confirmed the plausibility of the results. For a light manufacturing facility, fluctuations of production process operating patterns have less impact than expected on building thermal performance. Energy retrofitting could decrease the heating demand by 52% and the thermally refurbished naturally ventilated industrial hall can achieve acceptable levels of thermal comfort by diminishing indoor temperature peaks up to 6 °C.

Paper 3, in the second part of the investigation, further addresses the calibration of the BEM model and performs a parametric assessment of passive measures against summer overheating, incorporating the fluctuating characteristics of internal heat gains of the manufacturing processes, under current production levels and hypothetical future scenarios. It is illustrated that the limited similar research efforts do not consider the dynamic nature of industrial buildings, hence the fact that due to production demand alterations or change of manufacturing equipment, internal heat gains in the building may change and initially satisfying measures to improve indoor microclimate may fail to respond to future conditions. This is a crucial point for assessing the performance of IPFs via BEM, not only in energy retrofits, but also in the planning of new IPFs. For example, all kind of new IPFs in Germany are planned with the same default value of 40 W/m² (Brinks et al. 2016), which can lead to over- or under-dimensioning of HVAC systems. As a first step in increasing the reliability of simulation results, the BEM model of the IPF, as of Paper 2, was calibrated upon internal conditions monitoring in control zones of the facility. This enabled the assessment of various scenarios of internal heat gains and natural ventilation strategies, combined with building retrofit options, to provide significant information for decision-making. Waste heat gains from machinery were modelled as input schedules on daily basis, as of Paper 2. Results from a total of 120 variants were classified and evaluated by adaptive comfort and workplace regulation criteria, while differences between the two approaches were discussed. Through the discussion of the results, the study provides suggestions regarding passive building retrofitting measures of operating IPFs to tackle summer overheating and resulting discomfort, according to climate conditions. This retrofit target should be equally considered with the reduction of heating demand, as existing IPFs often lack cooling systems, but will have to cope with the results of climate change and the increasing frequency and intensity of hot summer days in the near future.

Paper 2 thereby addresses and answers SQ3, as of section 1.2. It identifies a research gap in the field of BEM-based building energy retrofitting for the case of IPFs and determines the crucial modelling design parameters for a successful BEM-based assessment, on the case study of an appropriate operating IPF. Both Paper 2 and Paper 3 address and answer SQ4, as they present such a BEM implementation in a case study of an IPF, identifying possibilities and limitations. While energy retrofit scenarios are evaluated in Paper 2, considering actual manufacturing process loads in terms of waste heat, Paper 3 employs a calibrated BEM model to reflect the building situation prior to retrofitting for assessing the building's performance under various future scenarios of production process intensity, building retrofit options and passive conditioning strategies.

5.1.3 Paper 4

The fourth paper of this doctoral thesis focuses on the extensive research field of digitalisation in IPFs for enhancing energy and resource efficiency. It builds upon the BaMa research project, where a holistic modelling and simulation framework was developed, utilising modular digital twins (DTs) of all elements that may constitute a given IPF, namely production and logistic processes as well as the building, technical building services, and energy supply systems. The article analyses previous work and theoretical background on four key related areas of DTs in the manufacturing and AEC industries; holistic energy modelling and simulation of IPFs; BIM-based BEM; and the potentials of coupling visual programming with BIM. It then briefly presents the framework for a holistic DT ecosystem for IPFs, as proposed in BaMa. The novelty of the framework is that it addresses existing operating facilities and utilising a holistic hybrid simulation approach with discrete and continuous models solved simultaneously in a single solver platform. These form a holistic DT ecosystem of all factory subsystems, which are continually updated by monitoring data for a simulation-based optimisation. A detailed explanation of the building representation as a BEM model inside DT ecosystem is also provided.

Furthermore, a BIM-based data acquisition workflow for the creation of the BEM model is formulated. First, by defining exchange requirements from BIM to the BEM model of the holistic hybrid simulation and necessary interconnections of the BEM counterparts of the DT ecosystem to the rest of the virtual environment. Second, by specifying the required level of abstraction and BIM model simplification. And third, by proposing a method for semi-automated data acquisition directly from existing BIM models of IPFs by developing a visual programming script and post-processing spreadsheet functions. The aim is to provide a data structure that retains all the variables describing the physical reality at the level of abstraction chosen for the building component of the holistic hybrid simulation. As a proof-of-concept, the proposed workflow is compared to a manual one in terms of integrity and benefits through a comparative case study on the second, newly constructed industrial unit, as of Paper 1. Results proves the feasibility of the semi-automated workflow and the validity of the produced BEM representation of the building in the DT ecosystem, showing a satisfactory correlation to the data concerning the thermal view of the IPF, when the latter were collected manually from a developed model in a state-of-the-art BEM tool, namely EnergyPlus. In addition, the time required for the creation of the BEM model of the holistic hybrid simulation dramatically decreased with the proposed workflow, facilitating the implementation of the BaMa holistic DT framework in IPFs.

The proposed workflow contributes to the wider knowledge domain of hybrid simulation for both discrete and continuous cyber-physical systems insights for linking BIM models with the hybrid DEVS-based models and directly parametrising the building component for the simulation. In addition, findings of this study can help future research in the field of hybrid industrial simulations to prioritise the essential building-related information in the creation of the building DT models; and to enable reaching the desired complexity of a holistic DT-based facility representation, while omitting unnecessary domain-specific information and thus increasing the error rates and computational time of such models.

Paper 4 addresses and thereby answers SQ1, SQ5 and SQ6, as of section 1.2. The theoretical background analysis elaborates on industrial BIM-based BEM, regarding SQ1. As of SQ5, the requirements and accompanying processes for a BEM representation within the DT ecosystem of BaMa are thoroughly presented, while challenges regarding the creation of BEM based on BIM models are highlighted and the required level of BIM-to-BEM abstraction is outlined. As of SQ6, a semi-automated data acquisition workflow for creating the BEM part of the DT ecosystem from BIM via visual programming is proposed and a proof-of-concept case study application further examines the feasibility and validity of the workflow and its results. The findings elaborate on the facilitation of the BaMa framework implementation.

5.1.4 Paper 5

Paper 5 examines the characteristics of building modelling in simulation-based approaches for energy efficiency optimisation in IPFs. Based on the case study application presented in the previous papers, it compares the capabilities, benefits and limitations concerning BEM for simulation-based assessment, between its implementation with state-of-the-art BEM tools and in the case of a holistic hybrid simulation for a DT ecosystem, as proposed in the BaMa project. Table 2 provides an overview on that. Thereby, the use of BIM as a knowledge database for the creation of the simulation models is discussed. The suitability of each simulation approach is analysed, regarding available infrastructure, level of digitalisation and anticipated optimisation targets of an IPF. The two approaches have a fundamental difference in the way they treat the building, with BEM tools having it in their core, while holistic simulation-based approaches for IPFs, as that of BaMa, considering it as the boundary enclosing its core, namely the production process. BEM-based energy optimisation is suitable at a first stage for assessing the building and TBS optimisation potential, especially for older industrial buildings in terms of energy retrofitting. Yet when advancing on an integrated analysis of the whole factory, suitable for new or refurbished buildings, the hybrid nature of the BaMa approach, combining energy and materials flows, incorporates the multifaceted features of IPFs and can better predict energy saving potentials according to actual restrictions. The paper concludes that the actual condition of an IPF, the type and requirements of the manufacturing process, the level of implemented automation, as well as the available infrastructure, are decisive for the application of the appropriate simulation-based optimisation method.

Paper 5 addresses and thereby answers SQ7, as of section 1.2. It compares the results of the two case studies analysed in the previous papers in terms of potentials for optimising energy efficiency and modelling capabilities and limitations, while elaborating on the role of building modelling in the two simulation-based approaches.

Table 2. Capabilities comparison of both simulation approaches

	Building		TBS		Production		Logistics	
	Envelope	Daylight	HVAC	Media	Machinery	Process	Storage	Transport
BEM Tools	✔ detailed	✔ detailed	✔ detailed	X no input	✓ simple schedules & assumed or mean loads	X no input	X no input	X no input
BaMa DT ecosystem	✓ simple geometry	✓ simplified *limitations* - no daylight controls - simple shading factors - no geometry shades	✔ detailed *limitations* - no TABS - simple natural ventilation	✔ detailed	✔ detailed	✔ detailed	✔ detailed	✔ detailed

6 Conclusion

It is widely recognised, in research and in practice, that simulation-based assessment can provide insight on the energy saving potential of industrial production facilities (IPFs). However, especially in the industrial context, implementing such analysis often faces challenges on the process-design level, beside the technology related issues, due to the very large number of process stakeholders. There will always be a very heterogeneous software landscape using different data formats, granularity, etc.; each providing a digital interpretation of the physical world from different perspectives and modelling structures, originating from the needs of the associated discipline. A holistic assessment of the complex subsystems constituting an IPF, able to size full optimisation potential, requires therefore an interdisciplinary approach, extending over production and logistic processes as well as the building and technical building services (TBS). From this viewpoint, this doctoral thesis addresses an interdisciplinary research domain, extending over production engineering, energy systems, computer-aided automation and building technology, while focusing on the topic of the industrial building, as the physical space in which everything else is occurring. The main research question (RQ) *"How and to which extent can BIM-based building energy modelling be utilised in holistic simulation-based assessment of operating industrial production facilities towards energy-efficient optimisation?"* opened several topics, which were addressed through multiple methodological steps of the research design. The conducted work in this dissertation attempts to close the research gap of the utilisation of building energy modelling (BEM) in the holistic assessment of IPFs in operation. It does so by a thorough investigation towards the two main directions for achieving energy efficiency in the industrial sector, namely retrofitting and digitalisation (International Energy Agency 2021). Therefore, it focuses, on the one hand, on energy retrofitting concerning the optimisation potentials of industrial construction, and on the other, on the digital representation of the building in applications for IPFs of the Industry 4.0 era.

The novelties of this doctoral thesis lie in the following points. First, in the utilisation of geometrical and non-geometrical information contained in BIM models for the creation of BEM models of operating IPFs. Second, on the implementation of BEM, by state-of-the-art tools and methods, with active consideration and integration of production process loads in the exploration of thermal refurbishment strategies for the energy retrofitting of operational IPFs. Third, on the proposal of a BIM-based semi-automated workflow for acquiring data directly from already developed BIM models, to create a BEM representation for a holistic hybrid simulation within a digital twin (DT) ecosystem, enabling the integration of energy-related planning into the actual plant operation. Elaborating especially on the first two listed novel aspects of this work, the following should be mentioned. The first, accounts for one of the first occasions of analysing BIM-to-BEM processes and BEM assessment for existing industrial constructions, while analogous research is advanced in other building typologies or has been applied only in the planning of new IPFs (Kovacic et al. 2013). Concerning the second, while BEM utilisation is leading edge practise in buildings of the residential and tertiary sector, applications in industrial building retrofit are rare (Katunska et al. 2014; Mastrapostoli et al. 2014; Chowdhury et al. 2015; Ascione et al. 2020), and they do not include the dynamically changing internal heat gains in IPFs due to production demand fluctuations or change of manufacturing equipment over the life cycle of the facility.

Answering the main research question of this doctoral thesis, provides new knowledge on the “when”, “for what” and primarily for the “how” to utilise BEM for IPFs. Focusing on the “BIM-based” aspect, it can be concluded that already developed BIM models of new facilities or of older ones, created for an upcoming building refurbishment, could be used to provide necessary parametrisation data for the BEM models, for a BEM-DT of the building on the digital level and for analysing energy retrofitting measures, respectively. However, the process does not walk on a paved road, as interoperability of available BIM and BEM tools is in the focus of extended research for many years, but still does not provide the necessary results, as presented in Papers 1 and 4. Paper 1 illustrated the hurdles that make this process too work intense in the case of IPFs. BIM models hold yet potential to be used as input information for holistic industrial simulation tools and this thesis therefore proposed, a BIM to BEM procedure for the DT ecosystem (Paper 4), not utilising typical BEM tools. Furthermore, regarding BEM implementation for energy retrofitting of IPFs, detailed steps explaining model parametrisation and calibration while incorporating the thermal influence of the production process in a BEM tool, were presented in Paper 2 and 3. Findings regarding optimisation measures in the case study of a historical IPF, can also indicate suitable building retrofit measures for similar cases. Lastly, focusing on digitalisation, Paper 4, provided answers on how to integrate BEM in a simulation-based DT ecosystem by defining the required level of model abstraction, keeping only the essential information for a functional BEM representation, being as detailed as necessary and not as detailed as possible. Summing up, Paper 5 listed the condition of an IPF, the type and requirements of the manufacturing process, and the level of implemented automation as decisive factors for the application of the appropriate simulation-based optimisation method.

The contribution of the conducted work is assessed on two levels. On the level of energy retrofitting, it demonstrates the way to utilise BEM for optimising the building performance of IPFs, supporting the argument for the creation of a BIM model, where the facility can be well documented, providing a knowledge database for energy retrofit measures assessment with higher cost and time efficiency next to the basis for life-cycle operational management. On the level of IPF digitalisation, it contributes the necessary abstraction level for BEM in holistic applications, helping future research in the field of hybrid industrial simulations to prioritise the essential building-related information in the creation of the building DT models, to enable reaching the desired complexity of a holistic DT-based facility representation, while omitting unnecessary domain-specific information and thus increasing the error rates and computational time of such models. The proposed semi-automated workflow for a BIM-based creation of the building model within the BaMa holistic DT ecosystem could also be utilised outside the BaMa concept, when a building representation is required in a hybrid cyber-physical system simulation, based on DEVS formalism (Zeigler 2021).

Limitations of this study lie in the fact that the existence of BIM models of IPFs containing the information required for an energy retrofit or holistic analysis, does not entail a de facto faster modelling of the necessary BEM simulation model, due to the required simplification and filtering of provided data as well as interoperability issues of the different discipline-oriented software applications. Furthermore, the proposed semi-automated workflow from BIM to BEM for BaMa, with an algorithm based on a certain visual programming tool (Dynamo), can hinder its wider application, as compatibility cannot be guaranteed for the evolving software versions and due to the condition, that processed parameters must be called by name, thus requiring a certain naming structure during the modelling in BIM. Lastly, handling federated BIM models of large facilities, where large halls may be modelled divided into different files, can prove problematic. However, if these BIM models correspond to stand-alone thermal views of the facility accompanied by a certain production process, information from each of the BIM sub-models can be extracted separately and assessed as a group of buildings in a holistic DT ecosystem or regarding an energy retrofit.

Future steps of this research can include the investigation of more case studies regarding energy retrofitting of IPFs with different building typologies and types of manufacturing processes. The goal will be to have a bigger sample of buildings in order to make safer proposals for prioritising thermal refurbishment measures, according to certain categorisation criteria. In the field of an IPF digitalisation, it is stated that the current implementation of the proposed workflow for a BIM-based creation of the BEM representation within the BaMa holistic DT ecosystem can be regarded as a prototype for an automated data acquisition tool. In the future, the proposed workflow can be implemented in a single programming environment by developing a tool to provide direct connectivity between BIM models and future software implementation of the BaMa prototypical toolchain and thus a time-efficient exchange of information from BIM to the hybrid simulation models.

Scaling back up to the general goal of enhancing energy and resource efficiency in operating IPFs, it is argued that technological progress helps to reach the existential target of a fully sustainable society, in the not so far away future. This requires though a deliberate use of the available tools and processes, and a constant desire to overcome all challenges found in the way. In this sense, various stakeholders' or decision makers' will is the first and foremost prerequisite for implementing available knowledge and making energy and resource efficiency not just worlds on paper but a solid reality.

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Part II

Scientific peer-reviewed papers

Paper 1

Georgios Gourlis and Iva Kovacic

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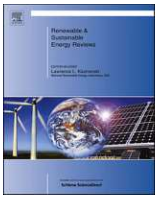

Building Information Modelling for analysis of energy efficient industrial buildings – A case study

Georgios Gourlis, Iva Kovacic*

Department for Industrial Building and Interdisciplinary Planning, Faculty of Civil Engineering, Vienna University of Technology, Karlsplatz 13/ e234-2, 1040 Vienna, Austria

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A B S T R A C T

Industrial buildings demand higher amount of energy than other building typologies, thus powerful modelling and simulation tools for energy-optimisation and identification of synergies-potentials between the building envelope, building services and production systems are needed.

Building Information Modelling (BIM), as emerging technology, bears promise to support processes integration thus enabling life-cycle management of buildings. BIM model serves as a joint knowledge database where data transfer between various models is possible; thereby enabling follow up studies, such as cost, thermal and structural analysis.

Adoption of BIM to BEM (building energy modelling) approach is particularly interesting for optimisation of industrial facilities. Multiple layers of interacting complex systems (building, services and machine floor layout) require careful modelling and control of geometry in terms of collisions, various adaptions due to the short product-life-cycles, as well as integrated energy performance analysis along interacting systems.

This paper explores the potentials and deficits of the modelling, analysis and optimisation of energy-efficient industrial buildings using BIM to BEM methodology, by means of case study research of two industrial facilities. Varying needs concerning the Level of Development and semantic differences in the modelling procedures of part-taking disciplines (architecture, structural engineering or analysis) were identified as problems; as well as time pressure as one of the main reasons for defects of building models. The identified deficits represent various types of uncertainties related to the integrated energy modelling, as BIM to BEM can be referred to. We conclude that as a first step of integrated modelling, an uncertainty-analysis should be carried out, and strategies how to deal with these developed. In order to minimise BIM to BEM uncertainties, not only interoperability issues of the software has to be improved (modelling uncertainty), but moreover, the redefinition of the design process and enhancement of individual capabilities is necessary (process uncertainty).

Contents

Abbreviations: AEC, Architecture Engineering Construction; BIM, Building Information Modelling; BEM, Building Energy Modelling; CAD, Computer Aided Design; ERP, Enterprise Resource Planning Software; FM, Facility Management; gbXML, Green Building Extensible Markup Language Schema; GFA, Gross Floor Area; GIS, Geographical Information Systems; HVAC, Heating Ventilation Air-Conditioning (Engineering); IFC, Industrial Foundation Classes Data Standard; MEP, Mechanical Electrical Plumbing (Engineering); TBS, Technical Building Services

* Corresponding author. Tel.: +43 58801 215 26.
E-mail addresses: georgios.gourlis@tuwien.ac.at (G. Gourlis), iva.kovacic@tuwien.ac.at (I. Kovacic).

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1. Introduction

Building stocks are responsible for 40% of energy consumption in the EU and for 36% of greenhouse gas emissions [1], the largest part of which occurs throughout the operation-phase. Recent research and practice has been largely focusing on analysis and optimisation of energy consumption of residential buildings [2,3], less so on public or commercial buildings (such as schools or offices) [4]. Optimisation of energy performance of industrial buildings has seldom been in the focus of research, due to the large energy-consumption of industrial production processes [5]. However, through recent policymaking – introduction of Energy Directive or Energy Performance of Buildings Directive [6], as well as to recent energy-availability issues, more integrated approaches regarding energy efficiency of industrial facilities have been proposed [7]. In this context, the balanced performance of building design, thermal envelope and HVAC systems, and use of synergies with relevant processes and occupancies has been increasingly advocated as the right approach [8]. Yet such an approach requires modelling, analysis and optimisation of complex systems, for which powerful computational tools are needed. Building Information Modelling, as “a digital representation of physical and functional characteristics of a facility” offers potentials for life-cycle modelling and management of buildings and building systems [9]. Through creation of a joint knowledge base – information rich building model – a follow up thermal, structural or cost analysis can be carried out. BIM, seen as multi-dimensional tool for life-cycle management, can be classified into 3D BIM – parametric building model, as an upgrade to a 2D CAD plan, 4D addressing time – scheduling and construction stages simulation, 5D cost – planning and estimation, 6D sustainability – thermal analysis and environmental assessment, eventually even automated building certification, and finally 7D as a fully mature, comprehensive model enabling facility management, maintenance and operation [10].

In this paper we will explore the potentials of energy-analysis and simulation on a case study of two industrial facilities using BIM to BEM (Building Information Modelling to Building Energy Modelling) approach, thereby addressing the issues of the so called 6D BIM – assessment of sustainability. We evaluated the modelling process and software-interfaces from BIM to follow up thermal simulation using BEM and tested the suitability of the models as joint knowledge base for life-cycle management of architectural, HVAC and shop-floor models. We will outline possible solutions for the minimisation of aforementioned uncertainties in such integrated modelling processes.

2. Literature review

2.1. *Building Information Modelling*

The common understanding of BIM terminology in the AEC industry in both practice and academia is multifaceted. Succar [11] delivers an overview of various BIM definitions. BIM terminus is originally coined by the CAD-software developer Autodesk [12], Graphisoft [13] was using Virtual Building, where as Eastman [14] introduces the Building Product Models.

BIM is defined as:

- The “new CAD” paradigm [15] – an advanced version of digital drafting tool.
- The building modelling **tool** providing possibilities of interaction with non CAD-based tools, such as quantity surveyors' or project management tools [16].
- A **methodology**:“… to manage the essential building design and project data in digital format throughout the building's life-cycle.” [17] (p. 403).
- The emerging new **paradigm**: “… an emerging technological and procedural shift in the Architecture, Engineering and Construction industry.” [10] (p. 357).
- Or according to the UK Government programme [18]: “… a collaborative **way of working**, underpinned by the digital technologies which unlock more efficient methods of designing, creating and maintaining our assets.”

BIM is often mentioned in relation to building product modelling, a predecessor terminus to BIM, dating from the 80ies [17]. The product models address the object-oriented modelling of the data-rich building components, incorporating 3D geometries, spatial information, thermal values, and material properties; parameters upon which data interoperability builds up [19].

To the most utilised BIM Tools count Autodesk Revit (as one stop shop, offering possibilities for architectural, structural and MEP modelling and even proprietary tools for thermal and daylight analysis), Archicad by Graphisoft primarily used for architectural modelling, Tekla by Trimble, as engineering modelling tool, Allplan by Nemetschek, Microstation by Bentley etc.

BIM has often been recognised in research and practice as a suitable tool for support of collaborative planning, facilitating communication and information exchange between diverse planning process participants [20]. More practice-oriented publications often advocate BIM benefits as maximisation of efficiency, quality and reducing time effort [21]. It is largely understood as object-oriented digital representation of a building or built environment, which enables interoperability and data-exchange in digital form [22]. In this context BIM addresses primarily the process of model-building and information exchange [11].

BIM, in addition to support of collaborative processes, can through its capability of attributing both spatial and geometrical as well as non-geometrical attributes to building elements be implemented in various areas of the AEC industry, such as sustainability analysis [23], structural analysis [24], thermal simulation [25], daylight simulation [26], construction management [27], cost estimation and planning [28], fire protection [29], safety on construction site [30], facility management [31] etc.

Therefore the development of functioning and open interfaces is one of the major tasks in the advancement and successful adoption of BIM technology in the industry. One of the most important, open non-proprietary interfaces is the Industrial Foundation Classes (IFC), developed and supported by buildingSMART (International Alliance for Interoperability), which also certifies the BIM software for IFC-import and export ability [32]. Despite the efforts towards providing maximum interoperability and advancement of the IFC standard, due to the highly fragmented AEC market and lack of process integration, software-interoperability remains one of the greatest challenges for successful BIM adoption. A large number of software still offers proprietary, software-specific interfaces, trying to provide in such way a one-stop shop solution in form of "One-Platform-BIM". However, through current strategy by public policy to mandate BIM use in public projects – such as the UK Government Construction Strategy – not only should BIM use be enhanced for the integration of the fragmented AEC industry at the design and planning stage, but moreover for achieving an added value along the life-cycle [33].

Successful BIM use throughout the life-cycle is related to the efficient data- and model-exchange among various stakeholders from the AEC industry, which again calls for improvement of interfaces, creation of joint working platforms such as "Cloud BIM information exchange mechanisms" [10], as well as exact analysis of actual needs of each discipline in order to provide and transfer what is actually needed instead of what is available.

It can be concluded that a joint understanding of BIM is lacking in the AEC industry – it is simultaneously understood as a software, designing and planning method or a new integrated procedure in the AEC industry [34]. The lack of joint understanding poses great challenges for a successful implementation and use of full potentials along the whole value-chain, particularly regarding the problem-solving of interoperability issues.

2.2. *BIM for industrial facilities*

Adoption of BIM is particularly beneficial for design, planning, optimisation and management of industrial facilities. Industrial facilities as building typology are particularly demanding in terms of design, due to the diverging interior climate requirements of various functional units (office, production, storage), regulations of vertical and horizontal circulation and accessibility (e.g. employees vs. customers) and finally interactions of various systems such as building and structural components, HVAC and machine floor layout and infrastructure. The design process requires sound validation and design review (e.g. in terms of collisions), which is enhanced through BIM modelling approach combined with automated model checking and analysis tools, such as Solibri Checker or Tekla BIMsight.

Different than other building typologies, where economic life-cycles range from 50 to 80 years, industrial buildings are characterised by relative short life-cycles ranging from 15 up to 30 years, as determined by the short product-life-cycles. A prerequisite for achieving economic and environmental sustainability is the prolongation of the building's life duration, which calls for the highest possible flexibility and expandability of the layout, posing challenges on the structural design. Further on, depending on the production process, there are higher internal heating loads than in other building typologies, which can be used for heating of accompanying offices and supporting facilities, for warm water supply etc. The use of such synergy effects, as well as optimisation of the load bearing structure in terms of flexibility, calls for careful modelling and analysis of the systems – building structure and envelope, HVAC and energy supply – and even coupling the production-system models already in the early design phases. A comprehensive BIM model, as a joint knowledge base of spatial, geometrical, energy and cost data offers potential for coupling with computational energy analysis or even enterprise resources planning tools, not only for the design, but moreover for the management of an industrial facility along its life-cycle.

The most commonly utilised tool for modelling of industrial facilities is the Autodesk REVIT software [35], which offers architectural, structural and HVAC modules (Revit MEP); in so called One-Platform-BIM, reducing in this way data transfer via interfaces. Despite the One-Platform solution for the facility side, the tool (equipment) and shop-layout suppliers use wide range of various software tools, most of which are not IFC capable, which poses large problems for BIM utilisation in industrial construction.

Use of BIM for design and life-cycle management of industrial facilities is increasing in the practice, however due to the confidentiality and data protection there are still a very few published studies identifying the potentials and limits of BIM in industrial construction.

Huang et al. [36] identify the BIM potential for life-cycle management of industrial parks in Taiwan, underlining the advantages of combining BIM based visualisation, GIS and ICT solutions, for successful management of industrial parks. The multi-modular system architecture offers navigation support and utilities and facilities are modelled with BIM, therefore users can retrieve drawing and attribute data in real time of e.g. pipeline and utilities systems. Wang et al. [37] explore the possibilities in the design of industrial facilities from the pre-design (workshop design) till construction using Autodesk Revit Software, and interface (DXF) towards workflow-software for optimisation of production-workflows. The parametric model delivers statistical and analytical data, maintenance drawings etc.

Especially interesting is the use of BIM for design of semi-conductor production facilities, due to the very short planning and construction time horizons (10 months from pre-design till take over) – where BIM can show advantages in reduction of planning time through reduction of changes (visualisation of collisions, automated extraction of cost and time relevant data) and allowing coupling of the facility supply with the tools. On the concrete case study of a semi-conductor facility the information of the tool supplier, facility- and tool-layout designer was exchanged using BIM [38]. Tool Information Model was imported in Revit MEP application (facility supply model) testing the Industrial Foundation Classes (IFC) interface; however it was found that the IFC standard does not match the SEMI Standard (semi-conductor industry standard) thus allowing the data exchange only in one way.

A special focus of this research is the use of BIM for energy-optimisation of industrial facilities based on integrated approach, including consideration of waste heat from machines, machining processes, occupancy related interior gains as well as solar gains [39].

2.3. *BIM to BEM*

The utilisation of BIM for building performance modelling and analysis is an increasing research topic in the academic community, due to the BIM potentials for integration of the geometrical, material, technical, structural, and HVAC data on the one hand, as well as stricter requirements and policies for sustainable construction on the other. Several tools have already been introduced for BIM-based and -supported semi-automated or even automated energy analysis. A prototypical Design Performance Viewer (DPV) tool was developed for Autodesk Revit architectural modelling software, intended for the calculation of energy and exergy in the early design stages by Schlueter and Thesseling [40]. The same modelling software was tested for automated assessment of sustainability certificates, extruding necessary information for relevant indicators [41]. Utilising BIM application programming interface (API) and Modelica-based BEM, Jeong et al. [42] presented an automated framework for simulating and visualising energy analysis results back inside the BIM software Revit, providing direct feedback to designers. Also integrated in Revit, BPOpt combined visual programming-based parametric BIM with building thermal and daylighting simulations, and was tested in the case of a residential building, where automatically collected data from the BIM model were used for minimising energy consumption while maximising appropriate daylighting level, according to LEED requirements [43].

Different to the One-Platform-BIM solutions, Lawrence Berkeley National Laboratory developed the Space Boundary Tool (SBT) for a semi-automated process for transformation of BIM to BEM models, using open-BIM approach via IFC interface, thus providing for a more generic workflow [44,45]. Welle et al. [46] and Ahn et al. [47] also created IFC-based tools for enabling automated thermal simulation with EnergyPlus by creating input data files (IDF) containing geometry, thermal space boundaries and material information from the BIM model, aiming to improve the accuracy and modelling time of the BEM models. Whereas Cemesova et al. [48] proposed a tool for combining BIM IFC-based geometry and information from the Passive House Planning Package (PHPP) design tool to assess energy performance and decision making for PassivHaus certifications.

In all referenced studies, interoperability and data-transfer as well as ease of use from BIM to BEM systems play a crucial role in order to reduce the re-modelling efforts and easy creation of building energy models [44]. Clarke and Hensen [49] state that the core issue for design process integration is how to transfer information between tools, without the need to access different BIM models. Information exchange from BIM to BEM software is most commonly provided via the already discussed reference standard of IFC and via the gbXML (green building extensible markup language) data format, developed for the energy simulation domain and therefore supported by many analysis tools. Detailed examination of properties, comparison and limitations of the two approaches are described in [50,51]. On one hand gbXML is simpler and easier to understand and implement by BEM software developers, therefore thermal simulation tools such as IES-VE [52], EnergyPlus [53], eQUEST [54] and similar expert tools still only support this format and not IFC import. On the other, IFC is the only open ISO standardised interface in the building data exchange context [55], becoming the primary BIM language able to comprise several types of BIM information across all disciplines and lifecycle phases. Researchers intently explore the capabilities of both gbXML [56,57] and IFC [58,59] schemas, but also examine approaches not embracing these data formats [40,42,43]. However under the prism of open-BIM, using standard data transfer schemas facilitates the BIM to BEM procedure among different tools.

El Asmi et al. [59] reviewed the technological stand of BIM to BEM data formats and concluded that even the most advanced and extended data framework fails to generate reliable BEM models from BIM modes, including all required information. Worth mentioning is the limited interoperability of HVAC system components, which is not improved in the latest version of the IFC format IFC4 [60], a field particular important in the context of industrial buildings.

Experiment results on the interconnection of BIM and BEM tools showed that there are often problems in data transferability such as error-prone geometry leading to inconsistencies and loss of information (e.g. material properties) [61–63]. BIM models contain a greater degree of information than required and can be translated for a thermal energy analysis [64] – displaying too high Level of Development. For example BEM model can contain a large number of thermal zones when imported from BIM (every room is translated to a thermal zone), therefore methods are tested for reducing this information to the required extent [65]. The numerous geometry-related modelling problems in data transfer from BIM to BEM are mostly associated to the varying boundaries of room stamps and thermal zones, as well as to wrong interpretations of non-planar geometry [61], leading to duplicate or missing objects and missing or incorrect space volumes [62]. Operative cause is that in architectural models a room stamp identifies an area in m^2 of a specific functional unit (interior boundaries of walls), whereas most building energy models need a boundary adjusted thermal zone definition, which includes centreline of horizontal or vertical partitions and is not interested in their thickness [66]. This leads to inaccurate analytical representations of the building design that need to be manually transformed for further use for performance simulation [67]. A recent practise oriented case study showed that large and complex “realistic” BIM models may completely fail to be transferred to BEM and a trial and error process has to be employed, without providing a guaranteed outcome [68].

2.4. Uncertainties in energy modelling

To summarise, automated and semi-automated processes for error free data transfer have been developed to assist BIM–BEM software communication without human intervention [44–46], however these require custom software plug-ins and programming skills or a specific design methodology during the creation of the BIM model [41,62], an attribute that existing BIM models, designed by planers and architects, do not have. In the practice BEM models based on BIM data export are intensively reworked by simulation experts in order to be used for further analysis, this though bears the risk of arbitrary building definitions based on personal understanding and expertise, being also time consuming. Such procedures may contribute to the fact that predictions for energy consumption of BEM models often deviate from actual measured data, resulting in the case of complex non-residential buildings in under-predictions in the order of 30% [69].

Various difficulties burdening the energy modelling and optimisation process can be assigned to the uncertainties identified in integrated energy modelling processes by [70]. The uncertainties using the BIM modelling and follow up analysis and simulation approach can be met at linguistic level (various planning disciplines of various professional languages) [71], as epistemic uncertainties (model structure and software/hardware errors) [72], and also planning procedural uncertainties (resources and time) [73].

None of the afore mentioned tools or processes has found wide application in the practice, due to the formerly explored reasons – the knowledge-transfer gap between the partaking disciplines or the lack of strategies for dealing with uncertainties when integrated energy modelling is applied within the state-of-the-art design process.

3. Methodology

In order to evaluate the potentials of BIM for design and energy-optimisation of industrial facilities case study methodology was used. Case studies are often used for theory building, serving as singular “experiments” [74]. Multiple case studies build again a series of related experiments, extending the emerging theory [75]. However, differently than laboratory experiments, which isolate the phenomena from the context, case studies are strongly related to the real-word context in which they occur, thus providing the knowledge of what was planned and what actually has occurred [76].

Next to the case study, thermal simulation modelling was applied. For the energy and thermal modelling of the building a so called “white box” approach was used [77], which uses physics based equations to model building or building systems. The “black box” approach, on the other side, is based mostly on probabilistic model, using statistical data. Generally the “white-box” simulation model consists of the input parameters such as weather conditions, and parametric description of building elements; the simulation engine calculates the internal loads and carries out system analysis, whereas the output parameters are energy performance indicators.

Foucquier et al. [78] identify as examples of physical models the CFD (computational fluid dynamics), zonal, and multizone (nodal) approach. In multizone approach the building is divided in a number of various zones – homogenous volumina characterised by uniform state variables. Short computational time is identified as main advantage of the multizone approach, however as a drawback the difficulty to represent and study large volume systems, a problem which was also met during the modelling of the conducted case study.

4. Case study

The cases include an existing construction (Case B), where an own BIM model was created based on the provided documentation and a new industrial construction (Case M), with pre-modelled architectural and TBS model.

The Case B (Fig. 1) is a partially historic metal-cutting and forming production facility, with numerous additions dating from varying periods, for which own BIM model was created based on the existing documentation (2D plans in .dwg and .pdf data formats) and transferred to BEM – EnergyPlus v8.1 via OpenStudio SketchUp Plug-in v1.5.3 [53,79] (Fig. 2). The Case M (Fig. 3) is a new construction of a food industry consisting of two blocks – bakery and meat factory. For this case an architectural model (Autodesk Revit 2014) was obtained from the architectural office, and had to be re-modelled in OpenStudio SketchUp Plug-in for the BEM purposes (Fig. 4). Table 1 displays the basic data on the cases, such as gross floor area (GFA), volume, building envelope characteristics, and year of construction.

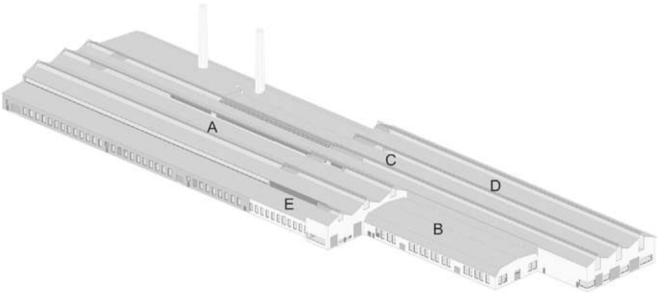


Fig. 1. Case B Architectural Mode – newly modelled in Revit-Software.

Software used in the modelling process included on the BIM side Autodesk REVIT for architecture and technical building services (TBS); and EnergyPlus via SketchUp and OpenStudio Plug-in for BEM (Fig. 5). The BIM models were transferred in the thermal simulation software by creating the building energy models (or re-modelling the BIM-models) and finally assessing optimisation potentials; observing and recording the process using so called mistake trees.

5. Results

The greatest challenge thereby was the simplification of the architectural models, and re-definition of the boundaries essential for the thermal zones-definition as needed by the simulation, as well as the application/transfer of the material and construction bound data. Whenever necessary, special care was given to dividing the extensive area of the industrial halls according to type functions that are taking place and indoor climate requirements, therefore so called air-walls were used to define thermal zones where no physical boundary existed in the BIM model.

The BIM model (geometry) of the cases was exported via gbXML format in the OpenStudio Plug-in for SketchUp, a tool that has direct connection with the simulation engine of EnergyPlus (Fig. 6). The procedure from BIM to energy analysis software in many cases requires manual corrections at the middle stage of the transition, since geometry and space boundary information can contain errors that affect the simulations input data, as was the

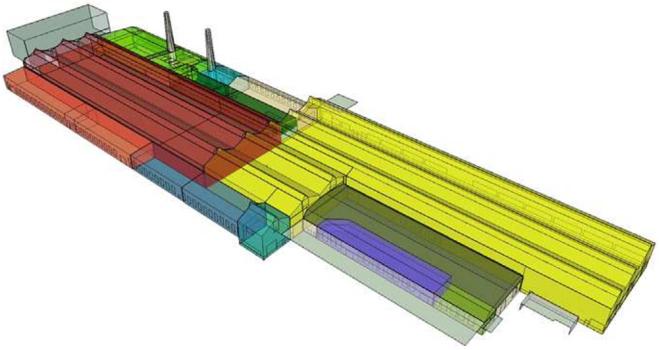


Fig. 2. Case B BEM Model – thermal zones.

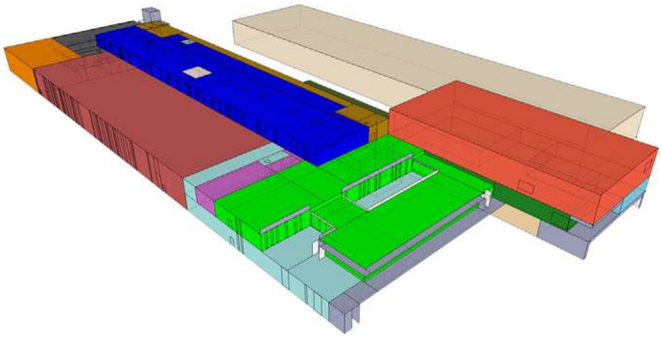


Fig. 4. Case M BEM Model – thermal zones.

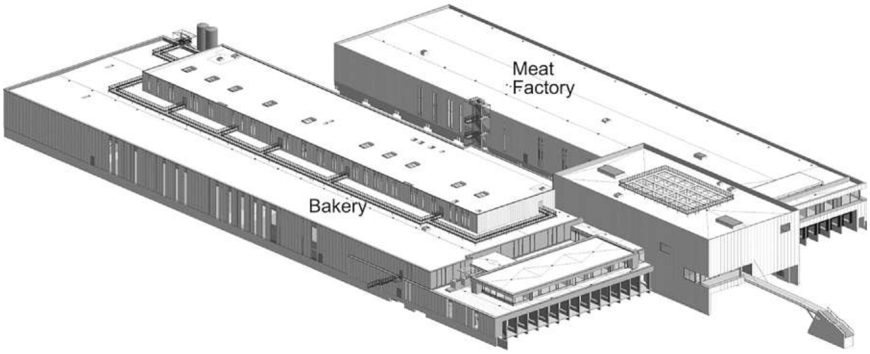


Fig. 3. Case M Architectural Model – as obtained in Revit-Software.

Table 1
Description of the cases.

	Case B	**Case M**
	Historical metal-band cutting and forming factory	New construction bakery and meat factory
GFA	20,273 m^2	28,526 m^2
Volume GV	200,854 m^3	173,710 m^3
U-values Facade	Existing hall Outside 600 mm solid brickwork 1,400 kg/m^3 20 mm cement plaster **U-value: 0.833 W/m^2 K**	Bakery facade Outside 30 mm wood sheathing 100 mm air gap 240 mm EPS rigid foam insulation 300 mm reinforced concrete **U-value: 0.438 W/m^2 K**
	New hall Outside 35 mm trapezoidal sheet metal 30 mm air gap – fasteners 100 mm stone wool insulation 6 mm cassette profile **U-value: 0.353 W/m^2 K**	Bakery offices facade Outside 140 mm wooden prefabricated Element (beech-oak) 180 mm EPS rigid foam insulation **U-value: 0.187 W/m^2 K**
	New polishing hall (refurbishment) Outside 35 mm trapezoidal sheet metal 30 mm air gap – fasteners 150 mm stone wool insulation 6 mm cassette profile **U-value: 0.233 W/m^2 K**	Meat factory façade Outside 140 mm steel PUR 30/035 foam sandwich façade panel **U-value: 0.240 W/m^2 K**
		Meat factory offices façade Outside 60 mm middleweight concrete 1,800 kg/m^3 80 mm reinforced concrete 60 mm middleweight concrete 1,800 kg/m^3 140 mm steel PUR 30/035 foam sandwich façade panel **U-value: 0.232 W/m^2 K**
Year of construction	In different phases from 1900 until 2015 A: Historical part 1900–1920 B: before 1930 C: 1997 D: 1999 E: New polishing hall 2015	2012–2013

case with Case M. Major difficulty, shown in Fig. 7, was that the architectural BIM model was built on the principle of using non-compound space dividing elements (walls, slabs, etc.), resulting in wrong interpretations of thermal zone boundaries, as centrelines of adjacent spaces did not coincide and had to be manually modified. In Case B, where the BIM model was initially designed for export to external software; the inconsistencies were kept to a minimum level. Material characteristics of the building elements were applied directly on the EnergyPlus models, as it was not possible to export them via gbXML from the BIM model (e.g. thermal conductivity, density and specific heat capacity of construction layers). It is already reported that Revit fails to export materials properties in the gbXML file [63].

The mistake tree in Fig. 8 thoroughly analyses the transfer and re-modelling process or adoption steps necessary to obtain a functioning model for both cases.

6. Discussion

On a case study of two industrial facilities, BIM software and modelling process was applied and evaluated for suitability for energy-optimised design of industrial facilities. In the first step the architectural and TBS modelling was carried out, in the second step the building performance analysis and optimisation, through so called BIM to BEM approach – architectural digital building model was transferred into building energy model system, for analysis and simulation. Thereby following observations of the modelling process were captured using mistake-tree technique.

The new facility – Case M – was "pre-modelled" by the architectural office, without knowledge that later on a thermal simulation will be undertaken. Thereby the modelling did not consider the specific modelling requirements of thermal simulation software displaying too many room stamps and boundary surfaces. This resulted in many geometrical errors in the BEM model; finally requiring significant re-modelling efforts of both original model and BEM models by the building physicist.

The existing facility – Case B – was modelled and analysed out of "one hand", which resulted in immediate creation of a customised, simplified model; however this model is not fit for the architectural purposes due to the oversimplification. Despite the simplified modelling in Revit, the boundary conditions of BEM model still had to be repaired after gbXML export.

In both cases the materials and constructions had to be manually applied in EnergyPlus, despite the fact that the Case M architectural model contained very detailed information of materials and constructions.

This test implies that BIM to BEM approach is still not mature enough for everyday application, still requiring large amount of adoption and remodelling. Crucial for the successful collaboration

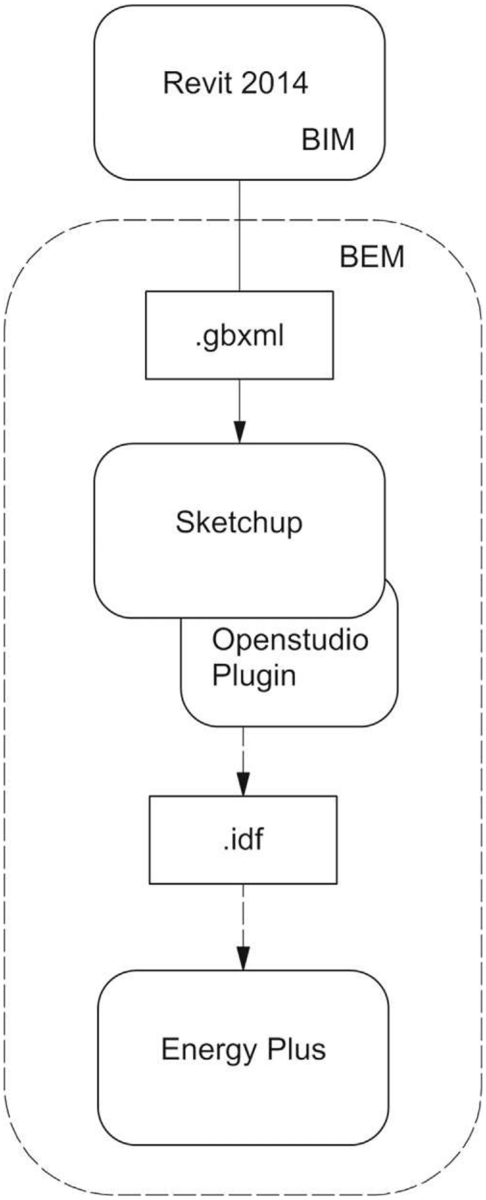


Fig. 5. Work-flow – software constellations applied in the modelling process.

and efficient data transfer is the overcoming of the "discipline interest conflict". On the one hand the architectural model is very detailed, including a large number of room stamps and very high granulation and detailed product information; on the other the energy model is simplified requiring basic information on geometry and thermal zones. Thereby a modelling standard has to be established at the beginning of the design process defining the required Level of Detail. This should be applied for each design stage to guide information exchange required for energy performance analysis and improve the implementation of BIM for energy efficient buildings [80].

In any case, currently only "one-way" BIM is possible – return of the building performance simulation or optimisation information in the original model is not possible – therefore again remodelling efforts are necessary, together with well documented changes-management. This results in a BIM to BEM approach where the BIM-model is not used as adaptive design and management tool, but solemnly as extensive building and TBS database.

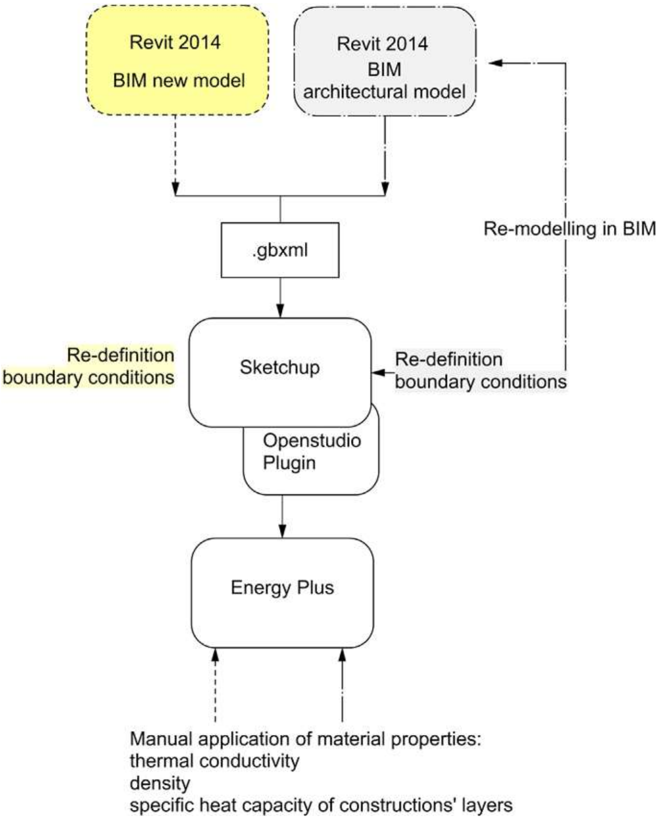


Fig. 6. Work-flow – recording of the modelling process and transfer from BIM to BEM.

According to [70] there are different types of uncertainties when applying integrated energy modelling, a process similar to the one in the case study.

Thereby [70] differentiates between:

1. Linguistic uncertainty – vagueness, ambiguity and underspecify [71]
2. Knowledge (epistemic) uncertainty – Model inputs and parameters, Model structure, Model Technical, Model output [72]
3. Process uncertainty – Communication, Available Time, Resources [73]

At the Case B knowledge uncertainty was met through possible oversimplification of the architectural model, as well as technical difficulties in the modelling procedure.

At the Case M however all of the three uncertainty types were met – linguistic (underspecify), knowledge – lacking inputs and parameters needed for BEM, technical software difficulties, as well as process uncertainty through over-proportional consumption of time-resources for model-repair.

It is demonstrated, that with the increasing number of partaking disciplines and models, the number of uncertainties is increasing, however even the low number of uncertainties (as in Case B) can have huge impact on the life-cycle optimisation, through oversimplification of the model. Therefore, prior to the modelling process, it is important to identify all of the uncertainties and related risks, due to the fact that a few key-parameters can have large impact on the simulation, much more than the large number of uncertainties with little impact, which still provide a valid model.

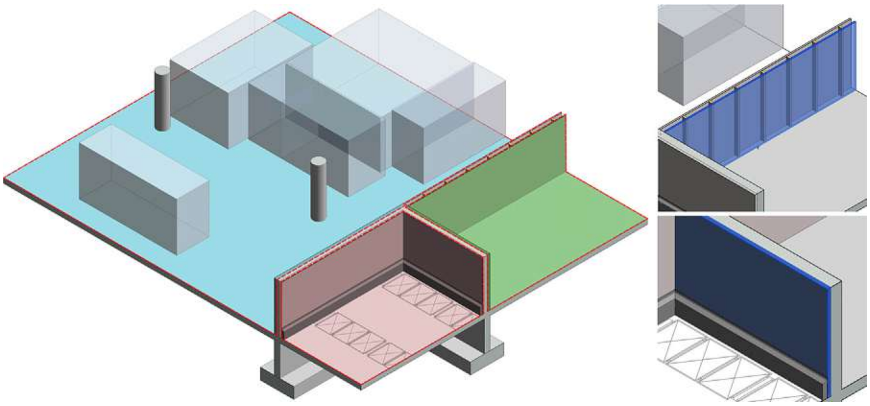


Fig. 7. Case M non-adjusted thermal zone boundaries – non-compound walls.

7. Conclusions

Despite the increasing importance of BIM in AEC, the potentials of BIM technology remain still largely unexplored in the industrial construction, partly due to the data protection and secrecy in the industry. BIM however bears large potentials for life-cycle management of industrial facilities through possibility of integration of building models and products, HVAC, machines and equipment.

The slow BIM adoption in industrial construction has several causes:

- Duration times of design, planning and construction processes for industrial facilities are very short, due to the short life-cycle of the products and the need to bring the product on the market as soon as possible. From the pre-design till operation there is often less than 12 months. Due to the fragmented AEC in the European region, BOT (built-operate-transfer) commissioning models are still seldom. Thereby a large number of stakeholders is participating in design and construction process of industrial facility (architects, engineers, HVAC engineers, factory designers, logistics) all of which use own software solutions. BIM supported design and construction requires more intensive coordination and communication effort even before the design starts, in order to determine the modelling and data-transfer standards and framework. The fragmentation of the AEC industry together with the enormous time-pressure in industrial construction, represent the major obstacles towards the adoption of fully functioning BIM supported value chain.
- BIM to BEM approach in industrial construction is a completely novel aspect, since energy optimisation of industrial buildings is not in focus of an enterprise – building related energy consumption is relatively low in relation to the process-related consumption. Thereby when keeping the above mentioned time pressure for design and construction in mind, the time as well as financial resources for a thorough thermal building performance simulation and optimisation are often lacking. The necessary efforts are not often too large in comparison with possible benefits, the process is too complicated and time intensive, especially if not “designed” from the beginning of the design process, as demonstrated on the Case M.
- However, a coupled simulation with holistic approach including building, building systems, machines and processes would allow identification of synergy potentials and thereby much larger energy savings on larger level of an enterprise [7].
- In order to enable full benefits of BIM for design, construction and operation of industrial facilities, further development of open interfaces is necessary. In case of an automated BIM to BEM less time resources and efforts would be necessary and this optimisation would become a part of a standardised design process.

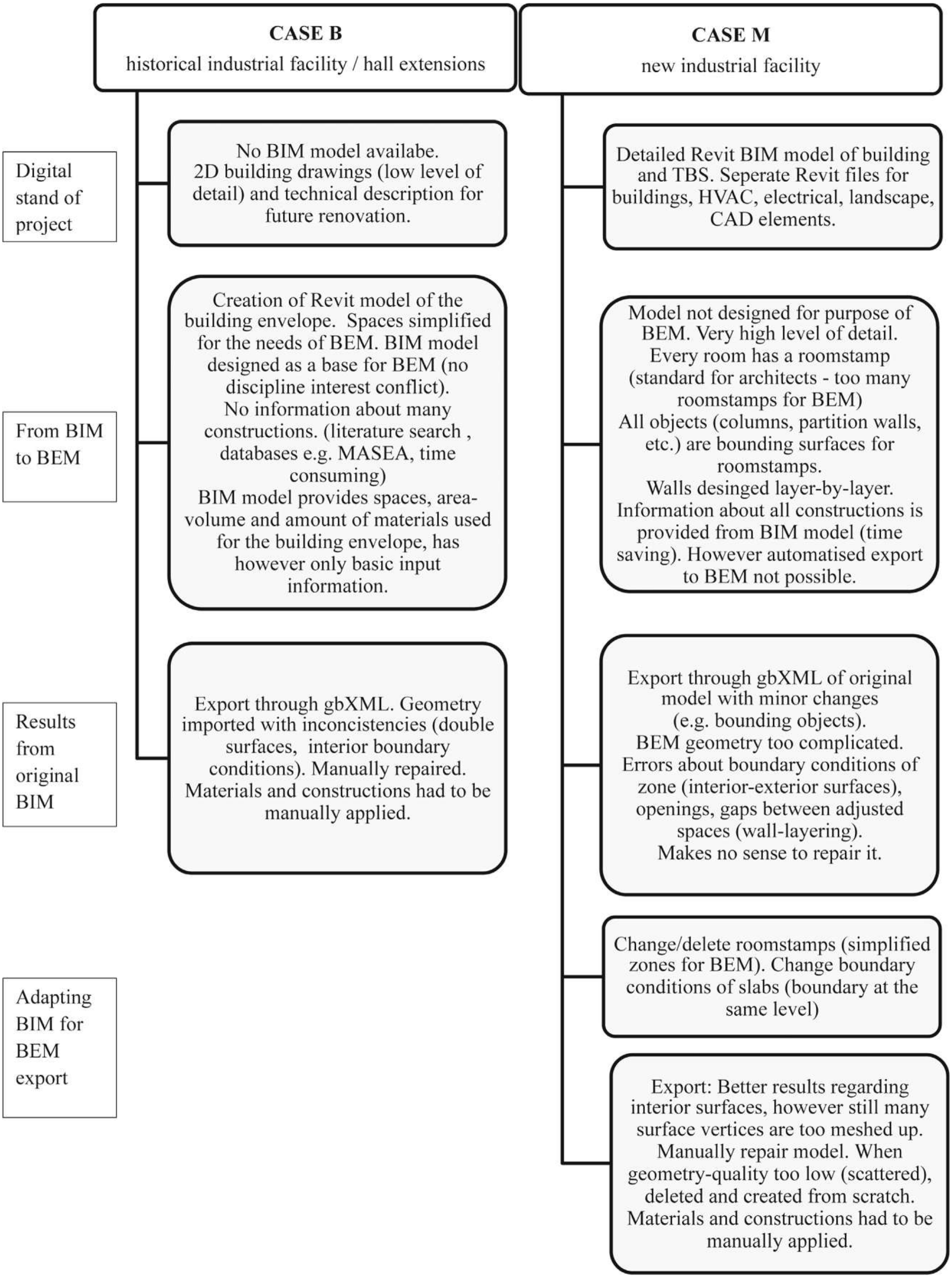
Full potentials for BIM as industrial facility management tool lie however in the integration of several systems – building models, HVAC, equipment and infrastructure, which again call for a possibility of coupling several software-platforms, such as CAD, ERP, GIS, and equipment-CAD.

In this paper a BIM for BEM workflow for design and optimisation of industrial facilities was demonstrated and evaluated. Thereby advantages of a modelling-process, where requirements for BEM were known from the beginning of the design and the modelling was made by “one hand” were identified. When this is not the case, but different planning process stakeholders are involved in the creation and subsequently in the analysis of a building model without previous coordination of modelling standards, as currently is the practice, the result is additional re-modelling or even creation of a new BEM model. Such process is time intensive and prone to errors, and is also contributing to the reluctance of both planners and investors to adopt the building performance analysis and thermal simulation as standard design-optimisation procedure.

Through application of 3D BIM modelling in design of industrial facilities, and follow up BEM modelling and energy analysis, energy performance of the building can be assessed and optimised. Coupling of 3D information rich building and HVAC models with further models such as machines and production systems allows a more holistic energy analysis and simulation, which can provide up to 50% savings in over-all energy consumption of industrial facility [39].

Sustainability assessment (6D BIM) – life-cycle assessment and life-cycle costing are further benefits of BIM application in the design phase. Parametric modelling of building elements and components enables inclusion of cost or environmental indicators, allowing an automated life-cycle costing or life-cycle assessment and calculation of materials CO_2 footprint as well as grey energy. Regarding the longest life-cycle phase of a facility operation, in the current practise actual knowledge of the building and its infrastructure is mostly bound to the person of the facility manager. Through creation of a BIM model, the facility is well documented, and possible energy retrofit measurements can be carried out with higher cost and time efficiency.

The path towards successful BIM adoption for design-optimisation, but moreover for life-cycle management in the industrial construction will have to address problems on the process-design level, beside the technology related issues; especially in the industrial context where due to the very large number of process stakeholders there will always be a very heterogeneous software



No BIM model availabe. 2D building drawings (low level of detail) and technical description for future renovation.

Detailed Revit BIM model of building and TBS. Seperate Revit files for buildings, HVAC, electrical, landscape, CAD elements.

Creation of Revit model of the building envelope. Spaces simplified for the needs of BEM. BIM model designed as a base for BEM (no discipline interest conflict). No information about many constructions. (literature search , databases e.g. MASEA, time consuming) BIM model provides spaces, area-volume and amount of materials used for the building envelope, has however only basic input information.

Model not designed for purpose of BEM. Very high level of detail. Every room has a roomstamp (standard for architects - too many roomstamps for BEM) All objects (columns, partition walls, etc.) are bounding surfaces for roomstamps. Walls desinged layer-by-layer. Information about all constructions is provided from BIM model (time saving). However automatised export to BEM not possible.

Export through gbXML. Geometry imported with inconcistencies (double surfaces, interior boundary conditions). Manually repaired. Materials and constructions had to be manually applied.

Export through gbXML of original model with minor changes (e.g. bounding objects). BEM geometry too complicated. Errors about boundary conditions of zone (interior-exterior surfaces), openings, gaps between adjusted spaces (wall-layering). Makes no sense to repair it.

Change/delete roomstamps (simplified zones for BEM). Change boundary conditions of slabs (boundary at the same level)

Export: Better results regarding interior surfaces, however still many surface vertices are too meshed up. Manually repair model. When geometry-quality too low (scattered), deleted and created from scratch. Materials and constructions had to be manually applied.

Fig. 8. Mistake Tree – recording the modelling process and transfer from BIM to BEM.

landscape using different data formats, granularity etc. The rethinking of the process can lead towards adoption of an actor network perspective, which is confronted with creation of new routines and relationships initiated through use of BIM [81] as well as establishment of enterprise-aims and abilities (e.g. delivering BIM-FM service) based on individual competencies [82].

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Paper 2

Georgios Gourlis and Iva Kovacic

"A study on building performance analysis for energy retrofit of existing industrial facilities"

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A study on building performance analysis for energy retrofit of existing industrial facilities

Georgios Gourlis [*], Iva Kovacic

Department of Industrial Building and Interdisciplinary Planning, Faculty of Civil Engineering, Vienna University of Technology, Karlsplatz 13/234-2, 1040 Vienna, Austria

HIGHLIGHTS

- Thermal simulation of a historical industrial hall with limited data availability.
- Considering waste heat from machinery after measuring production fluctuations.
- Test of retrofit alternatives for roof and skylights.
- Results indicate a significant reduction in heating energy demand up to 52%.
- After retrofit naturally ventilated hall can achieve thermal comfort in summer.

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Overheating

ABSTRACT

Due to the strengthening of regulations and codes on building energy performance, as well as with the application of national legislations regarding energy management and efficiency, existing industrial facilities are using thermal refurbishment and renovation as impetus for increasing their overall energy efficiency. This paper analyzes a building envelope refurbishment for a case study of an existing historical industrial facility. Critical parameters affecting energy performance of industrial buildings were identified by reviewing relevant literate. Two retrofit scenarios were developed and dynamic thermal simulation using EnergyPlus was implemented to evaluate the potential for improvement. Thereby the impact of interior loads was considered, determined by measurements conducted on factory machines, occupancy and lighting operation patterns. However, information regarding constructions of the existing facility and installed technical building services is limited. There is also uncertainty in the quantification of natural ventilation air change rate for such buildings. To overcome these limitations a study of various material databases was carried out, in order to assess data for building envelope composition. Input values for missing data were provided based on literature, allowing a fair comparison between refurbishment alternatives. Simulation results showed that the heating demand of the facility could be reduced up to 52%, indicating a significant potential for energy savings. Beyond that, thermal performance against summer overheating also depicted considerable improvements as regards to hours exceeding thermal comfort levels.

1. Introduction

The industrial sector is one of the largest energy consumers reaching 25.6% of the total energy consumption in Europe in 2012 [1]. Apart from the energy used by manufacturing procedures, production facilities also consume considerable amounts of energy for building conditioning. The strengthening of regulations and codes on building energy performance [2], increasing energy costs, as well as the adoption of the ISO 50001 standard on energy management systems by national legislations in order to promote energy efficiency [3], lead existing industrial facilities to use thermal refurbishment and renovation of the building envelope as impetus for improving their overall energy competence.

A leading edge practice in building refurbishments implements dynamic model-based energy simulation tools for estimating energy savings from retrofit alternatives [4], in particular, when this is applied in the early design stages of the process to size the influence of refurbishment measures [5]. Furthermore it should be mentioned that BIM is increasingly used in combination with energy modeling tools [6], serving as knowledge database for

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[*] Corresponding author.
E-mail addresses: georgios.gourlis@tuwien.ac.at (G. Gourlis), iva.kovacic@tuwien.ac.at (I. Kovacic).

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Nomenclature

ACH	Air Changes per Hour
BIM	Building Information Modeling
CIBSE	Chartered Institution of Building Services Engineers
Dfb	Humid continental climate
DoE	United States Department of Energy
EPS	Expanded Polystyrene
gbXML	green building Extensible Markup Language schema
GFA	Gross Floor Area
HVAC	Heating, Ventilation and Air Conditioning
ISO	International Organization for Standardization
PU	Polyurethane
T_{max}	maximum acceptable operative temperature, °C
T_{op}	actual operative temperature, °C
T_{rm}	running mean outdoor temperature, °C
ΔT	difference between actual and maximum operative temperature, always rounded to the nearest whole degree

necessary information input; an approach also followed in the current research. Potential of BIM use in building refurbishment is reviewed in [7]. Authors state that BIM should be applied from the early stages of a project and that it can assist environmental performance analysis of design alternatives; however solid framework about the process is lacking. Conversion of available data to semantic BIM objects requires high modeling effort and expertise, thus BIM is seldom applied in existing buildings yet [8].

Conducted energy retrofit studies have mainly focused on buildings of the residential [9] and tertiary sector [10]; fields where researchers have achieved significant advancements in developing models and frameworks for identifying the most effective thermal building envelope refurbishment and systems upgrade options. Sophisticated tools have been proposed for thermal optimization and refurbishment of office and commercial buildings. Based on standardized data for such building types, benchmarking values and pre-simulated results a web-based toolkit enables fast calculation of retrofit alternatives and evaluation of multi-criteria parameters like energy and costs savings [11], while another software solution provides information based on a matrix of retrofit measures and economic uncertainty scenarios [12]. Industrial facilities, on the other hand, are seldom studied under an energy retrofit perspective [13], with efforts focusing on thermal envelope when structural upgrades are compulsory [14] or on installed technical building services when these are identified as inefficient, e.g. heating [15], ventilation [16]. Industrial heritage has also been studied under an energy retrofit perspective, however mostly concerning ex-industrial facilities and their transformation to other uses as housing [17], or mixed-use developments [18].

State-of-the-art approach in building refurbishment requires detailed monitoring and in-situ investigation of the pre-renovation state in order to calibrate the simulation models [19] and so enable reliable evaluation of different retrofit alternatives, related to envelope thermal properties [20]. Especially in the case of historical buildings, extensive examination of the building fabric is mandatory as each case is unique and therefore poses challenges in defining a solid model for energy performance assessment [21]. However implementing this approach is not always feasible. When information is lacking, a common alternative is the use of industry standards for construction materials and systems at the time of a building's construction [22], together with referential values on typical energy performance for buildings of that type. As regards industrial buildings, large-scale building monitoring and measurements necessitate special equipment, resulting in important investments [23]. Data unavailability is also enhanced by the fact that many companies do not track their energy consumption, thus lacking awareness of their energy needs on individual systems [24]. Consequently, the high complexity in terms of energy supply and consumption as well as diverse building typology of industrial facilities makes it difficult to define benchmarks for energy performance comparison.

Even with calibrated building energy models, predicting energy savings with simulation tools has received critique as in many occasions fails to integrate the role of occupants' behavior as an imponderable factor on the end energy performance [25]. It can be contented that in industrial facilities equipment and machinery are a substitute for this uncertainty factor, as according to Vaghefi industrial loads are often extremely large, non-stationary with random fluctuation over time [26], while thermally contributing to the indoor climate. One of the rare occasions when industrial production process energy consumption benchmark values are provided is in CIBSE Guide F [27]. However the diversity of machinery setups, based on production capabilities and needs, among facilities operating in the same industry branch, makes the use of such referential values in case of industrial building refurbishments inconsistent, as they may not comply to reality. A parametric simulation study about the impact of process loads and occupancy patterns on annual energy demand of a simple hypothetical industrial building observed that the optimum building envelope can differ according to manufacturing conditions, with actual heat emissions, air change rates and daylighting controls having a great influence on the energy performance [28]. Furthermore, on the case of an existing industrial hall in Slovakia, analysis of thermal energy demand and saving potential via measurements, static calculations and dynamic simulations also showed that real interior gains from machinery are crucial for realistic modeling of the building [29]. It is thereby illustrated that thermal simulation of industrial facilities is highly case oriented. Nonetheless, through analyzing research conducted on case studies, parameters affecting energy performance can be identified.

As regards thermal envelope refurbishment, a European research project, including studies on renovation strategies of existing industrial buildings using steel-based technologies, employed thermal simulations and experimental "before and after" measurements (e.g. air tightness tests, wall thermography) to derive empirical relationships for the energy demands of industrial facilities [30]. Results of typical 1960's/70's halls in the UK showed that U-value improvement of roof elements had higher impact on the energy demand compared to wall elements and together with upgraded skylights and gutter U-values reduced energy consumption by 49% compared to "before renovation". Mastrapostoli et al. [31] also pinpointed roof's significance as cool roof coating essentially decreased summer cooling loads by 73% with a minor heating penalty for an industrial building in the Netherlands.

Moreover, daylight potential of roofs is recognized as regulatory factor of industrial building energy performance. Chen et al. [32] implemented in-field measurements and simulation models on a single floor factory with a hackle-shape roof in China, where daylighting control showed large energy savings in electrical lighting consumption. Wang et al. [33] in the case of a large workshop with skylights, also in China, developed a solution for lighting control based on a sensor network, realizing lighting energy savings of up to an average of 80% on cloudy days. Furthermore, for a light steel structure industrial shed in the UK, complying with local building regulations, researchers studied the influence on energy performance and space overheating when introducing skylights and proposed that unwanted summer solar gains could be remedied by the application of ridge natural ventilation [34]. Brinks et al. [35] indicate that for such light steel constructions, typical for new industrial buildings, summer overheating is a minor problem in Central European climate. This however is depending on machinery internal loads as well as orientation and surface of glazed surfaces.

Taking aforementioned into account, a gap was identified in exploration of thermal refurbishment strategies for existing industrial facilities in operation with actual production process loads. Therefore, this study presents a novel approach to assess the improvement potential on energy consumption and indoor climate of historical industrial halls in operation through application of dynamic thermal simulation modeling. The paper is structured in three more sections. In Section 2 the case study and method for compiling the factory thermal model are thoroughly presented while results of thermal retrofit measures on energy and thermal performance are evaluated in Section 3. Section 4 summarizes the main conclusions and highlights further development needed.

2. Method

For the analysis and simulation of building performance, a case study method is used. A dynamic thermal simulation is carried out using EnergyPlus v8.1 [36], a validated whole building simulation software developed by DoE [37].

A detailed hourly weather file from Meteonorm 7.0 is used, providing data for a typical year [38]. The energy consumption of the facility including heating demand, lighting, machinery and electric equipment is hourly calculated and aggregated on annual level. To carry out the simulations, due to lack of available data, assumptions regarding referential values are assessed and a sensitivity analysis of internal gains due to manufacturing process is undertaken. Thermal performance regarding summer overheating is tested under the adaptive comfort approach of the European standard EN15251. The standard uses on an exponentially weighted running mean of the outdoor temperature and indicating that comfort range relates to a person's thermal history with more recent experiences having a higher influence [39].

2.1. The case study

The case study focuses on an existing single-story industrial facility, operating in the sector of metal processing, categorized as light manufacturing industry and located in Berndorf, Lower Austria. The building measures a gross floor area of about 20,000 m^2 and is illustrated in Fig. 1. The climate of the region is cold in winter and relatively warm in summer, with precipitation throughout the year and significant rainfalls in summer, classified as Dfb according to Köppen and Geiger [40]. Average temperatures in winter are around 0 °C with a minimum of -12 °C and in summer temperature ranges from 15 °C to 25 °C, rising occasionally above 30 °C [38].

Recorded often as a common practice in industrial buildings, the manufacturing hall that stands today is a result of multiple expansions to a 1920's historical industrial hall as well as the attachment of a neighboring old hall. It has a length of 280 m and a maximum width of 80 m divided in six spans with varying widths from 11.4 m to 15 m, covered by pitched and shed roofs. Hall heights are also varying from 6.5 m to 13.4 m. The building is oriented along the west-east axis. There is a clear distinction in terms of building envelope constructions between the west old and the newer east part. Thick brick masonry walls and uninsulated roof skin (wood sheathing and bituminous layer) versus insulated metal cassette walls and sandwich roof panels respectively. The steel structural system of the roof also depicts this difference, on one side bulky old trusses and on the other a modern framework. The space where most of the production occurs is a single extensive 13,470 m^2 hall (Area 1, 2) spreading along the whole building, the rest are separate workshops and smaller manufacturing spaces as well as storage and some office areas.

The factory is naturally ventilated, uses ceiling radiative panels for heating in the production halls and workshops, fan heaters in storage areas and radiators in offices; no mechanical cooling system is installed. Furthermore, there are neither building automation systems nor an energy management and monitoring system installed.

An extensive refurbishment is planned for the historical west part of the facility, including a partial expansion, new fenestration and structural-thermal retrofit of the roof skin and skylights. The effect of the roof on the energy performance of the old part is crucial since it covers 82% of the external building envelope area in comparison to 18% of exterior facade.

2.2. Building model

A base case model of the existing building was created in BIM software to serve as a knowledge-database for further analysis providing among other information about material types and quantities. Construction data from available floor plans were used; however in some cases these were lacking details and on site auditing was carried out to complete them. Although the refurbishment concerns the old west part of the building, the whole facility was modeled to analyze its effects on the total energy performance, as the main production hall extents along both the older

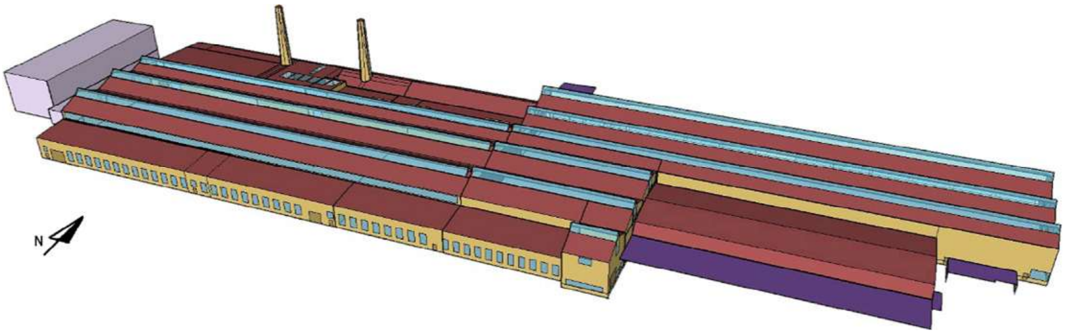

Fig. 1. 3D model of the facility.

Table 1
Building elements *U*-values.

Building elements	W/m^2 K
U-value roof old part	1.64
U-value roof newer part	0.33
U-value wall old part	0.83
U-value wall newer part	0.35
U-value floor	0.8
U-value skylights	4.7
U-value old windows	5
U-value new windows	1.2
U-value doors	2.2
U-value sectional doors	2.7

and newer part of the factory. The geometry of the BIM model was exported via Green Building XML (gbXML) format in OpenStudio v.1.5.3 plugin for SketchUp, a tool that has direct connection with the simulation engine of EnergyPlus [41].

Semantic material properties (e.g. thermal conductivity, density and specific heat capacity of construction layers) were collected from the database of Archiphysik 11 building energy certification software [42], which is based on Austrian regulations and standards, as well as from the online databases Baubook [43] and MASEA [44]. The MASEA database was specially used for the historical part of the facility as it contains data about old material and construction types and was developed to serve as information basis to old building refurbishments. Average *U*-values of the building elements are listed in Table 1.

Due to the lack of detailed information about the roof structural system, as well as machinery sizes and average volumes of metal products present in the building, no additional internal thermal mass of that kind was given as an input. Although a complete model would represent reality more accurate, the amount of internal thermal mass in an industrial building can also vary greatly over different periods, for example storage of raw material and finished goods, thus making it difficult to determine.

The building is divided in seven areas according to building constructions and space usage. Fig. 2 shows the areas marked on the floor plan. Area 1 and 2 corresponds to the main production hall for the old and newer part respectively. Area 3 houses the polishing hall for which an expansion is planned by demolishing most of the existing structure and rebuilding a wider, double height space. Area 4 contains workshops and storage spaces at two levels. Area 5 consists of office spaces and staff services. Areas 6 and 7 are located in the neighboring hall used as a smaller manufacturing hall and a two level storage respectively. Areas 1, 3, 4 and 5 constitute the part of the building under renovation.

2.3. Refurbishment scenarios

Two refurbishment scenarios are proposed for the west historical part of the facility, as presented in Table 2. Expansion of the polishing hall is a prerequisite according to manufacturing needs of the facility and is included in both scenarios. Its new wall construction has an improved *U*-value, 0.23 W/m^2 K, than the minimum required from regulations, 0.35 W/m^2 K [45]. The primary difference between refurbishments scenarios lays in the roof retrofit options. Scenario 1 (S1) insulates the existing roof and maintains its saddle skylights, hence minimizing interruptions in the manufacturing processes beneath due to internal construction works. Scenario 2 (S2) removes the existing construction and uses prefabricated roof elements. It also replaces skylights while modifying their design (raised monitor roof) and reducing their total area (see Fig. 3). No insulating measures are applied on the exterior brick masonry facades, except changing the old windows in the main hall and workshops areas (254 m^2 total window area). A window refurbishment has already been realized in the office area and thus included in the base case scenario.

2.4. Design parameters

Input parameters used for the simulation in this research are defined upon studying the facility in terms of occupancy schedules, manufacturing operating times and building systems availability, in this case lighting and heating.

HVAC parameters: The building is heated from October to April and there is no mechanical cooling system during the summer. Heating temperature set-points for factory and office areas are listed in Table 3. There is no adequate information available about the installed heating systems in order to be modeled in detail. However, since this paper is focused on the energy demand side and the optimization potential of a building envelope refurbishment, heating is simulated under an ideal loads control system. This is the predicted theoretical amount of energy that must be added to heat the facility according to the temperature set-point.

Ventilation and particularly infiltration rates are in practice dominant factors regarding building envelope performance, yet for industrial buildings such rates are difficult to be determined and often require large-scaled equipment. Measurements on case studies in Europe and the US has shown that air tightness can differ between geographical locations, is unrelated to age or construction materials and depends also on the architectural characteristic of a building type [46]. The building shape has a decisive impact on infiltration; large industrial buildings have lower air change rates than small buildings, but increased hall height enhances infiltration due to stack and wind effects [47].

These trends however cannot be generalized, thence defining air change rates for existing naturally ventilated buildings, as the case study, is a challenge. The studied facility has currently no special requirements for ventilation and pollutants removals. Facade and roof openings are operated locally by workers when needed and according to managements observations no ventilation pattern can be assumed. Furthermore based upon production needs

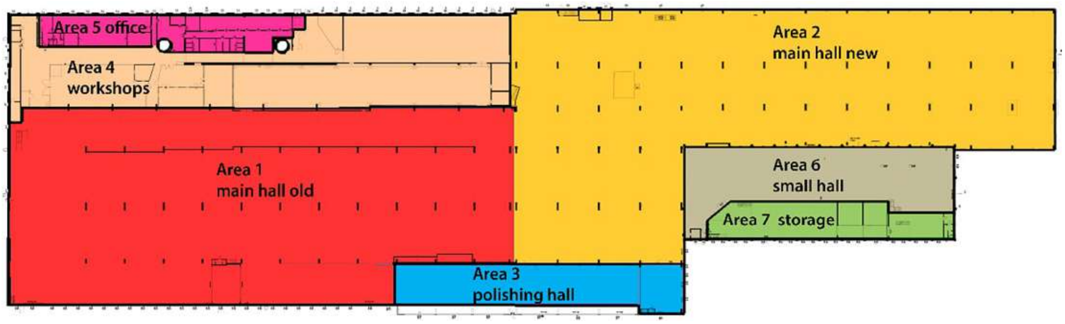

Fig. 2. Areas layout of the industrial facility.

Table 2
Overview of base case and refurbishment scenarios.

	Base Case	S1	S2
Roof retrofit	–	Yes	Yes
U-value (W/m^2 K)	1.6	0.17	0.14
Area (m^2)	11,392	11,392	11,398
Construction	Solid wood sheathing and waterproofing bituminous sheet	20 cm EPS insulation and waterproofing bituminous sheet on existing roof	Lightweight prefabricated roof elements: timber ribs, clad top/bottom, sandwiched 22 cm stone wool insulation
New skylights	–	–	Yes
U-value (W/m^2 K)	4.7	4.7	1.7
Area (m^2)	2307	2307	910
		12% of floor area	5% of floor area
Window renovation	–	Yes	Yes
U-value (W/m^2 K)	5	1.2	1.2
Expansion	–	Yes	Yes

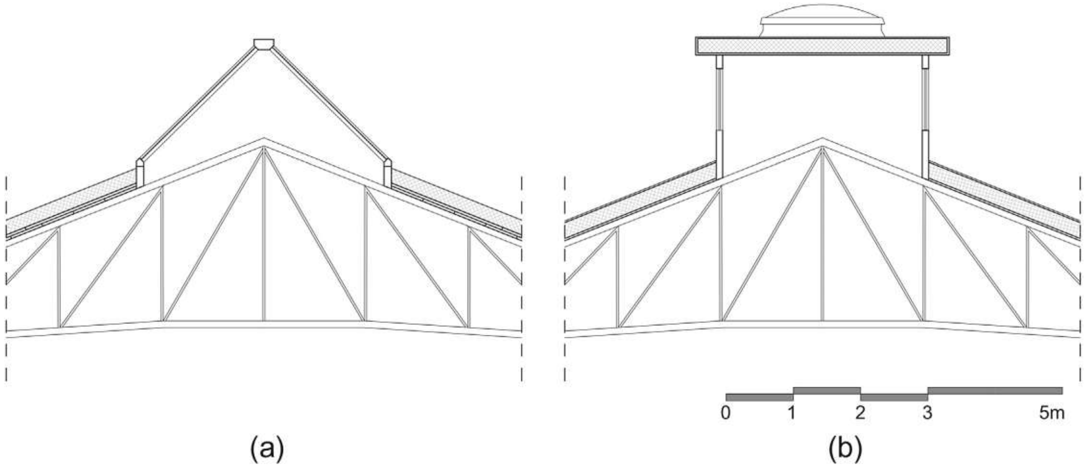

Fig. 3. Skylight design: (a) existing saddle skylights (S1), (b) new monitored roof skylights (S2).

Table 3
Temperature set-points and air change rates.

Heating set-point factory (°C)	18
Heating set-point factory set back (night/weekend) (°C)	12
Heating set-point office (°C)	21
Heating set-point office set back (night/weekend) (°C)	18
Winter air change rate – ACH (h^{-1})	0.2
Summer air change rate – ACH (h^{-1})	1

sectional doors may stay open all year-round for long periods, thus contributing randomly on the hall ventilation. In this paper, infiltration and ventilation for factory areas are assumed as constant effective air change rates, differing in summer and winter, allowing a fair comparison between different building envelope design solutions. For office ventilation, air change rates are scheduled consequent to occupancy. Model input data that pertain to temperature set-points and air change rates are summarized in Table 3.

Internal heat gains: Internal heat gains associated with people, lighting and -particularly important for industrial facilities-machinery and manufacturing processes are taken into consideration. Design parameters are summarized in Table 4.

Occupancy: The facility is set to operate in three shifts during weekdays and in one shift during the weekend. Shift I from 6 am to 2 pm, shift II from 2 pm to 22 pm and shift III from 22 pm to 6 am. Weekdays start with shift III on Sunday night and end with shift II on Friday afternoon. According to a typical week operation schedule there is full complement of workforce in the first shift, 90% in the second and 30% in the third. During weekends the factory operates only in the morning shift with 30% complement. The total number of employees is distributed according to working plan in the facility areas and is assumed to perform medium-light work (225 W per person) [48]. Offices are occupied only on weekdays from 7 am to 7 pm and people are set to perform seated activity (108 W per person) [48].

Lighting: Lighting is modeled according to the electrical plan with suspended fluorescent lamp luminaires of 120 W. It is controlled manually and according to a four week measurement of the lighting distributor, lights in manufacturing halls are always operating on a 24 h basis during weekdays and in the morning shift on weekends. Office lighting is operated upon occupancy only on weekdays.

Machinery: In contrast to other types of non-residential buildings, energy demand of building services concerning heating and cooling in industrial facilities is greatly affected by internal heat gains from machinery and manufacturing processes. There is a lack of empirical information regarding such heat emissions as they may be significantly varying between different industry types. In addition changes in product demand, economic cycles or other seasonal factors can also cause fluctuations in emitted heating loads. A parametric simulation study showed that the amount of process loads in relation to the characteristics of the building envelope, such as degree of insulation, has a considerable influence on the energy performance of a factory [28]. Given the fact that most of electrical energy consumed by a metal processing production machine is transformed into heat as it cannot be stored inside the machine [49], it can be assumed that there is a direct correlation between energy consumption and internal gains from the manufacturing process.

Table 4
Occupancy and internal heat gain rates from lighting and machinery per facility area.

Description		Area 1 main hall west	Area 2 main hall east	Area 3 polishing	Area 4 work-shops	Area 5 office	Area 6 small hall	Area 7 storage
Area (m^2)		6749	6718	874	2685	888[a]	1175	1185[a]
Maximum number of people	Weekday	15	9	2	5	14	3	2
	Weekend	5	3	–	2	–	1	–
Lighting heat emission rates (W/m^2)		8.4	7.2	9.3	7.3	6.2	6.5	3.7
Machinery heat emission rates (W/m^2)		5.4	4.4	1.5	1.7	–	3	–

[a] Area on two levels.

In the present study, energy consumption measurements were performed for a period of a month on the more energy intensive machines in the factory as well as the air compressors. Due to the order based manufacture procedure (production on demand – per order), production cycles and operation schedules are constantly changing, as there are also layoff periods for some machines. The goal of the measurement was to gain insight into operating patterns, serving as input for the simulation, and size the amount of waste heat that is emitted into the hall.

The data analysis showed that there are lots of fluctuations in the production process on a daily and weekly basis, thus making it difficult to define an input schedule. Therefore, two variants were produced based on mean values and tested in the thermal simulation models. The first (Var. 1) calculated mean wattage values for working days and separate ones for the weekends. The second (Var. 2) defined productive and non-productive phases within the days of a week and calculated mean wattage values for the phases. The effect of their heat emissions on the mean air temperature in the main hall areas of the building was tested by simulating a free running mode (no active heating system) for a weekday, where more process loads occur, during extreme outdoor temperature conditions. Both variants led to similar results (see Fig. 4).

For the simulation runs of the different renovation scenarios, Var. 1 was selected as it performed better in terms of computation time. From an average of 21 machines operating in the facility, resulting average values for internal heat gains per area are presented in Table 4.

2.5. Assessing overheating risk

Thermal performance of refurbishment scenarios under a constant ventilation air change rate of 1 h^{-1} is assessed in this study according to EN15251 adaptive comfort model for naturally ventilated existing buildings without mechanical cooling (category III) [50]. Maximum acceptable indoor temperature is calculated as:

$$T_{\max} = 0.33 \cdot T_{\mathrm{rm}} + 22.8 \tag{1}$$

Performance against overheating is evaluated by the number of hours that exceed the upper limit of comfort temperature by one degree or more [51]. Hourly temperature difference is calculated as:

$$\Delta T = T_{\mathrm{op}} - T_{\max} \tag{2}$$

3. Results and discussion

This section presents and discusses simulation results for annual energy demand and summer thermal performance, also comparing them to similar published work on industrial buildings.

3.1. Energy performance

The predicted energy demand of the facility comprises that for heating, lighting and manufacturing process. Fig. 5 presents the predicted annual energy demand of the base case and the two refurbishment scenarios. Input parameters for lighting and production, as described in the previous section, are constant for all cases for the purpose of comparing the effects of the building envelope retrofit. Both refurbishment scenarios are performing better than the base case with the total energy demand being reduced from 2934 MW h to 2479 MW h and 2267 MW h for S1 and S2 respectively, thus by 16% and 23%. Energy required for the production process in this case study is relative low compared to that required from building services. Due to the very strict and specific require-

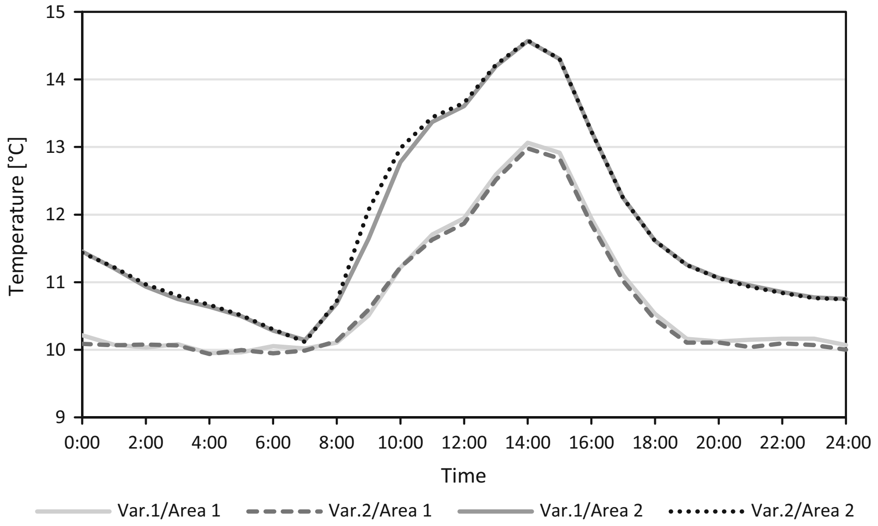

Fig. 4. Main hall temperatures with machinery heat emissions on the coldest winter day.

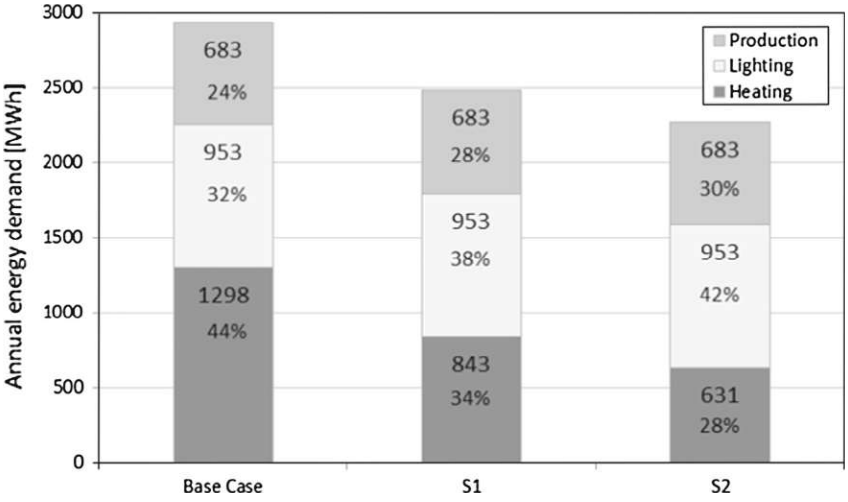

Fig. 5. Facility annual energy demand.

Table 5
Annual energy saving for heating.

Scenario	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Area 7	Total facility
S1	30%	4%	21%	62%	27%	0%	0%	36%
S2	73%	9%	23%	69%	31%	0%	0%	52%

ments for steady illumination of the manufacturing areas, lights are continuously switched on during the working shifts. Simulation results show that lighting needs after renovation become the largest energy consumer, hence holding a considerable potential for further improvement of the overall energy performance.

Refurbishment measures (roof insulation, window renovation) improve the heating energy demand in both scenarios. Contrary to S1, which preserves the extensive area of continues saddle skylights of the base case; S2 features a smaller area of new skylights with better thermal performance and raised monitor roof design. Whereas both new roof constructions have relatively same *U*-values (0.17 W/m^2 K for S1 and 0.14 W/m^2 K for S2), S2 results in a greater reduction in heating demand of 52% (see Table 5), thus signifying the effect of skylights on the energy performance.

Fig. 6 and Table 5 show the annual heating demand and percentage savings per facility area as well as in total. Direct advantages are reported for renovated Areas 1, 3, 4 and 5, a slight improvement in the east newer part of the main hall (Area 2) and no effects on the neighboring building (Areas 6, 7). Although the polishing hall (Area 3) has lower heating demand in both refurbishment scenarios, results cannot be compared with the base case as in both variants its volume has increased due to the expansion. The refurbished part of the main hall (Area 1) depicts the highest difference on the effects of S1 and S2. Hence being the building area with the highest internal heat gain rate, insulating the roof and furthermore dramatically improving the heat loss from skylights in S2 results to only a quarter of the initial heating demand. For workshops and offices (Areas 4 and 5), S1 and S2 display a relative similar percentage savings in heating demand, which for the

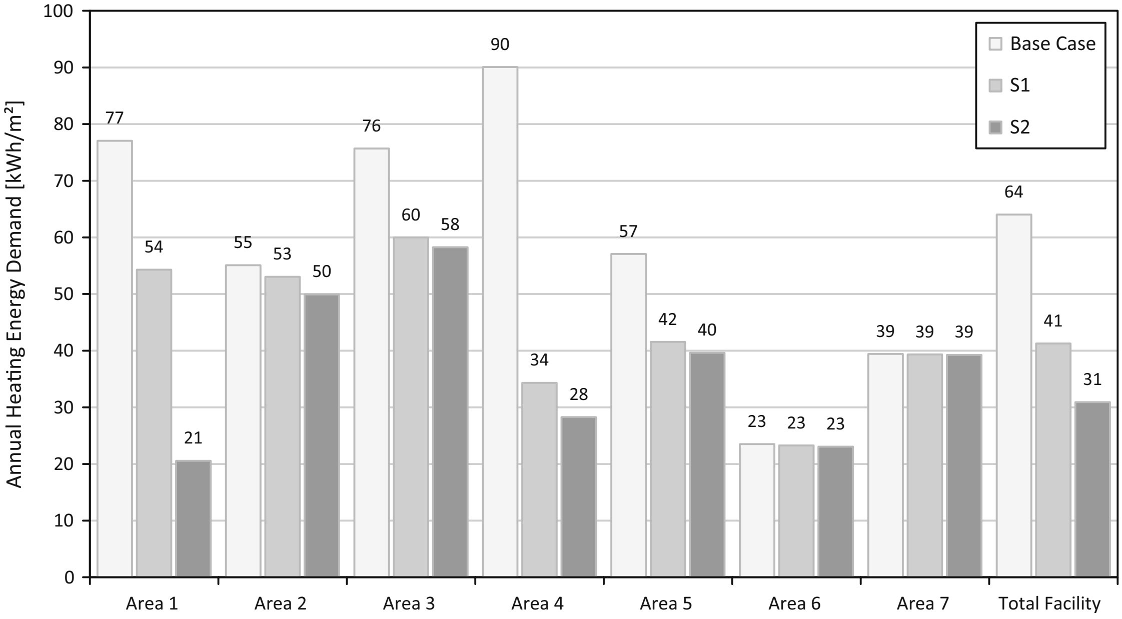

Fig. 6. Annual heating energy demand per facility area.

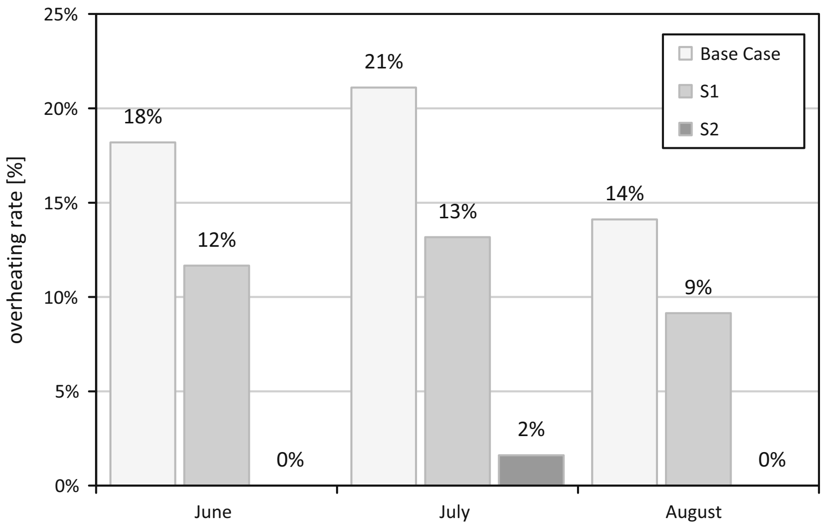

Fig. 7. Overheating hours of Area 1 during the summer months.

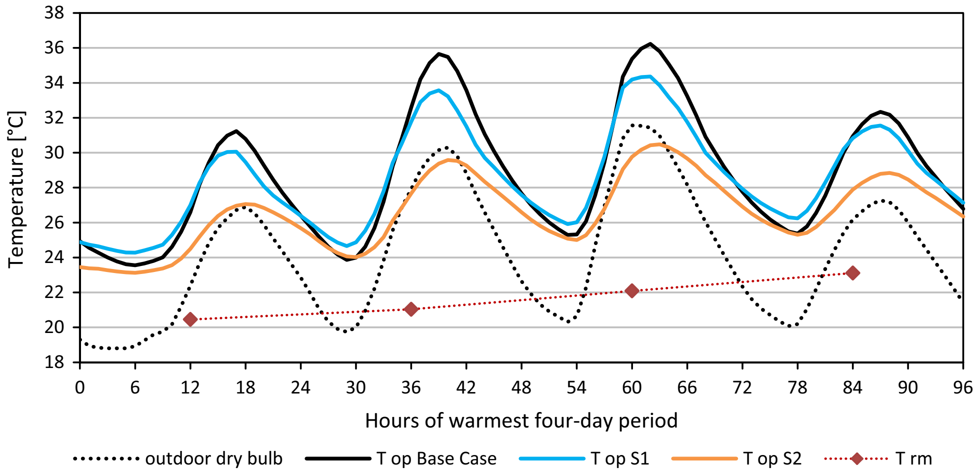

Fig. 8. Thermal performance of Area 1 during the warmest four-day period.

first ranges around 65% and for the second 29%. The significant reduction in the workshops area results from the improvement of the roof insulation, as there are no large skylights present. Offices (Area 5) are a compact space compared to the other facility areas and the reduction in their heating demand is mostly caused by the improvement of the thermal performance of its neighboring workshops area (Area 4).

3.2. Thermal performance against overheating

The thermal performance of both refurbishment scenarios is tested to highlight their potential against summer overheating. Hours that exceed the upper limit of indoor comfort temperature (T_{max}) are calculated per summer month for the base case and refurbishment scenarios. Fig. 7 shows a comparison for the west part of the main production hall (Area 1), where S2 achieves an impressive reduction. To further investigate the thermal performance of the retrofit alternatives, a four-day period is selected, when overheating is most likely to occur. During this period outdoor temperature is 89% of the time above 20 °C, even at nights, reaching a maximum of 31.5 °C. Fig. 8 and Table 6 present the results of the test. In reference to the base case, S1 manages to reduce indoor operative temperature at daily peaks by a maximum of 2.3 °C but results to increased values during early morning hours. S2 shows a mean reduction in operative temperature of 2.1 °C from the base case, compared to only 0.2 °C of S1 and performs much better at peaks. Critical factor for the significantly improved indoor conditions in S2 is the renovation of the roof skylights. Whereas in S1 skylights geometry admits daylight from above, performing as horizontal glazing, in S2 daylight comes from vertical north and south orientations, hence improving overheating conditions [35]. Consequently, the use of glazing with lower thermal transmittance and the new skylight design, which also reduces the total transparent roof surface area, provide an acceptable indoor climate during the studied period.

Table 6
Operative temperature reduction in reference to base case and overheating hours.

	Base case	S1	S2
Mean temperature reduction	–	0.2 °C	2.1 °C
Maximum temperature reduction	–	2.3 °C	6.3 °C
Hours exceeding T_{max} ($\Delta T \geqslant 1$)	28	18	0

3.3. Comparison with other studies

Results of this study are compared with similar published work on industrial buildings as shown in Table 7. Although each case is unique, interesting relations can be observed. All buildings are single-story facilities with skylights; however areas of transparent surfaces are varying. Other diverse factors are the local climate, building geometry and orientation, thermal envelope construction types, operation schedules and levels of internal heat gains, as well as different air tightness and ventilation states, something which has great impact on heating and cooling loads. However, all buildings were simulated under natural ventilation, with air heating or cooling systems and no automated daylighting or shading control.

The facility under review in this paper is the only massive construction with extensive use of thick masonry walls. Katunsky et al. [29] is a steel–concrete structure of hollow clay block bricks with poor insulation and large single pane facades. Lawson et al. [30], which is the only example of thermal industrial refurbishment, investigates a non-operating steel frame building with a deteriorated envelope of asbestos cement sheet cladding, missing insulation, with single pane windows and single polycarbonate skylights, also having extreme air leakage due to its degraded status. Renovation completely removed existing cladding and installed new built-up sandwich panel roofing and wall system, double glazed windows, triple layer polycarbonate skylights, as well as new more efficient lighting. The building was also simulated in different locations in the UK. Mastrapostoli et al. [31] study a chemical production and storage shed with plain 15 cm insulated brick walls, 5 cm sandwich roof panels and double windows, results prior to the application of a cool roof which was the focus of the study. Lee et al. [28] and Kovacic et al. [52] are designs for new steel frame industrial buildings. Lee et al. [28] provides the optimum thermal envelope and amount of skylights area for a hypothetical facility with low process loads and constant set-points, 18 °C for heating and a rather high 30 °C for cooling. Results for [52] refer to the actual design of a low-energy new factory, with diverse functions and workshops and constructions with improved thermal properties. Heating and cooling set-point are set at 18 °C and 28 °C respectively, implementing also set back functions.

In the presented case study, for S2 there is a 52% decrease in heating demand, whereas by the industrial sheds in the UK, there is a vast decrease of 88–90%. Nevertheless, actual consumptions after retrofit lie in the same range, much higher than those for new designed facilities. Katunska et al. [14] also report up to 47% energy savings for heating after extensive thermal retrofit, yet energy consumption data are not available, thus not included in Table 7. Juxtaposed with [28], the case study is performing much better even prior to the refurbishment. However no direct comparison is valid, given the fact of high ventilation needs for the building in [31] due to its use, considering also the fact that infiltration of large facilities (over 10,000 m^2) is generally lower than smaller ones [47].

As regards thermal performance, results of the hottest days of S1, where 12% of floor area are skylights, are compared with a similar study for an industrial shed in London, also with 12% of skylights area [34]. Indoor temperature for S1 is 24–34 °C with outdoor being 24–36 °C, while in London indoor temperature is 28–37 °C with outdoor 20–34 °C. Therefore the refurbished case study is providing an acceptable indoor climate for a naturally ventilated building without cooling, in particular when S2 scenario is applied.

Table 7
Energy performance comparison of industrial buildings.

Reference	Location	Year built	GFA (m^2)	Internal gains[b] (W/m^2)	Operation (h/d)	Simulated HVAC	Annual heating (kW h/m^2)		Annual cooling (kW h/m^2)	Annual lighting (kW h/m^2)
						All: natural ventilation	Before existing	After new		
Case study	Berndorf AT	1920's[a]	20,274	11.4	24 h/5 d 8 h/2 d	Air heating	64	31[c]	–	48[c]
[28]	Kosice, SK	x	648	16.85	x	Air heating	62	–	–	x
[29]	Manchester UK	1960's	10,000	Before 16.9 After 14.5	12 h/7 d	Air heating	240.4	29.3	–	Before 46.5
	Glasgow UK						307.3	39.1	–	After 39
[30]	Oss, NL	1997	1685	28.7	x	Air heat./cooling	139	–	9.7	x
[27]	Amsterdam NL	New	4000	21	24 h/7 d	Air heat./cooling	–	2	10	104
[52]	Vienna AT	New	14,373	17.6	24 h/7 d	Air heat./cooling	–	8	52	x

x – Unknown value.
[a] Built in phases – additions to a 1920's hall (30's, 80's, 90's).
[b] Area weighted gains for equipment and lighting of production halls – no office areas included.
[c] Results for S2 refurbishment scenario.

4. Conclusions

Achieving overall energy efficiency in industrial buildings demands concurrent assessment of the synergy effect of production processes, technical building services and the building itself. In the course of this paper, potential energy savings of existing industrial facilities were investigated through case study analysis on the thermal refurbishment of a historical production hall. In literature, such buildings have been studied under an energy retrofit perspective, however mostly in the context of transformation-process of industrial heritage to other uses as housing or commerce. The presented study focuses on a factory building in operation, describing the steps for creation of its thermal model by applying a BIM to BEM approach, along with challenges met in the process. Actual process loads were taken into account in a simulation-based assessment of retrofit alternatives, providing a more realistic model. Contrary to other non-residential buildings, thermal simulation of industrial facilities requires accurate information about waste heat emissions from machinery for a reliable estimation of their energy performance. For a light manufacturing facility though, fluctuations of operating patterns have less impact than expected on building thermal performance.

The improvement of the building envelope through application of following measures: insulated roof and replacement of windows and skylights; resulted in a significant heating energy demand reduction for the facility by 52%. Comparison of retrofit scenarios also highlighted that roof design, as regards skylights, has a great influence on building performance and should be taken into consideration in industrial refurbishments. Overheating analysis, tested during the warmest summer days, indicates that the thermally refurbished naturally ventilated historical industrial hall can achieve acceptable levels of thermal comfort by diminishing indoor temperature peaks up to 6 °C.

Provided that production needs can be successfully addressed, revitalizing existing industrial building fabric, besides energy efficiency, promotes the goal of resilient infrastructure by extending its life-cycle [53]. The findings of this study will prompt industrial facilities to consider the effect of the building envelope on their overall energy performance, especially when structural retrofit is mandatory.

4.1. Future research

Our future efforts will concentrate on further verification of the simulation outcome; to this end data loggers are installed in the facility collecting indoor climate condition data in order to calibrate the model and document "lessons learned". Also, as this study identified large optimization potential for electrical lighting, implementing automated daylight and shading control strategies will provide a more comprehensive view in how to achieve energy efficiency in industrial building refurbishments.

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Paper 3

Georgios Gourlis and Iva Kovacic

"Passive measures for preventing summer overheating in industrial buildings under consideration of varying manufacturing process loads"

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Passive measures for preventing summer overheating in industrial buildings under consideration of varying manufacturing process loads

Georgios Gourlis*, Iva Kovacic

Department for Industrial Building and Interdisciplinary Planning, Faculty of Civil Engineering, Vienna University of Technology, Karlsplatz 13/234-2, 1040, Vienna, Austria

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A B S T R A C T

Industrial buildings implement retrofit measures to reduce energy demand for space conditioning, with primary focus given to heating loads, as they often lack cooling systems. An optimized refurbishment should be able though to tackle summer overheating, since studies indicate an increase in the frequency and intensity of hot days during summer. Furthermore production fluctuations have an impact on manufacturing process loads and thus internal heat gains, affecting building performance. If production levels alter in the long term, an initially satisfying option may fail to respond to the future conditions. This paper presents retrofit alternatives for a case study in Austria. A thorough picture of the initial state was achieved by measurements of indoor climate conditions. Based on a calibrated dynamic thermal simulation model, optimization measures and natural ventilation patterns were tested under current production levels and hypothetical future scenarios for their adequacy to minimize overheating without the installation of an active cooling system. Results were classified and evaluated by adaptive comfort and workplace regulation criteria, while differences between the two approaches were discussed. There are measure constellations diminishing overheating risk for all internal heat gain conditions, whose applicability can adapt to the prevailing needs of the facility at the time.

1. Introduction

Overheating in buildings is a critical source of concern among the building industry, especially for existing constructions that were not designed to cope with the challenges of climate change. Indoor thermal environments are going to be affected by global warming and the predicted increase in the frequency of hot days, as well as intensity and duration of global heatwaves [1]. Warmer summers are expected in central Europe [2] and today's extreme conditions in southern Mediterranean regions may be the norm in the next decades of the century [3]. Moreover, it is shown that excessive heat while working, generally above 30 °C, creates health risks and reduces work capacity and labor productivity [4]. In manufacturing or warehouse environments, heat stress poses an occupational health hazard and an economic threat, as it has negative effects on workers, production levels and even the quality of produced or stored goods [5]. Predictive models suggest that productivity may decrease globally by up to 20% in hot months by 2050 [6]. Central European regions will also be affected [7].

The strengthening of regulations and codes on building energy performance drives existing industrial buildings to implement retrofit measures in order to reduce energy demand for space conditioning, with primary focus given to heating loads, as in many cases factories are not equipped with mechanical cooling systems. Even workplaces where high temperature manufacturing processes occur, as hot steel beam manufacturing plants, lack this kind of systems [8]. In such free-running buildings though, during the non-heating season avoiding thermal discomfort is the key issue in contrast to energy use, since they use little or no energy to regulate indoor conditions. Typical passive cooling strategies are the opening of doors and windows to move more air through the workplace, sometimes assisted by the use of fans, given the fact that there are no special requirements of indoor air quality concerning contaminants or dust levels that could cause damage to products or precision manufacturing machinery.

Building performance regarding overheating has been mainly studied in the residential sector as well as in offices. Overheating in UK passive-house standard social housing was explored by [9] and

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* Corresponding author.
E-mail addresses: georgios.gourlis@tuwien.ac.at (G. Gourlis), iva.kovacic@tuwien.ac.at (I. Kovacic).

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their future performance by [10]. Risks in future climates have been also investigated in Scandinavian dwellings [11], as well as in multiple European locations under the adaptive approach [12]. Jenkins [13] developed a probabilistic tool for assessing future climate overheating risk tested for building of domestic and educational use. Ascione et al. [14] studied solar shading strategies for reducing summer overheating in a modern well-insulated multi-story office building in Berlin, while [15] analyzed cool coated shading systems used in housing. In terms of energy refurbishment measures, [16] showed that improvement of air tightness and increased floor insulation in single family houses in moderate climates mainly focused on heating energy savings may increase overheating risk and appropriate ventilation rates, shading and glazing with lower g-values should be considered.

Further than improving occupants' thermal comfort, building-related passive measures contribute in reducing necessary energy loads. Hiyama and Glicksman [17] studied how natural ventilation air change rates reduce cooling loads while improving office space thermal comfort among different climatic conditions in the US, considering different internal gains scenarios. van Hooff et al. [18] showed that passive measures along with appropriate natural ventilation largely reduced cooling energy for a typical Dutch terraced house. From a large scale perceptive, [19] investigated the influence of natural ventilation techniques for cooling of the residential sector in Mexico finding considerable fossil-fuel-based energy reductions and thus decrease of CO_2 emissions of the country's energy system.

In the context of industrial buildings though, studies on work-space indoor climate and overheating are limited. Under the perspective of reducing cooling loads, a cool roof application on an industrial building was tested in the Netherlands [20], while overheating was evaluated for the rooflight area of a modern industrial shed in the UK in regard to electrical lighting savings [21]. In case studies under hot-humid climate conditions, the potential of passive cooling strategies to improve thermal comfort conditions of workers was addressed in Colombia [22], and poor thermal performance was observed in a garment factory with low quality building envelope in Bangladesh [23]. However the dynamic nature of industrial buildings is not taken into account in previous research efforts. This would include a consideration of the fact that due to production demand fluctuations or change of manufacturing equipment internal heat gains in the building may alter and initially satisfying measures to improve indoor microclimate may fail to respond to future conditions.

This paper presents an ongoing research within the project "BAMA: Balanced Manufacturing" funded by the Austrian research agency, and builds up upon the analysis on retrofitting measures to existing, historical industrial facilities, presented in [24]. Focus of this paper is the development and analysis of stepwise building-related passive optimization measures and natural ventilation scenarios for improvement of the indoor climate and reduction of summer overheating causing thermal discomfort, thus enhancing workers' fatigue risk. These are evaluated under varying manufacturing process load levels for a case study of a historical industrial facility in Austria. Goal is to examine the feasibility of such measures to tackle overheating risk without the installation of mechanical cooling system, thus preventing an increase of the facility's energy demand. After reviewing thermal comfort models and overheating benchmarks two methods are utilized for assessing results of a calibrated thermal simulation model. Results of 120 simulated alternatives are classified according to levels of production and in addition uncertainties regarding assessment criteria are discussed. Finally suggestions are made considering suitable retrofits according to the prevailing needs of the facility at the time, hence supporting decision making for a more cost-effective initial investment.

2. Thermal comfort and overheating

In this chapter the most commonly applied thermal comfort models and overheating evaluation criteria are presented and discussed.

2.1. PMV/PPD model

The most influential model for assessing thermal comfort has been the one based on the work of Fanger, who introduced the Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD) indices [25]. According to Fanger, factors affecting the sense of comfort are the level of activity, the amount of clothing, the air temperature, the mean radiant temperature, the air humidity and the air velocity. Further physiological factors as skin temperature, heart rate variation and electroencephalograph are investigated in advanced thermo-physiological models in order to assess human thermal sensation [26,27], however such parameters are still on a research level and not used in daily design practice of built environments.

ISO 7730 implements the PMV/PPD model referring to mechanically conditioned buildings, rating their thermal environment as quality A, B or C according to the degree of individual control on indoor temperature, with A representing less control options and being superior to the other [28]. Although comfort limits depend on building types and use, the Standard generally considers operative temperatures over 26 °C in summer as too warm and uncomfortable, however industrial spaces are not listed among the building types.

2.2. Adaptive comfort model

The adaptive approach is based on the principle that people are not passive receptors of their thermal environment, but continually interact with it [29]. It is now regarded as the standard approach to evaluate thermal comfort in naturally ventilated buildings, where indoor conditions are less easy to control. Moreover, it has been adopted by international standards in Europe - EN 15251 - and in the United States - ASHRAE Standard 55-2010 [30,31]. The adaptive model relies on actual weather data for defining the outdoor temperature and not on historic monthly means, providing higher variability [29]. According to EN 15251, in free-running non-mechanically cooled buildings (NCBs), where the occupants have access to operable windows and are relatively free to adjust their clothing ensembles, only the operative temperature is considered to define the sense of comfort. Limiting comfort values are determined in terms of allowable deviation of operative temperature from the adaptive comfort temperature and are calculated as a function of the exponentially-weighted running mean of the outdoor temperature. Buildings are classified in four categories, with buildings serving sensitive occupants having a narrow acceptable temperature range and further categories applying to spaces for occupants with normal and moderate expectations (Table 1). EN 15251 is applicable mainly in non-industrial buildings where the criteria for indoor environment are set by the human occupancy and where production processes do not have a major impact on indoor environment.

Based on EN 15251, the Chartered Institution of Building Services Engineers (CIBSE) introduced a method for overheating assessment in Technical Memorandum 52 (TM52) addressing several facets of the problem: number of occurrences, severity and absolute upper acceptability [32]. In comparison to the past CISBE approach [33], where overheating is evaluated only by hours

Table 1
Suggested applicability of the categories of EN 15251 for NCBs.

Category	Explanation	Deviation from adaptive comfort temperature
I	High level of expectation only used for spaces occupied by very sensitive and fragile persons	±2 K
II	Normal expectation for new buildings and renovations	±3 K
III	A moderate expectation (used for existing buildings)	±4 K
IV	Values outside the criteria for the above categories (only acceptable for a limited periods)	±>4 K

exceeding a single limit temperature[1] and is unrelated to building types, the new criteria provide a comprehensive evaluation with acceptable room temperatures related to outdoor climatic conditions and the expectation of occupants of different building categories.

2.3. *Occupational safety and health*

National legislations worldwide set limits to workplace temperatures. According to the World Health Organization suggestions, optimum indoor air temperature should range between 18 °C and 24 °C to avoid health risks for the general population [34]. Examining European legislation, limits are varying on national level, especially those referring to maximum temperatures as people's acclimatization to regional climate is also taken into account. In Germany, maximum workplace temperature should be lower than 26 °C [35], whereas in Austria limit is set to 25 °C [36]. In the UK there is no legislation on maximum safe temperature; however the Trades Union Congress (TUC) has called for a legally enforceable limit at 27 °C for manual workers [37]. However warmer temperatures are acceptable in warmer climates as these of southern Europe. In Greece no set limit is applied as legislation only states that workspace temperature must be in accordance to the physical effort demanded. Only in case of strenuous outside activities, a work halt is prescribed during afternoon hours when outdoor dry bulb temperature is over 36 °C [38]. In Cyprus limits of summer thermal comfort in workspaces differ between non-acclimatized and acclimatized workers, ranging from 28 °C to 30 °C respectively for normal physical work and 26.5 °C–28.5 °C for intense manual labor [39].

On the other hand, minimum air temperatures in industrial workspaces, where intense work is expected, are 12 °C in Germany and Austria [35,36] and 13 °C in the UK [37], while 16 °C are considered comfortable for lighter factory work.

3. Method

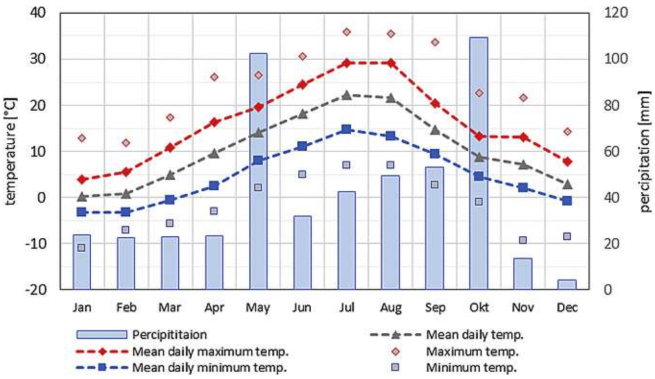

Fig. 1. Climate conditions of Berndorf, Lower Austria in 2015.

This paper conducts a case study research employing parametric dynamic thermal simulations on a calibrated EnergyPlus thermal model of an existing industrial facility. Building envelope retrofit solutions are investigated for reducing overheating in the main manufacturing hall. In-situ monitoring of indoor air temperature and relative humidity was conducted in the facility during 2015. Weather data from a local meteorological station were provided for the same period by the Austrian central institution for meteorology and geodynamics - ZAMG (Fig. 1). Compared to a Typical Meteorological Year (TMY) obtained from Meteonorm 7.0 [40], actual weather data for the June–August period in 2015 recorded higher amount of warmer temperatures as seen in Fig. 2, thus overheating risk was higher. Mean global horizontal and direct normal irradiance (GHI, DNI) were also higher than the typical year. Bearing this in mind, the study was carried out for the warmer than average summer of 2015, as such conditions may occur more often in the future.

3.1. *Case study*

The building, located in Berndorf, Lower Austria, is a single-story metal processing factory, categorized as light manufacturing industry and measuring a gross floor area of about 20,000 m^2. The facility is a result of multiple expansions to a 1920s historical industrial hall as well as the attachment of a smaller neighboring building. It has a length of 280 m and a maximum width of 80 m divided in six spans with varying widths from 11.4 m to 15 m, covered by pitched and shed roofs. Hall heights are also varying from 6.5 m to 13.4 m. The main manufacturing hall (13,470 m^2) spreads along the whole building; however there is a clear distinction in terms of building envelope constructions between the west old and the newer east part. Thick brick masonry walls and uninsulated roof skin (wood sheathing and bituminous layer) versus insulated metal cassette walls and sandwich roof panels respectively. The roof skin on the old part is covered by a black colored water proofing asphalt coating, whereas the exterior surface of the metal sandwich panels on the newer part is colored light grey. There is an extensive surface of saddle skylights on both parts, consisting of single pane wired glazing. The old part of the building is equipped with single glazing windows on thin iron framing, whereas the newer part with double glazing windows on aluminum framing without thermal break. No shading systems are used. The building is naturally ventilated, no mechanical cooling system is installed and heating in winter is provided by ceiling radiative panels. The factory is operating on a 3-shift basis on weekdays and on an 8-h shift on weekends summing up to 131 occupied hours per week (1727 h for the Jun–Aug period). The focus of this paper lies in the analysis of the older part of the main hall, illustrated in Fig. 3 with an area of 6749 m^2, where overheating issues were reported to be the most intense, as shown in Table 2.

3.2. *Internal heat gains*

Internal heat gains (IHG) associated with people, lighting and

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[1] [33] specifies overheating as exceeding 28 °C for more than 1% of occupied hours or exceeding 25 °C for more than 5% of occupied hours.

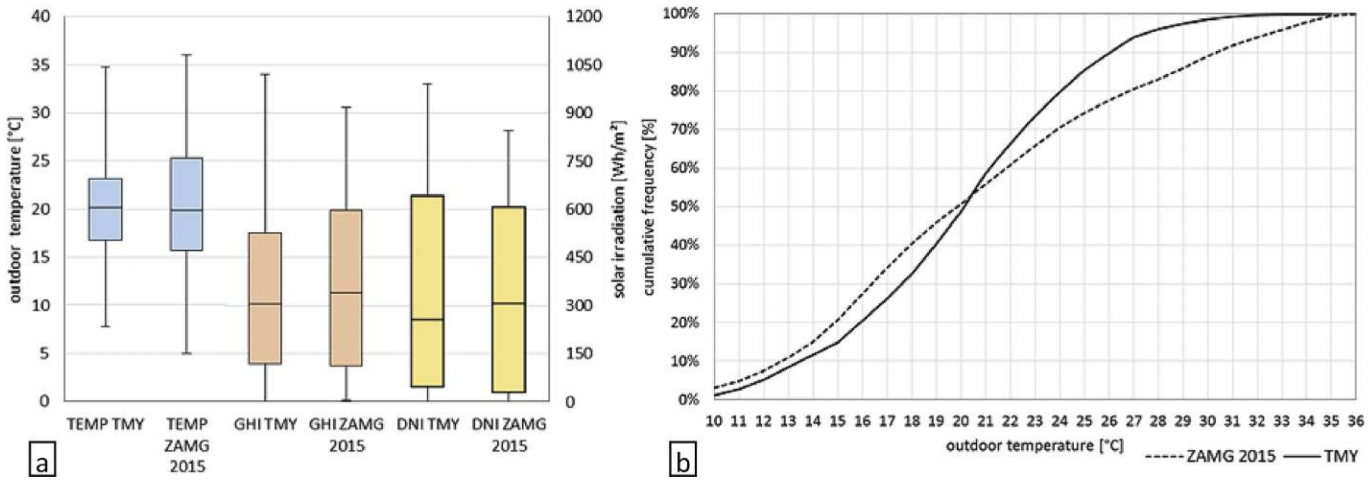

Fig. 2. Comparison of TMY and ZAMG weather data for the Jun–Aug period, (a) outdoor temperature, global horizontal irradiance, direct normal irradiance, (b) accumulated outdoor temperature.

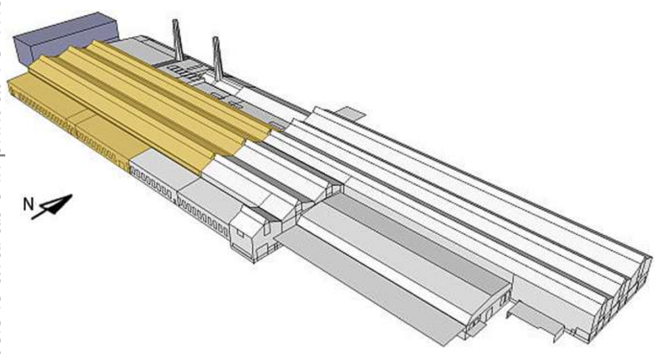

Fig. 3. 3D view of the case study, highlighted the old part of the main hall.

Table 2
Overheating during occupied hours according to measured data of Jun–Aug 2015.

	CZ1: main hallold part	CZ2: main hall old part - near south facade	CZ3: workshops - storage	CZ4: main hall new part	CZ5: small hall
$T_{air} > 26\,^{\circ}C$	43.0%	46.3%	37.0%	39.1%	35.4%
$T_{air} > 30\,^{\circ}C$	14.8%	16.0%	8.0%	10.7%	4.1%

machinery are taken into consideration as they directly affect the indoor climate.

In accordance to a typical week operation plan, there is 100% complement of workforce in the morning shift, 90% in the afternoon and 30% in the night. During weekends there is only a morning 8-h shift with 30% of workforce. For the studied area of the factory, this translates to a maximum number of 15 employees during weekdays and 5 over the weekend. They are assumed to perform medium-light work (225 W per person) [41].

Lighting is controlled manually and is operated on a 24 h basis during weekdays as well as during the morning shifts on weekends. It is provided by suspended fluorescent lamp luminaires of 120 W, resulting in an 8.4 W/m^2 heat emission rate.

Internal gains from manufacturing process loads in industrial buildings have a great influence on indoor thermal environment and largely affect energy demand for building conditioning. Brinks et al. [42] criticize the fact that only default values are considered when planning new industrial facilities (e.g. 40 W/m^2 for all production buildings in Germany) and actual level of internal gains should be examined for defining an optimum building envelope. The same principle should apply for retrofit measures of existing buildings. In addition, manufacturing conditions can vary greatly over time even within the same facility depending on production demand, economic cycles or seasonal changes, altering heat emissions.

For this case study, measurements were performed on installed machinery to size the amount of waste heat and determine operating pattern schedules [24]. To assess the impact of internal heat gains on overheating, three states of production conditions are analyzed (Table 3). Additional to the current operation schedule with production fluctuations on daily and weekly basis (IHG1), two more production process alternatives are investigated. The state when all installed machinery is fully operating on work hours (IHG2) and a hypothetical scenario when automated laser CNC machines with higher heat emissions are fully operating during work hours (IHG3). Heat gains from people and electrical lighting, as described above, are kept constant for all scenarios.

3.3. *Thermal model calibration*

A detailed thermal model of the facility was created as described in [24]. Since the building is operating during summer in a free-running mode, a manual, evidence-based iterative calibration process through indoor air temperature monitored in multiple control thermal zones was used to adjust the simulation outcome to the measured data [45]. This requires error indices that provide accurate evaluation in terms of discrepancies between predicted and actual values [46]. Five control zones were established (CZ1-CZ5) collecting data on 10 min intervals during 2015, which were then averaged on hourly basis. Three error indices were utilized in the calibration process, $MBE_{\%}$, RMSE and Pearson's Index (r), according to formulae (1), (2) and (3) respectively:

Table 3
Manufacturing internal gains scenarios.

	IHG1	IHG2	IHG3
	current production conditions[a]	full operation of existing machinery during work hours	full operation of laser CNC machinery during work hours
Weighted average IHG rate according to schedule of operational hours	5.4 W/m^2	13.0 W/m^2	25.4 W/m^2
Maximum IHG rate at 100% operation of active machines	8.5 W/m^2	17.0 W/m^{2}[b]	37.0 W/m^{2}[c]

[a] Inactive machines due to current reduced production demand.

[b] CIBSE benchmark for light manufacturing is 16.5 W/m^2 [43].

[c] Waste heat emissions for laser CNC metal cutting machinery [44].

$$MBE_{\%} = \frac{\sum_{i=1}^{N}(M_i - S_i)}{\sum_{i=1}^{N} M_i} \tag{1}$$

$$RSME = \sqrt{\frac{\sum_{i=1}^{N}(M_i - S_i)^2}{N}} \tag{2}$$

$$r = \frac{\sum_{i=1}^{N}(M_i \cdot S_i) - \left(\sum_{i=1}^{N} M_i \cdot \sum_{i=1}^{N} \frac{S_i}{N}\right)}{\sqrt{\left(\sum_{i=1}^{N} M_i^2 - \frac{\left(\sum_{i=1}^{N} M_i\right)^2}{N}\right) \cdot \left(\sum_{i=1}^{N} S_i^2 - \frac{\left(\sum_{i=1}^{N} S_i\right)^2}{N}\right)}} \tag{3}$$

where M_{i} and S_i correspond to measured and simulated air temperatures (°C) at instance i, and N is the number of intervals of the calculation period. A positive value of MBE$_{\%}$ represents that the model overestimates indoor temperatures, while a negative indicates otherwise. However it can give misleading indication due to sign error compensations, therefore RMSE is also used as it provides an absolute value of discrepancies between measured and simulated values. In this context, the higher the RMSE value, the lower the reliability of the model. The correlation between predicted and real values is of significant importance for model calibration with CZ temperatures [46]. Pearson's index ranges from -1 to 1, with negative values showing opposite correlation and the model being not representative of the actual building performance, positive values show direct correlation and in the case of $r = 0$, no correlation exists. Absolute error values ε_i were also assed using equation (4):

$$\varepsilon_i = M_i - S_i \tag{4}$$

3.4. Overheating evaluation

Assessment of indoor thermal environments during the warm season in NCBs is usually performed using the adaptive approach [47]. However, workspace temperatures are governed by varying safety regulations and legislation. This study evaluates overheating in a free-running naturally ventilated industrial hall according to two methods. The multifaceted adaptive approach of CIBSE TM52 for occupants expectations of a category III existing building [32], as well as, the condition that mean hourly air temperature in the hall should not exceed 26 °C during work hours. The last approach derived as a relative mean value of European regulations, also considering the climatic location of the case study.

The adaptive approach of TM52 on the other hand sets three criteria for measuring building overheating defined in terms of ΔT - difference between actual T_{op} the limiting $T_{\max}$ according to EN 15251, always rounded to the nearest integer. First criterion is *hours of exceedence (H_e)* and sets a limit of 3% to the number of occupied hours that ΔT is equal or greater than one during the cooling season. The criterion of *daily weighted exceedence (W_e)* deals with the severity of overheating and shall be less or equal to 6 in any one day and is calculated by formula (5):

$$W_e = \sum\left(h_e \cdot w_f\right) = (h_{e0} \cdot 0) + (h_{e1} \cdot 1) + (h_{e2} \cdot 2) + (h_{e3} \cdot 3) \tag{5}$$

Where the weighting factor $w_f = 0$ if $\Delta\mathrm{T} \leq 0$, otherwise $w_f = \Delta\mathrm{T}$ and h_{ey} is the number of hours when $w_f = y$. The third criterion *upper limit temperature (T_{upp})* sets an absolute maximum acceptable indoor operative temperature beyond which adaptive actions are insufficient to restore personal comfort and shall never be exceeded. It is defined as $T_{\max} + 4$ K. Although the adaptive approach does not include industrial buildings as an applicable category, the indoor environment of this case study is not regulated by special production requirements but from the occupants through natural ventilation. Furthermore, the impact of internal gains from manufacturing processes is given as a controlled input to the simulation models. Therefore, testing the performance of the building with an established standard for NCBs and a method that rates multiple aspects of the overheating situation, can provide a better insight to the effects of various optimization measures.

3.5. Optimization measures

The option of installing a mechanical cooling system to regulate indoor temperature has been taken into account in order to size the amount of energy that would be required for space conditioning and is a priori conserved by the passive solutions. Considering an ideal loads air cooling system, the older part of the main hall would have a cooling demand of 139,518 kWh for the summer period, accounting for 20.67 kWh/m^2. Such an approach to resolve the overheating issue of the building would bring, except of the initial installation costs, additional yearly expenses due to the increment of the facility's energy usage.

Examining passive measures, building-related interventions ranging from less cost-intensive to large refurbishment alternatives are tested in a series of simulations for their adequacy to tackle summer overheating. Initially different patterns of night natural ventilation are evaluated, as a passive and commonly used strategy to minimize discomfort, which can easily be implemented. To prevent overcooling during the night shift on weekdays, night ventilation is ceased when outdoor temperature is below 10 °C. Furthermore, three types of retrofit options of the building envelope are evaluated. First measure is the application of a water based elastomeric cool roof coating on the existing roof construction, with 0.87 solar reflectance and 0.87 infrared emittance as described in [20]. Second measure involves exterior solar shadings, white venetian blinds on the south oriented facade windows and light grey roller shades on the south side of the saddle shaped roof skylights over the main hall. Shades are operated automatically and are activated when solar irradiance on the glazing surface is higher than 100 W/m^2 and outdoor temperature is over 20 °C. Such auto-activation strategy – shading devices are deployed when needed and otherwise are retracted – improves daylight admission, compared to fixed shading solutions, while protecting from excess solar gains during warm temperature conditions. Third retrofit measure is the thermal improvement of the building fabric. Following findings of previous research on reducing the heating demand of the building [24], emphasis is given on the uninsulated roof on the older part of the building (total surface 11,392 m^2), which covers 68% of its external thermal envelope area. Therefore an addition of 20 cm of EPS insulation is considered with an improvement of the roof surface U-value from 1.6 to 0.17 W/m^2·K. Moreover existing windows and skylights are upgraded with a U-value improvement from 5 to 1.2 W/m^2·K for windows and from 4.7 to 1.7 W/m^2·K for skylights.

4. Results

4.1. *Calibrated base case model*

A temperature calibration process is commonly combined in case studies with energy consumption calibration [48], however in this case no space conditioning is applied thus energy data do not exist. The goal of the calibration was to adjust the EnergyPlus model to the measured temperature data from the installed sensors in five control zones, given the actual local weather conditions for the summer of 2015. A trial and error process of adjusting the input parameters of the simulation model was therefore deployed. The final calibrated model is a result of several iterations, each with incremental correlation between measured and simulated values. The variables that significantly affected the model were the rate of ACH and the building's internal mass. There is great uncertainty for both parameters, as a naturally ventilated building is highly affected by weather conditions on site and actual internal mass is difficult to determine due to the complexity of installed equipment and considerable variations of raw material storage levels. Fig. 4 shows the comparison of statistical error indices for the initial and final model. After the calibration process RMSE values decrease and there is a significant correlation for r between temperature variables with most zones achieving a value of more than 0.9. MBE$_{\%}$ values range between −1% and +1.5% with CZ1, where building thermal performance against overheating is studied, having a very low −0.36%. The ε_i histogram in Fig. 5a has a bimodal spread with its center at around 0 °C and errors having an equal distribution on both sides of the peak. The scatterplot in Fig. 5b shows an almost constant spread of errors indicating a consistent accuracy across predicted temperatures. In fact, the simulated temperature trend in Fig. 5c approaches actual measured values to a large extent, nevertheless the model presents some errors in the lower peaks.

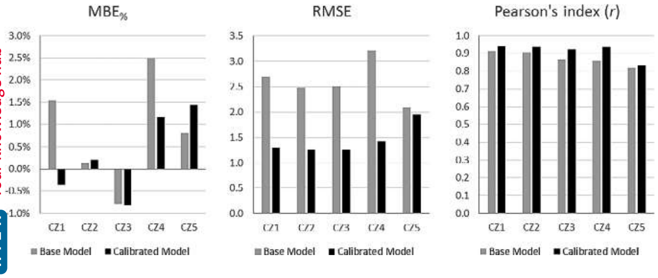

Fig. 4. Error indices of base case and calibrated model for the Jun–Aug period.

4.2. *Optimization measures evaluation*

In order to decrease overheating problems and improve the thermal performance of the industrial hall, following alternative solutions are considered as seen in Table 4. First, four air change rate patterns alternating between day and night are evaluated for the current state of the building envelope and the three different IHG conditions. Then seven retrofit scenarios are tested for each ventilation alternative and IHG condition. Scenario 0 (S0) and ventilation ACH pattern 0 (V0) represent the current state and operation of the facility.

Table 5 Presents results of the three criteria of TM52 adaptive approach for assessing overheating. Criterion H_e presents the percentage of occupied hours during summer when overheating occurs. Criterion W_e shows the number of days that the hall is severely overheated and last criterion T_{upp} counts the number of hours when the absolute max temperature is exceeded. The building should fulfill all criteria to avoid discomfort due to overheating.

Table 6 lists the percentage of comfort hours during occupancy time and operation of the facility according to the adaptive approach of EN 15251 and to the set limit air temperature of 26 °C derived from the workspace regulations. In the first approach, the sense of comfort is defined in accordance to the deviation of the operative temperature from the adaptive comfort temperature for an existing building where occupants have moderate expectations. In the second, all instances below the set limit are considered as comfortable.

The best performing ventilation alternative for each instance is highlighted with red numbers. Especially for the adaptive approach, marked green are occasions when the examined hall is not overheating as of Table 5. For occasions where the best performing ventilation alterative in regard to comfort hours fails to pass the TM52 criteria, marked in bold numbers are the instances with no overheating risk and a high percentage of comfort hours.

5. Discussion

5.1. *Calibration uncertainty*

Given the varying character of uncertainties in the calibration process, as described in section 4.1, simulated results lie within a small margin of error. The calibrated model demonstrated air temperature prediction accuracy of ±1.5 °C for 75% and of ±2.5 °C for 95% of hourly instances during the summer period for CZ1 in the old part of the main manufacturing hall. This deviation could result from alternating ventilation rates during the measurement period, whereas in the models they stay constant, and was most reported at low peaks not affecting overheating records.

5.2. *Assessment method comparison*

This research employs two assessment methods for sizing overheating and evaluating the impact of different passive measures. The industry standard approach for free-running buildings through the adaptive thermal comfort model conforming to EN 15251, with multiple overheating assessment criteria as of TM52 and the fixed single threshold approach of work health regulations. The first evaluates thermal discomfort based on the combined effects of the mean radiant and air temperature of the space, whereas the second only according to the mean air temperature. Both methods do not consider factors such as indoor air humidity, air speed and clothing condition that would intensify or relieve the sense of overheating. However, it is assumed that occupants are able to relatively adjust their clothing and influence the local air movement by operable windows. Indoor relative humidity in this

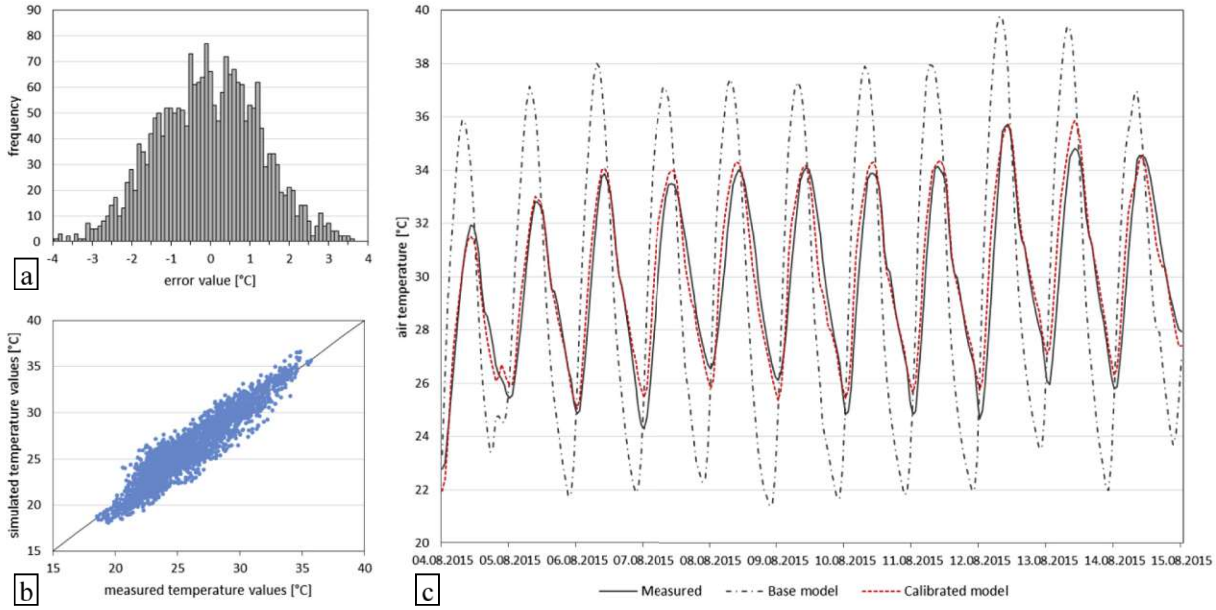

Fig. 5. Calibrated model for CZ1, (a) histogram of hourly temperature error values – (b) hourly based scatterplot of measured versus simulated temperatures – (c) air temperature trends.

Table 4
Refurbishment strategies for preventing summer overheating.

Ventilation ACH patterns [$^{-h}$]	V0	Current state: day 1.7 ACH/night 0.9 ACH
	V1	Constant day & night: 1.7 ACH
	V2	Reversed: day 0.9 ACH/night 1.7 ACH
	V3	Increased night ventilation (night = day x 1.5): day 1.7 ACH/night 2.6 ACH
	V4	Increased night ventilation (night = day x 2): day 1.7 ACH/night 3.4 ACH
Building retrofit options	S0	Current state of the building envelope
	S1	Cool roof coating (on existing roof)
	S2	Solar shading
	S3	Solar shading + Cool roof
	S4	Thermal envelope refurbishment (new windows and skylights + roof insulation)
	S5	Thermal envelope refurbishment + Cool roof
	S6	Thermal envelope refurbishment + Solar shading
	S7	Thermal envelope refurbishment + Solar shading + Cool roof

case study fluctuates between 35% and 70%, mainly laying within the acceptable rates of 40%–60% and with higher values being recorded overnight due to night ventilation. Taking previous into consideration, we argue that overheating and the impact of optimization measures can be qualitative assessed by the implemented methods, although the number of comfortable hours may not accurately comply with a potential survey after the application of the selected measures.

Results of comfort occupied hours depict a clear deference between the two overheating assessment methods. According to the adaptive approach, the thermal environment in the current factory condition (IHG1, S0-V0) is 74.2% comfortable, while only 49.4% of the time air temperature lies below the 26 °C regulations limit. Worth mentioning is the fact that for the air temperature criterion, all hours below 26 °C are regarded as comfortable with the lowest air temperature recorded among all simulated scenarios during occupancy hours being 15 °C, over the 12 °C minimum temperature regulation limit. On the other hand, EN 15251 is largely derived from field surveys in offices [49], therefore its comfort limits may not be appropriate for industrial workspaces. Even in a study of two offices in the UK, indoor environments that the Standard would specify as too cold were found to be comfortable and those predicted as comfortable were regarded as warm or hot [50]. The adaptive capacity of factory workers may also vary when compared to office workers as the first are likely to tolerate a greater range thermal environments given the nature of their work and their comfort expectations. Thus the adaptive approach as currently described in EN 15251 and incorporated in TM52 cannot be implemented in naturally ventilated industrial buildings for assessing overheating thermal discomfort. Then again, the static single threshold air temperature limit of the workspace regulations lacks many aspects of measuring the overheating situation and does not consider the fact that people acclimatize to the local prevailing outdoor temperature conditions.

Reconsidering the limits of the adaptive comfort approach in free-running buildings other than offices has been suggested also for dwellings and in particular bedrooms [51]. In the case of industrial spaces, occupants are expected to have higher levels of physical activity, we argue therefore that values below the minimum limit of the acceptable operative temperature ($T_{\min}$) could be counted as comfortable (see Fig. 6), while $T_{\max}$ should be reconsidered upon industrial workspace environment legislation. Such an investigation would be beyond the scope of this paper, however, further research on case studies can provide planners with valuable information regarding refurbishment of industrial facilities.

Table 5
TM52 overheating criteria for all simulated scenarios.

IHG1

	V0		V1		V2		V3		V4	
S0	21.3%	(He) FAIL	15.1%	(He) FAIL	20.7%	(He) FAIL	12.1%	(He) FAIL	10.2%	(He) FAIL
	40	(We) FAIL	35	(We) FAIL	45	(We) FAIL	30	(We) FAIL	23	(We) FAIL
	9	(Tupp) FAIL	2	(Tupp) FAIL	4	(Tupp) FAIL	0	(Tupp) PASS	0	(Tupp) PASS
S1	4.9%	(He) FAIL	2.1%	(He) PASS	2.3%	(He) PASS	1.1%	(He) PASS	0.6%	(He) PASS
	5	(We) FAIL	1	(We) FAIL	1	(We) FAIL	1	(We) FAIL	0	(We) PASS
	0	(Tupp) PASS	0	(Tupp) PASS	0	(Tupp) PASS	0	(Tupp) PASS	0	(Tupp) PASS
S2	5.7%	(He) FAIL	3.0%	(He) PASS	3.1%	(He) FAIL	1.4%	(He) PASS	0.8%	(He) PASS
	10	(We) FAIL	3	(We) FAIL	3	(We) FAIL	2	(We) FAIL	1	(We) FAIL
	0	(Tupp) PASS	0	(Tupp) PASS	0	(Tupp) PASS	0	(Tupp) PASS	0	(Tupp) PASS
S3	0.0%	(He) PASS	0.0%	(He) PASS	0.0%	(He) PASS	0.0%	(He) PASS	0.0%	(He) PASS
	0	(We) PASS	0	(We) PASS	0	(We) PASS	0	(We) PASS	0	(We) PASS
	0	(Tupp) PASS	0	(Tupp) PASS	0	(Tupp) PASS	0	(Tupp) PASS	0	(Tupp) PASS
S4	6.0%	(He) FAIL	1.6%	(He) PASS	1.9%	(He) PASS	0.6%	(He) PASS	0.1%	(He) PASS
	5	(We) FAIL	1	(We) FAIL	1	(We) FAIL	0	(We) PASS	0	(We) PASS
	0	(Tupp) PASS	0	(Tupp) PASS	0	(Tupp) PASS	0	(Tupp) PASS	0	(Tupp) PASS
S5	5.8%	(He) FAIL	1.0%	(He) PASS	1.7%	(He) PASS	0.2%	(He) PASS	0.0%	(He) PASS
	5	(We) FAIL	0	(We) PASS	1	(We) FAIL	0	(We) PASS	0	(We) PASS
	0	(Tupp) PASS	0	(Tupp) PASS	0	(Tupp) PASS	0	(Tupp) PASS	0	(Tupp) PASS
S6	0.0%	(He) PASS	0.0%	(He) PASS	0.0%	(He) PASS	0.0%	(He) PASS	0.0%	(He) PASS
	0	(We) PASS	0	(We) PASS	0	(We) PASS	0	(We) PASS	0	(We) PASS
	0	(Tupp) PASS	0	(Tupp) PASS	0	(Tupp) PASS	0	(Tupp) PASS	0	(Tupp) PASS
S7	0.0%	(He) PASS	0.0%	(He) PASS	0.0%	(He) PASS	0.0%	(He) PASS	0.0%	(He) PASS
	0	(We) PASS	0	(We) PASS	0	(We) PASS	0	(We) PASS	0	(We) PASS
	0	(Tupp) PASS	0	(Tupp) PASS	0	(Tupp) PASS	0	(Tupp) PASS	0	(Tupp) PASS

IHG2

	V0		V1		V2		V3		V4	
S0	28.9%	(He) FAIL	21.4%	(He) FAIL	27.8%	(He) FAIL	17.3%	(He) FAIL	14.2%	(He) FAIL
	40	(We) FAIL	35	(We) FAIL	45	(We) FAIL	30	(We) FAIL	23	(We) FAIL
	40	(Tupp) FAIL	10	(Tupp) FAIL	32	(Tupp) FAIL	5	(Tupp) FAIL	0	(Tupp) PASS
S1	10.2%	(He) FAIL	6.2%	(He) FAIL	8.0%	(He) FAIL	4.5%	(He) FAIL	2.5%	(He) PASS
	20	(We) FAIL	8	(We) FAIL	15	(We) FAIL	4	(We) FAIL	2	(We) FAIL
	0	(Tupp) PASS	0	(Tupp) PASS	0	(Tupp) PASS	0	(Tupp) PASS	0	(Tupp) PASS
S2	11.4%	(He) FAIL	7.0%	(He) FAIL	9.3%	(He) FAIL	4.5%	(He) FAIL	3.1%	(He) FAIL
	23	(We) FAIL	14	(We) FAIL	17	(We) FAIL	5	(We) FAIL	4	(We) FAIL
	0	(Tupp) PASS	0	(Tupp) PASS	0	(Tupp) PASS	0	(Tupp) PASS	0	(Tupp) PASS
S3	0.3%	(He) PASS	0.0%	(He) PASS	0.0%	(He) PASS	0.0%	(He) PASS	0.0%	(He) PASS
	0	(We) PASS	0	(We) PASS	0	(We) PASS	0	(We) PASS	0	(We) PASS
	0	(Tupp) PASS	0	(Tupp) PASS	0	(Tupp) PASS	0	(Tupp) PASS	0	(Tupp) PASS
S4	14.1%	(He) FAIL	7.0%	(He) FAIL	10.5%	(He) FAIL	3.6%	(He) FAIL	1.4%	(He) PASS
	27	(We) FAIL	12	(We) FAIL	19	(We) FAIL	3	(We) FAIL	1	(We) FAIL
	0	(Tupp) PASS	0	(Tupp) PASS	0	(Tupp) PASS	0	(Tupp) PASS	0	(Tupp) PASS
S5	13.9%	(He) FAIL	5.2%	(He) FAIL	10.2%	(He) FAIL	2.0%	(He) PASS	0.8%	(He) PASS
	27	(We) FAIL	4	(We) FAIL	18	(We) FAIL	1	(We) FAIL	0	(We) PASS
	0	(Tupp) PASS	0	(Tupp) PASS	0	(Tupp) PASS	0	(Tupp) PASS	0	(Tupp) PASS
S6	1.1%	(He) PASS	0.1%	(He) PASS	0.0%	(He) PASS	0.0%	(He) PASS	0.0%	(He) PASS
	1	(We) FAIL	0	(We) PASS	0	(We) PASS	0	(We) PASS	0	(We) PASS
	0	(Tupp) PASS	0	(Tupp) PASS	0	(Tupp) PASS	0	(Tupp) PASS	0	(Tupp) PASS
S7	0.4%	(He) PASS	0.0%	(He) PASS	0.0%	(He) PASS	0.0%	(He) PASS	0.0%	(He) PASS
	0	(We) PASS	0	(We) PASS	0	(We) PASS	0	(We) PASS	0	(We) PASS
	0	(Tupp) PASS	0	(Tupp) PASS	0	(Tupp) PASS	0	(Tupp) PASS	0	(Tupp) PASS

IHG3

	V0		V1		V2		V3		V4	
S0	41.9%	(He) FAIL	31.4%	(He) FAIL	40.9%	(He) FAIL	26.0%	(He) FAIL	22.9%	(He) FAIL
	40	(We) FAIL	35	(We) FAIL	45	(We) FAIL	30	(We) FAIL	23	(We) FAIL
	162	(Tupp) FAIL	74	(Tupp) FAIL	187	(Tupp) FAIL	35	(Tupp) FAIL	15	(Tupp) FAIL
S1	20.8%	(He) FAIL	14.5%	(He) FAIL	20.7%	(He) FAIL	11.6%	(He) FAIL	8.8%	(He) FAIL
	36	(We) FAIL	30	(We) FAIL	37	(We) FAIL	21	(We) FAIL	18	(We) FAIL
	3	(Tupp) FAIL	0	(Tupp) PASS	1	(Tupp) FAIL	0	(Tupp) PASS	0	(Tupp) PASS
S2	23.9%	(He) FAIL	16.5%	(He) FAIL	23.5%	(He) FAIL	12.3%	(He) FAIL	10.1%	(He) FAIL
	42	(We) FAIL	32	(We) FAIL	43	(We) FAIL	24	(We) FAIL	18	(We) FAIL
	6	(Tupp) FAIL	0	(Tupp) PASS	5	(Tupp) FAIL	0	(Tupp) PASS	0	(Tupp) PASS
S3	4.2%	(He) FAIL	1.4%	(He) PASS	2.0%	(He) PASS	0.7%	(He) PASS	0.5%	(He) PASS
	3	(We) FAIL	1	(We) FAIL	1	(We) FAIL	1	(We) FAIL	0	(We) PASS
	0	(Tupp) PASS	0	(Tupp) PASS	0	(Tupp) PASS	0	(Tupp) PASS	0	(Tupp) PASS
S4	31.7%	(He) FAIL	18.5%	(He) FAIL	30.2%	(He) FAIL	12.8%	(He) FAIL	9.0%	(He) FAIL
	43	(We) FAIL	33	(We) FAIL	50	(We) FAIL	22	(We) FAIL	17	(We) FAIL
	17	(Tupp) FAIL	0	(Tupp) PASS	6	(Tupp) FAIL	0	(Tupp) PASS	0	(Tupp) PASS
S5	31.7%	(He) FAIL	16.1%	(He) FAIL	29.7%	(He) FAIL	10.9%	(He) FAIL	7.5%	(He) FAIL
	43	(We) FAIL	31	(We) FAIL	50	(We) FAIL	20	(We) FAIL	13	(We) FAIL
	0	(Tupp) PASS	0	(Tupp) PASS	0	(Tupp) PASS	0	(Tupp) PASS	0	(Tupp) PASS
S6	12.7%	(He) FAIL	4.6%	(He) FAIL	8.6%	(He) FAIL	2.0%	(He) PASS	0.7%	(He) PASS
	19	(We) FAIL	5	(We) FAIL	14	(We) FAIL	1	(We) FAIL	1	(We) FAIL
	0	(Tupp) PASS	0	(Tupp) PASS	0	(Tupp) PASS	0	(Tupp) PASS	0	(Tupp) PASS
S7	9.0%	(He) FAIL	3.4%	(He) FAIL	5.7%	(He) FAIL	0.9%	(He) PASS	0.4%	(He) PASS
	13	(We) FAIL	3	(We) FAIL	6	(We) FAIL	1	(We) FAIL	0	(We) PASS
	0	(Tupp) PASS	0	(Tupp) PASS	0	(Tupp) PASS	0	(Tupp) PASS	0	(Tupp) PASS

Table 6
Summer comfort occupied hours and overheating risk for all simulated scenarios.

		IHG1 - current condition					IHG2 - full facility operation					IHG3 - laser CNC machinery				
		V0	V1	V2	V3	V4	V0	V1	V2	V3	V4	V0	V1	V2	V3	V4
EN 15251 / TM52 % of comfort hours Jun-Aug	S0	74.2%	**78.1%**	75.6%	77.4%	75.1%	67.0%	74.6%	67.9%	**75.7%**	74.6%	52.8%	64.4%	54.4%	70.5%	**72.4%**
	S1	88.0%	83.3%	**89.5%**	77.5%	**72.0%**	86.2%	85.1%	**87.9%**	81.5%	77.8%	74.0%	81.6%	74.7%	**83.0%**	80.3%
	S2	90.1%	87.4%	**92.5%**	82.0%	76.8%	84.3%	**87.8%**	86.2%	85.2%	80.5%	70.6%	79.3%	70.9%	**83.3%**	82.9%
	S3	**86.2%**	73.7%	79.4%	65.1%	59.8%	**96.2%**	85.3%	92.6%	76.5%	71.2%	92.3%	94.4%	**95.0%**	89.6%	**83.4%**
	S4	90.8%	91.7%	**95.1%**	**87.7%**	81.1%	81.1%	89.2%	85.4%	90.0%	**86.6%**	62.1%	77.2%	63.6%	83.0%	**86.1%**
	S5	90.9%	**92.3%**	**95.2%**	85.4%	78.6%	81.2%	**91.1%**	85.8%	90.4%	**85.4%**	62.3%	80.0%	63.9%	85.1%	**87.1%**
	S6	**99.1%**	88.8%	97.0%	76.9%	68.7%	96.9%	98.3%	**99.5%**	89.6%	81.0%	81.7%	91.1%	86.5%	**95.1%**	93.2%
	S7	**98.0%**	84.2%	93.6%	72.5%	65.4%	98.5%	96.9%	**99.9%**	86.4%	78.2%	85.6%	93.7%	90.6%	**95.7%**	**93.2%**

		IHG1 - current condition					IHG2 - full facility operation					IHG3 - laser CNC machinery				
		V0	V1	V2	V3	V4	V0	V1	V2	V3	V4	V0	V1	V2	V3	V4
Tair ≤ 26 °C % of comfort hours Jun-Aug	S0	49.4%	59.1%	51.1%	63.4%	**66.0%**	40.0%	51.5%	40.4%	57.8%	**61.0%**	22.6%	37.2%	24.2%	46.4%	**51.9%**
	S1	64.6%	69.5%	66.4%	72.1%	**73.5%**	56.3%	63.5%	57.2%	67.1%	**69.0%**	22.6%	51.0%	39.4%	57.1%	**60.8%**
	S2	62.7%	68.2%	63.8%	71.2%	**72.6%**	53.0%	61.8%	53.7%	65.8%	**68.0%**	34.2%	48.5%	34.9%	55.1%	**58.5%**
	S3	75.4%	78.6%	80.1%	80.8%	**81.4%**	68.3%	72.8%	70.6%	75.6%	**77.5%**	53.6%	62.3%	52.6%	66.0%	**68.0%**
	S4	60.0%	68.1%	62.6%	72.0%	**74.3%**	47.5%	60.3%	48.1%	66.0%	**68.6%**	21.8%	42.4%	25.6%	51.7%	**57.5%**
	S5	60.0%	69.8%	63.0%	73.5%	**75.7%**	47.5%	62.5%	48.5%	66.9%	**70.0%**	21.9%	44.2%	25.9%	54.1%	**59.1%**
	S6	71.0%	76.5%	76.1%	79.2%	**81.1%**	61.1%	69.4%	62.8%	73.3%	**76.0%**	35.7%	52.9%	37.9%	60.8%	**65.0%**
	S7	73.5%	77.8%	79.4%	80.7%	**82.5%**	63.6%	71.1%	66.1%	74.9%	**77.5%**	39.8%	55.4%	40.7%	62.9%	**66.7%**

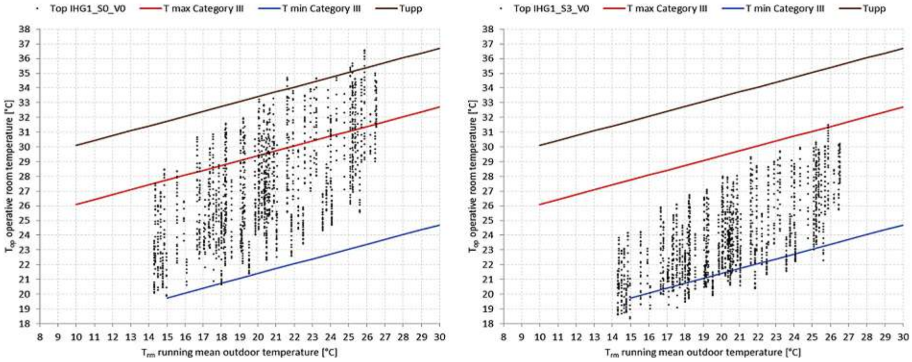

Fig. 6. Spread of Top according to EN 15251 category III for S0-V0 and S3-V0 under current manufacturing processes (IHG1).

5.3. *Performance against overheating*

Comparing the simulation results to the base case for each IHG condition, all optimization measures provide a higher percentage of comfort hours, with more efficient solutions containing additional to night ventilation, building fabric improvements with cool roof coating and automatically controlled solar shading (see Table 6). Such practice a priori conserves additional energy for cooling by preventing the installation of an active cooling system and consequently an increase of 20.67 kWh/m^2 in the yearly energy demand (as stated in 3.5).

Considering the air temperate criterion of 26 °C, increased ACH in V4 provides always the higher percentage of comfortable hours and the most effective retrofit strategy for IHG2 and IHG3 is S3 by applying a cool roof and solar shading. Also in the current IHG1, S3 performs equally well to the far more expensive alternative of S7, which includes thermal refurbishment. Despite of the improvement, a considerable amount of occupied hours, 19%–32% depending on the thermal gains from manufacturing processes, are considered are too warm according to workspace regulations even after the application of the best performing measures.

Examining results of the adaptive approach, none of the passive solutions only by means of ventilation alternatives succeeds to overcome overheating (see Table 5). However, for the current IHG1 condition, even a cool roof coating on the existing roof (S1) largely diminishes the problem by failing W_e criterion, describing overheating severity, only for 1 day with most ACH patterns. The application only of automatically controlled solar shading (S2) could also prove feasible combined with high night ventilation air change rates (V3-V4), when it also fails the W_e criterion for 2 and 1 days respectively. These results are within the tolerance of simulation errors, therefore such single retrofit measures should not be rejected for the current state of low manufacturing heat gains. In future production conditions though neither S1 nor S2 will not be adequate to keep the hall from excessive indoor heat. Addition of solar shading (S3) results in the elimination of overheating for both IHG2 and IHG3 when adopting an appropriate ventilation strategy. For IHG3, increased night ventilation (V4) plays a crucial role in cooling down the hall. Retrofits like S6 and S7 would also be effective in battling high temperatures for all internal heat gain conditions, yet for this case study an acceptable indoor thermal environment during summer can be achieved without an extensive refurbishment of the building skin, keeping interventions cost at lower levels.

As reported by the results of both assessment methods, application of thermal insulation on the roof (S4-S7) does not lead to negative effects and increase of the overheating problem, even for the condition with high internal heat gains (IHG3), when an appropriate natural ventilation strategy is utilized. Nevertheless, the examined building has thick brick masonry walls with high thermal storage capacity, something that is not the common case for existing industrial facilities. Therefore, based on manufacturing heat gains, thermal insulation should also be considered as a measure for preventing overheating, providing also energy savings though decrease of heating demand in winter.

6. Conclusion

This paper has investigated the feasibility of passive building-related optimization measures to tackle thermal discomfort caused by summer overheating in an existing industrial hall in Berndorf, Lower Austria, during the warmer than average summer of 2015. Given the fact the facility is not equipped with a mechanical cooling system, passive retrofit options can prevent the installation of an active system, thus avoiding additional energy consumption for space conditioning. Novelty of the study lies in evaluating thermal building performance in accordance to actual current internal heat gains form manufacturing process loads and future possible conditions. Combinations of natural ventilation patterns and building envelope retrofit measures proved to efficiently reduce overheating during occupancy work hours without mechanical cooling for all IHG levels. However the assessment of thermally comfortable hours diverges greatly between the adaptive approach and the exceedance of a fixed maximum room air temperature. According to the second approach there should always be an increased ACH during the night for higher amount of comfortable temperatures, whereas this practice results in values regarded as too cold by the adaptive approach. Further research is therefore needed on adjusting the comfort temperature limits in natural ventilated industrial buildings.

More in detail, either the application of cool coating on the existing roof or solar heat gains control via automatically deployed exterior shading induced an improved thermal environment for the current factory conditions with overheating occurring less than 1% of the time. Hence implementing only such a measure would be a sufficient cost-effective investment. As IHG increase though, they separately fail overheating evaluation. Yet a combination of both (S3) achieves a comfortable environment for most of the time for all IHG scenarios. For the case study an overall thermal refurbishment of the building skin would not be necessary for the goal of overheating elimination as it would increase investment costs without offering considerable advantages. However, even for warm summer months in the region, it would not be counterproductive yet with high IHG, as night natural ventilation proved capable of keeping the hall from overheating. Therefore thermal improvement of the building envelope should be considered as an option for an optimum retrofit strategy for a whole year round comfortable thermal environment also in regard to reducing heating energy demand during winter.

In every occasion regional climate conditions should be considered for determining the applicability of retrofit measures. In case of colder climates, where overheating problems are reported, permanent solutions with an application of a cool roof coating should be carefully studied before implemented, as they would affect the solar heat gains also in winter, thus increasing the heating demand. On the other hand, for warmer climates than that of the case study, cool roof and exterior solar shading would be certainly beneficial. Particular caution though should be paid for the application of additional insulation, as natural ventilation strategies may not succeed to dissipate excessive internal heat.

Findings of the current paper can prompt industrial facilities to consider improvement of their building envelope and passive cooling strategies for coping with overheating problems. Lest such approach is proven not entirely feasible, hybrid solutions of passive and active measures to minimize cooling loads should be examined, as this study indicated the large impact of passive options on the thermal environment of an industrial hall.

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NOMENCLATURE

ACH	Air Changes per Hour
CIBSE	Charted Institution of Building Services Engineers
CZ	Control Zone
DNI	Direct Normal Irradiance
EPS	Expanded Polystyrene
H_e	hours of exceedance
GHI	Global Horizontal Irradiance
IHG	Internal Heat Gains
$\mathrm{MBE}_{\%}$	Mean Bias Error
MCBs	Mechanically Cooled Buildings
NCBs	Non-mechanically Cooled Buildings
r	Pearson's Index
RMSE	Root Mean Square Error
$\mathrm{T}_{\mathrm{air}}$	air temperature in °C
TM52	Technical Memorandum 52
T_{max}	maximum acceptable operative temperature in °C
T_{min}	minimum acceptable operative temperature in °C
TMY	Typical Meteorological Year
T_{op}	actual operative temperature in °C
T_{rm}	running mean outdoor temperature in °C
T_{upp}	upper limit temperature in °C
W_e	daily weighted exceedance in degree hours
w_f	weighting factor
ZAMG	Austrian central institution for meteorology and geodynamics
$\Delta\mathrm{T}$	difference between actual and maximum operative temperature in °K

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Paper 4

Georgios Gourlis and Iva Kovacic

"A holistic digital twin simulation framework for industrial facilities: BIM-based data acquisition for building energy modeling"

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EDITED BY
Abid Nadeem,
Nazarbayev University, Kazakhstan

REVIEWED BY
Saeed Reza Mohandes,
The University of Manchester,
United Kingdom
Hande Aladağ,
Yıldız Technical University, Turkey

*CORRESPONDENCE
Georgios Gourlis,
georgios.gourlis@tuwien.ac.at

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A holistic digital twin simulation framework for industrial facilities: BIM-based data acquisition for building energy modeling

Georgios Gourlis* and Iva Kovacic

Department of Integrated Planning and Industrial Building, Institute of Interdisciplinary Construction Process Management, Faculty for Civil Engineering, TU Wien, Vienna, Austria

Energy and resource efficiency as well as reduction of emissions are nowadays significant objectives for production companies. Industry 4.0, through extensive digitalization along the value chain, enables the achievement of these objectives not only in the construction of new facilities but also in existing facilities as well. This requires an interdisciplinary approach, extending over production and logistic processes as well as the building, technical building services, and energy supply systems, consolidated through integrated modeling and simulation-based optimization. The research question this study addresses is how to digitally couple these subsystems and optimize the overall system's performance in terms of energy and resource efficiency, by distancing from silo-field thinking while using an integrated analysis approach. The article briefly presents a holistic modeling and simulation framework, utilizing modular digital twins (DTs) of all elements that may constitute a given industrial unit. The integration of multiple DTs of these subsystems in a hybrid (continuous and discrete) simulation forms a holistic DT ecosystem of an existing facility. The particular focus of the study is the building representation in this DT ecosystem for energy-efficient production. Based on a methodology including hybrid simulation, building information modeling (BIM), and visual programming, a semi-automated data acquisition workflow was proposed. The hybrid simulation is based on Discrete Event System Specification (DEVS) formalism, where the building is incorporated as a building energy model (BEM). Within the abstracted representation of the overall system, the article explores the possibilities of parametrizing the DT of the building, interconnected with the rest of the factory elements, by acquiring information directly from existing BIM models. Through a comparative case study, the proposed workflow is

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Abbreviations: AEC, architectural engineering construction; API, application programming interface; BEM, building energy modeling; BIM, building information modeling; CAD, computer-aided design; DESS, Differential Equation System Specification; DEVS, Discrete Event System Specification; DT, digital twin; ERP, enterprise resource planning; FVM, finite volume model; GA, genetic algorithm; gbXML, Green Building Extensible Markup Language; IFC, Industry Foundation Classes; MABEM, manual BEM-based workflow; MES, manufacturing execution system; MPS, manufacturing process simulation; SADYN, semi-automated Dynamo-based workflow; TBS, technical building services.

compared to a manual one in terms of integrity and benefits. The study's contribution lies in: *1*) the detection of the required building level of abstraction for a holistic DT ecosystem, *2*) the definition of the interconnections between the building-related counterparts and the rest of the virtual environment as well as the data required for their parameterization, and *3*) proposing a semi-automated workflow *via* virtual programming, for BIM-based creation of the building model within a holistic DT ecosystem.

KEYWORDS

building information modeling, modular digital twins, hybrid simulation, dynamo, energy modeling, holistic industrial modeling, industrial facilities

Introduction

Traditionally, four objectives have determined the criteria for decision-making in the manufacturing sector, namely costs, time, quality, and flexibility (Chryssolouris, 1992). However, increasing energy and raw material prices, necessary investments for compliance with environmental and political targets as well as raising public awareness of resource consumption and climate change, posing a challenge to corporate images, have led production companies to include energy and resource efficiency as an additional decision-making objective.

Significant benefits can be gained by utilizing simulations for predicting the energy consumption of the whole manufacturing process, including production chains as well as auxiliary systems (Thiede et al., 2013). It requires the modeling of complex systems, with both continuous and discrete aspects, to assess the performance and interaction of machinery and manufacturing processes with auxiliary components such as the technical building services (TBS) and the industrial building itself. These are thus considered subsystems of the overall system of an industrial unit. Using one model executed by a single simulation engine is regarded as a classic simulation, whereas co-simulation uses different sets of models simulated by their accompanying simulation engines, results of which are interconnected and refeed the models' parameters (Steinbrink et al., 2018). Furthermore, hybrid simulation refers to the existence of multiple models, which are though executed by one simulation engine. Previous comprehensive simulation-based approaches have combined and assessed the multiple subsystems of industrial environments, utilizing co-simulation of separate tools (Bleicher et al., 2014; Sun et al., 2016; Thiede et al., 2016; Herrmann and Thiede, 2019) or by combining different applications in a single environment simulation (Despeisse et al., 2013). The first combine best-of-class tools under technically challenging conditions of combining continuous time-driven with discrete event simulation models, for example, building performance simulation with manufacturing process simulation, which poses a challenge in terms of practical implementation. On the contrary, the second approach included manufacturing procedures in a building energy modeling (BEM) tool. However, this faces the limitations of simplistic modeling of manufacturing processes, incorporated in the time-driven continuous simulation, modeled as thermal zones or assumed as internal thermal load with a defined operating schedule, based on external process level simulations (Garwood et al., 2018a). Hybrid simulation approaches in industrial engineering, where discrete and continuous sub-models are solved simultaneously are not known to the authors. Furthermore, previous efforts focused exclusively on the analysis and planning of new industrial facilities, lacking the ability to assess and optimize energy and resource flows during actual operation, where initial models can be continually updated by monitoring data.

In the course of the Industry 4.0 developments, there is rapidly evolving research concerning the implementation of virtual models of physical systems, which are updated by real-time data obtained from sensors, commonly known as digital twins (DTs), as first proposed by Grieves (2014). The primary utilization of DTs in manufacturing-related research and applications includes engineered products, production machines, or manufacturing processes and focuses on production planning and monitoring, resource management, and predictive maintenance (Lo et al., 2021). Much of the already conducted research is asset specific, where the various physical assets of an industrial facility are represented by a set of very detailed but separated DTs, addressing from single components or machines up to production lines or shop floors (Melesse et al., 2021). Comprehensive modeling and simulation of industrial DT concepts are scarce, as the one proposed by Becue et al. (2020) refers to production and logistics processes within a factory unit or even among more industrial units. However, the relation of the manufacturing process with the industrial building that houses it has not yet been addressed in such concepts.

Scaling up from the machines' level to the building, building information modeling (BIM), defined as "a digital representation of physical and functional characteristics of a facility" (BuildingSMARTalliance, 2007), forms the source of information for a DT of the building. BIM-based DTs in an industrial context have been studied principally in terms of a detailed geometric representation of existing facilities, linked with a navigation framework supporting human and robot movements (Delbrügger et al., 2017), or real geometric configuration of the

DT regarding complicated shapes (Agapaki & Brilakis, 2022). No research regarding BEM as well as energy and thermal performance of an industrial building assessed *via* BIM-based DTs is known to the authors. It should be also noted that the process of BIM-based BEM is not yet standardized, as recent studies showed that there is no solid workflow able to generate reliable models ready for analysis (Bastos Porsani et al., 2021) and BIM tools as well as data transfer formats should be further developed to contain and transfer all required data (Gao et al., 2019).

Taking the aforementioned particulars into account, a gap is identified within the interdisciplinary research domain, integrating production and logistic processes as well as the building, technical building services, and energy supply systems, thus allowing integrated modeling and holistic simulation-based optimization. The research problem is how to digitally couple these subsystems and optimize the overall system's performance in terms of energy and resource efficiency, instead of insular optimizations of singular domains, as it still is the state-of-the art; which does not lead to an overall achievement of sustainable production. Therefore, a holistic framework and an accompanying prototypical toolchain for DT-based hybrid simulation and optimization of existing manufacturing facilities' operations were proposed within the research project Balanced Manufacturing (BaMa). The goal was to couple the objectives of sustainability with competitiveness taking into account energy consumption and related carbon emissions, production costs, and time (BaMa, 2018). The holistic nature of the approach lies in the incorporation of all elements of a factory, including the building and TBS together with the manufacturing processes and logistics. The hybrid nature of the simulation lies in the fact that both continuous and discrete aspects are addressed in a single environment of interconnected DT components of all subsystems, forming a holistic DT ecosystem of the whole facility. This has the advantage that the various sub-models must not be split into different simulation environments along the boundaries of discrete and continuous modeling, where important synergies may be neglected or partially evaluated (Heinzl et al., 2018). In this respect, the inclusion of various aspects of each subsystem involved requires a certain level of abstraction so that the DT sub-models can be combined and solved by a single simulation engine. About building-related attributes can serve as a knowledge database and input information to the holistic DT models and the hybrid simulation. Still, data-rich BIM models need to be simplified to provide only certain information, essential for the accomplishment of the integrated hybrid simulation analysis. The building DT in the proposed framework differentiates from common building DTs, as it does not utilize a BIM model as the DT by itself, but creates an abstracted representation of the building's spatial relations with the production and logistic processes as well as a BEM, by extracting information from a BIM model.

The scope of the article is the building representation of the proposed holistic DT-based framework for modeling and simulating industrial facilities. It presents the proposed framework and further focuses on the use of BIM models for creating and parametrizing the building-related part in the hybrid simulation environment. Data exchange requirements from BIM models are defined and model simplification principles are analyzed. It is examined, how and to which extent building-related attributes regarding BEM can be integrated into the modular hybrid simulation models *via* a semi-automated data acquisition workflow. The novelty of the work lies in the creation of the building component of the hybrid simulation model of an industrial facility, in the holistic BaMa DT ecosystem, with data acquired directly from a BIM model. Therefore, the feasibility of the proposed semi-automated data acquisition workflow based on visual programming is investigated and tested for its integrity in a comparative case study against a manual process of acquiring the necessary building-related data.

Figure 1 shows the structure of the study. *Theoretical background* provides a theoretical background on the related topics of DTs in the manufacturing and AEC industries, holistic energy modeling and simulation of industrial facilities, BIM-based BEM, and the potential of coupling visual programming with BIM. *BaMa: a framework for a holistic digital twin ecosystem* gives an overview of the BaMa framework for a holistic DT ecosystem in industrial facilities, explaining the role of the building in the hybrid simulation environment. *Scope of research, tools, and methods* presents the methodology and sets the research questions. *Building energy modeling procedure within the BaMa digital twin framework* then proposes a workflow for BIM-based data acquisition for the abstracted building representation and the BEM model within the BaMa DT ecosystem. *In Evaluation of the proposed data acquisition workflows* the proposed workflow is evaluated by a comparative case study. Finally, the results of the comparative case study application, identifying strengths and limitations of the suggested procedure are discussed together with the challenges and opportunities for holistic modeling and simulation as of the proposed framework.

Theoretical background

This section outlines the key related works in four main research areas relevant to this study: *1*) digital twins (DTs) in the manufacturing and AEC industries, *2*) holistic energy modeling and simulation of industrial facilities, and *3*) BIM-based BEM and *4*) the potentials of coupling visual programming with BIM.

Digital twins in manufacturing and AEC

The original concept of a digital twin was introduced by Grieves in 2003 on product lifecycle management in the field of

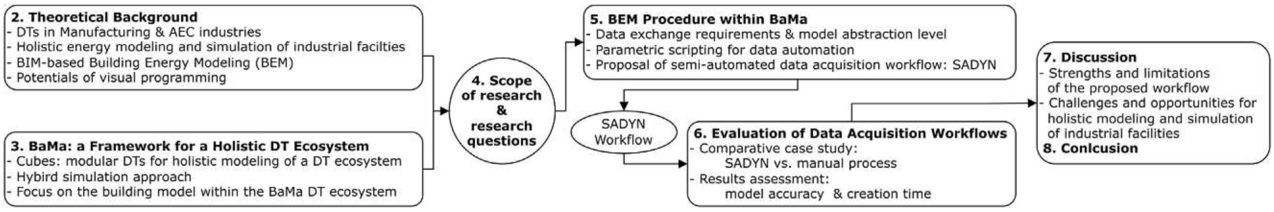

FIGURE 1
Structure of research.

manufacturing engineering (Grieves, 2014). Since then, it has grown across various industries and it has been given a variety of definitions and characterizations. A generalized and consolidated definition, avoiding industry-specific characteristics was recently provided by VanDerHorn and Mahadevan (2021), where a DT is "a virtual representation of a physical system (and its associated environment and processes) that is updated through the exchange of information between the physical and virtual systems." This virtual representation is an idealized form of the physical reality, based on the interpretation of the data collected from the physical world, considering a certain level of abstraction imposed by the scope of the created model. The primary motivation for the use of a DT is the monitoring of the system of interest as it changes over time. The DT virtual representation describes a single instance of the physical system and is updated at frequent intervals (VanDerHorn and Mahadevan, 2021).

Manufacturing-related DT research is mainly focusing on products' design and lifecycle (Tao et al., 2018; Lo et al., 2021), production lines and machinery, (Cimino et al., 2019), predictive maintenance (Aivaliotis et al., 2019), and equipment energy consumption management (Zhang et al., 2018). Applications of DTs also considering the auxiliary components of a factory are less common, such as the study by Blume et al. (2020) on DTs for TBS operation in factories, on a case study of a cooling tower. Manufacturing-related DTs are usually high-fidelity virtual representations of systems and processes and are monitored in real-time, with DT update frequencies in the scale of seconds or less. Furthermore, they generally focus on the low field level of the automation pyramid, (Martinez et al., 2021), that of sensors and actuators for collecting production data and executing commands (ANSI/ISA-95, 2018).

DTs in the AEC industry are up-to-date dynamic models of a physical asset or a facility, including all structured and unstructured information of the project used to model, simulate, understand, predict, and optimize aspects of the physical asset (Alizadehsalehi and Yitmen, 2021). BIM as a digital platform is directly related to the implantation of DTs in the AEC, as the latter evolve from detailed BIM models by integrating simulations, real-time monitoring, and AI. As in product design applications, DTs in the AEC can be utilized before the physical system really exists. In the design phase, they can create a solution virtually and accurately assess its operation (Deng et al., 2021). In the build phase, DTs can provide the construction specifications to the different providers and enhance the procurement process (Shirowzhan et al., 2020). Finally, in the operation phase, when the physical asset is equipped with enough sensors, backed by AI, they provide predictive maintenance and performance optimization by enabling the system to automatically modify its operation or indicate the need for human intervention (Boje et al., 2020).

It should be noted, that in the case of DTs referring to the built environment, the physical system of interest is usually a whole construction project, building, or even part of a city, with various aspects and interconnections to be considered. Unlike manufacturing DTs, where the model may consist of a single machine or production line (modeled in detail as a system together with its environment influences), AEC DTs are usually extensive and detailed virtual representations of the physical reality, resulting in very high levels of model fidelity. However, a DT is not destined to be an exact representation of reality, as the level of model detail directly relates to the level of abstraction of reality chosen for the virtual representation, defined by the scope and required outcomes of the particular use case (VanDerHorn and Mahadevan, 2021). Considering this position, a building DT can also be outlined by a greater abstraction level, if this complies with the intended use of the model.

Holistic energy modeling and simulation of industrial facilities

Although the utilization of BEM for assessing the building energy performance is a common practice in the AEC industry, in the field of industrial buildings is still a relatively young approach (Moynihan and Triantafillu, 2012; Wright et al., 2013; Lee et al., 2014; Gourlis and Kovacic, 2016; Del Giudice et al., 2021). Assessing and optimizing industrial facilities from an energy use perspective are more challenging than buildings in the residential and tertiary sector, as internal heat gains from manufacturing activities can have a significant impact on the indoor conditions and their scheduling can vary greatly over time, given production demand and economic cycles (Liu et al., 2013; Gourlis and Kovacic, 2017a). Production-related internal gains can be assumed based on installed equipment or directly measured in the case of an operating facility, with the first potentially leading to disputable results and the second being restrictive to existing production configurations. In any case, when using BEM software, simplistic operating schedules defining either maximum loads (Moynihan and Triantafillu, 2012; Lee et al., 2014) or daily patterns (Gourlis and Kovacic, 2016) can be considered within the software environment of BEM tools, as current software cannot accurately incorporate industrial processes (Wright et al., 2013).

Hesselbach et al. (2008) were one of the first to point out that the complex and dynamic interdependencies of machines and production processes, operational management, technical building services, and the building climate could only be analyzed *via* a holistic view of the facility. According to Duflou et al. (2012), a holistic understanding of the different levels of manufacturing processes, from unit-processing and multi-machine levels to a factory level or even further on multi-factory and supply-chain levels are essential for developing the next generation of manufacturing facilities. Coupling of BEM capabilities with manufacturing process simulation (MPS), generally used for optimizing manufacturing process line and plant's throughput, offers such a solution, up to the whole factory level. Garwood et al. (2018a) produced a comprehensive review of energy simulation tools and methods for the manufacturing sector, focusing on the combination of BEM with MPS. They categorize holistic approaches into two types, co-simulation and hybrid simulation solutions. Co-simulation uses a state-of-the-art software platform for each discipline and couples them to share data between simulation iterations. The hybrid simulation uses a single solver platform capable of modeling all entities, flows, and interdependencies achieving a maximum level of interaction between various processes. This level of high interaction between systems may not be achieved by a compartmentalized co-simulation solution, as information, for example, about internal heat gains, can be only unidirectional from one software to another (MPS to BEM) and is not modeled in a bidirectional manner among different facility subsystems, being the case in coupling Simulink/MATLAB with EnergyPlus (Brundage et al., 2014).

It is worth noting, however, that holistic simulation solutions may not be suitable for small- or medium-sized enterprises, as these usually require considerable effort in the modeling process, and in the case of simpler systems, energy metering and static numerical calculations would be more appropriate. For more complex systems and large automated production lines, holistic simulations can reveal synergies and optimization potential on multiple levels, from machine to production line and the whole factory. Large enterprises may already have BIM models of their facilities containing the information required for the holistic analysis; however, this does not entail a *de facto* faster modeling of the necessary simulation model, due to the required simplification and filtering of provided data as well as interoperability issues of the different discipline-oriented software applications.

Challenges in BIM-based building energy modeling

The use of BIM data for facilitating the creation of BEM models to asses building thermal and energy performance has been a topic of thorough research, both academic and industrial, barring a huge potential for building design process optimization. BIM models, considered knowledge databases, can contain most information required for a BEM analysis; however, BIM-based BEM still poses great challenges. These can be briefly sorted into two main fields, being the discipline-specific requirements between the BIM and BEM authoring sides, resulting in the necessity of BIM simplification for performing BEM simulations, and the interoperability issues between BIM and BEM software.

It is known that different software applications typically reflect different "views" of the same building and each must deal with issues unique to its discipline (Bazjanac and Kiviniemi, 2007). These essential discipline-specific differences in the "view" of the building, with usually that of the architect creating the original BIM model not complying with that of the simulation expert further utilizing the BIM model for BEM analysis, can be exceeded by following guidelines during the creation of the initial BIM model (Maile et al., 2013; Senave and Boeykens, 2015). However, such an approach is hard to implement in practice, especially in large industrial building projects where the shared BIM model is altered by various disciplines. The major challenge here lies in the geometrical representation of the building, as BEM requires a much simpler geometry than computer-aided design (CAD) software. BEM implements a finite volume model (FVM) of buildings and room envelopes to simulate the thermal performance of each thermal volume relative to each other and the surrounding environment of the building. The highly detailed and accurate modeling of the building is not required in BEM as small discrepancies will not have a significantly detrimental effect on the overall building performance (Garwood et al., 2018b). BIM-originated geometry must, therefore, be simplified and reduced to be used for BEM, also contributing to shorter computational times in simulating complex models (Lagüela et al., 2014; Choi et al., 2016). The preparation or simplification can be performed automatically to some extent but also needs manual efforts (Ladenhauf et al., 2016; Pinheiro et al., 2018). Furthermore, insufficient construction or material information in BIM objects, not defined by the original BIM authoring side, poses another barrier for BIM-based BEM (Kim et al., 2016).

Concerning data interoperability, the two prevalent data exchange schemata for BIM-based BEM are IFC (Industry

Foundation Classes) and gbXML (Green Building Extensible Markup Language), developed by BuildingSmart and Green Building Studio Inc., respectively. Although IFC, being the only ISO-certified schema (ISO EN, 2016), has been developed with a wider scope for providing BIM interoperability among different domains and disciplines from building construction to building operation, gbXML is focused on the energy simulation domain, adopted by several BEM software vendors as a *de facto* standard for importing BIM data (Bahar et al., 2013). Since the IFC version IFC4 add2 in July 2016 (BuildingSmart, 2022), both exchange schemata can contain the necessary information for a BEM analysis as building geometry, thermal zones, construction types, and material properties, whereas only limited data related to HVAC systems (Kamel and Memari, 2019). Differences lie in the fact that gbXML can only export rectangular geometry from BIM models, which is not the case for IFC, but it is the only one to provide information on the location of the building (Kamel and Memari, 2019). Further on, geometry in gbXML is defined utilizing centerline representation (Pinheiro et al., 2018), while IFC is capable of exporting second-level space boundaries by using standardized Model View Definitions (MVDs), which specify how each object or information should be represented for a particular, discipline-specific view (Venugopal et al., 2012). The first can lead gbXML-generated BEM to an increased zone volume and a potential overestimation of the resulting energy consumption (Bazjanac et al., 2016), however, second-level space boundary data in IFC are often missing or incorrect, hindering the BEM creation process with manual corrections or requiring specific algorithms to produce valid data (Lilis et al., 2017).

Regardless of the selected schema, information loss during data exchange from BIM to BEM is a frequently reported problem (El Asmi et al., 2015; Sanhudo et al., 2018; Gao et al., 2019; Kamel and Memari, 2019). Kamel and Memari (2019) divide the causes of interoperability issues into four categories where *1*) the BIM software may not transfer all the required information in the exchange file, for example, the IFC exporter of Revit (version 2018) is not exporting information about thermal and optical properties of construction materials, although IFC can incorporate them (Lilis et al., 2018); *2*) the exchange file may not be able to save all the information properly, for example, building location, HVAC properties, and building usage; *3*) the BEM software may not be able to read all the information in the data exchange file; *4*) information may not be mapped and transferred properly to the BEM and energy simulations engine's file format.

Potentials of visual programming and BIM

Taking the aforementioned particulars into account, we conclude that BIM-based BEM is undergoing rapid and intense development but there is no guarantee in generating automated or with limited additional effort reliable BEM models. Considering also that currently available BEM solutions are not capable of modeling manufacturing processes in industrial facilities, and a further examination of alternative methods to retrieve information from digital building models for holistic energy efficiency industrial applications is performed.

In this scope, the utilization of visual programming in the AEC industry can lower the hurdle for acquiring essential data from BIM models and simultaneously reveal great potential for data analysis and processing tasks (Preidel et al., 2017). Being more user-friendly than typical programming languages, visual programming is mainly used in the AEC field for generative purposes of parametric geometry and semantic information (Hummpi and Österlud, 2016), as well as for checking or querying information on existing models (Amann et al., 2018). Dynamo is a graphical algorithm editor linked with Autodesk Revit using the Revit API and allowing users to create algorithmic scripts by connecting nodes. As a parametric modeling engine, Dynamo extends Revit's capabilities by adding a level of associativity that does not exist in the off-the-shelf application, including driving parameters based on external inputs (Kensek, 2014). One of its features is the facilitation of categorizing and managing information from large amounts of components in a BIM model, as in the case of high-rise buildings (Gan et al., 2018). In the field of building energy analysis, Dynamo has been used as a medium to facilitate interoperability *via* gbXML between the BIM model and BEM tools concerning adaptive facades with building integrated photovoltaics (Somboonwit et al., 2017); or functioning as a platform for deploying algorithmic building performance simulations directly in the BIM environment of Revit, without the need of two separate models and a data exchange schema (Kensek, 2015; Dong et al., 2021).

BaMa: a framework for a holistic digital twin ecosystem

In the course of previous research within a funded research project Balanced Manufacturing (BaMa) a DT framework for software architecture and a prototypical toolchain were proposed, enabling large industrial facilities to integrate energy-related planning into the actual plant operation. A holistic approach addressing all subsystems of a facility (production process, logistics, TBS, and the building itself) was chosen, considering both ecological and economic aspects as optimization targets. The DT simulation-based framework enables monitoring, predicting, and optimizing energy demand and the associated carbon emissions as well as costs, to be linked to the existing industrial automation systems of the facility. BaMa, therefore, does not just assess the optimization potential of designed or existing production but introduces energy efficiency as a steering value into a factory's

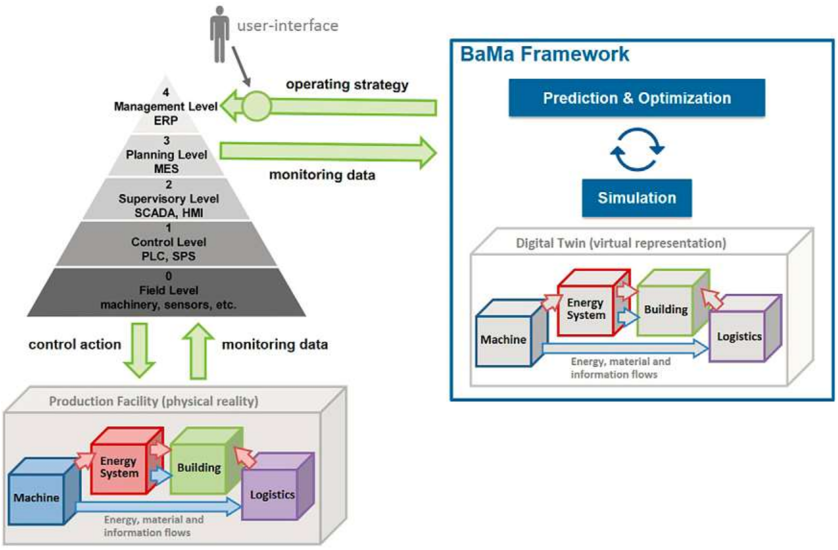

FIGURE 2
Schematic representation of the BaMa framework's components and interconnectivity (adapted from BaMa, 2018).

operational planning and can be utilized iteratively, such as an advanced planning and scheduling system would support a cost and/or time-efficient production process (Chryssolouris, 1992). The novelty of the BaMa framework lies in the fact that it addresses existing operation facilities and utilizes a holistic hybrid simulation approach with discrete and continuous models solved simultaneously in a single solver platform. These form a holistic DT ecosystem of all factory subsystems, which are continually updated by monitoring data for a simulation-based optimization.

The BaMa holistic DT ecosystem consists of three main parts: constant monitoring, simulation-based predictions, and multicriteria genetic algorithmic optimization. Figure 2 shows a schematic representation of the system's components and interconnectivity. BaMa acquires real-time data from various sensors attached to the production process and the building technical systems, referring to the logistic flows and storage as well as monitoring the space's indoor conditions or outdoor weather data. It reports back on the planning and management levels, automation pyramid level 3: manufacturing execution system (MES) and level 4: enterprise resource planning (ERP), as defined by standard ANSI/ISA-95 (2018). However, offline data collection is also relevant, including physical inspections and changes regarding the physical relations of the modeled subsystems (e.g., machinery is removed from a certain space or a big hall is structurally and thermally divided into smaller ones). The monitoring of resource consumption and required conditions of all subsystems is compatible with the energy management standard ISO 50001. The prediction of the energy and resource demand, performed by the hybrid simulation, is based on the real-time monitoring data from the four subsystems comprising a factory—production equipment and processes, logistics, TBS, and the building—extended by day-ahead production plans and forecasting data (e.g., weather information). The optimization of the plant operation *via* a genetic algorithm (GA) regards the targets of energy, time, and costs as well as restrictions resulting from given degrees of freedom, resource availability, and product quality. The GA's primary aim is to minimize energy demand with the utilization of synergies, peak load management, and efficient use of available equipment (Sobottka et al., 2017). Its prototypical deployment in an operating industrial baking facility indicated a reduction of the overall energy consumption by up to 30% (Sihn et al., 2018).

BaMa digital twin: the modular cubes

BaMa implements a generic modular approach to create a facility's DT and models a unified virtual representation of all four factory subsystems in a single solver platform, aiming for the flexibility and reusability of the modular models for a variety of industrial facility types. The core modular element of BaMa DT is the *cube*. Cubes are the components of the DT, representing physical parts of the facility, and are mapped into mathematically formulated virtual counterparts in the DT. They decompose the overall physical system into manageable elements with well-defined interfaces at a chosen level of abstraction and are assembled each time in virtual constellations representing a unique plant, enabling the analysis of complex and

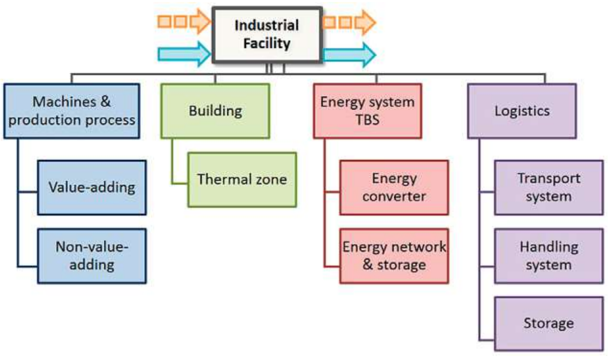

FIGURE 3
Overview of the BaMa cube classes and sub-classes.

heterogeneous processes. From a top-down view, cubes can be considered as black box models of, for example, a machine, a room, or a piping grid, arranged hierarchically, meaning that a cube can be contained in another cube. The level of abstraction of each cube must correspond to the intended use of the resulting model. The data abstraction process requires, thus, a detailed observation and understating of the reality and a further interpretation process of the data which will consist of the idealized virtual representation, providing the relevant evidence about the reality. The resulting cube models have interfaces consisting of three distinct types of data exchange: energy flow, material flow, and information flow. Energy flows are described by continuous values that require a time-driven modeling approach, whereas material and product flows are discrete entities demanding event-driven modeling. Both carry related carbon emissions and cost weights for assessing the ecological and economic performance of the production. Last, information flows can exchange various information needed for the internal calculations of a cube. The process of determining the modular parts that consists of the entire facility, as well as their interrelationships, is defined inside BaMa as *cubing*. For example, cubing is performed to analyze a production line in all its stages as well as for defining the thermal view of the building envelope. Data of the relevant physical system, parameters outside the selected physical system that affect it, and also its interconnections to other physical systems, are collected, interpreted, and stored in the virtual representation. A detailed description of the BaMa methodology is available in Leobner et al. (2015) and Leobner (2016).

BaMa cubes are divided into four classes, which include different generic cube types aiming to be able to model all the functions within the factory (Figure 3). The building-related cubes are further explained in *Building model within the BaMa digitaltwin ecosystem*; however, a detailed description of all other cube models would be beyond the scope of this study. Further information is available in Raich et al. (2016), Smolek et al. (2017), and Smolek et al. (2018).

BaMa hybrid simulation

Although attempts have been made for a holistic simulation of industrial facilities, most of them focus on machine and process levels, neglecting details and interdependencies with the built environment of an industrial facility (Mawson and Hughes 2019). Furthermore, a recent review acknowledged that no simulation software is capable of performing holistic modeling in a single solver platform across all production facility partial systems and linking those models together (Garwood et al., 2018a). Despeisse et al. (2013) have presented an approach for holistic industrial facility simulation within single time-driven BEM software. However, this approach is limited to simple production processes that can be modeled as thermal zones and is not capable of managing intricate production lines. Those could be simulated in separate software and be given afterward as a simplistic schedule for internal thermal loads back in the BEM software. In the scope of BaMa, the necessity of combing time-driven (continuous state) with event-driven (discrete state) modular cube interfaces in a single modeling environment led to the implementation of the Discrete Event and Differential Equation System Specification (DEV&DESS) (Zeigler et al., 2000), as a hybrid Discrete Event System Specification DEVS formalism (Zeigler, 2006), based on Parallel DEVS (P-DEVS) (Chow and Zeigler, 1994). Such kind of simulation environment is increasingly being adopted as the preferred approach to intelligent hybrid (continuous and discrete) cyber-physical system design (Zeigler, 2021).

The desired flexibility of *cubes* as modular elements further required a strict interface definition. Since none of the existing building performance simulation tools and data exchange schemata such as IFC and gbXML are compliant with the BaMa interface definitions, a new building thermal simulation solution was created inside the BaMa framework and required input information had to be defined and structured to apply the cube approach. The capabilities of the BaMa hybrid simulation, originally implemented in MATLAB, were tested with a simple prototype (Smolek et al., 2018) and were validated against EnergyPlus (Gourlis et al., 2017). The simulation results of an actual facility modeled with the hybrid BaMa approach, including the building, ventilation systems, and manufacturing procedures, were also found to comply with available monitoring data, proving the reliability of the models (Smolek et al., 2017).

Building model within the BaMa digital twin ecosystem

Industrial buildings' main function is to house the necessary equipment and provide an appropriate indoor environment for production and its accompanying activities, for both employees and industrial operations. The first is achieved by the spaces' layout and the building structure, while the second is by the performance of the building envelope in combination with the use of TBS and the impact of production processes. The proposed BaMa framework does not aim to optimize the building design or the envelope quality and actual building performance, but considers the building as a fixed boundary of the examined overall system, influenced by external and internal conditions and having an impact on the final overall energy demand. Thus, the objective is the actual performance of the building which is assessed in the three parts of the BaMa framework as follows: *1*) by monitoring space conditions to avoid violations of required conditions and comfort, *2*) by predicting heating or cooling demand based on current weather conditions or forecast data and the actual production schedule *via* the hybrid simulation models, and *3*) by optimizing the heating or cooling schedules according to the proposed production plan.

Crucial points in the creation of the building component of the facility's DT are the identification of the intended outcomes and the definition of the model scope. Identifying the target outcomes enables the scope of the modeled DT to be realistically bounded to achieve these outcomes, which should be measurable and quantifiable (VanDerHorn & Mahadevan, 2021). Outcomes of the building components of the BaMa DT implementation are primarily the actual energy demand for heating and cooling of the industrial facility and secondarily the maintenance of the required indoor climate conditions. Based on these targets, the DT scope regarding the building-related physical system is the definition of the building geometry and structure in a multi-zoned thermal model of the facility (as in typical BEM applications), at a certain level of abstraction though, so that it will not add additional complexity to the whole holistic DT ecosystem of the facility.

On the inputs side, the DT models are fed with statistical parameters and state variables. The first does not usually change over the course of the simulation unless an adaptation of the model behavior is needed, whereas the second refers to dynamic values, collected by sensors. In the case of the building DT, the real-time data deriving from sensor monitoring space conditions (e.g., air temperature, relative humidity, CO_2, and air quality levels) feed constantly the hybrid simulation as state variables. Furthermore, monitoring information of the TBS is also fed to the BEM part of the hybrid simulation, such as temperature and air speed of the air supply ducts or, for example, temperature and flow rates from the circulating medium of ceiling radiant panels. Last, heat gains from machinery and the production processes are collected and fed to the building DT by sensors measuring the electrical consumption of motors and thermometers in the case of heat-intensive processes, such as ovens. This kind of state variables, combined with the fixed parameters already provided to the models (e.g., the air volume of a thermal zone, the air volume of the industrial oven, product size, and temperature after exiting the oven process) manage to depict the actual physical reality in the holistic DT ecosystem, serving as the base of simulation-based optimization.

The building is analyzed in BaMa, such as the other three subsystems of the factory, by the previously described modular concept of *cubes* to form the holistic DT of the facility. The building is thus virtually represented by the building and the thermal zone cubes. Building-related cubes have no discrete entities directly interacting with them, thus there is no need for discrete interfaces and models to handle explicitly continuous flows of information and energy. For the assessment of the building-related energy demand, the facility is divided into thermal zones, as is the usual practice in BEM. At the building level, the BEM part of the hybrid simulation, such as other commercial BEM tools, delivers the required heating and cooling demands for each zone, which is then provided, or not, by the TBS cubes, such as the HVAC models inside other BEM tools.

The "building cube" constitutes the construction elements of the facility. It describes the heat transfer through the building envelope into the thermal zones, natural and forced convection on the walls, and solar irradiance on opaque and transparent elements. Inputs are the temperatures of all thermal zones coming according to the occasion either from monitoring data or simulation outcomes, as well as the thermal boundary conditions (outdoor, ground, or other non-simulation temperatures), which are constant parameters. Other inputs are the solar radiation per square meter and the forced convection heat transfer coefficients; the latter, depending on exterior wall perimeter, roughness, area, wind speed, and wind direction, are not calculated inside the cube model due to time efficiency. The net heat gain or loss is calculated as an output result for all thermal zones. The basis underneath the building cube is a resistance-capacitance model, using one capacitance representing the thermal storage potential of the wall or slab and two resistances. The thermal capacity is lumped together, resulting in a single thermal storage potential parameter per wall or slab element. The topology of the building elements is handled by matrices, which relate the position of zones and boundary conditions to each other.

The "thermal zone cube" defines the thermal capacity of the thermal zone's content with a single internal temperature, considered to have a homogeneous air distribution throughout its volume. Inputs present are the heat transfer *via* zone boundaries, which is calculated in the building cube, the ambient temperature, which affects the zone infiltration, waste heat internal gains calculated by the production process cubes based on real-time sensor data, and the provided heating and cooling load capacities by the TBS cubes. The temperature in the thermal zone is calculated from the balance of the heat flows over the system boundary as an output. Additional outputs are the heating, cooling, and ventilation demand, as determined by the thermal zone cube for the next time step. To carry out the necessary calculations, both cube types need to have several parameters defined, resulting in the aforedescribed outputs as new state variables of the DT in the optimization procedure (Figure 4).

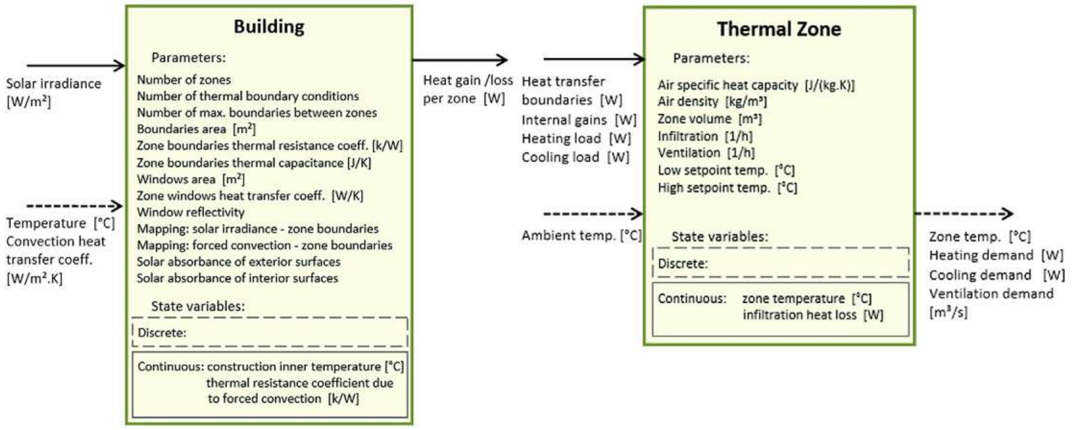

FIGURE 4
Schematic representation of the building and thermal zone cubes.

The use of the hybrid simulation models composed of interconnected cubes results in predicting heating and cooling demands for the virtual counterpart of an operating industrial facility with the actual production plan and occurring process waste heat being integrated into the dynamic model. This poses a clear advantage to methods using co-simulation solutions with assumed internal gains or averaged measurement values, by having to integrate only one model in the facility's automation system for providing optimized production and auxiliary equipment schedules. However, the BaMa building simulation solution has limitations compared to traditional BEM software due to its rather abstract perception of the building. The impact of shading geometry on the building envelope or dynamic shading options is not addressed, as in the case of shades, only a total g-factor can be defined, based on a set diminution factor (F_c value), and applied to the transparent element. Moreover, natural ventilation strategies cannot be thoroughly examined, being limited to predefined increases or decreases of infiltration rates. Another point is that BaMa cube models cannot address thermally activated building components (Gourlis and Kovacic, 2020) Nevertheless, BaMa is not a framework for optimizing the design or technology of the industrial building itself or of available TBS but focuses on the interaction of all subsystems in terms of energy efficiency. To this extent, it allows a qualitative and quantitative analysis of the whole industrial facility.

Scope of research, tools, and methods

The scope of research is the building representation in the proposed holistic DT ecosystem for energy-efficient manufacturing. The novel contribution of the study is the creation of the building-related components within the presented holistic DT simulation-based framework using BIM models for acquiring data for the building representation and parameterization, as presented in *Building model within the BaMa digital twin ecosystem*. This study explores the potential of utilizing visual programming for extracting information from BIM models to the building-related part of the hybrid simulation to form the building DT, as defined in the proposed framework in *BaMa hybrid simulation* and *Building model within the BaMa digital twin ecosystem*. The utilization of a common data exchange schema for BIM to BEM interoperability, described in *Challenges in BIM-based building energy modeling*, is not selected by this study, as the data structure of such schemata is incompatible with the building representation of a DT with a high level of abstraction compared to that of traditional BIM-based DTs. The abstracted DT of the building maintains the spatial relations with the production and logistic processes as well as an appropriate BEM representation by extracting information from a BIM model, functioning as a knowledge database. A workflow linking BIM data with the hybrid simulation models *via* visual programming is proposed and subsequently, a comparative case study is utilized as a testbed for evaluation. The development of the proposed workflow has included the modeling of various industrial use cases to identify the necessary simplification stages for pre-processing an existing architectural BIM model, to be used as an input for an abstracted building representation in the hybrid simulation. Thereupon resulting are building-related data exchange requirements and a semi-automated data acquisition workflow, continuing previous work on data transfer from BIM to BEM for industrial buildings (Gourlis and Kovacic, 2017b) and further the holistic DT hybrid simulation *via* a manual information workflow (Gourlis et al., 2017).

The proposed workflow and comparative study should answer the research questions:

1. To what extent can the creation of the idealized digital representation of the building in the holistic DT ecosystem be automated based on available BIM models?
2. Does the proposed data acquisition and modeling workflow deliver an accurate BEM representation of the building in the holistic DT ecosystem?
3. Can the proposed workflow facilitate the implementation of the BaMa DT framework in industrial facilities?

The tools used in this study are Autodesk Revit as a BIM authoring tool, Dynamo for visual programming to scripting the proposed algorithm, and MS Excel as a post-processing database and input structuring tool for the BaMa framework and its accompanying prototypical toolchain. Revit is selected for being one of the most utilized BIM software worldwide and Dynamo for the fact that allows visual programming within the Revit environment. In Revit physical properties such as thickness (m), density (kg/m³), thermal conductivity (W/m·K), and specific heat capacity (J/kg·K) can be assigned to all material layers of construction elements, as well as specific details for windows as g-factor and visible transmittance. With this information, Revit allows the calculation of thermal resistance and thermal mass of the used constructions. These as well as building geometry and topology information, together with space-related data can be managed and structured with Dynamo and then exported in a spreadsheet database for further processing. Information related to the building and thermal zone cube types, as described in *Building model within the BaMa digital twin ecosystem*, can be then formatted in.csv data, ready to be read by the hybrid simulation, and implemented in MATLAB or C++ applications.

Building energy modeling procedure within the BaMa digital twin framework

The proposed workflow is formulated as follows: definition of data exchange requirements, BIM model simplification, model pre-processing; visual programming for accumulating and managing information of the BIM model, and post-processing. The aim was to provide a data structure that retains all the variables describing the physical reality at the level of abstraction chosen for the building component of the holistic hybrid simulation. The defined *cube* computational models will then describe how the parameters and variables of interest relate to each other within the holistic DT hybrid simulation.

Analysis and definition of data required for the building energy modeling

A set of use cases has been used to define building-related information exchange requirements, along with information about TBS, production processes, and logistics, needed for the hybrid simulation models. First simple prototypes were developed to test modular *cubes* (Raich et al., 2016; Smolek et al., 2018), which then evolved into models of real manufacturing facilities from project partners (Gourlis et al., 2017; Smolek et al., 2017). For the domain of BEM inside the hybrid simulation, necessary input for the two related cube types, as described in *Building model within the BaMa digital twin ecosystem* and Figure 4, was identified based on traditional requirements of BEM tools assorted appropriately to the cube approach.

Table 1 summarizes the necessary building-related data input in the BaMa DT framework. Information is divided into two categories, those related to the building elements such as walls, slabs, and windows and those related to the thermal zones. The first contains information on geometry, element topology and type, space boundaries, and material properties, while the second space-related information, zone set-point temperatures, occupancy, non-dynamic lighting gains, and air change requirements. The table outlines whether necessary information is provided by or can be defined in the BIM model, if it is required to develop a functional hybrid simulation model and whether data can be acquired in an automated way. BIM models can contain the required information directly as needed for the input in the hybrid simulation model, for example, construction type, or include the necessary data and additional information so that the desired value can be calculated afterward, for example, boundary condition. Any additional information defined in BIM, for example, zone set-point temperatures, can facilitate the post-processing. All material properties of opaque and transparent elements must be defined in the BIM model, otherwise default values will be applied, which may though lead to calculation errors.

The last column of Table 1 informs on which input values can be acquired "as they are" from the BIM model and which require additional mapping or further post-processing. The difference between these two procedures lies in the required level of data modification. For additional mapping, the required data exist in the correct form in the BIM model but are not correlated with each element to be used in BaMa. This applies to the material and type-related attributes that are defined for an object type (e.g., wall or window) but the actual elements placed in the model do not have these details as attributes. A simple mapping of the object type parameters with the model elements' topology is thus required. In the case of post-processing, the necessary information is not contained in the desired form in the BIM model but can be calculated or defined based on other

TABLE 1 Data exchange requirements from BIM to BaMa.

Category	Information type	Unit	Available in BIM	Required for BaMa model	Automated acquisition
Building elements	Element ID		✓	prereq	Post-processing
	Zone Name		✓	prereq	✓
	Element type		✓	prereq	✓
	Position in zone		✓	prereq	✓
	Orientation for exterior elements		✓	prereq	Post-processing
	Boundary condition		✓	prereq	Post-processing
	Adjacent construction		✓	prereq	Post-processing
	Construction type		✓	prereq	✓
	Element area	m^2	✓	prereq	Post-processing
	Perimeter for exterior elements	m	✓	prereq	Post-processing
	R-value	$m^2 \cdot K/W$	✓	prereq	✓ + mapping
	Thermal mass	kJ/K	✓	prereq	✓ + mapping
	Air resistance Rsi & Rse	$m^2 \cdot K/W$	—	prereq	Post-processing
	Roughness of exterior elements		(✓)	prereq	✓ + mapping
	Absorptance of exterior elements		(✓)	prereq	✓ + mapping
	g-factor		(✓)	window prereq	✓ + mapping
	Visible transmittance (Tvis)		(✓)	window prereq	✓ + mapping
Thermal zones	Zone ID		✓	prereq	✓
	Zone name		✓	prereq	✓
	Zone level		✓	prereq	✓
	Zone area	m^2	✓	prereq	✓
	Zone volume	m^3	✓	prereq	✓
	Conditioned	Y/N	(✓)	prereq	✓
	Low set-point temp	°C	(✓)	prereq if cond Y	✓
	High set-point temp	°C	(✓)	prereq if cond Y	✓
	Occupancy	Nr of people	(✓)	Optional	✓
	Lighting gains	W or W/m^2	(✓)	Optional	✓
	Infiltration ACH	1/h	(✓)	Optional	✓
	Ventilation ACH	1/h	(✓)	Optional	✓
	Starting zone temp	°C	(✓)	prereq	✓
Info to facilitate post-processing	Element level		✓		✓
	Exterior element		(✓)		✓
	Element to ground		(✓)		✓
	Host element for doors and windows		✓		✓

prereq, prerequisite; (✓),available if defined or else default value.

information acquired from the BIM model. The workflow is described in detail in *Data acquisition workflows.*

BIM model simplification

A common practice in every simulation approach is to reduce the complexity of the model and therefore parameters input while maintaining the validity of the simulation results, concerning the question that the simulation is being used to address (Frantz, 1995). An as-built BIM model of an industrial facility contains a significant amount of information irrelevant to the required data for a thermal building simulation, as it is not originally developed for such a purpose. Applying the cube approach requires an appropriate definition of thermal zones according to a BEM discipline view, as discussed in *Challenges in BIM-based building energy modeling*, based on space usage and

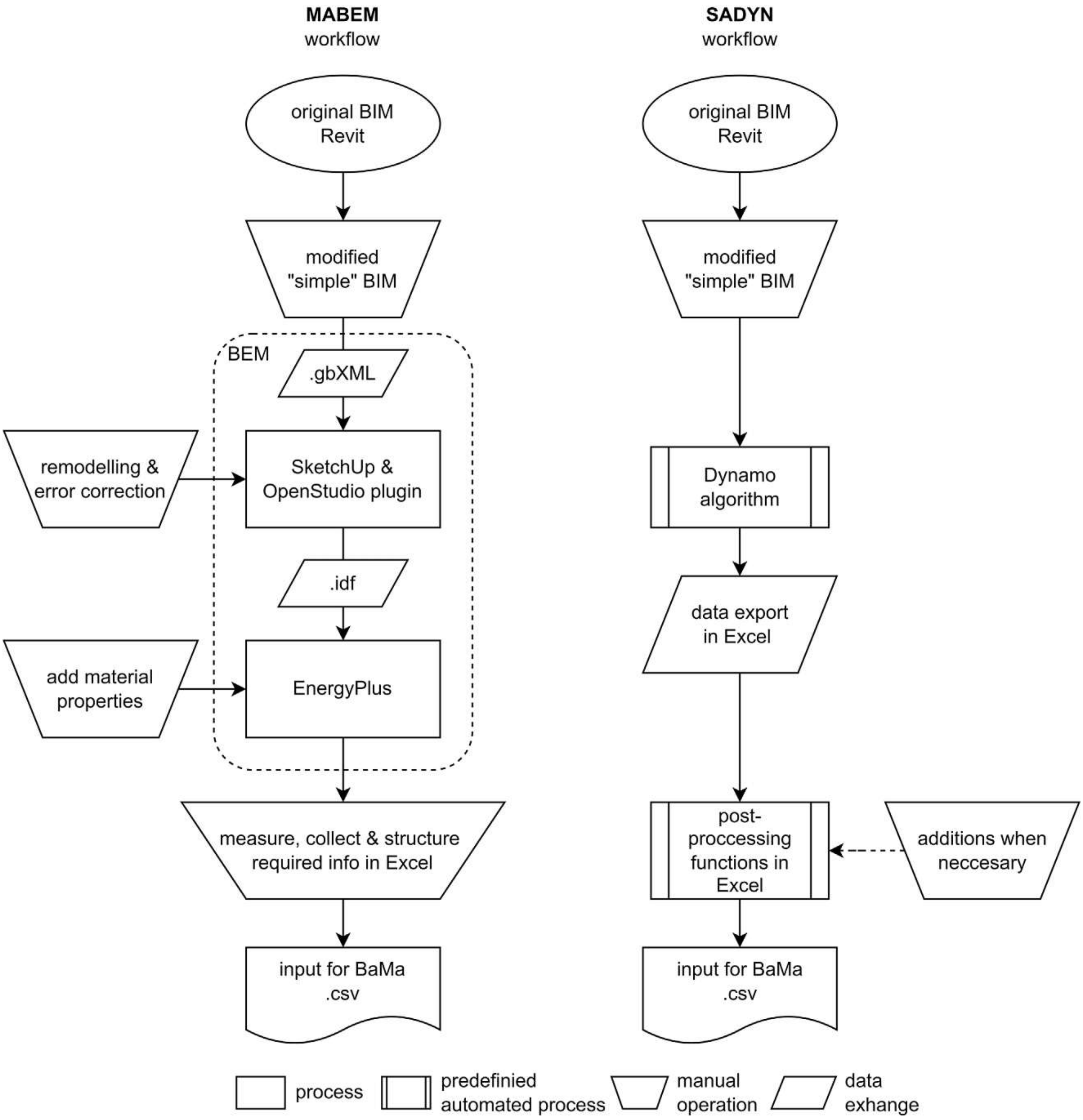

FIGURE 5
Workflows: (left) manual BEM-based data acquisition–MABEM, (right) semi-automated dynamo-based data acquisition–SADYN.

type of production processes, conditioning requirements as well as building geometry and construction properties. This constitutes the first stage of model abstraction in BIM by redefining the model's room-stamps used in the architectural plans with new, representing the necessary thermal zones. The original geometry (e.g., interior partitions) may also be simplified as it is usually too rich and not relevant in the context of building simulation (Choi et al., 2016). This leads to a redefinition of internal boundaries and simplification of construction types in case different wall types with similar thermal properties are used, being the second stage of abstraction. Extensive geometric simplification of the building envelope can affect the building's performance and must be avoided. The described model abstraction is manual work performed in the pre-processing phase and results in a new "simple" BIM. This is utilized then as the knowledge database from where input values for creation and parameterization of the simulation model are acquired. Further pre-processing actions at the BIM model level are discussed in the following section.

Data acquisition workflows

The procedure of acquiring building-related information from the as-built BIM model of an industrial building and transforming these into *cube*-structured data, readable by the BaMa hybrid simulation implemented in MATLAB, was performed utilizing two different workflows (Figure 5). The type of data acquired is analyzed in *Analysis and definition of data required for the building energy modeling* and Table 1.

The first workflow is a manual process, based on a developed BEM in EnergyPlus that has been used for validating the results of the thermal building simulation solution inside the BaMa DT framework. However, the so-called manual BEM-based workflow (MABEM) is a time-intensive process, which includes the interoperability problems from BIM to BEM and extensive remodeling and redefinition of element properties, analyzed in previous related work (Gourlis and Kovacic, 2017b). Through the MABEM workflow, a fully functional BEM model is created in EnergyPlus, although such a model is not necessary when applying the BaMa holistic DT framework in an industrial facility. It is only used for providing the required building-related data, categorized as building element and thermal zone data as of Table 1. These are collected or measured manually and are structured in input lists for the BaMa hybrid simulation. The MABEM workflow is not further presented in this section as the steps for creating a BEM model are already published (Gourlis and Kovacic, 2017b) and the rest is a non-standardized manual data collection work.

The second workflow, presented in detail in the following subsections, was created to accelerate the process, allowing a direct acquisition of necessary information from BIM to BaMa. It utilizes a visual programming script for extracting and structuring data directly from a simplified BIM model in a spreadsheet database. Predefined post-processing functions subsequently correct inconsistencies and arrange the data so they can be imported into the hybrid simulation model. If needed, additional information is integrated manually. The semi-automated Dynamo workflow (SADYN) counts three parts—pre-processing in the BIM environment, the Dynamo script, and post-processing in Excel.

Pre-processing in BIM

As the original BIM models are too detailed for either a BEM simulation or for the BaMa framework, both workflows require manual abstraction and editing. The thermal zone separation according to the *cube* concept requires new room stamps. For the BaMa hybrid simulation, all zones, corresponding to the defined cubes, must have physical boundaries, meaning that the use of room separation lines is to be avoided as no fictional partitions are considered, contrary to the air-wall approach utilized in many BEM tools. Moreover, columns, beams, and freestanding partitions inside zones must be set as non-bounding objects. Elements such as walls and slabs should be modeled as compound objects, as with non-compound elements (separate parallel laid layers); problems arise with adjacencies between zones and inaccurate thermal properties when only the room-stamp bounding construction layer is considered. Curtain walls are to be avoided, since they are managed as walls by BIM authoring tools, without thermal mass or visual light transmittance values, and cause problems regarding their orientation faces. Finally, for elements used in the thermal envelope, an additional property should be set defining their role as an exterior element or element to ground. This can be also determined by the element's function, which categorizes each element as exterior and interior, given the fact that only appropriate element types are used at the right positions in the model.

Furthermore, in case of an incomplete definition of element properties in the BIM model, missing information must be provided. This is crucial concerning material semantic properties of all elements, which should be defined accordingly, as BIM software calculates thermal mass and resistance based on the construction layers. For an accurate thermal analysis, default values should be replaced appropriately. This affects information such as material roughness and absorptance as well as glazing g-factor and visible transmittance , which are defined in the BIM model material database. Last, zone-related properties, such as space conditioning state, set-point temperatures, and air change rates can be easily determined in the pre-processing stage in BIM and then automatically sorted in input information to the BaMa hybrid simulation.

BIM visual programming script

The main function of the proposed visual programming script in Dynamo is to accumulate, organize, and link together the appropriate building-related information (*Analysis and definition of data required for the building energy modeling*) contained in the BIM model. This is achieved *via* managing data lists with built-in dynamo nodes as well as custom nodes provided by "packages" of freely available, open-source collections of custom nodes. Figure 6 depicts an overview of the nodes consisting of the visual programming script with a description of the function of each section. Thermal zone and building element information is managed and arranged according to the model's room stamps. The light blue section of the script reads and organizes all the

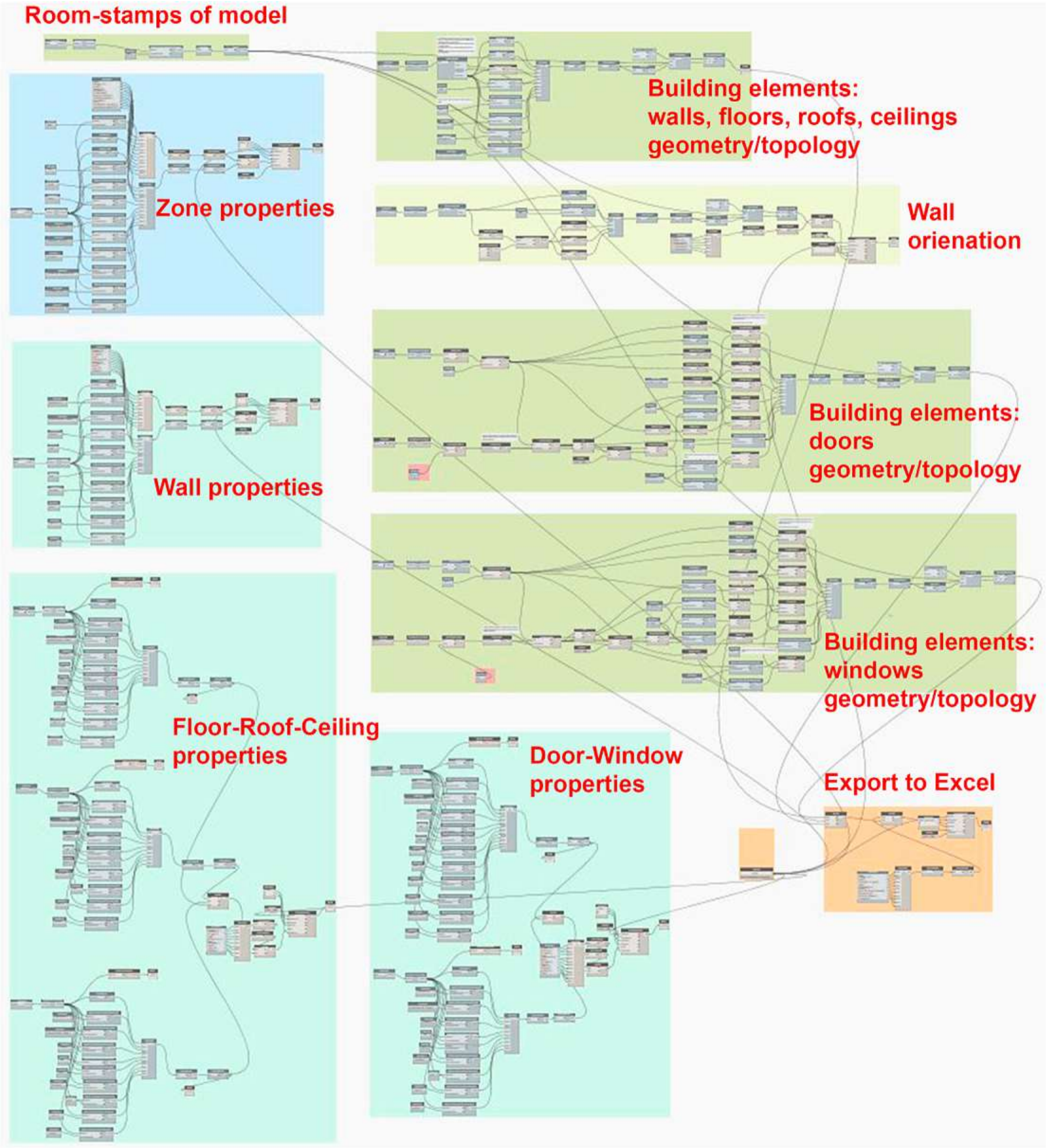

FIGURE 6
Overview of the Dynamo algorithm.

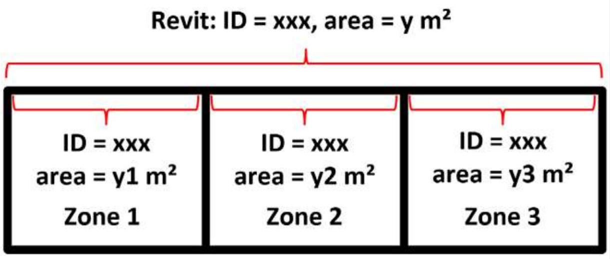

FIGURE 7
Problems of unique element IDs.

necessary thermal zone attributes. The green sections of the script handle the geometry, type, and topology of the building elements (walls, slabs, windows, and doors) that correspond to each thermal zone. This means that although in a BIM Revit model a single element, for example, an exterior wall, can be the boundary of multiple zones, its area is, respectively, divided and allocated to each zone. Wall orientation is obtained separately and is assigned to each wall element and its nested doors and windows in the post-processing phase. The turquoise-colored sections collect the object type parameters and material properties corresponding to the appropriate building elements available in the BIM model (construction type, R-value, thermal

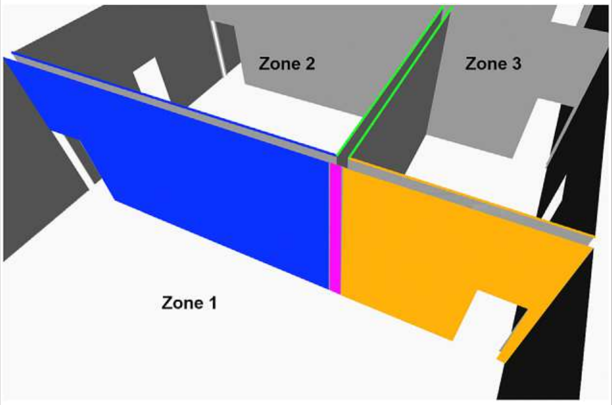

FIGURE 8
Interior boundary adjacencies.

mass, roughness, absorptance, g-factor, and visible transmittance). However, this information is not allocated based on room stamps but is mapped in the post-processing phase to the actual building elements of each zone. Last, the orange section exports the obtained data to MS Excel.

The visual programming script is capable of automatically acquiring the required information from the BIM model; however, the following limitations must be acknowledged. First, the produced output fails to provide unique IDs for each building element. This results in elements situated in different zones, with different surface areas having the same ID. Using again the exterior wall example, a single element in Revit with a unique ID will be divided into multiple elements, corresponding to the actual thermal zones, but with the same ID (Figure 7). Additionally, this zone division of the host elements (walls and ceilings) does not consider the area of their nested elements (windows and doors) when calculating the final surface area, leading to inconsistencies. Furthermore, in the case of interior elements, the script does not automatically define the adjacent elements of the neighbor zone. Nevertheless, these problems can be resolved in the following post-processing phase.

Finally, the unrestricted application of the proposed algorithm can be hindered by the fact that compatibility cannot be guaranteed for the evolving Dynamo versions in all systems and due to the condition, that processed parameters must be called by the name. Even for such general parameters, there can be differences in terminology among object families in the BIM authoring software (e.g., for a door: height—rough height). Thus, depending on the used family attributes' names, the script should be adjusted to deliver all necessary information.

Post-processing by spreadsheet functions

For overcoming the limitations of the visual programming script and completing all required information on the building elements, the data output requires further processing for an automated input to the BaMa DT. Thus, mapping or post-processing is conducted *via* an Excel tool, containing predefined functions.

Mapping refers to the process of correlating the material properties as object type parameters of each construction type, namely, R-value, thermal mass, roughness, absorptance, g-factor, and visible transmittance, with the actual building element of each zone. The data here are extracted from BIM by the visual programming script in different lists and only require a simple name-based matching of the construction types to enrich the information of each building element.

Post-processing actions correct inconsistencies of the BIM exported data or add further information by using additional exported properties, which are not used directly in the final data lists for BaMa, such as host elements, exterior or ground elements, and element level. First, all building elements obtain new unique IDs sorting out the problem described in 5.3.2. This is crucial for assigning later correct adjacencies for interior building elements. Regarding element orientation, based on their host element information, windows and doors are assigned the appropriate orientation given the fact that they are hosted in exterior building elements. In the case of curtain walls, BIM extracted orientation properties are incorrectly inversed and are adjusted when required. Moreover, post-processing functions calculate the correct surface area of each wall element, subtracting hosted doors and windows when necessary.

Determinative is the process of defining boundary conditions and element adjacencies. After classifying exterior and ground elements, the remaining interior elements are compared in terms of having the same construction type, surface area, and original element ID but belonging to different zones. Here, the initial drawback of the Dynamo export is positively used to help identify adjacent elements and the building topology. In case all comparisons, including the thermal zone, are equal, the element is regarded as an internal zone partition, not belonging to the zone thermal boundary, and is omitted from the final data. Exported wall elements with a surface area smaller than the product of "room height × 0.30 cm" are regarded as adiabatic and are also omitted from the final data lists for BaMa, as they mostly refer to the wall thickness dividing two rooms adjacent to the room where this wall is located, for example, the magenta-colored wall surface in Figure 8, or are surfaces of internal partitions. In the case of remaining elements with no set boundary conditions, either as exterior, ground, or adjacent to specific construction, these are also regarded as adiabatic.

Last, the air resistance values Rse and Rsi are added to each building element according to its position in the zone. According to EN ISO 6946, Rse is determined for exterior elements with 0.4 $m^2 \cdot K/W$ and for ground elements with

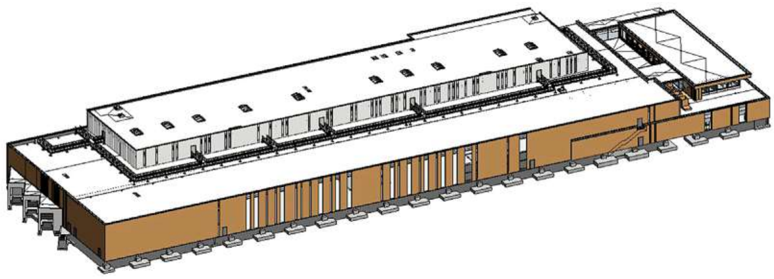

FIGURE 9
3D view of the case study BIM model in Revit.

TABLE 2 Comparison of case study data for BaMa input.

Comparison		Data acquisition workflow		Percentage change of SADYN results in reference to MABEM
		MABEM	SADYN	
Size figures	Number of zones-"cubes"	12	12	0%
	Net floor area	11,123 m^2	11,012 m^2	−1.0%
	Net volume	76,109 m^3	69,717 m^3	−8.4%
Building elements	Number of elements			
	Walls	79	308	+289.9%
	Floors/ceilings/roofs	41	93	+126.8%
	Windows/skylights	9	60	+566.7%
	Doors	31	101	+225.8%
	Sum total	160	562	+251.3%
	Elements' area			
	Walls	8,198 m^2	7,543 m^2	−8.0%
	Floors/ceilings/roofs	22,402 m^2	22,180 m^2	−1.0%
	Windows	614 m^2	693 m^2	+12.9%
	Skylights	60 m^2	64 m^2	+6.7%
	Doors	329 m^2	370 m^2	+12.3%
	Sum of vertical elements	9,141 m^2	8,606 m^2	−5.9%
	Sum of horizontal elements	22,462 m^2	22,244 m^2	−1.0%
	Sum total	31,603 m^2	30,850 m^2	−2.4%
Creation time	Pre-processing phase	30 h	30 h	0%
	Main process phase	71 h	4 h	−94.4%
	Post-processing phase	24 h	5 h	−79.2%
	Sum total	125 h	39 h	−68.8%

0 m^2·K/W. Rsi determined for at top positioned exterior elements is 0.1 m^2·K/W and for bottom positioned exterior or ground elements is 0.17 m^2·K/W. In all other cases, Rsi is set to 0.13 m^2 K/W. Here, it should be mentioned that although it would be possible to add an air material to the construction types originally in the BIM model in the pre-processing phase and edit the thermal resistance Rsi and Rse as appropriate to have their values already calculated, it

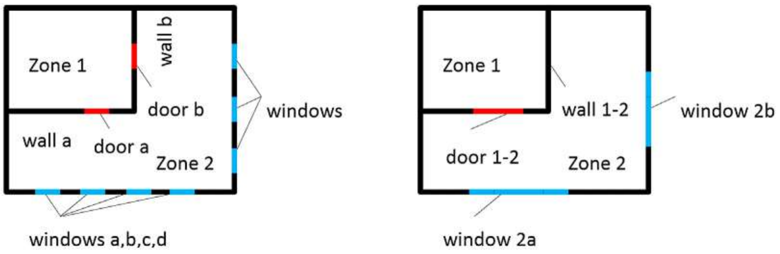

FIGURE 10
Number of elements in model: (left) detailed elements, (right) aggregated elements.

would not be feasible, as it would require the creation of different structures for floors according to the correct Rsi. Therefore, the calculation during post-processing was preferred.

Evaluation of the proposed data acquisition workflows

Both workflows, as of *Data acquisition workflows*, were applied in a case study to test the feasibility and reliability of the proposed semi-automated workflow (SADYN) at extracting information from a BIM model and structuring them as input for the holistic hybrid simulation. The goal was to compare the input information that results from both workflows. Data produced by the manual workflow (MABEM) are regarded as the reference point. We examined if SADYN results in a valid representation of the building model, so that the holistic BaMa framework and its accompanying toolchain can be implemented based directly on BIM model data, without the middle step of creating a BEM model. Differences between the results of the two workflows are identified and evaluated, assessing data consistency and implementation times.

Comparative case study

An industrial bakery building in Austria was used as a case study. The building has a rectangular shape housing its production areas mainly in double-height spaces on the ground floor, with peripheral and administration areas in the mezzanine and upper level (Figure 9). The BIM model, originally modeled in Revit, displayed a detailed representation of the building for the construction stage in LOD 400 (level of development), thus providing comprehensive information on the material properties of the building elements and constructions, and information regarding space conditioning, lighting and occupancy loads of the factory's spaces. It also included numerous geometrical elements non-relevant for the thermal representation of the building in the abstracted DT representation, as well as a high room-stamp partition, concerning the architectural room schedule. For enabling further processing *via* the visual programming script, an extended manual effort in the initial pre-processing phase was required. Existing room stamps were deleted or modified and new ones were defined to correspond with the desired thermal zone separation of the building, according to the required BaMa *cubes*.

Both data acquisition workflows, namely, MABEM and SADYN, have been implemented in the case study building model, comparing the geometric characteristics of the thermal zones and the building elements defining them, thus the whole building (Table 2). Having as a reference the results of the MABEM workflow, the relative change in the SADYN workflow results shows the visual-script-computed building has a net floor area of all thermal zones smaller than that manually calculated by 1% and their volume by 8.4%. Thus, SADYN is producing a reliable representation of the building for its use in BaMa, with a negligible variation from the BEM model size. The small net floor area deviation is caused by the definition of thermal zones in the MABEM workflow at the walls or slabs centerlines, which is not the case for room-stamp size calculation in Revit. This factor also affects the space volume, together with the fact that internal wall partitions in zones, when present, are also subtracted from the net zone volume, not considered in the BEM modeling of the MABEM workflow.

Table 2 further compares the actual building elements measured from the BEM model or calculated by the visual programming script and post-processing functions in the two workflows respectively. A great difference is noted in the number of actual elements forming each zone. In total, the elements to be imported in the hybrid simulation are 3.5 times more, that is, an increase of 251.3% . The explanation for this is that the instances of the same building construction, for example, a brick wall, an interior door, or a double-glazed window, between two adjacent zones or to the outside have been aggregated in one element with the equivalent surface area during the manual compilation of the data lists in the MABEM workflow. For interior elements, this is performed regardless of their orientation and position. Exterior elements are aggregated considering the different orientations. For example, in Figure 10 walls "a" and "b" are aggregated in the walls "1–2," whereas windows "a, b, c, d" and "e, f, g" in windows "2a" and "2b" respectively.

Despite the significantly increased number of building elements, the total surface area of all elements is only deviating by 2.4% from the BEM-based data, being slightly smaller. Though the deviation of horizontal elements, mainly floor slabs, is 1% smaller with SADYN, vertical elements vary more regarding the BEM-based element data. The walls' surface of the semi-automated workflow is 8% smaller with a factor contributing to this difference being the omission of adiabatic surfaces, as described in 5.3.3, and the use of interior elements boundaries instead of centerlines. On the other hand, windows and doors are calculated with larger areas, which are to be attributed to the framing of these elements, not considered in the MABEM workflow.

Finally, the results show that the time required for creating the building input data for the BaMa hybrid simulation model dramatically decreased when using SADYN. The main process and post-processing time were reduced to about 1/10 of the equivalent MABEM time. The whole creation of the building component of the holistic DT simulation with SADYN requires approximately one-third of the time required for the MABEM workflow.

Discussion

This study explored the possibilities of automated creation of the building competent for a holistic DT modeling and simulation framework for industrial facilities, as proposed in the BaMa research project, to enhance its implementation for energy and recourse efficient production. It analyzed the use of existing BIM models as the required data sources for the abstracted representation of the building in a holistic DT ecosystem. Although data management and analysis *via* visual programming is not a novelty in the AEC industry, it has never been used in the frame of a holistic simulation framework of energy and resource-efficient manufacturing, where thermal energy synergies of the production processes, the building space around them, and the TBS systems are constantly assessed to be optimized. The main theoretical contributions of the current study to the knowledge domain are: *1*) the defection of the required building level of abstraction in a holistic DT representation of all subsystems of an industrial facility, *2*) the definition of the interconnections of the building-related counterparts of the DT to the rest of the virtual environment as well as the data required for their parameterization, and *3*) the proposed semi-automated workflow for BIM-based creation of the building model within the holistic DT ecosystem. The last could also be utilized outside the BaMa concept, when a building representation is required in a hybrid cyber-physical system simulation, based on DEVS formalism (Zeigler, 2021). The parameterization of the building component of the hybrid simulation could be thus linked directly with a BIM model *via* the proposed SADYN workflow.

A discussion of the research questions set in *Scope of research, tools, and methods* is provided below.

Research question 1 on the extent of automated creation of the idealized digital representation of the building in the holistic DT ecosystem, based on available BIM models, is answered as follows. The comparative study of the proposed SADYN workflow proves the feasibility of acquiring directly from a BIM model the required data for the building representation of an industrial facility in the proposed holistic approach of the BaMa DT framework. The process is not fully automated, as it requires manual user intervention, at a great amount in the initial phase and much less later. The required existence of physical boundaries in the BIM models, as described in *Pre-processing in BIM* may pose a limitation to handling federated BIM models of large facilities, where large halls may be modeled divided into different files. However, if these models correspond to stand-alone thermal views of the facility accompanied by a certain production process, information from each of the BIM sub-models can be extracted separately and assessed as a group of buildings in the holistic DT ecosystem.

The main achievement of the SADYN workflow is omitting the need for the creation of an additional BEM model of the building for performing integrated hybrid simulations (including manufacturing processes, logistics, TBS, and the building). In other words, the thermal view of the building according to required thermal zoning, corresponding to the previously defined *cubes*, can be performed in BIM at the pre-processing simplification stage. This is the only stage where expert knowledge is required and must be carried out "manually." Parallelly, the building model is enriched with all other information required for further analysis. Ascribed to the scope and target outcomes of the BaMa DT, no virtual visualization of the building itself is required for the analysis, thus no 3D model is created in the building DT, as is regularly the case in DTs of the built environment. The building in the holistic DT ecosystem consists of fixed information regarding the space geometry, structures, and thermal zones' topography, as well as real-time updated built environment data. These are indoor space temperatures, humidity, and air quality levels; outdoor climate data; and thermal comfort indices together with real-time production process data in terms of internal heat gains.

Research question 2 addresses the ability of the proposed data acquisition and modeling workflow to deliver an accurate BEM representation of the building in the holistic DT ecosystem. The results of the SADYN workflow showed a satisfactory correlation with the data collected manually from a developed BEM model of the same facility. The small deviation of the building's size does not have a noticeable impact on the hybrid simulation results, allowing the intended level of a qualitative and quantitative assessment of the building as a part of the whole industrial system under examination. However, a drawback of the SADYN workflow is the larger number of data inputs, as the building surfaces and elements are more fragmented. In MABEM for example, all window surfaces of a zone with the same direction are gathered and reported as one element, which is not the case with SADYN. Contributing to this larger data number is the initial modeling of the building in the BIM software, as one wall may consist of more aligned elements which are then exported separately. Additionally, if two zones have adjacencies with varying element topology, MABEM sums up all walls of the same type in one export element with an appropriate surface. SADYN again lists all separate adjacent elements between the two zones. This can increase the computational time, though it is not expected to reduce the overall runtime efficiency of the simulation below the acceptable point for coupling it with the optimization functions of the GA (Sihn et al., 2018). Furthermore, the proposed visual programming script may not apply to every BIM model, as different BIM object families can differ in the way they define essential parameters, thus requiring adjustment of the script.

Research question 3 examines if the proposed workflow can facilitate the implementation of the BaMa DT framework in industrial facilities. The results of the comparative case study showed the BIM-based creation of the building counterpart as a subsystem in the BaMa DT framework with SADYN required approximately one-third of the time required for the MABEM workflow. This assists a time-efficient implementation of the BaMa toolchain in production companies by using existing BIM models as the basis for the modular *cube* approach, as of *Building model within the BaMa digital twin ecosystem*, and then exporting the appropriately structured data in the hybrid simulation. An additional effort to import the data in a BEM tool and repair any inconsistencies is thus omitted, reducing the total model editing time. From this point onward, the SADYN workflow is much more time efficient as required data for the holistic hybrid simulation can be quickly produced *via* the next two stages of exporting data *via* the proposed visual programming script and adjusting them by predefined spreadsheet functions, to be finally given as an input parameter to the general simulation model.

Conclusion

The study presented an integrated approach for simulation and optimization of industrial facilities and processes, thereby addressing an interdisciplinary research domain. Through a holistic simulation framework, energy and resource consumption can be reduced while maximizing energy efficiency and production throughput. The novelty of the proposed framework is the integration of DTs of the various disciplines (production planning, building planning, logistics, and energy management) in a holistic DT ecosystem *via* hybrid simulation, capable of incorporating both continuous and discrete aspects of different discipline models in a single solver platform. The BaMa framework is built upon a generic and modular logic for modeling the DTs of physical reality, aiming to address as many industrial conditions as possible, making it easily adaptable and applicable to various industrial manufacturing types. This approach requires a certain level of abstraction, which always corresponds to the intended use of the resulting DT.

Focusing on the building DT within the proposed holistic DT modeling and simulation framework, this study presented a semi-automated workflow to acquire all necessary data for the representation of the building directly from a BIM model. This was achieved in three steps by simplifying the original BIM model to meet the scope of the building DT in the holistic ecosystem; by using visual programming to gather, organize and export structured building data directly from the BIM model; and finally, by post-processing of the data with spreadsheet functions, rendering them ready for import in the hybrid simulation. A comparative case study proved the feasibility of the proposed semi-automated workflow, identifying the omission of a BEM model creation of the facility as its main advantage.

The first contribution of this study lies in the detection of the required level of abstraction for building models for a holistic DT ecosystem. A highly abstracted BEM representation, outside of the typical BEM tools was analyzed and the definition of the interconnections between the building-related counterparts and the rest of the virtual environment as well as the data required for their parameterization were highlighted. This can help future research in the field of hybrid industrial simulations to prioritize the essential building-related information in the creation of the building DT models, to enable reaching the desired complexity of a holistic DT-based facility representation while omitting unnecessary domain-specific information and thus increasing the error rates and computational time of such models.

Moreover, in the field of holistic industrial production concepts, the study contributes a DT-based application of such a concept, enabled through a semi-automated workflow for BIM-based creation of the building DT model *via* visual programming. This provides efficient data exchange and time-saving DT modeling and simulations through simplified BIM models. It facilitates the creation of the holistic DT ecosystem through direct production and parameterization of the building DT and thus provides an additional incentive to companies' decision makers implementing an approach such as the BaMa framework. Furthermore, the proposed workflow contributes to the wider knowledge domain of hybrid simulation for both discrete and continuous cyber-physical system insights for linking BIM models with the hybrid

DEVS-based models and directly parametrizing the building component for the simulation. Such hybrid models can incorporate multiple engineering domains, for example, built environment and manufacturing in complex integrated DT representations, amending the assessment of interactions and synergies of the different systems' components. The translation of the building-related part from a BIM model to the generic DEVS formalism, also adopted in BaMa, could therefore be assisted by the proposed workflow. The current implementation of the workflow *via* a Dynamo script and predefined post-processing spreadsheet functions can be regarded as a prototype for an automated data acquisition tool. In future, the proposed workflow can be implemented in a single programming environment by developing a tool to provide direct connectivity between BIM models and future software implementation of the BaMa prototypical toolchain and thus a time-efficient exchange of information from BIM to the hybrid simulation models.

Scaling back up to the BaMa holistic DT framework, it must be noted that it is not an off-the-shelf DT framework, such as solutions provided by the original equipment manufacturer for common industry cases. It lacks complex software constellations through different interconnected software platforms and thus has much shorter run times. However, the development of the DT ecosystem by the combination of the modular parts of the hybrid simulation surely poses a challenge for the actual implementation of the framework. Therefore, large and more complex industries rather than small or medium enterprises are more suitable for its application, where the necessary automation infrastructure is available and the implementation effort corresponds to the size of the resulting savings in absolute terms. In future, such holistic solutions could be fully integrated into the ERP system of an industrial facility for an entirely automated energy and resource efficiency optimization.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material; further inquiries can be directed to the corresponding author.

Author contributions

Conceptualization, GG; methodology, GG and IK; workflows and case study implementation and writing–original draft preparation, GG; contribution to contents, review, editing, and supervision, IK.

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Conflict of interest

Publisher's note

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Paper 5

Georgios Gourlis and Iva Kovacic

"Energy efficient operation of industrial facilities: the role of the building in simulation-based optimization"

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Energy efficient operation of industrial facilities: the role of the building in simulation-based optimization

G Gourlis and I Kovacic

Integrated Planning and Industrial Building, Faculty of Civil Engineering, TU Wien, Austria

Email: georgios.gourlis@tuwien.ac.at

Abstract. Energy efficiency of industrial facilities is a set goal towards developing a sustainable future. Many production facilities though are still not operated at a highly efficient rate in terms of energy use. The complexity of industrial environments requires an integrated analysis of all subsystems – production processes, logistics, building and technical building services – to grasp full optimization potentials. The use of simulation tools provides significant benefit in energy demand modeling and prediction, making its application essential for planning and management of energy efficient industrial facilities. Building Energy Modeling (BEM) and Manufacturing Process Simulation (MPS) have been used by researchers for analyzing mostly building related and process related conditions respectively. A novel approach is the holistic assessment by combining capabilities of BEM and MPS into one simulation environment. Such a hybrid simulation application has been developed within the research project Balanced Manufacturing (BaMa), addressing all subsystems of a production plant. However, the actual condition of a facility, the type and requirements of the manufacturing process, the level of implemented automation as well as the available infrastructure are decisive for the application of the appropriate simulation-based optimization method. Focusing on the subsystem of the building, this paper examines its function within two different approaches for energy demand optimization, through the use cases of industrial facilities with different characteristics. The first case focuses on the building and its components, utilizing BEM, the second on the production processes, utilizing the BaMa method. Thereby the use of Building Information Modeling (BIM) as knowledge database for the simulations models is discussed and the integration of all industrial subsystems is analyzed. The role of the building in each case is highlighted, addressing its benefits and drawbacks.

1. Introduction

The industrial sector holds an important position in developing a sustainable future. Energy efficiency is certainly a major aspect towards this direction with a positive economic and environmental impact. Globally the industrial energy consumption accounted for 54% in 2014, deviating depending on the region, with the US and the EU accounting for 34% and 25% respectively, whereas China for 72% [1]. Although energy efficient operation has not been an initial objective for many production facilities, the increasing energy and raw material prices, the necessity of complying with stricter regulations as well as the rising public awareness on resource consumption and climate change, which pose a challenge on corporate images, leads the manufacturing industry to monitor, manage and try to reduce its energy demand.

State-of-the-art towards achieving industrial energy efficiency is the utilization of simulation tools for predicting energy demand and identifying optimization potentials [2]. Building Energy Modeling (BEM) and Manufacturing Process Simulation (MPS) are mature simulation analysis techniques which find application in the industrial sector. BEM is usually used to analyze thermal building envelopes in the residential and commercial sector and its application on industrial facilities has begun in the recent years [3, 4]. MPS is traditionally used for optimizing manufacturing process lines, analyzing machinery utilization and throughput. Regarding energy assessment, commercially available BEM software usually limit their scope on a certain area, that of the building and HVAC systems [5]. MPS on the other hand do not focus on the energy use between manufacturing equipment, utilities or the building [6]. The complexity of industrial environments requires, however, an integrated analysis of all interconnected subsystems –production process, logistics, technical building services (TBS) and the building– by combining capabilities of BEM and MPS to grasp full optimization potentials [7].

Such an approach for a holistic assessment was developed within the research project Balanced Manufacturing (BaMa) [8]. Utilizing a single hybrid simulation environment, BaMa implemented continuous aspects of energy flows, addressed in BEM, and discrete aspects of material flows, addressed in MPS. The project resulted in a simulation-based toolchain that integrates energy demand as well as carbon emissions as control parameters in industrial facilities and introduces energy efficiency as a steering value into a factory's operational planning.

This paper examines the role of the building in simulation-based approaches for energy efficiency optimization in manufacturing plants. Based on the use cases of two operating factories, the study compares the BEM and the hybrid BaMa approaches aiming to identify benefits and drawbacks of each. Thereby the use of Building Information Modeling (BIM) as a knowledge database for the simulation model is discussed. The suitability of each method is analyzed, regarding available infrastructure, level of digitalization and anticipated optimization targets of an industrial facility.

2. Industrial simulation-based energy assessment

Simulation approaches used in the industrial sector can be categorized in those focusing on the energy modeling of the building envelope utilizing BEM, those focusing on the energy modeling of the manufacturing process chain utilizing MPS and last the holistic methods taken into account both the building and the processes [9]. This study investigates the building related aspects, therefore solely MPS methods will not be further analyzed.

As already mentioned, industrial plants are consisted of four interconnected subsystems, a schematic representation of which is shown in Figure 1. Parameters concerning the subsystem of the building, that have an impact on the energy demand, are mainly located in the building envelope and daylight conditions, e.g. solar gains. TBS is the actual consumer of the energy demand for heating, cooling and ventilation of the spaces (HVAC) as well as for the media flows, such as compressed air, cooling water or steam. Due to their nature, building and TBS subsystems are modeled with continuous flows in energy simulations. On the production level, machine and production chain models have energy as well as material flows of products. These processes constitute the manufacturing energy demand and are mainly addressed via Discrete Event Simulation (DES). Lastly, logistics during the production process with transport and handling actions or afterwards as storage contribute to the total energy demand of the facility, also incorporating material flows, therefore modeled with DES methods.

2.1. BEM-based industrial modeling

BEM simulation by default implements a time-driven modeling approach, where time is a variable that is incremented at predefined intervals and all computation is conducted for each time-step. Usually the main objective of BEM models is to find optimum solutions regarding the building geometry and thermal envelope as well as HVAC systems configurations. Available BEM software couple thermal building models and HVAC models, commonly utilizing a simpler thermal view of the building's spaces than that of CAD models. However, the employment of BEM simulation in industrial facilities for assessing their energy demand is more challenging than in buildings of the residential and tertiary sector, as internal heat gains from manufacturing activities can have a significant impact on the desired indoor conditions and their scheduling can vary greatly overtime, given production demand and economic cycles [10]. Therefore, manufacturing internal gains are usually introduced in these models as simplistic operating schedules, as current tools cannot accurately incorporate the discrete character of industrial processes [11]. These heat gains can be either assumed based on installed equipment loads or directly measured in case of an operating production chain, with the first though potentially leading to disputable results and the second being restrictive to existing production configurations. The examination of alternative more efficient machinery configurations is thus a laborious procedure. Furthermore, logistics related energy demand is possible to be assessed, except auxiliary energy from HVAC components, regarding special temperature conditions for sensitive products in storage rooms.

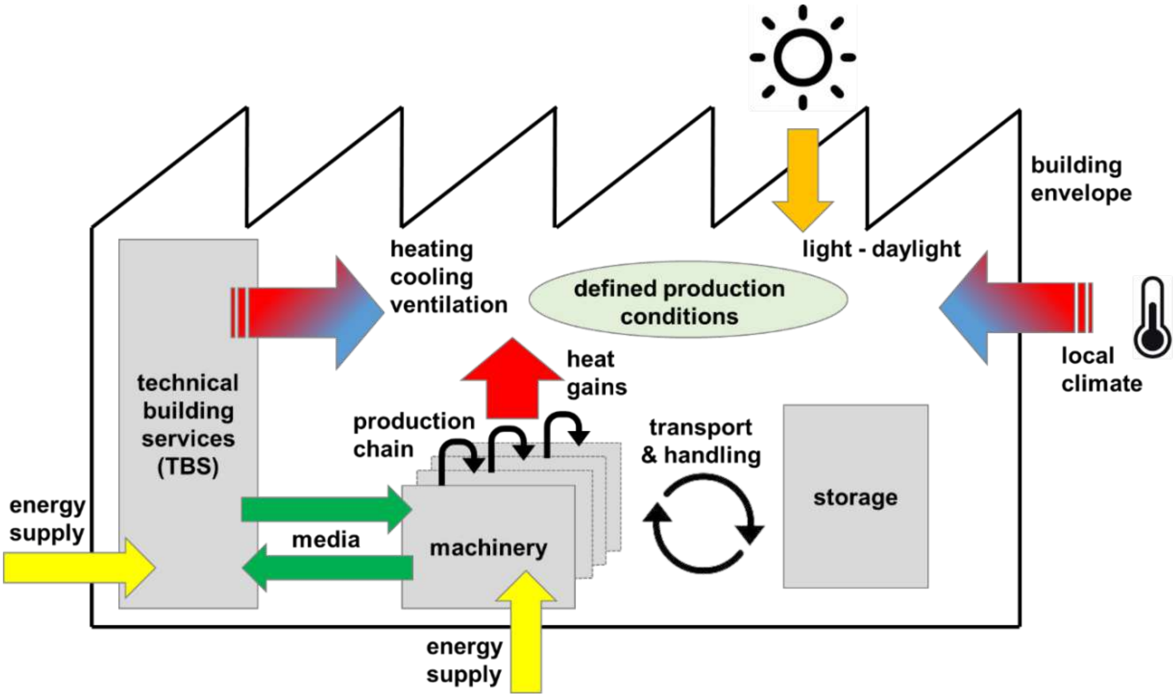

Figure 1. Energy flows and interaction of subsystems within a factory.

2.2. BaMa modeling approach

BaMa implements a generic modular approach to model all factory subsystems in a single platform, aiming to the flexibility and reusability of the models. The core modular element of BaMa is the *cube*. Cubes represent physical parts of the facility and are mapped into mathematically formulated virtual counterparts in a simulation model. They are defined and connected through common interfaces, combining three kinds of flows: energy, material (incorporating the immediate value stream of products) and information (control and demand related). Energy flows and related carbon emissions are treated as continuous values, whereas material and product flows as discrete entities. This resulted in creating a hybrid simulation environment based on the Discrete Event and Differential Equation System Specification (DEV&DESS) [12] as a hybrid Discrete Event System Specification DEVS formalism [13], based on Parallel DEVS (P-DEVS) [14].

The holistic BaMa approach links the four subsystems of building, TBS, production processes and logistics, by incorporating them in a hybrid simulation-based toolchain for monitoring, predicting and optimizing industrial energy demand. Components of all subsystems are modelled as cubes. The building subsystem consists of the *building* and the *thermal zone* cubes. The first represents the solid constructions, i.e. walls and slabs, and calculates the heat exchange between neighboring thermal zones and to the outside. The second describes the thermal condition of a space, calculating the heating and cooling demand. Comprehensive information on the cube models can be found in [15], as a detailed presentation would go beyond the scope of this paper.

The aim of the BaMa toolchain regarding the role of the building is to deliver information about auxiliary energy demand, such as space heating and cooling, based on weather conditions and production schedules. Together with production and logistics needs, the toolchain can predict the energy demand of the entire facility. This enables optimization of the systems' operation via algorithms, by using parameters as energy saving, costs reduction or time as target functions. An extensive description of the BaMa methodology is available in [16, 17].

2.3. BIM as input database

BIM, defined as "a digital representation of physical and functional characteristics of a facility" [18], offers potentials through the creation of a joint knowledge database, for follow up analysis of buildings and building systems in terms of energy performance. Still, data rich BIM models need to be simplified to provide only that information, essential for the accomplishment of a simulation analysis. Extensive research has been conducted on data transfer from BIM to BEM tools, but the process of BIM-based BEM is still in development, not yet being able to generate reliable models ready for analysis from initial architectural BIM models, with information loss being a common problem [19]. In the field of industrial facilities, BIM becomes a favored tool for designing, planning and managing this complex building typology, providing benefits in terms of collisions from the integrated discipline models (e.g. architectural, structural, MEP, machine floor layout and infrastructure). However, research on industrial BIM-based BEM assessment shows interoperability issues and portrays the procedure as too work intense [20]. BIM models hold yet potential to be used as input information for holistic industrial simulation tools, as that of BaMa [21].

3. Use case application

The two simulation approaches, BEM and BaMa, have been applied in two operating industrial facilities in Austria. Use case A lays focus on improving the building itself, while objective of use case B lies in the energy optimization of the production process. Consequently, the BEM approach was applied in use case A and BaMa in use case B. Further characteristics of each facility, decisive for the application of each methodology as presented below.

The BIM models of both use cases in Autodesk Revit are shown in Figure 2. The model of use case A was constructed from available documentation and on- site audit to serve as an input model for BEM, whereas in use case B the original architectural BIM model of the building was used [20]. In both cases, BIM models were simplified in respect to the actual geometry and space partitioning to facilitate data transfer to BEM and BaMa respectively. Use case A was modelled from scratch according to these principles. In use case B, the original model was modified by redefining room-stamps and internal boundaries, representing the necessary thermal zones, corresponding to the modular cube approach of BaMa.

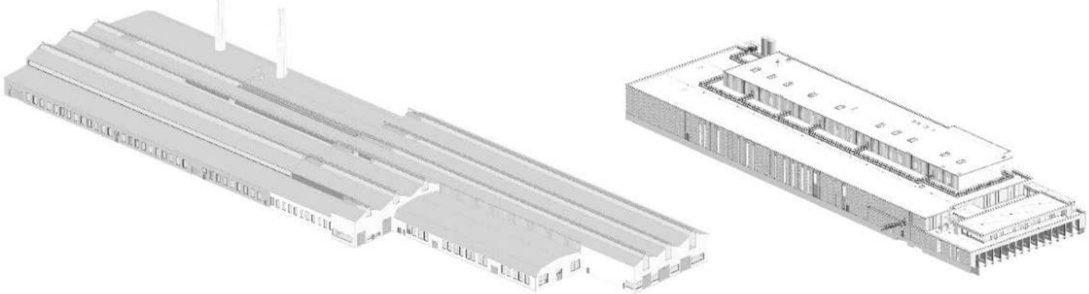

Figure 2. BIM Models of use cases A (left) and B (right).

3.1. Use case A – BEM

Use case A studies a single story metal processing facility, categorized as light manufacturing with a gross floor area of about 20,000 m². Typical for existing industrial building, this facility is a result of multiple expansions to a 1920s historical hall until the 1990s, with different building envelope constructions according to each phase. The older part of the factory has thick brick masonry walls and an uninsulated wood sheathing roof, whereas newer spaces, insulated metal cassette walls and sandwich roof panels. Figure 3 shows the thermal model of the building simulated with EnergyPlus [22]. The building is naturally ventilated, uses ceiling radiative panels and local fan coils for heating and there is no mechanical cooling. There are no building management systems (BMS), no energy monitoring systems and no automated production planning system. The manufacturing process chain is highly variable based on production orders demand with no standard-defined sequence and is planned manually according to daily necessities. On the other hand, machinery used is highly automated. Therefore, use case A is characterized by an overall very low level of digitalization.

The objective of use case A was to assess the energy optimization potential linked with the refurbishment of the older part of the building. Especially the impact of retrofitting the roof, which measures 82% of the building envelope area. Thus, a BEM approach was selected, with manufacturing heat gains calculated based on machinery energy consumption measurements during a period of a typical production month. Machinery operational hourly schedules were defined according to mean values of the monitored machinery on daily basis. Energy consumption of electrical lighting was also monitored and provided as an input to the BEM model. Regarding the building envelope, its geometry was exported in BEM from the created BIM model, however, semantic data regarding constructions were added manually.

Results showed, that the replacement of the older part of the roof with a new insulated roof skin as well as the replacement and area reduction of existing saddle single glazed skylights with raised monitor roof double glazing skylights, largely contributed in 52% reduction of the building's annual heating demand. Thus BEM provided an optimized configuration for the building envelope retrofit. A detailed presentation of this use case can be found in [23].

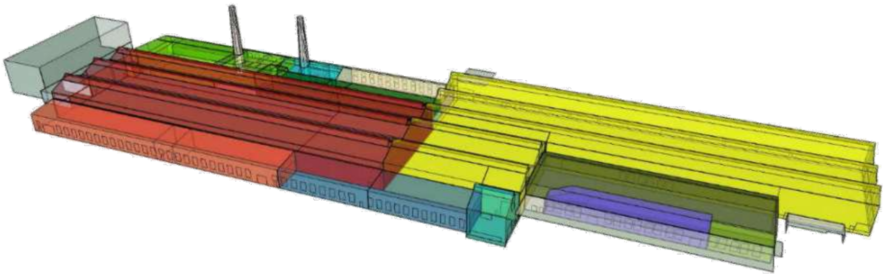

Figure 3. Thermal model of use case A, on the left side the older and on the right side the newer building part.

3.2. Use case B – BaMa

Use case B examines an industrial bakery, considered as moderately energy intensive and featuring a complex material flow. The factory is housed in a recently constructed new building, with production areas arranged mainly in double-height spaces on the ground floor and peripheral and administration areas in the mezzanine and upper level. The gross floor area measures circa 12,000 m². The building is heated and cooled via a mechanical ventilation system, having strict conditioning requirements for production spaces with an air temperature range between 24°C and 26°C. The cold storage and freezer specifications require a maximum temperature of 4°C and -22°C respectively. In packaging and commissioning spaces as well as in the raw material storage the temperature is allowed to range between 18°C and 26°C. These requirements are controlled by the buildings management system (BMS), which is embedded in factory's operational planning system together with the enterprise-resource-planning system (ERP). Production consists of nine major highly automated machines, linked by nine conveyor belts with junctions as well as three storage units. The products, baked or deep-frozen, use different material flow paths – mainly with and without passing through an industrial oven – and require different process parameters, e.g. temperatures and processing times on machines. Use case B is depicts a high level of industrial digitalization.

As this use case deals with a new factory, all subsystems are considered to be planned in a relative optimum way. This means that the building envelope, the efficiency of the TBS and the machinery itself are the "best in class" regarding their performance. Therefore, the energy optimization potential in here lies in the efficient operation of the production process, taking into account synergies of all interconnected subsystems. Therefore, the BaMa approach is applied, dividing the facility in *cubes*, as of section 2.2. The structure of the hybrid simulation model, including both energy and material flows is shown in Figure 4. The building is simplified in four thermal zones cubes, corresponding all production areas, the packaging and commissioning area, administration spaces and the technical rooms. Boundary conditions and adjacencies of these four zones are defined by the building cube. Data for the parametrization of the building and thermal zone cubes are collected manually from the simplified BIM model of the facility.

The whole BaMa toolchain is implemented by first monitoring actual operational information from the BMS and ERP systems, using them afterwards to parametrize the hybrid simulation model and lastly employing a genetic algorithm (GA) which considers the targets of energy, time and costs efficiency as well as restrictions resulting from given degrees of freedom, resource availability and product quality. The GA aims especially in minimizing energy demand with the utilization of synergies, peak load management and efficient use of available equipment. Further details can be found in [24]. Results indicated a reduction of the overall energy consumption up to 30% [25].

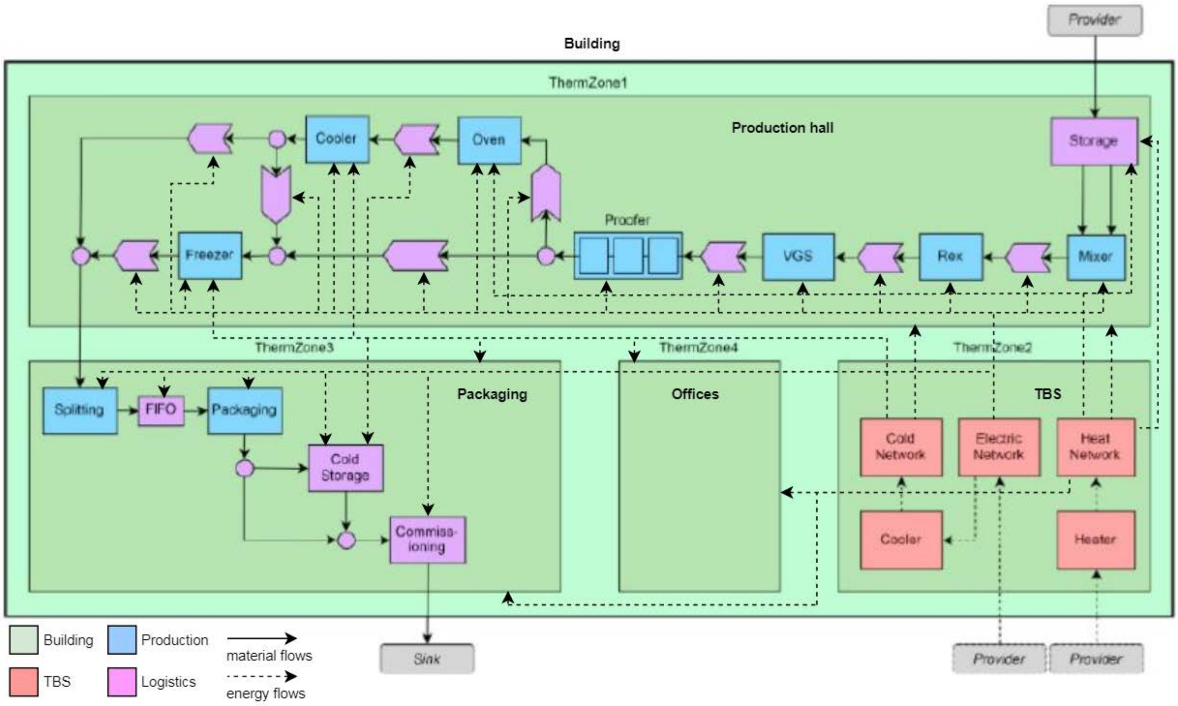

Figure 4. Structure of hybrid simulation model in BaMa for use case B.

4. Discussion

The two use cases presented in section 3 designate the wide spectrum of goals regarding industrial energy efficiency. There are various factors influencing the final energy demand of a facility, which is becoming an additional management objective alongside product quality, costs and time efficiency.

Available infrastructure and the level of digitalization are decisive for setting the optimization targets and consequently the suitable tools to achieve them.

The holistic simulation-based assessment of all subsystems constituting a factory, as that of BaMa, is suggested as the most comprehensive approach [9]. However, use case A points out that older factories, with a low digitalization level are probably not capable of deploying holistic methodologies. There the subsystems of the building and the TBS, from an energy assessment point of view, can be regarded as equal to the manufacturing processes in terms of their energy saving potential. Therefore, the BEM-based building envelope optimization of use case A is an essential step towards an improvement of the overall energy efficiency.

This brings us to the point of assessing the role of building modeling in the two presented simulation-based approaches for energy efficiency optimization in manufacturing plants. The two approaches have a fundamental difference in the way the treat the building, with BEM having it in its core, while BaMa considering it as the boundary enclosing its core, namely the production process. The building in BaMa is thus an auxiliary component of the industrial facility.

This difference can be seen in the capabilities comparison of both simulation approaches in Table 1. BEM provides detailed modeling options for building characteristics as well as HVAC systems, whereas the only further industrial subsystem that is included is machinery, in a simplistic manner. On the other hand, the BaMa hybrid simulation includes all industrial subsystems, with that of the building though being intensely simplified. The simplified building model, lacks a detailed representation of the geometry and addresses daylight and solar gains only by a total g-factor of the transparent elements, based on a set diminution factor of any existing shading (Fc value), not considering shading geometry of the building constructions. Furthermore, thermally activated building systems (TABS) and natural ventilation strategies cannot be modelled in the BaMa hybrid simulation. It should be noted though that the building models in BaMa are not utilized like traditional BEM for a building thermal and energy performance assessment but serve the role of interacting with other subsystems and the external environment, as the hybrid simulation is not aiming to optimize the design or technology of the industrial building itself or of the available TBS. To this extent it allows a qualitative and quantitative analysis of the whole industrial facility in terms of energy efficiency.

Table 1. Capabilities comparison of both simulation approaches.

	Building		**TBS**		**Production**		**Logistics**	
	Envelope	Daylight	HVAC	Media	Machinery	Prod. chain	Storage	Transport
BEM	✔ detailed	✔ detailed	✔ detailed	X no input	✓ - simple schedule - assumed or mean loads	X no input	X no input	X no input
BaMa	✓ simple geometry	✓ - no daylight control - simple shading factors - no geometry shades	✔ - detailed - no TABS - no natural ventilation	✔ detailed	✔ detailed	✔ detailed	✔ detailed	✔ detailed

Taking aforementioned into account, it can be argued that BEM-based energy optimization is suitable at a first stage for assessing the building and TBS optimization potential, especially for older industrial buildings. Yet when advancing on an integrated analysis of the whole factory, suitable for new or refurbished buildings, the hybrid nature of the BaMa approach, combining energy and materials flows, incorporates the multifaceted features of manufacturing plants and can better predict energy saving potentials according to actual restrictions.

Under this perspective, already developed BIM models of new facilities, like that in use case B, or older ones after an extensive building refurbishment, like use case A, could be used to provide necessary parametrization data for the simplified building models in holistic tools such as the BaMa toolchain. In use case B this has been done manually, however, a potential automated acquisition of building and TBS related information from BIM models could assist the implementation of such simulation-based methodologies in operating industrial facilities.

5. Conclusion

Simulation-based optimization can provide insight on the energy saving potential of manufacturing facilities. This paper studied two simulation approaches for energy modeling of industrial environments, with one focusing on the building aspect utilizing BEM and another focusing on the production processes, incorporating the building and TBS as auxiliary systems in a hybrid simulation within the developed BaMa toolchain. Use case applications showed that the level of digitalization of the factory and available infrastructure are decisive factors for selecting the appropriate method. In older facilities which have a building refurbishment potential, the modeling of the building holds an important role towards energy efficiency. With this regarded as the first step, the next one is a holistic assessment of all factory subsystems, where a simplified building modeling serves the role of providing the boundary between the production processes and the external environment, influenced by internal and external conditions and having an impact on the final overall energy demand.

In the case of the BaMa toolchain, further research is necessary for acquiring data available in existing BIM models to facilitate the parametrization of the building related subsystems in the hybrid simulation model environment. This would promote BaMa implementation in operating manufacturing plants in order to provide valid optimization alternatives of the production planning, based on actual capacities and limitations.

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