Dicle Üniversitesi Fen Bilimleri Enstitüsü Dergisi

Dicle University Journal of the Institute of Natural and Applied Science

https://dergipark.org.tr/tr/pub/dufed

Derleme Makalesi / Review Article

An Overview of Hygrothermal Simulation Tools

Higrotermal Simülasyon Araçlarına Genel Bir Bakış

Yusuf YILDIZ

Balıkesir University, Faculty of Architecture, Department of Architecture, 10140, Balıkesir, Turkey

ARTICLE INFO

Article History

Received, 05 April 2021
Revised, 01 June 2021
Accepted, 14 June 2021
Available Online, 05 November 2021

Keywords

Hygrothermal analysis, Simulation, Moisture

ABSTRACT

Hygrothermal (humidity-thermal) behavior of building components exposed to weather conditions is an important part of the overall performance of a building. Estimating and modeling moisture often involves complex calculations. Today, apart from the experimental methods, mostly the hygrothermal behavior of the building envelope can be estimated with simulation programs. While the demand for simulation programs used to calculate energy performance in buildings is increasing, the interest in tools that calculate the hygrothermal behavior of the building and building envelope is still not at the expected level. The main purpose of this study is to examine the actively accessible hygrothermal analysis programs in general and to examine their usability in literature. Firstly, the simulation programs are overviewed. Later, to analyze the usability of these programs, the articles published between 2001-2019 were examined in electronic databases. As a result of the reviewing, eight programs were identified and it was found that Wufi, DELPHIN and IDA-ICE tools were used more in academic studies than other programs. However, although there was a slight increase in hygrothermal analysis program usage, it was observed that it was not at the desired level.

MAKALE BİLGİSİ

Makale Tarihi

Alınış, 05 Nisan 2021
Revize, 01 Haziran 2021
Kabul, 14 Haziran 2021
Online Yayınlama, 05 Kasım 2021

Anahtar Kelimeler

Higrotermal analiz, Simülasyon, Nem

ÖZ

Hava şartlarına maruz kalan yapı bileşenlerinin higrotermal (nemsel-ısıl) davranışı, bir binanın genel performansının önemli bir parçasını oluşturmaktadır. Nemin tahmin edilmesi ve modellenmesi genellikle karmaşık hesaplamaları içermektedir. Günümüzde, deneysel yöntemler dışında benzetim (simülasyon) programları ile çoğunlukla bina kabuğunun kullanım sırasındaki higrotermal davranışı tahmin edilebilmektedir. Binalarda enerji performansını hesaplamak için kullanılan simülasyon programlarına talep artarken, bina ve kabuğun higrotermal davranışını hesaplayan araçlara olan ilgi ise hala beklenen düzeyde değildir. Bu çalışmanın temel amacı, aktif olarak ulaşılabilen higrotermal analiz programlarını genel olarak irdelemek ve kullanılırlıklarını incelemektir. İlk olarak simülasyon programlarının özellikleri incelenerek genel bir bakış sunulmuştur. Daha sonra bu programların kullanılırlığını analiz etmek için 2001-2019 yılları arasında yayınlanan makaleler elektronik veri tabanlarında incelenmiştir. Tarama sonucunda 8 program tespit edilmiş ve bu programlardan Wufi, DELPHIN ve IDA-ICE araçlarının diğer

E-mail address: yusifyildiz@gmail.com.tr (Yusuf YILDIZ)

programlara göre akademik çalışmalarda daha fazla kullanıldığı bulunmuştur. Ayrıca higrotermal analiz program kullanılırlığında azda olsa artış olmasına rağmen istenilen seviyede olmadığı görülmüştür.

1. INTRODUCTION

In recent years, energy consumption and thermal comfort in the buildings are at the top of the topics that are widely studied. Moisture control has become as important as building energy performance, because indoor humidity is closely related to comfort and personal health, and also affects construction durability and energy consumption [1]. Moisture in building components can adversely affect the thermal performance of the building, as well as speed up aging and deterioration. High humidity levels in building materials can also cause microbiological growth, such as mold [2]. This can create uncomfortable indoor environments, impair user health and reduce the life of buildings. Moisture can also cause structural damage by decay in organic materials such as wood. High indoor humidity levels can affect the working efficiency of heating, ventilation and air conditioning systems; excessive moisture or hidden load may require more energy to dehumidify during cooling [3]. For these reasons, the estimation and control of moisture behavior in buildings and building components is as necessary as energy efficiency and thermal comfort. The interaction between the building envelope and the surrounding areas plays an important role in determining the hygrothermal behavior of a building. The comprehensive situation of all boundary conditions that trigger this interaction requires us to perform a detailed analysis of energy demands, internal conditions and hygrothermal conditions within the building envelope. The general purpose of the hygrothermal analysis is to evaluate the temperature and humidity conditions that may prevail in a whole or part of a time dependent or instantaneous building. The following preliminary information is needed to estimate the hygrothermal performance of the building structural element [4]:

- Geometry of the building element and all macro building details (building shape and height, etc.), building element assembly details and micro details (cracks, etc.),
- Boundary conditions; internal environment conditions involving the interaction of the building element with the internal environment, external environment conditions involving the interaction of the building element with the external environment, boundary conditions between the materials that make up the building element,
- Material properties and temperature, moisture content and change with age and chemical interactions with other materials,
- Physics, chemistry, thermodynamics and combined heat, air and moisture transport mathematics.

The hygrothermal performance of a building shell is related to knowing which materials should come together at the design stage, the temperature values of the material, the amount of water and moisture performance [5]. Moisture performance of a building element can be determined by various experiments, but it requires a long time and high cost. Different calculations can be made using analytical and graphical methods, but these methods also have limitations. For this reason, the use of computer models has become a necessity and become widespread today in the examination of humidity performance of buildings [6].

Simulation is a general term and is used for a variety of purposes such as thermal comfort, lighting, acoustics and energy consumption analysis, evaluation of different forms and designs in existing or new buildings. Different simulation programs have been developed depending on usage purpose. There are also special simulation programs used for moisture and thermal behavior calculations. In recent years, the use of tools that simulate the building envelope or heat, air and humidity conditions throughout the building has increased. Today, simulation programs that evaluate energy performance are used more frequently, while the number and use of simulations that evaluate moisture performance are relatively low. Although some simulation programs combine both heat and moisture transfer calculations, the number of models that model moisture transfer to life is still limited. Models used in simulation programs differ significantly according to their mathematical complexity and As Straube and Burnett [7] stated in her work, this complexity based on the degree to which the model including parameters such as moisture transfer size, flow type (steady state, semi-static or dynamic), quality and acess on information, and the stochastic nature (material properties, weather, building quality, etc.) of various data.

Eight hygrothermal simulation tools in this study were evaluated and presented in terms of their general features. Then, to analyze the usability of these programs, four electronic databases were scanned and the results were examined.

2. MATERIAL AND METHOD

The literature review is according to the studies on mentioned subject in scientific journals published between 2001-2019 by using a systematic review approach. This approach allows the identification of current relevant studies depending on a formerly designed research question [8]. In addition, this reduces the author's subjectivity because it provides transparency of results and reproducibility of the study [8]. The research consists primarily of brief introduction of hygrothermal analysis programs that are in active use and scanning related studies in the main online databases that covering academic studies in journals. Databases used for this study are Google Scholar, Web of

Science, Scopus and ScienceDirect, which contain academic articles related to energy and engineering fields and enable to make accurate and customized searches. Keywords “simulation name + hygrothermal” are determined to examine how much these programs are used in academic studies and the scan has been repeated as many times as necessary until the most recent research in this field has been identified. Some criteria for inclusion and exclusion were determined to identify the most relevant articles from the scientific literature. The study is restricted to researches published in academic peer-refereed journals. All other publications (eg conference papers, periodicals and working papers) and articles not written in English are also excluded.

3. HYGROTHERMAL SIMULATION PROGRAMS

In recent years, many simulation tools have been developed to analyze building performance from different perspectives. According to the list on the US Department of Energy's website, there are now more than 345 simulation tools for both commercial and research purposes [9].

The humidity problem in buildings has been studied since the first days of the last century, but in recent years, the general issue of moisture transfer in buildings has become a more important study area depending on the improvement in simulation programs. Heat & humidity conditions and transport in buildings and building components should be handled together. It is clear that high humidity affects negatively heat losses and temperature conditions in components of building causes moisture transfer. Investigation of heat and moisture movements is expressed as "hygrothermic" [10]. Hygrothermal models are necessary to simulate the combined transport of heat and moisture for one or multi-dimensional situations in the field of building physics [11]. Hygrothermal simulation provides a prediction of a designer's or engineer's moisture and temperature conditions and movements that may occur within the building or building envelope. However, one of the shortcomings in many building energy simulation programs is that it does not take into account the humidity in the building elements or ignore the external/internal humidity fluctuation. Therefore, hygrothermal simulation tools that calculate temporary temperature and humidity conditions in building envelope components under realistic boundary conditions are increasingly needed by architects and engineers [2]. Most of the hygrothermal simulation tools available in the literature are not currently available. For this reason, hygrothermal simulation programs that are open for use have been compiled in terms of their features in light of the information available and are summarized below:

Bsim

The Bsim simulation program was created by the Building Research Institute of Denmark Alborg University is a tool to make model (one-dimensional) for the transport of heat and moisture in

porous building materials. BSim2000, which is the updated version of the MATCH program, is also a performance analysis tool for indoor climate, energy consumption and analysis of the building's daylight performance. BSim is an integrated tool used to analyze buildings and active systems. This program is capable with analysis of indoor climate, energy consumption, daylight conditions, simultaneous simulation of moisture and energy transfer in buildings, integrated photovoltaic systems, natural ventilation and electrical efficiency. The BSim program package consists of six different fixed modules; SimView-Graphical user interface, Tsbi5-indoor climate and dynamic simulation of energy conditions, Xsun-sunlight and shadow analysis and simulation, SimLight-daylight calculation, SimDXF-CAD drawings import, SimDB-Structure and material database. It is also possible to use a number of additional sub-modules.

Tsbi5 is the main module of BSim [12]. This module provides dynamic simulation of indoor climate, energy and humidity conditions in buildings. The results can be used in many ways. Tsbi5 is also a module used for synchronous simulation of humidity and thermal conditions in spaces and building elements. The moisture module enables the analysis of humidity changes in indoor climate, moisture accumulation in structures and the risk of condensation on surfaces. For this purpose, the BSim database has been expanded with sorption and desorption properties for building materials. The program was last updated in 2020.

DELPHIN

DELPHIN has been developed for one- and two-dimensional combined heat, moisture and mass transfer calculations in porous building materials [14]. The tool is used to simulation of temporary mass and energy transport for standard and natural climate boundary conditions. Other usage areas are as follows [13]:

- Calculation of heat bridges, including evaluation of hygrothermally problem areas (surface condensation, interstitial condensation),
- Interior insulation design and evaluation,
- Ventilated facade systems, ventilated roofs,
- Temporary calculation of annual heating energy demand (taking into account the thermal conductivity due to humidity),
- Drying problems (basement, building moisture, flood, ...),
- Calculation of mould formation risks.

The program was last updated on 2021.

GLASTA

It is a reporting tool optimized for condensation/drying in multilayer structures with heat and steam simulation according to EN 13788 and DIN 4108. It is a one-dimensional model used for the prediction of heat and moisture in porous building materials. Monthly average temperature, vapor pressure or relative humidity values can be calculated with the program. It has also a weather database for more than 100 European regions [11]. The program was last updated on February 4, 2015 [15].

HAMLab

HAMLab (Heat, Air and Humidity Laboratory) was developed by students and researchers under the supervision of Jos van Schijndel at Eindhoven University of Technology and is a modelling toolkit for temperature, air and humidity calculation. It consists of models that can work in the Matlab/imulink/FemLab/ COMSOL environment. For example, HAMBase is one of the sub-units of the model and is used for the analysis of heat and moisture flows in buildings. The main goal of the model is to calculate the indoor thermal conditions and energy usage. With the model, indoor temperature, air humidity and energy consumption for heating and cooling in buildings can be calculated [16]. No information has been available on when it was updated lastly.

IDA-ICE

It is a detailed and dynamic multi-zone simulation tool for the calculation of the energy consumption of the buildings, as well as thermal indoor conditions, used mostly in the Scandinavian and Central European countries. It is a calculation tool with many features, including models for heat transfer in the building envelope, flow networks, daylight and energy systems analysis. The integrated airflow network incorporates a wide range of calculations such as thermal models, CO2, humidity and vertical temperature gradients [17]. To investigate the moisture transfer with the IDE-ICE program, commonly used wall model was changed with HAMWall, created by Kurnitski and Vuolle [18]. HAMWall can work as a single distanced model or as a component of a larger system. Transport of water as liquid is not modeled and hysteresis is not considered in this tool. It is also possible to examine the following conditions by using this tool [17]:

- The effects of buildings on indoor air quality and thermal comfort,
- The building materials and furniture as a moisture barrier to mitigate air humidity fluctuation,
- Hygrothermal analyse based on changing indoor climate conditions,
- The effect of ventilation system according to low or overpressure on hygrothermal conditions in the building envelope,

- The effect of moisture on the heating and cooling load.

A new version of the program was released in 2018 [19].

MATCH

MATCH is a model developed in Denmark. It can be used to temporary calculation of the movement of heat and moisture through composite structure constructions. The air flow can be calculated by using a different type of the tool. MATCH works based on the finite control volume method to make calculations for the temporary variation of both thermal and moisture dependent variables. Moisture movement is accepted to only cause by the steam flow. The tool was validated by comparing its results with the experimental data created from laboratory and field studies [18]. Its latest version was published in 2003 [20]. Among the advantages of the program are:

- Including the hygroscopic capacity of building materials,
- Including definition of the bidirectional interaction between heat and moisture transfer,
- A research-oriented and user-friendly tool for practitioners in the building design process.

MOIST

MOIST is a user-friendly simulation tool predicting one-dimensional transfer of heat and moisture. The wall, cathedral ceiling or low-pitched roof structure can be easily identified with MOIST. Then, the impacts of several parameters on the moisture accumulation in the building layers can be investigated. For example, the impact of climate change on moisture accumulation can be examined by defining the weather conditions for different cities. It can be determined whether a vapor retarder is required and its location within other materials if necessary. The user can change materials and their locations and can predict moisture in each of them as a function of time based on selected weather data [21].

The MOIST model has detailed capillary pressure curve. It also examines the impact of water vapor resistance offered by paint layers, walls and steam retardants. Algorithms in the program can predict moisture transfer through the capillary flow regime in the diffusion regime. The effect of water evaporating from one place and condensed elsewhere is included in the model. The model uses the moisture content, relative humidity and temperature of the building layers, as well as the database of heat and moisture properties for common building materials. During a simulation, the user can specify a constant indoor temperature and relative humidity or allow relative humidity to change and be calculated from the humidity balance of the entire building. The program can be used for the following wall, unventilated cathedral ceiling and low-pitched roof applications [22]:

- Estimating winter moisture content in the outer structure layers and determining whether a retarder is needed,
- Estimating the surface relative humidity in the building layers in hot and humid climates,
- Determination of drying rates for materials containing original building moisture,
- Investigation of the performance of cooling tanks,
- Analysis of impact of moisture on heat transfer.

One of the most important limitations of the program is that the model is one-dimensional. This means that the model does not include the effect of framing elements and two- and three-dimensional effects, such as vertical movement of moisture in the soil. Moreover, it does not include wetting a model building with rain and snow load insulation effect and change in roof absorption. In addition, the model does not include air movement, and the transfer of heat and moisture. The construction is assumed to be airtight [22]. The program was last updated in 1997 [23].

WUFI

The Hygrothermic Division in Fraunhofer IBP, Germany has created the WUFI simulation packages to make hygrothermic analysis. It can make dynamic simulations of combined heat and humidity transfer. The methods used are approved worldwide and make possible simulation of hygrothermal conditions in components and buildings depending on real climatic conditions. The tool works according to the latest information on vapor diffusion and fluid transfer in building materials. For boundary conditions, measured external climatic data, including precipitation and solar radiation, are used. The common feature of the WUFI family is that it is a dynamic, matched simulation of heat and humidity transport. However, WUFI is later divided into two categories [24]:

1. Simulation of building element (WUFI Pro and WUFI 2D): focuses on single or multi-layered building components such as walls and roofs exposed to the defined external and internal climate. These calculations evaluate issues covering whether one-dimensional cross-sections and/or cross sections such as balcony joints will sustain moisture-related damage. WUFI Pro is a basic tool to investigate the hygrothermal performance of one-dimensional building envelope sections. WUFI 2D is a higher version of WUFI Pro and is used for the evaluation of detailed geometries (building corners, window connections, basic interfaces, etc.).
2. Building simulation (WUFI Plus and WUFI Passive): the building deals with behavior in an integrated manner and takes into account the effects of moisture on indoor environment. The

main aim of this version is to evaluate indoor conditions and the energy requirements to maintain comfortable and healthy indoor environment [19].

WUFI Plus is the most extensive version within the Wufi simulation packages. It can simulate the indoor environment and its impact on comfort and energy consumption as well as the hygrothermal conditions in building elements defined by user. WUFI Plus is also capable of dynamic evaluation of thermal protection in summer. It can calculate the transient response of three-dimensional thermal bridges. According to results of WUFI Plus simulations, the user decides whether the building meets the passive house criteria.

WUFI Passive: It is different version of WUFI Plus. The main difference is that the dynamic hygrothermal simulation is only performed after the passive house criteria are met. Moreover, WUFI Passive works a quick monthly balance method that allows for optimization of passive house criteria and subsequent certification.

WUFI Plus Free and WUFI Passive Free: These are free versions and they do not make hybrid component simulation and room environment simulation. Also, databases are not changed with different values and results are not exported.

Results from simulations include graphs showing all moisture content and each layer in the system. There are also graphs showing temperature and relative humidity data for simulations. WUFI is used by building materials manufacturers, consultants, designers and experts in the field of hygrothermic. The program was last updated in 2019 [24].

4. SCANNING HYGROTHERMAL SIMULATION PROGRAMS IN DATABASES

Simulation programs are tools used to better understand events or processes after they are mathematically expressed and provide effective solutions and are often preferred to provide the necessary supporting information in decision making. Eight simulation tools that can actively represent the hygrothermal behavior of the buildings with different levels of detail and complexity have been identified.

Determined keywords (program name + hygrothermal) were scanned in Google Scholar, Web of Science, Scopus and ScienceDirect databases to evaluate how much these programs are preferred in academic studies. In this research, only articles published in peer-reviewed academic journals and written in English were included; conference papers, periodicals, books, theses, etc. other types of publications have been excluded from scanning.

The literature search carried out on 01.03.2021 and the results are given in Table 1. It is clear that results vary depending on the databases. It was found that WUFI program was the most used program in academic studies compared to other simulation tools. The DELPHIN program is the second most widely used simulation tool. IDA-ICE, Bsim and HamLab programs are other common tools used in literature. GLASTA is the least used simulation tool. Moist and Match programs have been scanned in detail but articles found are not related to the main topic, as moist and match evoke words with different meanings. Therefore, they were not included in the study.

Table 1. Scanning results in different databases

Tool name	**The number of the results**				
	Google Scholar	**Scopus**	**Science Direct**	**Web of Science**	**Total**
Wufi	542	258	159	76	1035
Bsim	128	11	4	1	144
Moist	*	*	*	*	0
Match	*	*	*	*	0
IDA-ICE	213	16	4	1	234
HamLab	83	2	5	*	90
GLASTA	*	3	2	*	5
DELPHIN	512	73	67	17	669

* No relationship was found between the results and the subject.

The number of articles is also examined according to years and we focused to articles published after 2000. Due to the possibility of classification by year, Scopus was chosen to continue with this review. According to results, there is no significant increase in the publications made between 2000-2019 regarding studies used hygrothermal simulation programs (Figure 1). Although Wufi and DELPHIN tools have been gaining popularity over the past years, no significant changes have been observed for other programs. One of the possible reasons for the increase in the use of the wufi program in academic studies is that wufi consists of several sub-programs that serve different purposes such as building component and whole building simulation. The other reason being this is that comprehensive features have been added to Wufi and DELPHIN.

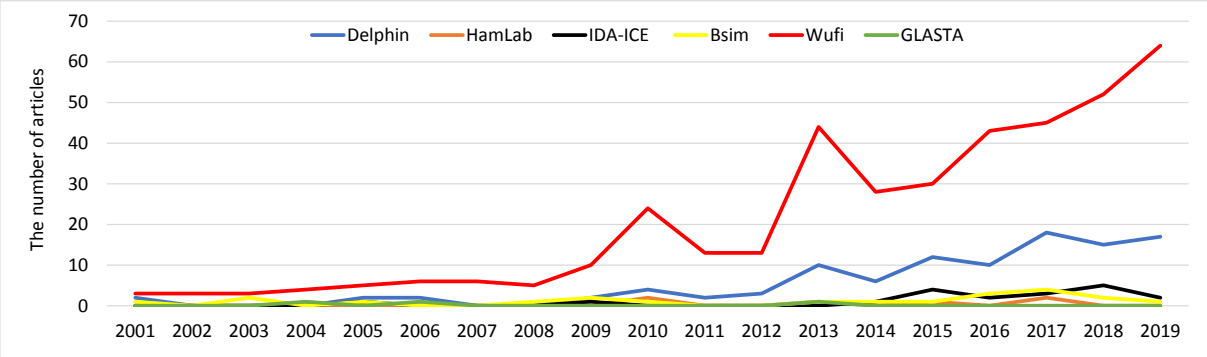

Figure 1. *Number of articles published from 2001 to 2019*

5. CONCLUSION

In this study, eight tools for hygrothermal analyse are examined with their general features and reviewed how much they are used in academic studies. The analysis focused on articles published in the last 20 years. According to results of scanning the literature, there are still few studies used tool for hygrothermal analysis. If the current growth trend in the number of studies continues in the coming years, it is likely that research on this subject will deepen and new perspectives can be brought to the subject of hygrothermal analysis. The increase of these studies might be related to the developments in hygrothermal analysis programs.

The eight toolkits and their general information are summarized in Table 2. According to this, Moist and Match tools were updated before 2015, while rest of them were updated newly. All of tools are actually simulation engines except for HamLab. Most of the tools are optimized to run simulations at the building component scale, only wufi seem, focusing more on the whole building scale. The database reviews showed that there was no free simulation tool for hygrothermal analyse. From our point of view, it was a barrier to their widespread use. There are various reasons that affect usage of simulation programs. These can be explored in other studies to obtain detailed information. Finally, since program capacity and features will affect preferences, researcher will select simulation tools that are more suitable for their own problems. Supporting the use of hygrothermal modelling in building design will also be encouraging for the proliferation of programs. The information in this review can help users in both academia and industry know and choose appropriate tools to address moisture issues in buildings.

As with any research study, there are some limitations to this article. This review gives a snapshot of the current state of scientific research. The option to analyze only peer-reviewd scientific journal articles may potentially have excluded relevant some articles.

Table 2. The evaluation of eight simulation tools

Tool	Wufi					Bsim	Moist	Match	IDA-ICE	HamLab	GLASTA	DELPHIN
	Pro	2D	Plus	Passive	Plus/Passive Free							
Last releases	2019					2020	1997	2003	2018	No information	2015	2021
Developer	Fraunhofer IBP					AALBORG University	The National Institute of Standards and Technology (NIST)	Danish Technical University	EQUA Simulation AB (Swedish company)	Eindhoven University of Technology	Physibel (Belgium company)	Institute of Building Climatology at TU Dresden
Analysis	1-D calculation	1-D and 2-D calculation	2-D and 3-D calculation, building simulation		1-D calculation, building simulation	1-D calculation	1-D calculation	1-D calculation	1-D calculation	1-D, 2-D and 3-D calculation, building simulation	1-D calculation	1-D and 2-D calculation
Web site	https://wufi.de/de/					https://sbi.dk/bsim/Pages/Kort-om-BSim.aspx	https://www.nist.gov/programs-projects/moist	Not exist	https://www.equa.se/en/ida-ice	http://sts.bwk.tue.nl/hamlab	https://www.physibel.be/en/products/glasta	http://bauklimatik-dresden.de/
Status	Active					Active	Active	Not active	Active	Active	Active	Active
Availability	Free of charge[1] time limited	Time limited	Free of charge[1] time limited		Free of charge	Free demo, time limited	Free of charge	Not active	Time limited, trial version	Free of charge	Free demo, time limited	Free demo, time limited
Integration with other programs	Standalone					Standalone	Standalone	Standalone	Standalone, network	Under Matlab/Simulink and COMSOL	Standalone	Standalone, network

1: Limited features available

CONFLICTS OF INTEREST

No conflict of interest was declared by the authors.

REFERENCES

[1] Z. Huibo, Y. Hiroshi, "Analysis of indoor humidity environment in Chinese residential buildings". *Building and Environment*, vol. 45, pp. 2132–2140, 2010.

[2] H. M. Künzel, and D. Zirkelbach, "Advances in hygrothermal building component simulation: modelling moisture sources likely to occur due to rainwater leakage", *Journal of Building Performance Simulation*, vol. 6, no. 5, pp. 346-35, 2013.

[3] S. Pallin, P. Boundreaux, S. Shrestha, New. Joshua, Adams. M, *State-of-the-Art for Hygrothermal Simulation Tools*. (2017). Accessed: Jan. 10, 2021. [Online]. Available: https://info.ornl.gov/sites/publications/Files/Pub73069.pdf

[4] E. Edis, H. Kuş. "Determination of hygrothermal performance of building envelope by computer simulation", *Gazi Üniv. Müh. Mim. Fak. Der.*, vol. 29, no. 2, pp. 311-320, 2014.

[5] A. Ekşi, "Mevcut binaların cephelerinde dıştan ısı yalıtımı uygulamalarının İstanbul'da alanda incelenmesi ve higrotermal performansın benzetimle değerlendirilmesi", M.S. thesis, Dept. Architecture, Istanbul Technical University, İstanbul, Turkey, 2016.

[6] S. Chasan, "Dış cephe bitirme sistemlerinde ısı yalıtımının sıcaklık ve nem performansına etkisinin incelenmesi", M.S. thesis, Dept. Architecture, Trakya University, Edirne, Turkey, 2013.

[7] J. Straube, and E. F. P. Burnett, "Overview of hygrothermal (HAM) analysis methods", In: Trechsel HR (ed). ASTM manual 40-moisture analysis and condensation control in building envelopes, pp. 81-89, 1991.

[8] D. Denyer, D. Tranfield, "Producing a Systematic Review", The Sage handbook of organizational research methods, pp. 671-689, 2009.

[9] N. M. M. Ramos, J. M. P. Q. Delgado, E. Barreira, V. P. de. Freitas, "Exterior condensations on façades: numerical simulation of the undercooling phenomenon", *Journal of Building Performance Simulation*, vol. 6, no. 5, pp. 337-345, 2013.

[10] Wufi, *What is Wufi*. Accessed: Apr. 12, 2020. [Online]. https://wufi.de/en/software/what-is-wufi

[11] N. M. M. Ramos, J.M.P.Q. Delgado, E. Barreira, V. P. De Freitas, Hygrothermal Numerical Simulation: Application in Moisture Damage Prevention, Numerical Simulations-Examples and Applications in Computational Fluid Dynamics, Lutz Angermann (Ed.), InTech, 2010, pp. 97-122.

[12] Bsim. Accessed: Sept. 10, 2020. [Online]. https://sbi.dk/bsim/Pages/Kort-om-BSim.aspx

[13] A. Nicolai, J. Grunewald, J. J. Zhang, "Recent improvements in HAM simulation tools: Delphin 5 / CHAMPS-BES", in Proceedings of 12th Symposium for Building Physics, 2007, pp. 866-876, Dresden.

[14] Delphin. Accessed: August. 22, 2020. [Online]. http://bauklimatik-dresden.de/delphin/index.php?aLa=en

[15] Glasta. Accessed: October. 28, 2020. [Online]. http://www.physibel.be/v0n2gl.htm

[16] Hamlab. Accessed: November. 18, 2020. [Online]. https://archbpswiki.bwk.tue.nl/bpswiki/index.php/Hamlab
[17] J. M. P. Q. Delgado, E. Barreira, N.M.M., Ramos, V.P. de Freitas, "Hygrothermal Numerical Simulation Tools Applied to Building Physics", *Springer*, London, 2013.
[18] J. Kurnitski, and M. Vuolle, "Simultaneous calculation of heat, moisture and air transport in a modular simulation environment", *Proceedings of the Estonian Academy of Sciences*, vol. 6, no. 1, pp. 25-47, 2000.
[19] Ida-ice. Accessed: February. 2, 2020. [Online]. https://www.equa.se/en/ida-ice
[20] Match. Accessed: January. 7, 2020. [Online]. https://match-box.dk/what-is-match/
[21] A. Pehlevan, Y. Yaşar, S. Maçka, "Higrotermal performans açısından duvar konstrüksiyonu tasarımında bilgisayar modellerinin kullanımı", X. Ulusal Tesisat Mühendisleri Kongresi, pp. 371-385, İzmir. 2011.
[22] D. M. Burch and J. Chi, "Moist: A PC program for predicting heat and moisture transfer in building envelopes", Accessed: June. 12, 2020. [Online]. https://www.nist.gov/system/files/documents/2017/04/28/MoistManual.pdf
[23] Moist. Accessed: April. 25, 2020. [Online]. https://www.nist.gov/programs-projects/moist
[24] Wufi. Accessed: March. 25, 2021. [Online]. https://wufi.de/en/software/product-overview/