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Optimizing Livestock Microclimates: BES Models, Challenges, and Sustainable Solutions

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Efficient control of microclimate conditions in livestock buildings is crucial for sustainable livestock production. This paper explores the optimization of energy efficiency through measures such as minimizing energy consumption, adopting eco-friendly technologies, incorporating renewable energy sources, and analyzing economic parameters. Livestock production's impact on global food security is highlighted, emphasizing the importance of effective temperature control in optimizing production. The study delves into the energy consumption patterns in livestock buildings, particularly about heating and ventilation. The role of microclimatic parameters, categorized as physical, chemical, and biological, is crucial in ensuring favorable health conditions for animals. The study identifies a research gap in the existing literature regarding Building Energy Simulation (BES) models for cow housing, leading to the establishment of this study's goals and methodologies. The methodology involves defining the project scope, creating a logical framework, and conducting a comprehensive literature review. The evaluation of BES models for livestock housing is systematically carried out, covering various aspects such as model applications, validation techniques, and constraints. Findings include insights into the specific types of livestock housing considered, key journals publishing relevant works, and a chronological analysis of research output. The study identifies challenges and limitations surrounding BES models in livestock housing, emphasizing the need for standardized validation procedures for reliable and applicable simulation models. Microclimatic parameter analysis provides a detailed examination of sources influencing temperature, humidity, airflow, illumination, and gas content in livestock buildings. Building Performance Simulation (BPS) tools are discussed, highlighting their role in evaluating and analyzing buildings during design and retrofit phases. The study concludes with a focus on models for sustainable advancements in the cattle industry, emphasizing the role of BES models in integrating renewable energy sources and addressing environmental challenges. The paper provides a comprehensive overview of BES models for livestock housing, serving as a valuable reference for future research and contributing to the industry's resilience and sustainability.

Keywords: Microclimate Conditions, Livestock Buildings, Airflow, Illumination, and Gas Content.

Introduction:

Efficiently controlling microclimate conditions in livestock buildings is crucial for ensuring sustainable livestock production. The optimization of energy efficiency in these structures involves various measures aimed at reducing energy demands. This includes exploring opportunities for minimizing energy consumption, adopting new eco-friendly technologies, incorporating renewable energy sources, and conducting a detailed analysis of relevant economic parameters. Implementing energy optimization strategies at the early stages of design, while considering all pertinent factors, plays a key role in decreasing energy consumption [1].

A significant microclimate concern in livestock buildings is the concentration of dust. In recent years, research focusing on dust concentration production, the development of dust distribution models, and methods for reducing dust concentration have intensified. Over the past 10–15 years, there has been a growing body of evidence documenting the harmful effects of polluted emissions from livestock buildings on the health of both humans and animals. Pioneering researchers have observed a surge in interest from various authors since the early 1980s [2]. Their diverse areas of focus encompass dust production, types and characteristics, concentration and dimension measurement, threshold limits and standards, the impact of dust on health, environmental pollution, and the creation of models for dust concentration distribution and reduction. Several approaches can be employed to reduce dust concentration, including air filtration, treatment of dust sources, and ventilation. An investigation into the effectiveness of different indoor air filtration methods for reducing dust concentration found that wet or dry filtration methods were deemed impractical due to being both costly and complex for use in livestock buildings [3]. Cyclone-type devices, relying on centrifugal force for particle separation, exhibited significant inside pressure drops and, consequently, high energy consumption to overcome critical phases. While electrostatic sedimentation could be considered, its application and maintenance costs are currently prohibitive [4].

Ventilation remains one of the most effective methods for reducing indoor air pollutant concentration. However, recent research has placed a greater emphasis on investigating its actual impact on dust concentration [5]. Food products derived from animals play a crucial role in ensuring global food security, constituting approximately 18% of the world's calorie intake and 25% of protein consumption. Large livestock systems support at least 1.3 billion people, providing a significant portion of the world's food supply through intensive and cost-effective cattle rearing. Effective temperature control in livestock housing is paramount for optimizing production, as it directly influences various aspects of cow management. Maintaining ideal indoor temperatures and preventing heat stress have been shown to enhance both the quantity and quality of animal production [6].

In livestock barns with high cattle density, vibrating temperature control systems are commonly employed, resulting in substantial energy consumption that significantly impacts the overall energy usage of cattle operations. Complementary heating comprises approximately 96% of the total thermal energy used in grill dwellings, equivalent to around 140 kWhthm2 A1. Conversely, ventilation can constitute as little as 40% of the overall electrical energy usage (11 kWhel m2a1) or as much as 70% [7]. Ventilation may contribute to 50% of power consumption in chicken houses, amounting to about 20 kilowatt-hours per square meter annually. Similarly, the combined energy use of localized heating and ventilation in pig barns can make up 50% (37 kWhel m−2a−1) of the total electrical energy consumption [8]. Numerous authors in scientific literature emphasize the critical importance of establishing a favorable microclimate on farms, with factors like calf mortality significantly impacting profitability. For instance, a 20% calf mortality rate can lead to a 60% reduction in profitability. Creating a stable microclimate is identified as a crucial factor in reducing calf mortality. Additionally, ensuring climatically comfortable conditions for livestock breeding is essential for maintaining the animals' good health [9].

The microclimatic parameters within livestock buildings are categorized into three fundamental groups: physical (e.g., temperature, relative humidity, illumination, air-exchange rate, and air velocity), chemical (e.g., gases like O_2, CO_2, NH_3, H_2S, CO, and organic dust), and biological (e.g., pathogens and parasites). Effective microclimate control in livestock buildings should be viewed as a holistic mechanism, considering species, life stage, genetic potential, and nutritional period to establish favorable health conditions for the animals [10]. Statistics reveal that, on average, animals experience excessive heat 27% of the time and cold conditions 17% of the time when housed in livestock buildings. Existing literature provides various approaches for modeling microclimate management in livestock buildings. Strategies include humidity balance and heat-exchange models, sensible heat balance justification models, and black-box simulation methods. Challenges, such as difficulties in predicting indoor temperature during ventilation and inaccurate humidity predictions during natural ventilation, are acknowledged in these approaches [11].

Two primary methods for modeling microclimate regulation in agricultural premises are recognized: black-box simulation and mechanism modeling. The former relies on cause-and-effect relationships, employing intelligent algorithms like neural networks and support-vector models. However, it has drawbacks such as weak universality and limited justification of physical parameters [12]. The latter, which includes the proposed approach, involves mechanism modeling that considers physical laws and relationships. This method, evident in numerous studies, focuses on energy balance and mass-exchange approaches. Combining the "black-box" and "mechanism" methods in a single approach is rare in the literature. Such integrated approaches should not only address physical processes but also consider economic efficiency, time efficiency, and sustainability priorities. These factors become especially crucial in the context of increasing demand for renewable energy sources, driven by changing political events on the European continent [13].

The impact of climate management on energy use holds significance from both financial and environmental perspectives. From a financial standpoint, it represents a continuous cost for farmers, with electricity and heat charges accounting for a substantial portion of variable costs in contract grill production. In terms of the environment, temperature control contributes to about 8% of greenhouse gas emissions in the supply chains for pigs, eggs, and grills, primarily arising from the use of fossil fuels and grid power in cattle ranches. This connection between animal product prices and oil price volatility further elevates production costs, making farmers more vulnerable to financial instability and driving up the cost of finished goods [14]. The development of Livestock House Building Energy Simulation (BES) Models is crucial for addressing these challenges and optimizing energy efficiency in intensive livestock production [15].

The structural design of animal houses, encompassing the ventilation system and exhaust air discharge conditions, involves intricate considerations such as heat and mass balance calculations, as well as a thorough examination of airflow dynamics inside and outside the building. Various simulation methods play a crucial role in developing housing systems that not only maintain a comfortable biological climate inside but also minimize environmental impact [16]. [17] have introduced a simulation model for a modern swine confinement ventilation system, segregating the confinement into two zones: the area where the pigs are housed and the waste storage pit. Control of indoor air quality within the confinement is managed by two fans in the side wall of the room and one fan in the end wall of the pit. Indoor air quality, in this context, encompasses thermal and pollutant factors. Conservation equations for mass and energy are formulated for each zone, addressing concentrations of dust, ammonia, and water vapor [17]. Heat generation terms, accounting for thermal energy from lights, heaters, and pigs, as well as mass source terms for dust, water vapor, and ammonia, are incorporated into the equations. An icon-based software is employed to solve this system of equations representing the indoor air quality models. Simulation model results provide insights into temperature, humidity, and concentrations of ammonia and dust under varying conditions. The successful examination of example cases warrants further exploration of larger-scale models with increased complexity, components, control algorithms, and applications [18].

Simulation methods can be categorized based on building presentation, adopting either a single-zonal or poly-zonal model. Computer Fluid Dynamics (CFD) stands out as a powerful tool, offering precise data on the airflow field in specific spaces. CFD facilitates the prediction of air temperature, airflow direction, and velocity during the design phase, allowing for localized interventions and modifications until the desired state of relevant parameters is achieved. For comprehensive analyses, especially in programs that integrate thermal and CFD simulations, detailed verification of input data is crucial to ensure fast solution convergence. One of the key advantages of CFD is its ability to predict the flow field around and inside the building, providing flexibility for adjustments to the object [9] [10].

In recent years, researchers have explored novel approaches to address challenges related to internal climate conditions, the dependency of livestock systems on fossil fuels, and energy consumption in climate management. These innovative solutions primarily revolve around the adoption of renewable energy technologies and passive strategies, including solar panels, geothermal and aerothermal heat pumps, biogas-fed combined heat and power units, and solar panels. To evaluate the effectiveness and potential of these solutions, researchers employ complex BES models including mathematical models based on physics that calculate a building's energy performance and interior climatic conditions under specific boundary conditions [19]. The use of BES models for analyzing cow housing has witnessed a noticeable increase in recent years, especially for preliminary investigations and system improvement. This can be attributed to the time, cost, and flexibility advantages offered by BES models.

Additionally, there is a growing recognition that BES models will play a crucial role in future energy performance certification programs for animal facilities. While BES models have been extensively utilized by experts and scholars in the field of architecture to predict and assess the energy usage and internal environmental conditions of structures designed for human occupancy, it is deemed essential to employ BES models for evaluating environmental conditions. The existing literature features numerous studies providing comprehensive overviews of the current state of knowledge and insightful analyses on specific topics. The development and optimization of BES models, along with specific modeling considerations such as thermal and occupant zone modeling and infiltration rate computation, have been focal points of several research endeavors [20].

Research Gap, Goal, and Sources of Data for This Study:

The examination of energy and environmental impacts in cow housing, particularly through the use of BES models, holds significant potential. While livestock homes share similarities with human residences, notable differences, such as higher airflow rates for evaporative cooling and ventilation, demand a precise and comprehensive approach to calculating their energy usage. The absence of a well-defined and cohesive body of information specific to BES models for cow housing in the existing literature poses a substantial gap. This gap impedes the scalability of BES models and hinders their broader application in the livestock sector [21].

To address this gap, a substantial volume of data needs to be generated, accompanied by well-accepted and standardized methodologies for building and validating a considerable number of BES models. Establishing such standard practices is crucial for promoting BES models as the norm in both academic and industry research. The widespread adoption of BES models, especially in the planning and management phases of livestock housing, has the potential to significantly enhance energy efficiency. This study aims to facilitate the broader application of BES models in livestock farming by conducting a comprehensive investigation into their development, application, and validation in livestock households. Additionally, the study aims to elucidate the challenges that must be overcome for practitioners and scholars to embrace BES models more extensively [21]. To achieve these objectives, the study systematically reviews the results of recently concluded research projects, providing a unique and valuable contribution to the existing body of knowledge. Notably, there is a lack of previous reviews thoroughly analyzing BES models for housing cattle, making this study a valuable supplement to current research. The scientific contributions of this work include:

- A groundbreaking and comprehensive assessment of BES models for livestock housing built in recent years, providing a thorough review and examination of this specific subject.
- An in-depth review of validation techniques employed in BES models for livestock housing, accompanied by insightful ideas to enhance and standardize the validation process for future models, ultimately aiming to strengthen their reliability.
- A detailed review of the constraints that must be addressed to establish BES models as a commonly utilized approach, particularly within the industrial sector.

The study's findings consolidate the existing knowledge on Building Energy Simulation (BES) models for livestock buildings, offering valuable references that can elevate the standard of ongoing and future research in this field. Moreover, these conclusions have the potential to facilitate the widespread adoption of BES models in the cattle industry, yielding benefits in terms of energy efficiency, environmental impact, and operational costs [22]. The paper follows a structured format, beginning with an introduction and subsequently delving into the systematic evaluation technique applied to the collected BES models. Key conclusions are then discussed, followed by an examination of identified BES models. A critical discussion addresses the limitations of these models and suggests alternatives for BES validation. The study also explores how BES models can enhance resilience and environmental sustainability in the livestock industry. The paper concludes with final remarks.

Methodology:

The academic methodology employed for this study involves a structured and systematic approach, drawing from established practices in existing literature research. The methodology consists of two key phases:

Defining Project Scope and Logical Framework:

The initial step involves clearly defining the scope of the project. This includes identifying the research objectives, key areas of focus, and the specific context of the study—animal housing in crowded agricultural contexts with an emphasis on energy and climate regulation. A logical framework is constructed to provide a systematic structure for the literature review. This framework helps in organizing the research questions, objectives, and criteria for inclusion.

Literature Review Process:

A database is created for literature review, ensuring accessibility and organization of relevant scholarly papers. The Scopus® database is chosen for its comprehensive coverage of academic publications. Specific search parameters are set to target publications related to animal housing, energy, and climate regulation. Keyword combinations and alternative phrases are employed to cast a wide net. Inclusion criteria are established to delimit the scope and ensure a focused investigation. For this study, three inclusion criteria are applied to emphasize crowded agricultural contexts, energy-related topics, and climate regulation in animal housing. The screening process is implemented to filter and include relevant publications. The final selection comprises 42 publications, forming the basis for a comprehensive assessment.

Evaluation of BES Models:

The methodical approach involves evaluating the applicability, development, and verification of Building Energy Simulation (BES) models in the context of livestock housing. BES model applications are categorized into five fundamental classes: model-based investigation, energy appraisal, heat stress assessment, control approach enhancement, and integration of Renewable Energy Sources (RES). Limitations, biases, and potential risks are acknowledged, particularly the exclusion of Computational Fluid Dynamics (CFD) and Detailed Dynamic (DD) models due to their distinct features.

Insights and Future Directions:

Despite identified constraints, the study aims to provide a foundational understanding of BES models' applications in livestock housing. Insights derived from the assessment are intended to inform future research and contribute to advancements in the industry. This academic methodology ensures a rigorous and structured approach to the exploration and analysis of BES models in the specific context of energy and climate regulation in crowded agricultural settings.

Findings:

The study provides a detailed overview of the specific livestock housing types and ventilation systems considered, with a predominant focus on monogastric animals, particularly hens and pigs. Notably, BES models primarily depict housing for chickens, emphasizing grilling facilities. Duck homes are addressed by Lee et al., while laying hen houses are exclusively studied by [23] Piglet houses are covered, with a majority focusing on fattening pig houses. Unique contributions by [24] concentrate on livestock shelters for ruminants, such as a sheepfold and a dairy barn. Three studies adopt a more comprehensive approach, examining generic livestock homes. [25] contribute to this broader perspective. Among these, only the works of Lee et al. cover both mechanical and natural ventilation, making them exceptions. The overwhelming emphasis on mechanically ventilated livestock shelters may stem from their perceived energy efficiency, while the complexity of predicting natural ventilation flow rates limits the applicability and scalability of BES models in this context.

The study notes the key journals that have published the examined publications, with "Biosystems Engineering," "Computers and Electronics in Agriculture," and "Transactions of the ASABE" featuring prominently. Notably, publications also appear in energy-related journals like "Energy" and "Energy and Buildings," highlighting the multidisciplinary nature of the modeling work. The chronological analysis of publication years spanning 1998 to 2023 reveals a surge in research output since 2016, with an especially noticeable increase after 2020. This trend aligns with growing environmental concerns related to livestock systems, potentially influenced by policy initiatives like the European Green Deal and the Farm to Fork Strategy. The increasing relevance and popularity of the study topic are evident in this upward trend [7]. The creation of livestock house BES models is a focal point, with a critical examination highlighting fundamental differences. The analysis categorizes models into dynamic or steady-state and delves into whether bespoke models or existing tools were utilized. Core features, including the simulation time step, examined energy parameters, and the estimation of indoor air relative humidity, are thoroughly examined. The validation status is also disclosed for each model, providing a comprehensive understanding of the characteristics and distinctions among the studied BES models [26].

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Various approaches are employed in working with custom dynamic models. The ISO 13790 standard, utilizing the straightforward hourly technique, is often employed to replicate temperature patterns. Flexible, customizable techniques, such as the Simulink® program, are used in various BES models to evaluate air temperature, dust levels, and other parameters. Pre-made simulation tools like Transient System Simulation Tool (TRNSYS) and EnergyPlus (E+) have gained prominence since 2013, offering a unique and cutting-edge method. Twelve out of fifteen research investigations employed TRNSYS or E+, recognized as the most advanced tools for energy modeling in livestock buildings [32]. Comparatively, steady-state models, characterized by lesser complexity and longer simulation periods, are explored. While dynamic models offer detailed insights into a system's dynamics, steady-state models, with their simplified approach, are still utilized when system dynamics are not a priority or when a more straightforward model is necessary. Challenges persist in developing standardized protocols for BES models specifically designed for cow barns, hindering their extensive utilization in the industrial domain. The absence of globally accepted approaches remains a significant impediment to the widespread adoption of BES models in livestock housing research.

The validation status of the models, indicating whether they underwent validation, is a crucial element. Not all BES models underwent validation; three employed pre-existing validated models, 21 conducted model validation, and 18 did not validate the model. Validation availability seems influenced by the goal and scope of the study, with a higher occurrence of missing validation noted. Advances in sensor technology in recent decades have facilitated experimental validation through actual datasets [33]. The validation of BES models for livestock houses involves rigorous scrutiny of validation techniques, including duration, parameters tested (θair_i, φair_i, EH, and Efan), Goodness-of-Fit (GoF) indices, and validation thresholds. Real observed data serves as the fundamental basis for validation efforts. Variation exists in validation period duration, with sample sizes for indoor climate conditions (θair_i and φair_i) generally larger than those for energy parameters (EH and Efan). Validation procedures and sample sizes differ among studies, reflecting the diversity in validation approaches within the field. The last two columns in the evaluation show the Goodness-of-Fit (GoF) indices generated and the standards used to assess the model's accuracy. Various GoF measures are employed in the validation process of simulation models, with the study outlining three main approaches for GoF indices and thresholds [34].

The first approach involves computing GoF indices and comparing them to predefined boundaries. Commonly used metrics in this approach include Normalised Mean Bias Error (NMBE), Root Mean Square Error (RMSE), and the Coefficient of Variations of the RMSE (CVRMSE). These factors are compared with predetermined standards from guidelines and practices related to building energy modeling. Some studies, like Cho et al., align their methodology with guidelines from organizations such as the Federal Energy Management Program (FEMP), International Performance Measurements and Verification Protocol (IPMVP), and ASHRAE. Others, like [25], set clear-cut limits without explicitly citing sources. Haeussermann et al. considered the model reliable when standard deviations (σ) of differences between simulated and measured values fell within the accuracy range of the sensors used. [35]also employ this approach, assessing the inaccuracy level without depending on preset thresholds. Jackson et al., however, use a visual representation, presenting a line plot to demonstrate the simulation model's reliability without quantitatively evaluating differences between observed and simulated data.

The second approach establishes criteria values for GOF and coefficient of determination, as seen in studies by Nawalany and Silva et al. They set criteria at values above 75% and 80%, respectively, and concluded that the model was confirmed when the standard error between simulated and measured values was smaller than the estimated one. The third approach, as exemplified by [36] focuses on the topic of model calibration. Model calibration involves adjusting parameters to ensure anticipated outcomes closely match observed data. However, the review did not delve into this topic extensively due to a lack of academic literature. The study by Shin et al. focuses on calibration-related challenges, particularly those related to the calibration of simulated fans. Considerations like equipment load and infiltration rate are given considerable thought during optimization-based calibration of θair_i. [37] research delves into optimization-based calibration, providing information on parameters, starting values, and adjustment range. Costantino et al. used an optimization-based methodology, considering the direct saturation efficacy of evaporative pads as the calibration parameter. Silva et al. estimated a correction factor for heat sources in cow housing and calibrated the model using a sequential approximation technique.

The study delves into the challenges and limitations surrounding Building Energy Simulation (BES) models, particularly in the domain of livestock housing. Here are the key points discussed: BES models are primarily confined to academic environments and have limited integration into real-world industrial operations. Their broader adoption is hindered by constraints that need attention to enhance scalability and flexibility for livestock housing. The intricate modeling techniques, especially in dynamic models, pose challenges in creating reliable and adaptable BES models. A comprehensive understanding of physical processes, structures, and systems is required. While pre-configured simulation tools may assist, adjustments are often necessary for livestock operations. Fluid evaluations in BES models are limited, and typically suitable for fully enclosed livestock facilities with mechanical ventilation. Computational Fluid Dynamics or detailed dynamic models are preferred for naturally ventilated buildings or those with hybrid ventilation systems. Model validation is crucial, yet there are variations in validation techniques across studies. Some use predefined Goodness-of-Fit indices, while others lack standardized criteria. The reliability of BES models is a concern, necessitating standardized validation protocols. The scalability of BES models may be hindered by intricate techniques and the need for adaptations for accurate simulation of cow houses. Ongoing research should focus on constructing tailored BES models for livestock operations, enhancing efficiency in energy modeling [38].

The reliability of simulation models, including BES models, is a potential limitation. Model validation becomes critical in addressing this issue. However, there is a lack of consensus on validation techniques, with variations in approaches and standards across studies. The study underscores the importance of both validation and verification for BES models. Verification ensures faithful representation of the model, while validation assesses accuracy in representing the real world. Both processes are vital for establishing trust in numerical models. In summary, the study highlights challenges with BES models in livestock housing, emphasizing the need for ongoing research and standardized validation procedures for reliable and applicable simulation models.

Microclimatic Parameter Analysis:

The analysis of microclimatic parameters in livestock housing involves a comprehensive examination of sources influencing temperature, humidity, airflow rate, airflow velocity, illumination, and the content of gases. Temperature changes are primarily attributed to mechanical impacts like heaters, convectors (T1), ventilation (T2), illumination (T3), and the regulation of solar radiation (SR). The economic advantage of each source is determined by the cost of emitted heating power per hour. Similarly, humidity changes are influenced by mechanical impacts (H1), indoor temperature/BGT (H2), and ventilation (H3), with economic prioritization based on the cost of moisture absorbed or emitted per hour. Ventilation, a crucial parameter, is directly regulated through technical solutions, measured by the cost of a change in airflow rate. Airflow velocity, adjustable through mechanical impact (AV1) and ventilation (AV2), is assessed based on the costs per change in speed. Illumination levels, controlled by natural solar radiation and artificial lighting, are compared in absolute values. Oxygen content, expressed as a percentage, and greenhouse gases, measured in parts per million, are assessed for sources influencing their concentration changes. Notably, sources with a one-time impact are assumed to have zero marginal cost due to their short-term and one-time nature. For instance, obscured sunlight can alter solar radiation levels or enable more intensive natural ventilation, assuming negligible costs per unit of the variable parameter.

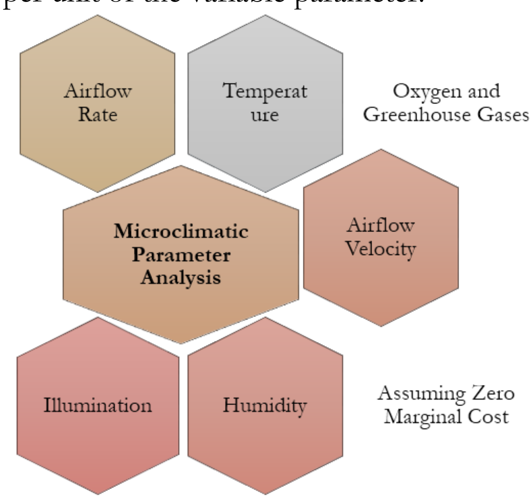

Figure 1: Parameters of Microclimate.

Building Performance Simulation Tools:

Building performance simulation tools play a crucial role in evaluating and analyzing buildings during both design and retrofit phases. These tools simulate the physical behaviors of a system, helping to understand and simplify the complex interactions within a building. The process involves creating physical and mathematical models, with the latter being analytical and often involving numerical approximations. Classification of BPS tools can be based on calculation methods, modeling levels, and usage areas. The tools are broadly categorized as simplified (static) or detailed (dynamic). Dynamic simulation tools, such as Energy Plus and TRNSYS, use numerical methods to calculate building energy loads and thermal system interactions, providing accurate results on an hourly basis [39].

Design tools, like Revit and Sketch Up, are generally static and used in the early design phase. On the other hand, detailed simulation tools integrate dynamic calculations for building loads, energy consumption, and compliance with performance-based standards. These tools are crucial for a comprehensive analysis of building performance. Choosing the right BPS tool is a significant consideration, and selection criteria include accuracy, ease of use, and the specific needs of stakeholders. Stakeholders may be interested in various aspects, such as thermal load calculations, HVAC system sizing, energy conservation measures, and more. Despite the advancements in BPS tools, challenges persist. Interoperability issues, time-consuming modeling, conflicting performance requirements, and a lack of simulation guidance are identified challenges. Moreover, the gap between predicted and actual building performance, as well as the modeling of human-building interactions, presents ongoing challenges. Mitigating these challenges involves integrating models, ensuring data integration under Building Information Modeling, handling contradicting requirements, and incorporating simulation guidance in BPS tools. Verification of building performance goals, simulation of human-building interactions, and addressing technical domains' integration are crucial for effective BPS tools. However, BPS tools have evolved significantly, and ongoing research and development are essential to address challenges and improve their integration into the design process, making them more user-friendly and accurate across various building performance categories [40].

Models for Sustainable Advancements in the Cattle Industry:

Bio-Energy Systems models play a pivotal role in addressing challenges within the cattle industry, fostering resilience, and promoting environmental sustainability. This comprehensive approach involves integrating Renewable Energy Sources into intensive livestock systems, necessitating a combination of experimental and numerical methodologies. In this transformative process, experimental configurations provide insights into technological viability and practical challenges. Complementing these experiments, BES models offer several advantages, enabling standardized evaluations, exploratory outcomes, and extended financial analyses. The integration of RESs holds promise for reducing greenhouse gas emissions associated with livestock systems, an aspect where BES models are instrumental in assessing the environmental impact.

Furthermore, BES models are indispensable for examining the effects of climate change on the cattle industry. Precise assessments of future climate scenarios, including Shared Socioeconomic Pathways, facilitate the understanding of climate-related challenges such as heat waves. By evaluating different management strategies and farming practices, BES models contribute to optimizing energy usage, operational expenses, and animal welfare standards. As the cattle industry transforms, BES models provide a critical tool for decision-makers, enabling them to make informed choices that enhance sustainability, resilience, and economic viability [41].

Models for Livestock Housing:

In conclusion, this study extensively scrutinized Building Energy Simulation (BES) models for cow housing, aiming to promote their widespread application in both industry and research. A thorough analysis of forty-two academic publications spanning 25 years revealed a growing trend in the use of BES models for diverse tasks within cattle operations. Despite this, the study highlighted the absence of a universally acknowledged approach to address the modeling challenges in scientific publications. The evaluated BES models exhibited significant variations in design and verification procedures, emphasizing the need for standardization and explicit methodologies in future research. The findings of this analysis serve as a robust foundation for future investigations into the implementation and enhancement of BES models for livestock operations. Researchers can leverage the insights gained to develop and validate novel models effectively [41].

Additionally, adhering to the recommendations outlined in this study can streamline the validation process for new models, contributing to the development of marketable tools for energy management in livestock housing. The identified constraints hindering the widespread adoption of BES models in the cattle industry should be the focal point for future research endeavors. Acknowledging the financial support from the Next Generation EU program of the European Union and the Ministerial de Universidad, this research underscores the pivotal role of BES models in fostering a resilient and environmentally sustainable future for the cattle industry.

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