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A Sequential EnergyPlus–DSSAT Framework for Assessing Energy Use, Environmental Control and Wheat Production in Vertical Farming

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Abstract

Purpose: Engineering assessment of vertical wheat farming requires coordinated evaluation of energy use, environmental control and crop production. This study develops a sequential framework linking independent EnergyPlus and DSSAT CERES-Wheat simulations.

Methods: The interface translates lighting and thermal inputs, reconciles crop-cycle outputs with annual facility energy, and applies crop-input-state equivalence checks to determine when crop simulations require re-execution or conditional reuse. A hypothetical five-tier wheat facility in Timimoun, Algeria, provides a computational demonstration, including a matched-envelope LED-efficiency comparison, output verification, crop plausibility assessment and plant-load sensitivities.

Results: The reference crop simulation predicted 4,999 kg ha^{-1} of grain over 72 days. Increasing LED photon efficacy from 2.7 to 3.5 μmol J^{-1} reduced simulated annual electricity use from 6.806 to 5.331 GWh (21.7%) in a matched-envelope comparison, but annual hours above 60% relative humidity increased from four to 224. Daily maximum and minimum crop-zone temperatures agreed at DSSAT input precision (0.1°C) on all 72 days of the tested window. In a separate load sensitivity, increasing prescribed latent load from 80 to 547 W m^{-2} raised annual site energy by 19.0% and cooling electricity by 69.1%.

Conclusion: The sequential interface enables traceable comparative building–crop assessment and reveals energy–humidity-control trade-offs. Crop-output reuse is conditional on unchanged remaining crop inputs and cannot be assumed across untested annual cycles. The hypothetical facility has not been experimentally validated, and the approach is not dynamic crop–building co-simulation.

Keywords: Controlled-environment agriculture; Vertical wheat farming; EnergyPlus; DSSAT CERES-Wheat; Building–crop modelling; Environmental control

1. Introduction

Controlled-environment agriculture (CEA) enables crop production under managed environmental conditions that are partially or fully independent of outdoor climatic variability. In fully enclosed vertical farming systems, artificial lighting, heating, cooling, ventilation, moisture removal and carbon dioxide (CO_2) management are used to maintain conditions suitable for crop development. Although these systems offer opportunities for intensive production and repeated growing cycles, their operation is associated with substantial energy requirements. Artificial lighting and environmental conditioning are particularly important contributors to electricity demand, making energy performance a fundamental consideration in the engineering design and assessment of indoor farming facilities (Graamans et al., 2018). Consequently, evaluating such facilities requires more than quantifying building energy consumption independently of agricultural productivity. The growing environment maintained by the building influences crop development, while crop-lighting requirements and plant-related heat and moisture exchanges influence the building's operational performance.

This interdependence creates an important engineering challenge when evaluating technologies intended to improve the efficiency of controlled-environment production. For example, increasing the photon efficacy of light-emitting diode (LED) systems reduces the electrical power required to maintain a prescribed photosynthetic photon flux density (PPFD). However, changes in lighting power can also modify internal sensible heat gains, cooling requirements and moisture-removal performance. A reduction in electricity demand therefore does not necessarily demonstrate that the facility continues to maintain its intended growing conditions. Previous studies have established the importance of representing crop-related processes within building-energy assessment. Graamans et al. (2017) examined crop transpiration and its implications for plant-factory climate control, while Graamans et al. (2020) investigated interactions between building configuration, crop-related loads and energy demand. Liebman-Pelaez et al. (2021) incorporated plant evapotranspiration and cooling-system performance into an EnergyPlus model of an operational hydroponic container farm, demonstrating the relevance of crop-specific environmental processes to building simulation.

More recent research has advanced the integration of crop and building processes through dynamically coupled modelling approaches. Talbot and Monfet (2024a, 2024b) combined crop growth, crop energy balance and building simulation to examine the relationships between environmental conditions, energy consumption and crop productivity. Larochelle Martin and Monfet (2025) incorporated crop-level energy-balance calculations into EnergyPlus through its Python application programming interface, enabling crop sensible and latent heat exchanges to interact with building simulation. Esmaeli Sooderjani et al. (2026) developed a control-oriented modelling approach integrating crop growth, indoor environmental conditions and local environmental-control systems. These developments demonstrate the value of resolving plant–environment interactions within integrated simulation architectures. Such approaches are particularly relevant where short-timescale physiological feedback, canopy heat and moisture exchange, and environmental-control dynamics constitute the principal research objectives.

An alternative modelling approach involves retaining established process-based agronomic models as independent computational environments. Models such as the Decision Support System for Agrotechnology Transfer (DSSAT) CERES-Wheat simulate crop phenology, biomass accumulation, grain formation and responses to environmental and management conditions across a complete production cycle (Jones et al., 2003). Earlier applications of CERES-Wheat to controlled growth environments investigated radiation-use efficiency and temperature-control strategies, establishing precedents for process-based wheat modelling under managed environmental conditions (Tubiello et al., 1997; Volk et al., 1997). Asseng et al. (2020) further examined the potential productivity of wheat under intensive controlled-environment conditions while identifying substantial artificial-lighting energy requirements. Wheat therefore provides a relevant engineering demonstration case because its assessment involves both the energy required to establish controlled growing conditions and the simulation of reproductive development and grain production over a complete crop cycle.

However, integrating an independent process-based crop model with whole-building energy simulation introduces methodological challenges that are not resolved simply by combining the outputs of two software environments. The models represent related physical processes through different quantities, units, temporal

resolutions and spatial bases. Crop-light requirements, for example, are defined biologically through PPFD and photoperiod, represented in EnergyPlus through electrical lighting demand and associated internal heat gains, and supplied to DSSAT through a daily radiation input. These representations are physically related but are not interchangeable. Likewise, EnergyPlus can provide hourly or sub-hourly indoor air-temperature predictions, whereas DSSAT requires daily maximum and minimum temperatures. Crop-model outputs also relate to individual production cycles and productive growing area, while building-energy results commonly represent annual facility-level operation. Integrated assessment consequently requires explicit translation and reconciliation of these quantities, together with recognition of the assumptions introduced by the corresponding conversions.

A further challenge concerns the dependency of crop-model predictions on changes introduced within the building-energy model. Modifications to PPFD, photoperiod, realised indoor temperature or other crop-relevant conditions may alter crop development and require a new agronomic simulation. Conversely, improvements in equipment efficiency or changes to electricity-generation systems may affect building-energy performance without changing the environmental inputs represented by the crop model. Nevertheless, an energy-system modification cannot automatically be assumed to preserve crop conditions, because changes in electrical and thermal loads may also influence the realised indoor environment. Reusing crop-model outputs without verifying the relevant input conditions can therefore combine building-energy and crop-production results derived from incompatible simulation states. A transparent sequential assessment must consequently distinguish between modifications requiring crop-model re-execution and those permitting conditional reuse of previously accepted results, while retaining the provenance of each simulation output.

Although existing studies demonstrate important advances in crop-aware building simulation, dynamic plant–environment modelling and process-based agricultural prediction, a distinct methodological issue remains when established building-energy and crop-development models are retained as independent simulation engines. The contribution pursued here is not the introduction of a new crop-growth model, building-energy solver or fully bidirectional co-simulation architecture. Rather, it is the development and evaluation of an

explicit sequential interface that combines physically consistent cross-domain translation, dependency-based simulation decisions, traceable crop-output reuse and integrated assessment of energy and environmental-control performance. By distinguishing crop-input equivalence from the adequacy of building environmental control, the procedure supports comparative engineering assessments without assuming that lower energy consumption necessarily produces an acceptable growing environment.

Accordingly, this study develops a sequential interoperability framework linking EnergyPlus whole-building simulation with DSSAT CERES-Wheat for the assessment of controlled-environment wheat production. The specific objectives are to: (i) establish consistent transformations between crop-light requirements, electrical energy demand and crop-model environmental inputs; (ii) reconcile hourly building-environment predictions and annual energy outputs with daily crop-model inputs and crop-cycle production; (iii) establish dependency-based criteria for crop-model re-simulation and conditional output reuse, supported by scenario-level provenance; and (iv) evaluate the sensitivity of integrated engineering conclusions to lighting efficiency, environmental-control performance and prescribed plant-related thermal and moisture loads. Together, these objectives address the methodological requirements for conducting auditable comparative assessments using independent building and agricultural simulation models.

The framework is demonstrated using a hypothetical five-tier vertical wheat-production facility in the hot-arid climate of Timimoun, Algeria. The assessment combines EnergyPlus simulations of operational energy and indoor environmental conditions with DSSAT predictions of wheat development and grain production. Computational verification, crop-output plausibility assessment, cross-domain input-consistency checks and plant-load sensitivity analyses are used to examine the credibility and limitations of the integrated procedure. A representative matched-envelope comparison demonstrates that improved LED photon efficacy can reduce simulated annual electricity consumption by 21.7% while increasing the number of hours exceeding the specified relative-humidity threshold. Separate crop-moisture-load sensitivity analyses further demonstrate substantial variation in cooling electricity and environmental-control performance. These findings illustrate why lighting efficiency, crop-related loads and environmental-control adequacy must be considered together

in controlled-environment agricultural engineering. As the facility represents a computational demonstration rather than an operating farm, the results are interpreted as conditional comparative predictions, not empirically validated estimates of commercial performance.

2. State of the Art and Methodological Gap

2.1 Modelling approaches for integrated building–crop assessment

Research on controlled-environment agriculture (CEA) has established several approaches for evaluating the relationships between crop production, indoor environmental conditions and operational energy demand. These approaches differ primarily in their representation of crop processes, treatment of plant–environment feedback and level of computational integration. For the present study, the relevant distinction is between building-centred energy models incorporating crop-related loads, dynamically integrated crop–building models and independent process-based agronomic models. Each provides different analytical capabilities, and their suitability depends on the engineering questions being addressed.

Building-centred approaches have provided the basis for evaluating energy requirements and building-design strategies in controlled-environment production. Harbick and Albright (2016) assessed greenhouse and plant-factory energy consumption under contrasting climatic conditions, while Graamans et al. (2020) combined EnergyPlus with a crop-transpiration representation to investigate the influence of façade design on plant-factory energy demand. These studies demonstrated how lighting requirements, building configuration and plant-related heat and moisture exchanges affect environmental-conditioning loads. Graamans et al. (2017, 2018) further established the importance of crop-specific physical representation by examining crop transpiration and resource-use relationships, and Liebman-Pelaez et al. (2021) provided empirical support for crop-aware building-energy prediction through a calibrated EnergyPlus model of an operational hydroponic container farm.

A complementary research direction has focused on resolving crop–environment interactions within dynamically integrated simulation architectures. Talbot and Monfet (2024a, 2024b) coupled crop growth and energy-balance calculations with TRNSYS, enabling the combined evaluation of environmental conditions,

crop yield and building-energy performance. Larochelle Martin and Monfet (2025) incorporated crop-level sensible and latent heat exchanges into EnergyPlus through its Python application programming interface and an iterative solution procedure. Esmaeli Sooderjani et al. (2026) further demonstrated a dynamic control-oriented approach integrating crop growth, indoor climate states and environmental-control processes. These studies show the capabilities of architectures in which selected plant and environmental variables interact during simulation, particularly for investigating short-timescale feedback and control responses.

Independent process-based agronomic modelling provides a different capability by retaining established crop-development representations. Asseng et al. (2020), for example, employed DSSAT-NWheat and SIMPLE alongside controlled-environment wheat evidence to examine grain-production potential under intensive growing conditions. Such models support the assessment of phenological development, biomass accumulation and reproductive yield over a complete crop cycle. However, their agricultural input structures and computational responsibilities differ from those of whole-building energy models.

The methodological characteristics of these studies are compared in Table 1. The comparison focuses on the capabilities demonstrated by each approach and the remaining requirements relevant to sequential integration. It does not imply that dynamic integration, building-centred simulation or independent agronomic modelling is inherently preferable.

Table 1. Methodological positioning of representative building–crop modelling approaches for controlled-environment agriculture.

Study	Modelling approach	Principal contribution and scope
Harbick and Albright (2016)	Building heat-balance modelling with prescribed crop-light requirements	Evaluates greenhouse and plant-factory energy demand across climatic conditions; crop-development response is not recalculated dynamically.
Graamans et al. (2017, 2018)	Crop-transpiration, climate and resource-balance modelling	Quantifies crop-related moisture exchange and resource-use relationships; does not establish dependency-based output reuse between independent simulation engines.
Graamans et al. (2020)	EnergyPlus coupled with a crop-transpiration representation	Evaluates façade-related energy and environmental-conditioning implications; primarily focuses on building-side performance.
Liebman-Pelaez et al. (2021)	Empirically calibrated EnergyPlus incorporating plant evapotranspiration	Demonstrates crop-aware building-energy prediction supported by operational measurements; does not independently resolve cereal phenology and grain formation.
Talbot and Monfet (2024a, 2024b)	Dynamically integrated crop-growth and crop-energy-balance modelling in TRNSYS	Evaluates interactions between crop growth, environmental conditions and energy demand within an integrated architecture.

Study	Modelling approach	Principal contribution and scope
Larochelle Martin and Monfet (2025)	EnergyPlus Python API with iterative crop-energy-balance calculations	Resolves crop sensible and latent heat exchange during building simulation rather than coordinating an independent full-cycle agronomic engine.
Esmaeli Sooderjani et al. (2026)	Dynamic crop–climate–control modelling	Integrates crop growth, indoor climate and environmental-control dynamics, supported by experimental evaluation.
Asseng et al. (2020)	Process-based wheat models and controlled-environment experimental evidence	Applies agronomic models to indoor wheat productivity; does not develop an interface with whole-building energy simulation.

Source: Authors' synthesis of the cited publications.

The literature demonstrates that increasingly detailed crop-related processes can be represented within building or environmental-control models, while established agronomic models can provide complementary information on crop development and production. The resulting distinction is not simply one of model sophistication. Dynamically integrated approaches prioritise resolving interacting physiological and environmental states, whereas retaining an independent agronomic engine introduces additional requirements for the consistency, dependency, and provenance of information exchanged between simulation domains. These requirements form the focus of the present study.

2.2 Independent process-based crop models as an interoperability problem

When whole-building energy simulation and process-based crop modelling are performed in separate computational environments, their integration requires explicit management of the relationships between model inputs, outputs and underlying assumptions. Successful execution of both models does not, by itself, establish that their results represent a consistent production scenario. The central methodological issue is therefore the preservation of physical meaning and computational dependency when information is exchanged between independently developed simulation systems.

A first requirement concerns the interpretation of variables shared across modelling domains. Quantities describing the same growing condition may differ in their physical definitions and roles within each model. For example, crop-light exposure, electrical lighting demand and agricultural radiation inputs represent related but distinct aspects of controlled illumination. Their integration requires documented transformations and recognition of the assumptions introduced when artificial-light conditions are represented within an agronomic model originally developed for different radiation environments. Similar considerations apply to environmental variables that are prescribed in one model but calculated as realised conditions in another.

Without explicit interpretation, numerically compatible inputs may nevertheless represent physically different conditions.

A second requirement concerns temporal and spatial consistency. Building simulation and agronomic modelling commonly operate at different time resolutions and report outputs using different assessment periods and area definitions. This distinction is particularly relevant to multi-tier crop production, where productive growing surface and building floor area are not equivalent. Combining annual building-energy demand with crop-cycle yield consequently requires a common assessment basis and transparent treatment of the assumptions involved. These reconciliation procedures are essential for interpreting integrated energy-per-production indicators but do not, independently, establish the validity of the underlying crop or building predictions.

A third requirement concerns the propagation of scenario modifications between independent models. In comparative engineering assessments, a modification introduced in one domain does not necessarily require re-execution of every simulation component. The relevant dependency is determined by whether the modification changes an input represented by the receiving model. Crop-model results are conditional on the environmental, biological and management inputs from which they were generated. Reusing those results after an engineering modification is therefore justified only when the corresponding crop-relevant input state remains equivalent to that of the originating simulation.

This distinction is important because the nominal purpose of a modification does not necessarily determine its consequences across modelling domains. A change intended to improve electrical efficiency may also influence building heat gains and the simulated indoor environment. Conversely, modifications to electricity-generation systems may alter facility-level energy indicators without changing the crop-model inputs. A sequential assessment must therefore base re-simulation decisions on verified model dependencies rather than assumed similarities between scenarios. The provenance of reused results must also be retained so that inherited crop outputs are not misrepresented as independent simulation outcomes.

A fourth requirement concerns the credibility and interpretation of integrated results. Input consistency, computational verification and physical validation address different questions. Agreement between the crop-

relevant inputs of two scenarios may support reuse of a previously calculated crop response, but it does not establish that the building adequately maintains all intended environmental conditions. Similarly, successful model execution and biologically plausible outputs do not constitute empirical validation of an entire controlled-environment facility.

These distinctions are especially consequential where plant-related sensible and latent heat exchanges are represented through prescribed building loads rather than continuously updated from crop development. Such assumptions can influence environmental-conditioning predictions without being resolved directly by the independent crop model. Their effects must therefore be considered separately when interpreting the credibility of engineering comparisons.

The methodological requirements identified here can be summarised as physical consistency, temporal and spatial reconciliation, dependency-aware model execution, output provenance and explicit treatment of uncertainty. Together, they define the conditions under which independent building and crop simulations can support a coherent comparative assessment. The specific implementation of these requirements is developed in the subsequent methodological sections.

2.3. Research gap and positioning of the present study

The literature reviewed above establishes the value of building-energy simulation, dynamic crop–environment integration and process-based agronomic modelling for controlled-environment agriculture. However, these research directions address different computational responsibilities. Building-centred studies principally examine energy demand and environmental-conditioning processes; dynamically integrated approaches resolve selected plant–environment interactions during simulation; and independent agronomic models represent crop development and production within specialised agricultural frameworks.

The methodological gap considered here concerns how independently executed whole-building and process-based crop models can be coordinated so that comparative engineering scenarios remain physically consistent, computationally traceable and appropriately interpreted. Although the representative studies provide important components of integrated assessment, they do not, as reported, jointly document a dependency-aware procedure for the specific combination of independent whole-building and full-cycle wheat simulation

that governs crop-model re-execution, establishes conditions for output reuse, reconciles their different assessment bases and preserves the provenance of inherited results.

Addressing this gap requires more than establishing a pathway for transferring variables between software environments. In particular, a defensible comparative procedure must distinguish between changes that invalidate the environmental or management basis of a crop prediction and changes whose effects remain confined to the building-energy domain. It must also recognise that equivalence of crop-model inputs and adequacy of environmental control are separate assessment conditions. Without these distinctions, apparent improvements in energy performance may be evaluated using crop outputs that are no longer applicable, or may be interpreted without sufficient consideration of changes in the indoor environment.

The methodological contribution of the present study lies in establishing and evaluating a dependency-aware sequential procedure for integrating independently executed building-energy and process-based crop simulations. Rather than treating model integration as direct data exchange, the framework identifies crop-relevant conditions governing simulation validity, distinguishes modifications requiring crop-model re-execution from those permitting conditional output reuse, and preserves the provenance of inherited results. The procedure also provides a consistent basis for combining annual building-energy and crop-production quantities while assessing environmental-control performance and sensitivity to prescribed crop-related loads.

The framework is demonstrated through controlled-environment wheat-farming scenarios involving changes to crop-light exposure, lighting technology and building-related operating conditions. These comparisons are used to examine whether model-dependency decisions remain consistent with the translated crop inputs and whether improvements in energy performance are accompanied by acceptable environmental-control outcomes. The contribution is therefore evaluated through the application of explicit consistency and decision criteria, rather than through the combined execution of EnergyPlus and DSSAT alone.

The proposed approach does not replace dynamically integrated crop–building models or claim to reproduce continuous physiological feedback. Nor does it constitute an empirically calibrated prediction of commercial wheat-farm performance. Its intended contribution is a transparent and auditable methodology for

comparative engineering assessment using independent disciplinary models, with the limitations of sequential coupling and simplified crop-related loads explicitly recognised.

3. Proposed Sequential Interoperability Framework

3.1 Framework architecture and model roles

The proposed framework integrates whole-building energy simulation and process-based crop modelling through a sequential procedure in which both simulation engines retain their independent computational structures. Rather than introducing a new simulation solver or continuous runtime coupling, the framework establishes an explicit interface for exchanging crop-relevant information, evaluating model dependencies and combining outputs on a consistent assessment basis.

EnergyPlus represents the building envelope, internal heat gains, artificial-lighting electricity, environmental-conditioning systems, auxiliary equipment and, where applicable, electricity-generation systems. Its principal outputs for the integrated assessment are operational energy use and the realised indoor thermal conditions. EnergyPlus is an established whole-building energy simulation program (Crawley et al., 2001). DSSAT CERES-Wheat independently simulates crop phenology, biomass accumulation, maturity and grain yield under prescribed environmental and management conditions (Jones et al., 2003). This separation preserves the established computational responsibilities of each model while requiring the exchanged information to be interpreted consistently.

The framework comprises four interconnected operations: cross-domain translation of crop-relevant variables; dependency-based coordination of model execution; temporal and spatial reconciliation of building and crop outputs; and scenario-level provenance and credibility assessment. The interface links the resulting information without modifying the governing equations of either simulation engine. In the documented implementation, Microsoft Excel supported input preparation, variable conversions, output reconciliation and maintenance of the scenario register, while EnergyPlus and DSSAT retained their respective input and output files. The procedure therefore represents a documented sequential workflow rather than an automated or dynamically coupled simulation environment.

Figure 1 illustrates the framework architecture, showing the progression from scenario definition through building-energy simulation, cross-domain information preparation, crop simulation and integrated performance assessment.

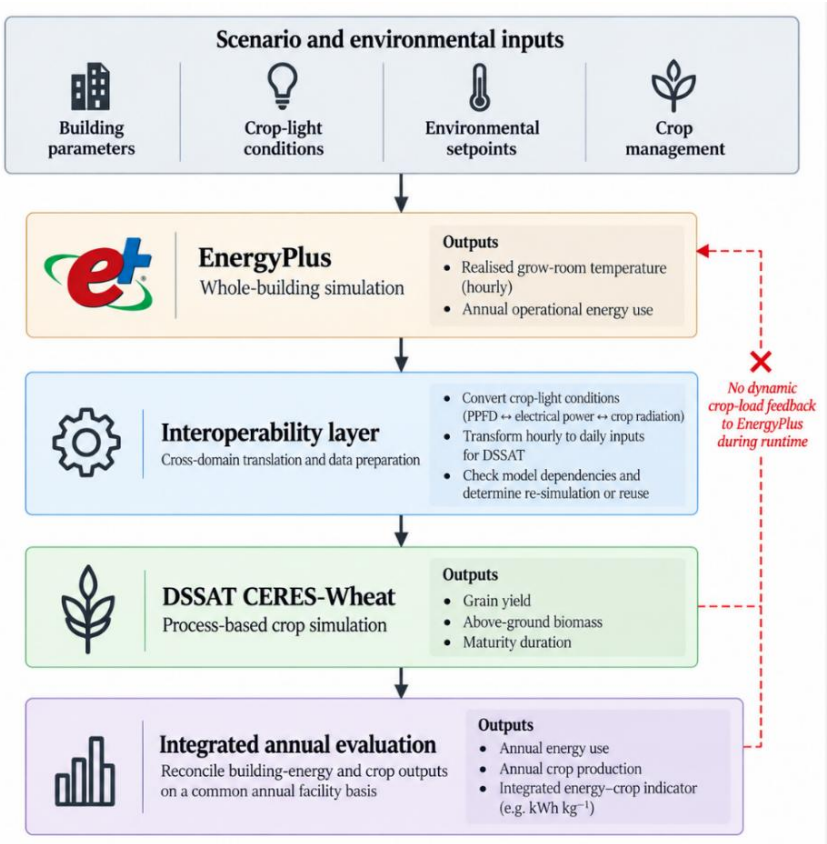


Fig. 1 Architecture of the sequential EnergyPlus–DSSAT interoperability framework
Source: Authors' own elaboration.

3.2. Cross-domain information and translation responsibilities

The interoperability interface defines the information exchanged between the two simulation domains according to its physical meaning, units, originating model, temporal resolution, spatial basis and role in the

receiving model. This distinction is necessary because related quantities may serve different computational purposes and cannot be transferred as directly equivalent inputs.

For crop lighting, prescribed photosynthetic photon flux density (PPFD) and photoperiod determine crop photon exposure, while LED photon efficacy determines the corresponding electrical lighting demand and associated heat gains represented in EnergyPlus. DSSAT instead requires an equivalent daily radiation representation. The interface therefore maintains separate building-energy and crop-radiation quantities derived from the prescribed lighting conditions.

Indoor temperature is transferred through a different pathway. Rather than assuming that prescribed thermostat setpoints represent the actual growing environment, the interface derives daily maximum and minimum temperatures from the realised EnergyPlus grow-room air-temperature outputs. Other crop-relevant variables, including controlled photoperiod, CO_2 concentration and management conditions, are specified within the DSSAT representation where applicable.

These relationships establish the responsibilities of each simulation domain and identify which inputs may be affected by engineering modifications. The corresponding conversion equations, assumptions and input-file procedures are presented in Section 5.

3.3. Sequential coupling strategy and model boundaries

The framework follows a sequential execution strategy in which information is exchanged at defined stages rather than continuously between simulation engines. EnergyPlus first evaluates the building-energy state and indoor thermal conditions, after which the relevant environmental information is prepared for crop-response simulation. Accepted crop outputs are subsequently reconciled with building-energy results for integrated assessment.

This architecture does not reproduce fully bidirectional plant–building feedback. In particular, DSSAT-predicted crop development, biomass accumulation and associated physiological changes do not dynamically update the plant-related sensible and latent loads represented in EnergyPlus. These loads remain prescribed within the building model, and their influence is examined through separate sensitivity analyses.

The resulting framework is therefore intended for comparative energy–crop assessment rather than short-timescale prediction of interacting canopy processes and environmental-control responses. Its interpretation depends on the consistency of exchanged inputs and explicit recognition of the physical processes not resolved by sequential coupling.

3.4. Sequential model execution, state equivalence and provenance

The execution sequence is determined by the dependencies introduced by each scenario modification. A change affecting building-energy performance requires reassessment of the corresponding EnergyPlus state, while a modification affecting crop-relevant inputs requires a new DSSAT simulation. Where a modification changes both domains, both model states must be reassessed before their outputs are integrated.

The crop-relevant state comprises the environmental, biological and management inputs represented within DSSAT, including prescribed crop-light exposure, translated daily temperature, CO_2 concentration, genotype, planting density and crop-management configuration. A previously accepted crop result may be reused only when the corresponding input state remains equivalent to that of its originating simulation. This assessment is based on the values and precision represented in the crop-model input files, rather than on nominal scenario classifications or an assumed absence of changes in crop productivity.

Consequently, improvements in equipment efficiency or modifications to electricity-generation systems do not automatically justify crop-output reuse. Their effects on the realised building environment must first be assessed to determine whether any translated crop-relevant input has changed. Where crop-relevant input equivalence cannot be established for the applicable simulation period, DSSAT must be re-executed or the inherited crop output explicitly classified as provisional rather than independently verified.

The framework maintains scenario-level provenance to support these decisions. Each integrated scenario identifies the corresponding EnergyPlus simulation, the originating DSSAT simulation, any inherited crop outputs and the outcome of the applicable equivalence assessment. Accepted crop-cycle grain yield and biomass are scaled to the effective productive growing area and annualised before integration with facility-level annual building-energy results.

This procedure distinguishes newly generated results from conditionally reused outputs and provides an auditable basis for evaluating scenarios without assuming that every engineering modification requires execution of both simulation engines. The detailed dependency criteria, reconciliation equations and implementation examples are presented in Section 6.

4. Timimoun Demonstration Case and Model Implementation

4.1. Computational case, climate and assessment boundary

The proposed framework was implemented using a purpose-modelled vertical wheat-production facility in Timimoun, Algeria. The facility represents a hypothetical computational case rather than an existing agricultural installation, providing a defined setting for evaluating the sequential building–crop modelling procedure. Timimoun was selected for its hot-arid climate, agricultural-resource constraints and relevance to energy-intensive controlled-environment production.

Annual building-energy simulations employed the location-specific TMYx weather file DZA_AR_Timimoun.AP.606070_TMYx.2009-2023.epw (Lawrie and Crawley, 2026). This dataset defines the external climatic conditions for EnergyPlus, while the indoor crop environment is represented separately within DSSAT. The resulting predictions are therefore conditional on the selected climate, building configuration and crop-management assumptions rather than empirically calibrated estimates of an operating facility.

The assessment boundary includes the grow room, service space, building envelope, artificial lighting, environmental-conditioning systems, fans and represented auxiliary equipment, together with electricity-generation systems where applicable. Crop performance is characterised by grain yield, above-ground biomass and maturity duration. Building-energy performance is assessed annually, while crop outputs are obtained for individual production cycles. Embodied energy, capital costs, labour, post-harvest processing and full life-cycle impacts are excluded from the present assessment.

4.2. Building geometry and crop-lighting reference

The modelled facility comprises a principal grow room measuring 40 m × 42 m × 10 m, corresponding to a floor area of 1,680 m² and an enclosed volume of 16,800 m³. An additional 131.04 m² of service and support

space brings the total modelled building floor area to 1,811.04 m². The cultivation arrangement consists of 32 growing rows distributed across five tiers, providing an effective productive growing area of 3,600 m² (0.36 ha).

The ratio of productive growing area to grow-room floor area is approximately 2.14. This distinction is retained throughout the assessment because building-related loads are represented on a thermal-zone basis, whereas crop-lighting requirements and simulated crop production relate to the productive cultivation surface.

The reference scenario (S18) specifies a photosynthetic photon flux density (PPFD) of 600 μmol m^{-2} s^{-1}, a 16 h photoperiod and an LED photon efficacy of 2.7 μmol J^{-1}. Artificial lighting operates from 10:00 to 02:00, contributing both electrical demand and internal heat gains to the building model. The conversion of crop-light requirements into building electrical loads and DSSAT-compatible radiation inputs is detailed in Section 5.

4.3. EnergyPlus model, plant loads and environmental control

The initial building geometry and simulation organisation were developed using SketchUp 2024 and OpenStudio 1.8, with subsequent scenario modifications implemented directly through EnergyPlus Input Data Files (IDFs). Early S18 and crop-load sensitivity simulations were performed using EnergyPlus 24.1, while later analyses, including the matched-envelope LED-efficacy comparison, were conducted using EnergyPlus 26.1 following a software update. The reference envelope construction and material specifications are documented in Supplementary Appendix A (Online Resource 1, Table A1).

The reference environmental-control configuration employs heating and cooling setpoints of 20°C and 22°C, respectively, with a 60% relative-humidity setting recorded in the ZoneControl:Humidistat object and used as the study-specific performance-assessment threshold. Building infiltration is set at 0.1 air changes per hour, and outdoor-air ventilation at 0.001 m^3 s^{-1} m^{-2} of grow-room floor area. Heating and cooling are represented through a packaged terminal air conditioner (PTAC) comprising a constant-volume fan, single-speed direct-expansion cooling coil and electric heating coil. The cooling system has a rated coefficient of performance of 3.0.

No dedicated dehumidification or reheat system is represented. Consequently, environmental-control performance is evaluated from the simulated zone-air temperature and relative-humidity outputs rather than assuming continuous achievement of the specified conditions. Compliance with the study-specific environmental criteria is assessed in Section 7.

Crop-related thermal and moisture exchanges are represented through prescribed sensible and latent internal loads of +40 and 80 W m^{-2} of grow-room floor area, respectively. These correspond to 67.2 kW of sensible load and 134.4 kW of latent load across the 1,680 m^2 grow room. The prescribed values establish a consistent reference representation rather than a dynamically calculated physiological response. Their influence on cooling demand and humidity-control performance is investigated through the plant-load sensitivity analyses presented in Section 7.4.

4.4. DSSAT indoor representation and reproducibility record

Crop development was simulated using DSSAT 4.8.5 CERES-Wheat, with the reference cultivar and ecotype coefficients documented in Supplementary Appendix A. The controlled-environment representation incorporates daily radiation, maximum and minimum temperatures, prescribed photoperiod and CO_2 concentration, together with crop-management inputs.

For the S18 reference scenario, the DSSAT weather representation specifies daily radiation of 15.1 MJ m^{-2} d^{-1} and daily maximum and minimum temperatures of 22.0°C. The controlled photoperiod is set to 16 h, with CO_2 concentration specified at 380 ppm. Indoor rainfall is set to zero, while crop water supply is represented through the irrigation-management configuration. Soil-water simulation and automatic irrigation are enabled, whereas nitrogen simulation is disabled.

The reference crop configuration specifies planting and emergence densities of 350 plants m^{-2}, a row spacing of 15 cm and a planting depth of 3 cm. These parameters define the crop-model reference state used for the comparative simulations. The corresponding genotype and crop-management specifications are documented in Supplementary Appendix A (Tables A2–A3), while environmental-input transformations and scenario-dependency procedures are detailed in Sections 5 and 6, respectively.

Use of generative AI in manuscript preparation. During preparation of this manuscript, ChatGPT was used to assist with the organisation, drafting, language editing and revision of manuscript text, and with summaries of analyses of the authors' simulation records. The underlying EnergyPlus and DSSAT simulation results originated from the authors' modelling work, not generative AI. The authors remain responsible for independently checking the scientific content, numerical results, references and interpretations, and for approving the final version before submission.

5. Cross-Domain Environmental Translation

5.1. Translation principles and variable semantics

The sequential EnergyPlus–DSSAT interface requires conversion of quantities that differ in physical definition, units and temporal or spatial resolution. For each transferred variable, the procedure identifies its originating representation, the transformation applied and its role in the receiving model. DSSAT refers to the agricultural simulation environment, whereas CERES-Wheat denotes the crop-development model executed within it.

The principal distinction concerns crop illumination. Photosynthetic photon flux density (PPFD) and photoperiod specify biological photon exposure, LED photon efficacy relates that exposure to electrical power, and DSSAT requires a daily radiation input compatible with its weather-file structure. The interface therefore separates energetic and radiometric representations rather than treating them as interchangeable quantities. For temperature, simulated zone-air conditions are aggregated into the daily extrema required by DSSAT.

Other inputs are prescribed directly or maintained within their respective simulation domains. Controlled photoperiod and CO_2 concentration are specified through DSSAT experiment settings, while rainfall and irrigation are represented separately. Productive growing area is distinguished from building floor area so that lighting loads and crop-production quantities retain their appropriate spatial bases. Table 2 summarises the resulting relationships.

Table 2. Cross-domain variable representations and dependency implications.

Quantity	Originating representation	Receiving-model representation	Translation and dependency
Crop-light intensity	PPFD and LED photon efficacy	EnergyPlus lighting load and internal heat gains	Electrical power derived from PPFD and efficacy; efficacy affects thermal loads.
Crop-light exposure	PPFD and photoperiod	DSSAT daily SRAD equivalent	Conversion through DLI and adopted radiometric factors; photon-exposure changes affect crop inputs.
Temperature	EnergyPlus Zone Mean Air Temperature	DSSAT TMAX and TMIN	Daily extrema derived from reported simulated temperatures, not thermostat setpoints.
Photoperiod	Prescribed lighting schedule	DSSAT EDAY	Controlled daylength imposed through crop-experiment inputs.
CO_2 concentration	Prescribed indoor concentration	DSSAT ECO2	Concentration specified separately from any represented CO_2 supply electricity.
Rainfall and irrigation	Enclosed crop environment and water-management assumptions	DSSAT RAIN and irrigation treatment	Rainfall set to zero; irrigation defined through crop management.
Growing area	Multi-tier productive surface versus grow-room floor area	Building lighting basis and crop-yield scaling	Separate 3,600 m² productive and 1,680 m² grow-room floor area.

Source: Authors' own elaboration.

5.2. Translating crop-light requirements

Crop-light requirements are expressed per unit productive growing area. For prescribed PPFD and constant LED photosynthetic photon efficacy, electrical lighting power density is calculated as:

$$P_{\mathrm{LED},g} = \frac{\mathrm{PPFD}}{\eta_{\mathrm{LED}}} \quad (1)$$

where P_LED,g is electrical lighting power per unit productive growing area (W m^{-2}), PPFD is expressed in μmol m^{-2} s^{-1}, and η_LED is LED photon efficacy (μmol J^{-1}). Under the S18 reference conditions of 600 μmol m^{-2} s^{-1} and 2.7 μmol J^{-1}, the resulting power density is 222.2 W m^{-2}.

To express this demand relative to the grow-room floor area used in the building model:

$$P_{\mathrm{LED},f} = P_{\mathrm{LED},g}\left(\frac{A_g}{A_f}\right) \quad (2)$$

where A_g is productive growing area (3,600 m²) and A_f is grow-room floor area (1,680 m²). Their ratio (approximately 2.14) gives a theoretical floor-area-equivalent lighting load of 476.2 W m^{-2}. The S18 EnergyPlus input uses 475 W m^{-2} (798 kW across the grow room), a difference of approximately 0.25% from

this analytical conversion (Supplementary Appendix A, Table A1). This distinguishes the illuminated multi-tier cultivation surface from the architectural floor-area basis of the building simulation.

For the crop model, prescribed photon exposure is first integrated over the photoperiod to obtain daily light integral (DLI):

$$\mathrm{DLI} = \mathrm{PPFD}\ t_p\ (3.6 \times 10^{-3}) \quad (3)$$

where t_p is photoperiod (h d^{-1}) and the factor 3.6×10^{-3} converts µmol m^{-2} s^{-1} multiplied by hours to mol m^{-2} d^{-1}. At 600 µmol m^{-2} s^{-1} over 16 h, DLI equals 34.56 mol m^{-2} d^{-1}. The corresponding photosynthetically active radiation (PAR) energy estimate is:

$$E_{\mathrm{PAR}} = \frac{\mathrm{DLI}}{k_{ph}} \quad (4)$$

where E_PAR is the estimated PAR energy (MJ m^{-2} d^{-1}) and k_ph = 4.57 mol photons MJ^{-1} PAR is the adopted photon-to-energy conversion coefficient. This is an approximation because the energy per mole of photons depends on spectral composition (McCree, 1972; Akitsu et al., 2015). The daily total-radiation equivalent used for DSSAT is then:

$$\mathrm{SRAD}_{eq} = \frac{E_{\mathrm{PAR}}}{f_{\mathrm{PAR}}} \quad (5)$$

where f_PAR = 0.50 is the assumed fraction of global solar radiation in the PAR waveband, based on relationships reported for natural sunlight (Tsubo and Walker, 2005). Together, Equations (3)–(5) yield an SRAD equivalent of approximately 15.1 MJ m^{-2} d^{-1} for the S18 lighting condition, matching the reference DSSAT weather input.

This is a model-compatible solar-radiation equivalent, not a measurement of total radiation emitted by the LEDs. Both the photon-to-energy coefficient and PAR fraction reflect solar-based radiometric approximations. Thus, the conversion does not establish spectral, canopy-interception or physiological equivalence under artificial illumination; its limitations are considered in Section 7.3.

For daylight-assisted scenarios, the conversion is applied to the prescribed total photon exposure reaching the crop, not solely to the LED-supplied fraction. Equivalent total photon exposure may therefore preserve the DSSAT radiation input even when the electrical-lighting contribution changes. The approximation does not

dynamically resolve optical losses, spectral differences, canopy interception or non-uniform exposure across tiers.

Figure 2 distinguishes the electrical and crop-radiation pathways and indicates how lighting-related heat gains may affect realised crop-zone temperature.

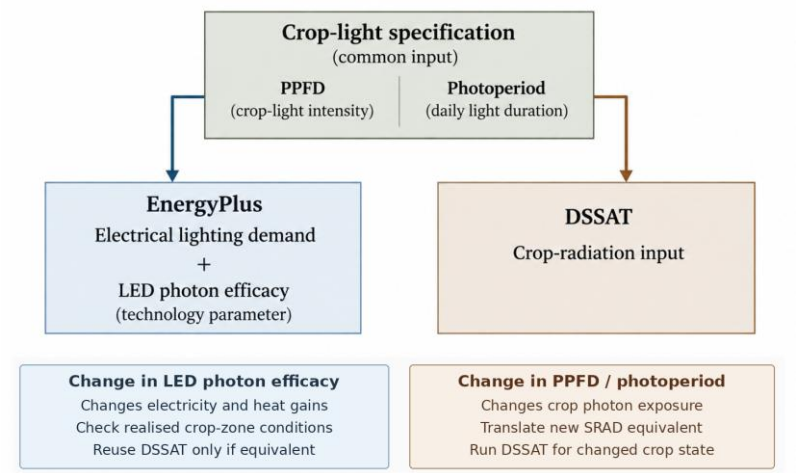


Fig. 2 Cross-domain crop-light translation and conditional scenario dependency for independently executed EnergyPlus and DSSAT models

Source: Authors' own elaboration.

5.3. Translating realised indoor temperature

EnergyPlus reports time-resolved zone-air temperatures, whereas DSSAT requires daily maximum and minimum values. The translation uses the grow-room Zone Mean Air Temperature output rather than prescribed thermostat setpoints. For each calendar day d:

$$T_{\max,d} = \max_{h \in d}\left(T_{\text{zone},h}\right) \quad (6)$$

$$T_{\min,d} = \min_{h \in d}\left(T_{\text{zone},h}\right) \quad (7)$$

where T_zone,h denotes the reported hourly simulated grow-room air temperature at interval h. The artificial-lighting schedule from 10:00 to 02:00 does not change calendar-day aggregation. Because the extrema are derived from the reported hourly series, shorter-duration fluctuations within reporting intervals may not be captured.

For the reference 72-day test window, the EnergyPlus 26.1 annual-run outputs produced daily crop-zone maximum and minimum temperatures that rounded to 22.0°C in S18 and S22 at the 0.1°C DSSAT-input precision (72 of 72 paired days). This confirms agreement at the represented daily precision for the tested

window, but neither sub-hourly equivalence nor annual crop-input equivalence. The supporting daily comparison is provided in Online Resource 2; original hourly output data are provided in Online Resource 3. The alignment of this simulation window with the DSSAT experiment calendar remains a documented modelling assumption rather than an independently verified crop-calendar audit.

5.4. Constructing the controlled DSSAT environment

The controlled-environment representation retains DSSAT daily weather-file and crop-experiment structures (DSSAT Foundation, n.d.) while replacing outdoor agricultural conditions with translated or prescribed indoor inputs. Daily SRAD is estimated through Equation (5), TMAX and TMIN through Equations (6)–(7), and precipitation is specified as zero:

$$\mathrm{RAIN} = 0\ \mathrm{mm\ d^{-1}}$$

Crop water supply is instead represented through irrigation-management settings. The resulting DSSAT weather records describe the prescribed indoor growing environment and are distinct from the external EPW weather data driving EnergyPlus.

Controlled photoperiod and CO_2 concentration are specified through the DSSAT experiment inputs independently of building-energy calculations. Cultivar coefficients, planting and emergence densities, row spacing and irrigation treatments remain documented in the crop-model configuration. Together, these environmental and management inputs define the crop-model state associated with each simulation.

6. Sequential Coupling and Model Orchestration

6.1. Sequential execution and model dependency

The workflow is implemented at scenario level, with each modification evaluated for its consequences in the building-energy and crop-development domains. A new EnergyPlus calculation is required when building configuration, equipment operation or represented loads change; an accepted building result may be retained where its inputs are unchanged. Realised indoor conditions from the applicable EnergyPlus run are then translated into DSSAT-compatible inputs. Crop-model execution is determined by the resulting input state,

rather than by scenario numbering or an assumption that every building modification requires a new crop simulation.

For this purpose, the crop-relevant state comprises the daily radiation and temperature inputs, photoperiod, CO_2 concentration, cultivar, planting and emergence densities, row spacing and represented management treatments. Equivalence is assessed for the relevant crop period by comparing the values recorded in the DSSAT weather, experiment and management inputs with those of the originating accepted crop run. Any difference in a represented crop input requires re-simulation. If equivalence cannot be established, an inherited result is classified as provisional rather than independently verified. Agreement at the 0.1°C precision used for the daily temperature inputs establishes equivalence at that representation only; it does not demonstrate identical sub-hourly or canopy conditions.

6.2. Crop-model re-simulation, conditional reuse and output traceability

The decision to rerun or reuse a crop simulation is made before annual building-energy and crop-production quantities are combined. A new DSSAT output is accepted only after successful execution and the crop-output checks described in Section 7. An existing result may be inherited when the complete represented crop-input state remains equivalent and the originating run is identifiable. Table 3 records the treatment of the principal scenario modifications.

Table 3. Criteria for DSSAT re-simulation and conditional reuse of an accepted crop output.

Scenario modification	Crop-relevant state	DSSAT treatment
PPFD or photoperiod changes	Changed	Re-simulate
Translated daily temperature changes	Changed	Re-simulate
Prescribed CO_2 concentration changes	Changed	Re-simulate
Genotype, establishment density, row spacing or management changes	Changed	Re-simulate
LED photon efficacy changes at fixed PPFD and photoperiod	Potentially equivalent	Reuse only after checking all translated crop inputs
PV, battery or other electricity-supply changes	Potentially equivalent	Reuse only if represented crop inputs are unchanged
Other building-side efficiency or equipment modifications	Potentially equivalent	Reuse only after full crop-input equivalence is established
Daylight substitutes for part of LED photon supply	Potentially equivalent	Reuse only if total represented photon exposure and all other crop inputs remain equivalent

Source: Authors' own elaboration.

The scenario register links each integrated result to its supplying EnergyPlus simulation and the originating DSSAT run, distinguishing newly calculated, conditionally reused and provisional crop outputs. In S20,

reducing PPFD from 600 to 500 μmol m^{-2} s^{-1} relative to the S18 reference changed crop-light exposure and required a new DSSAT simulation. In S22, LED photon efficacy increased from 2.7 to 3.5 μmol J^{-1} while the prescribed PPFD (600 μmol m^{-2} s^{-1}), photoperiod (16 h) and derived DSSAT radiation equivalent were retained. A field-by-field comparison of the 348 non-output-request EnergyPlus objects confirmed that the two matched-envelope IDFs differed only in the grow-room lighting-power density (475 versus 366.85 W m^{-2}). Direct comparison of the annual-run hourly results established matching rounded daily TMAX and TMIN inputs on 72 of 72 days in the tested reference window (Online Resources 1–3). The thesis scenario register identifies S18 as the source of the S22 crop output. Because a separate complete S18–S22 DSSAT weather/experiment-file audit was not available, reuse remains conditional on the remaining DSSAT inputs having been retained; first-window equivalence does not establish validity for subsequent cycles.

Figure 3 distinguishes direct crop-input modifications from the subsequent full equivalence check for the assessed crop period. Where equivalence is unconfirmed, DSSAT is re-executed or inherited output is designated provisional; the origin and scope of any reused result remain recorded. An equipment-efficiency improvement alone does not justify reuse.

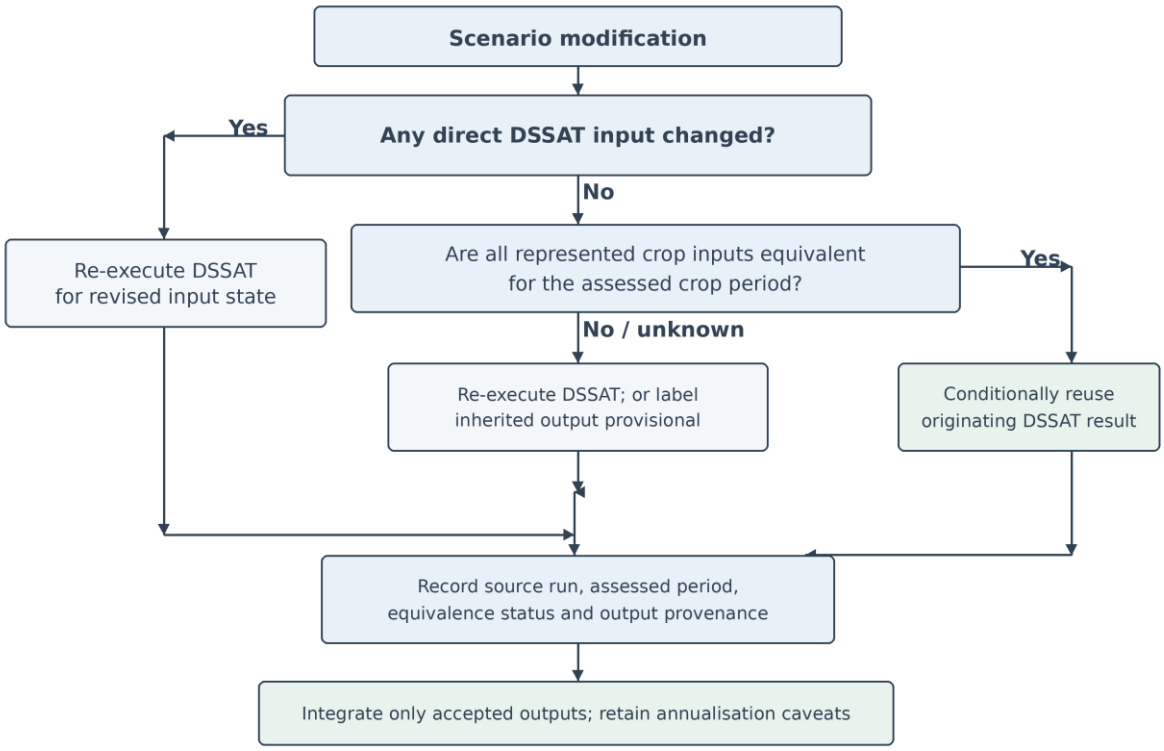


Fig. 3 Crop-relevant-state-equivalence procedure governing DSSAT re-simulation and conditional crop-output reuse
Source: Authors' own elaboration.

6.3. Reconciliation of crop-cycle and annual building outputs

EnergyPlus provides annual facility-energy quantities, whereas DSSAT reports grain yield and above-ground biomass per hectare for one simulated crop cycle. The effective productive area in the Timimoun case is 3,600 m² (0.36 ha); it is not the 1,680 m² grow-room floor area. Accordingly, crop outputs are first scaled to the productive area and then expressed on an annual potential-production basis.

$$A_g = 3{,}600\ \mathrm{m}^2 = 0.36\ \mathrm{ha}$$

For grain yield Y_c (kg ha^{-1} cycle^{-1}) and duration to crop maturity D_m (days), potential annual production is calculated as:

$$Y_{\mathrm{annual}} = Y_c A_g \left(\frac{365}{D_m}\right) \quad (8)$$

The corresponding potential annual above-ground biomass is calculated from DSSAT cycle biomass B_c (kg ha^{-1} cycle^{-1}):

$$B_{\mathrm{annual}} = B_c A_g \left(\frac{365}{D_m}\right) \quad (9)$$

Here, A_g is expressed in hectares and Y_{annual} and B_{annual} in kg yr^{-1}. The factor $365/D_m$ assumes successive crop cycles without harvesting, cleaning, maintenance or crop-establishment downtime. These are theoretical annualised outputs under the specified management conditions, not predictions of guaranteed commercial production. The spatial and temporal bases are retained explicitly when comparing production against annual building-energy results.

6.4. Integration of annual energy and crop production

Integrated performance is evaluated after the crop and building results have been placed on the same annual facility basis. EnergyPlus energy quantities reported in gigajoules are converted to kilowatt-hours using:

$$1\ \mathrm{GJ} = 277.7778\ \mathrm{kWh}$$

The energy numerator is the annual net site energy associated with the accepted EnergyPlus result. Gross operational demand, on-site generation and net energy are retained as distinct quantities in the scenario records, so an electricity-generation offset is not represented as a reduction in intrinsic building demand. The operational Energy Efficiency Index (EEI) is then defined as:

$$EEI = \frac{E_{\mathrm{net}}}{Y_{\mathrm{annual}}} \quad (10)$$

where E_{net} is annual net site energy (kWh yr^{-1}) and Y_{annual} is potential annual grain production (kg yr^{-1}). For scenarios inheriting crop output after equivalence was established for only one cycle, annual EEI remains conditional on the assumptions used to extend that crop response across the year. The resulting EEI (kWh kg^{-1}) expresses net operational energy per kilogram of modelled production within the stated assessment boundary, not life-cycle environmental impacts, economic viability or experimentally verified farm performance.

7. Verification, Credibility and Uncertainty

7.1. Credibility strategy and evidential status

The Timimoun vertical-wheat facility is a computational demonstration without corresponding monitored building or crop-production measurements. Model credibility is therefore evaluated through computational diagnostics, crop-output plausibility, consistency of exchanged inputs and sensitivity to prescribed plant-

related loads. These checks support interpretation of comparative engineering results but do not constitute empirical calibration or validation of the integrated facility (Roy and Oberkampf, 2011).

The assessment comprises four stages: (i) verification of EnergyPlus execution and indoor environmental performance; (ii) screening of DSSAT phenology, biomass and grain yield against model-consistency criteria and published wheat evidence; (iii) checking cross-domain input consistency and source-simulation provenance; and (iv) investigating sensitivity to crop-related sensible and latent loads. Figure 4 summarises this evidence sequence. The associated acceptance criteria distinguish computational validity from environmental-control adequacy and biological plausibility.

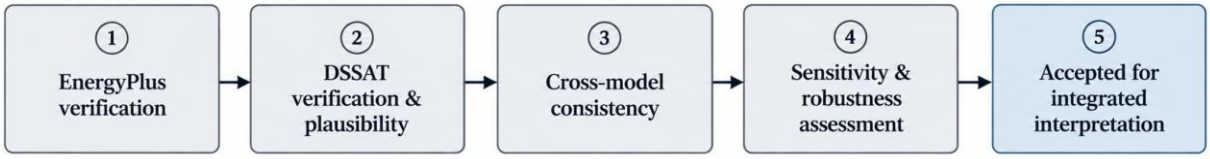


Fig. 4 Credibility-assessment sequence for the sequential EnergyPlus–DSSAT framework
Source: Authors' own elaboration.

7.2. Computational verification and acceptance criteria

EnergyPlus runs were screened for fatal or severe errors, availability of the required outputs and diagnostically relevant warnings. Environmental-control adequacy was assessed over 8,760 annual hours using study-specific criteria: at least 99% of hours within 19.5–22.5°C and at least 99% of hours at or below 60% relative humidity (RH), corresponding to no more than 87 whole-hour RH exceedances. A normalised zone-air residual threshold of ≤1% was specified as a supplementary numerical-consistency target; however, no calculated residual is reported for the evaluated scenarios, so compliance with this threshold is not claimed. These screening thresholds are specific to the computational case and are not experimentally established physiological limits for wheat.

The matched-envelope S18 reference satisfied the annual temperature and RH screening criteria, with zero hours outside the 19.5–22.5°C interval and four hours above 60% RH (99.954% RH compliance). In the separate latent-load cases of 228, 410 and 547 W m^{-2}, RH exceedance increased to 5,515, 5,825 and 5,840 hours, respectively, equivalent to compliance rates of 37.04%, 33.50% and 33.33%. Environmental-control failures are classified as limitations of the scenarios rather than suppressed from the energy comparisons.

Table 4 defines how execution quality, environmental performance, crop plausibility and cross-model consistency were classified before integrated interpretation.

Table 4. Computational acceptance and classification criteria for the sequential framework.

Component	Quantity assessed	Study-specific criterion	Interpretation if not met
EnergyPlus	Execution diagnostics	No fatal/severe errors; required outputs available	Investigate, correct or exclude from integrated assessment
EnergyPlus	Temperature control	≥99% of annual hours within 19.5–22.5°C	Classify as temperature-control limited
EnergyPlus	Humidity control	≥99% of annual hours at ≤60% RH	Classify as humidity-control limited
EnergyPlus	Zone-air balance (supplementary)	Target: normalised residual ≤1%; calculated value not reported	No pass/fail classification assigned without a calculated residual
DSSAT	Phenological completion	Maturity reached within simulated horizon	Exclude from representative annual production
DSSAT	Grain and biomass	Positive, physically consistent outputs; grain yield ≤ above-ground biomass	Exclude or investigate crop result
DSSAT	Biological plausibility	Coherent reproductive, canopy and stress response	Classify as representative, sensitivity-only or exclude
Integrated framework	Cross-domain consistency	Compatible crop inputs and recorded rerun/reuse provenance	Do not accept integration until consistency is resolved

Source: Authors' own elaboration.

In the matched-envelope EnergyPlus 26.1 comparison, increased LED photon efficacy (2.7 to 3.5 μmol J^{-1}) reduced annual simulated site electricity from 24,500.64 to 19,192.38 GJ (6.806 to 5.331 GWh; 21.7%). Annual hours above 60% RH increased from four to 224, exceeding the study-specific allowance of 87 hours; S22 also recorded three hours outside the 19.5–22.5°C temperature interval. Thus, lower energy use did not establish acceptable humidity control. The independently extracted 8,760-hour annual temperature–RH comparison and the 72-day daily-extrema test are provided as Online Resources 3 and 2, respectively.

Applying the S18 potential annualised production of 9,123.18 kg yr^{-1} to both EnergyPlus energy totals gives indicative operational energy-to-grain ratios of 746.0 kWh kg^{-1} (S18) and 584.4 kWh kg^{-1} (S22), a 21.7% reduction in the assumed ratio. The S22 denominator is inherited from the S18 DSSAT result: its first-window daily-temperature agreement does not validate identical crop output over repeated annual cycles, and S22 fails the study-specific humidity criterion. These ratios are therefore conditional scenario illustrations, not predictions of verified annual yield or acceptable farm operation.

7.3. DSSAT plausibility and quantitative wheat benchmarking

DSSAT CERES-Wheat outputs were assessed for successful progression to maturity, coherent phenological development, positive grain and biomass production, and grain yield not exceeding above-ground biomass.

The S18 simulation produced 4,999 kg ha^{-1} of grain over 72 days. Applied to the 0.36 ha productive growing area and annualised under uninterrupted cycles, this gives 9,123.18 kg yr^{-1}. This is simulated production potential, not an observed yield or a forecast incorporating operational turnaround.

For context, Asseng et al. (2020) reported a controlled-environment wheat harvest of approximately 14 ± 0.8 t ha^{-1} at 11% grain moisture and considered a theoretical annual potential of 70 ± 4 t ha^{-1} under five harvests. The S18 values of 4.999 t ha^{-1} per cycle and approximately 25.34 t ha^{-1} yr^{-1} are about 36% of those respective benchmarks. The comparison is contextual rather than validating: the published experiment used a PPFD of 1,400 µmol m^{-2} s^{-1} for 20 h d^{-1}, compared with 600 µmol m^{-2} s^{-1} for 16 h d^{-1} in S18; genotype, management, growth environment, model structure and reported grain-moisture bases may also differ.

A separate radiation-consistency check identified DSSAT-reported PARD of 30.2 mol m^{-2} d^{-1}, compared with the prescribed photon integral of 34.56 mol m^{-2} d^{-1}. The 12.6% difference demonstrates that the internal model diagnostic should not be interpreted as identical to photons delivered by the LED specification. It exposes a limitation of the radiation-equivalent representation rather than providing a spectral calibration or direct measure of canopy photon absorption. Consequently, crop plausibility is supported by internal consistency and literature-based context, not by a universal yield-validation threshold.

7.4. Coupling uncertainty and crop-load sensitivity

Plant-related sensible and latent exchanges were prescribed in EnergyPlus rather than updated from simulated crop physiology. The reference inputs were +40 W m^{-2} sensible and 80 W m^{-2} latent heat, both normalised to grow-room floor area. To examine the sensitivity of conditioning and humidity predictions to the latent-load assumption, alternative values were derived from assumed daily crop transpiration using the area-normalised mass–energy relationship in Equation (11).

$$q_{\mathrm{lat,f}} = \frac{T_{\mathrm{d}} \times 10^{-3} \times \rho_{\mathrm{w}} \times h_{\mathrm{fg}}}{t_{\mathrm{op}} \times 3600} \times \frac{A_{\mathrm{g}}}{A_{\mathrm{f}}} \quad (11)$$

Here q_lat,f is the floor-area-equivalent latent load (W m^{-2}), T_d is crop transpiration per unit productive growing area (L m^{-2} d^{-1}), ρ_w is water density (kg m^{-3}), h_fg is latent heat of vaporisation (J kg^{-1}), t_op is the assumed daily load period (h), and A_g/A_f is the ratio of productive growing area to grow-room floor area. The factor 10^{-3} converts litres to cubic metres.

Using a 16 h operating period and A_g/A_f = 3,600/1,680, transpiration assumptions of 2.5, 4.5 and 6.0 L m^{-2} d^{-1} correspond to approximately 228, 410 and 547 W m^{-2}. The S18 DSSAT summary separately reported 163 mm of seasonal crop transpiration over 72 days (approximately 2.26 L m^{-2} d^{-1}), equivalent to about 206 W m^{-2} when uniformly allocated over the same 16 h period. This model-derived average does not constitute an independent transpiration measurement or a time-varying canopy load (Wheeler and Sager, 1990).

The DSSAT-derived latent-load equivalent of approximately 206 W m^{-2} is about 2.6 times the prescribed EnergyPlus reference of 80 W m^{-2}. Although this estimate represents a seasonal transpiration total allocated uniformly over an assumed 16 h operating period, rather than a validated hourly load profile, the discrepancy highlights the sensitivity of the baseline to its moisture-load assumption. Accordingly, the favourable S18 RH compliance should not be interpreted as evidence that humidity control would remain adequate under physiologically representative crop-transpiration loads.

Across the four EnergyPlus cases, only the prescribed OtherEquipment latent power density was varied. Relative to the 80 W m^{-2} reference, annual net site energy increased from 6.806 GWh to 7.192, 7.709 and 8.097 GWh at 228, 410 and 547 W m^{-2} (+5.7%, +13.3% and +19.0%). Cooling electricity increased from 1.867 GWh to 2.253, 2.769 and 3.156 GWh (+20.7%, +48.3% and +69.1%). The substantial deterioration in RH compliance, despite few temperature-envelope exceedances, indicates that the simulated building response is strongly conditioned by the prescribed moisture load. Direct-expansion cooling-coil warnings in these runs further constrain interpretation; these cases are sensitivity tests, not validated predictions of dehumidification capability.

A separate sensible-load comparison at 410 W m^{-2} latent input changed prescribed sensible exchange from +40 to 0 and −40 W m^{-2}. Annual net site energy decreased from 7.709 to 7.542 and 7.374 GWh, while cooling electricity decreased from 2.769 to 2.628 and 2.486 GWh. RH exceedance nevertheless remained at 5,825, 5,840 and 5,840 annual hours, respectively. These results isolate sensitivities of the specified building and HVAC configuration; they do not demonstrate a general ranking of alternative farm designs or establish the actual plant-moisture exchange of an unbuilt facility.

8. Discussion

8.1. Interoperability as an explicit modelling interface

The principal contribution is a traceable interface specifying how results from independent building-energy and crop-development simulations can be interpreted and combined. This matters for energy-per-production assessment: an engineering modification may alter facility energy demand without changing the inputs governing modelled crop yield, whereas changed growing conditions require a new assessment of crop response. Distinguishing these cases reduces the risk of combining building and crop outputs representing incompatible scenarios.

Retaining EnergyPlus and DSSAT CERES-Wheat as independent tools allows input transformations, assumptions and output provenance to be examined separately. Such transparency is a methodological benefit, not evidence of improved predictive accuracy or computational speed. The value demonstrated here is a more auditable comparison of engineering scenarios under defined crop-input conditions, with uncertainty in both underlying models remaining relevant.

8.2. Conditional crop-output reuse and environmental-control assessment

The lighting cases illustrate why crop-model execution should depend on represented growing conditions rather than the nominal purpose of a technology change. Reduced photon supply changes a direct crop input, whereas increased LED photon efficacy changes electrical and thermal loads while prescribed crop photon exposure remains fixed. In the matched-envelope EnergyPlus 26.1 comparison, the first 72 annual-run days were equivalent for daily temperature extrema at DSSAT input precision, as demonstrated by the accompanying auditable output tables (Online Resources 2–3). The master scenario register records the S22 yield as inherited from S18, but independent item-by-item comparison of all DSSAT weather and experiment inputs was not available. Crop-output reuse and annualised energy-to-production ratios therefore remain conditional and cannot establish equivalence for later cycles.

The improved-efficacy case also demonstrates that crop-input equivalence does not establish adequate environmental control. Although electricity consumption decreased, annual relative-humidity exceedances increased beyond the study-specific acceptance criterion. Direct humidity effects on crop development are not

resolved by the present DSSAT representation. Consequently, an energy-saving scenario cannot be considered environmentally acceptable solely because its translated crop inputs are unchanged. Energy-per-yield comparisons should be accompanied by separate temperature- and humidity-control assessments.

8.3. Trade-off between sequential and dynamic coupling

The plant-load sensitivity tests reveal a limitation of the prescribed-load representation. The DSSAT-derived transpiration equivalent was substantially greater than the reference latent load, while higher prescribed moisture exchanges increased cooling demand and produced widespread humidity exceedances. The favourable reference humidity result is therefore conditional on a comparatively low latent-load assumption. These sensitivities were evaluated with one HVAC configuration and included cooling-coil warnings; they cannot be interpreted as measured transpiration, validated dehumidification performance or design-independent performance rankings.

Dynamic models are better suited to questions involving continuous feedback among plant transpiration, canopy energy exchange and environmental control (Talbot and Monfet, 2024a, 2024b; Larochelle Martin and Monfet, 2025). The sequential approach instead retains a full-cycle cereal model alongside whole-building energy simulation, with the limitations of prescribed building-side crop loads made explicit. These approaches are complementary: the present framework can support conditional comparison and identify cases requiring more detailed plant–air modelling, but cannot substitute for that feedback where it governs system performance.

8.4. Interpretation boundaries and transferability

The Timimoun facility is a hypothetical computational case rather than an operating farm with calibrated building and crop predictions. Its artificial-light representation relies on solar-derived radiometric approximations, and the discrepancy between prescribed photon exposure and DSSAT's internal radiation diagnostic limits claims of spectral equivalence. Zone-mean temperatures do not resolve canopy or tier-to-tier variation. Published indoor-wheat yields provide contextual benchmarks rather than validation of the selected CERES-Wheat configuration (Asseng et al., 2020). Annual production also assumes uninterrupted crop cycles without harvest or re-establishment downtime.

Transferability therefore concerns the interface procedure more directly than the numerical energy, humidity or grain-production estimates. Application to other crops, climates and facilities requires crop-specific translations, environmental criteria and state-equivalence checks, together with an appropriate representation of crop-related loads. Future evaluation should combine measured photon spectra, canopy conditions, transpiration, electricity and harvest data to test the model assumptions and determine where dynamic feedback materially changes engineering decisions. Pending such evidence, the framework is most appropriately used for transparent, conditional comparative assessment.

9. Conclusions

This study developed and computationally assessed a sequential EnergyPlus–DSSAT CERES-Wheat framework for comparing building energy and wheat production in controlled environments. Its contribution is a traceable procedure for translating crop-relevant inputs, determining when simulations require re-execution or conditional reuse, and reconciling crop-cycle production with annual facility energy. It does not constitute dynamic crop–building co-simulation.

In the Timimoun demonstration, reduced crop photon exposure required crop re-simulation; improved LED photon efficacy required assessment of both building-energy response and indirect thermal effects. The matched-envelope S18–S22 output comparison established identical rounded daily temperature extrema at 0.1°C precision on all 72 days of the tested reference window. The first-window test and prescribed lighting equivalence support only conditional reuse of the S18 crop output: complete DSSAT input-file equivalence and subsequent annual cycles were not independently verified.

Increasing LED photon efficacy from 2.7 to 3.5 μmol J^{-1} reduced annual simulated site electricity by 21.7% in the controlled comparison, while hours above 60% relative humidity rose from four to 224, exceeding the study-specific acceptance limit. Indicative energy-per-potential-grain ratios decreased under an inherited S18 annual yield assumption, but this does not establish environmentally acceptable operation or crop performance over untested cycles. Plant-moisture-load sensitivity further demonstrated dependence of cooling and humidity-control results on prescribed crop loads.

The case represents a hypothetical facility rather than an experimentally validated farm. Radiation-equivalence assumptions, prescribed plant loads and uninterrupted crop-cycle annualisation limit the interpretation of yield and energy-per-production estimates. Facility measurements and more detailed plant–air feedback are required before making predictive design or operational claims. Within these limitations, the framework supports transparent, conditional comparisons of controlled-environment agricultural systems.

Supplementary information: Online Resource 1 contains the reference model parameterisation, the matched-envelope S18–S22 input and output audit, and the interpretation limits (Supplementary Appendix A, Tables A1–A5). Online Resource 2 contains the 72-day daily TMAX/TMIN comparison at 0.1°C input precision. Online Resource 3 contains the 8,760-hour matched-envelope annual temperature and RH output comparison.

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- 02ESM1SupplementaryAppendixA.pdf
- 03ESM2S18S22DailyTemperature72days.csv
- 04ESM3S18S22AnnualHourlyTempRH.csv