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Modelling advanced HVAC technologies and BACS (Building Automation and Control System)

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Abstract

Building Automation and Control Systems (BACS) are widely recognised as a cost-effective means of reducing the energy use of new and existing buildings. The European standard EN ISO 52120-1:2022, with its companions ISO 52120-2 and EN ISO 16484-4, formalises this potential by grading building automation into efficiency classes A–D and by defining, function by function, the control capability required at each class. Despite the regulatory importance of this framework, its individual functions are rarely represented explicitly in building energy models. This thesis addresses that gap: it assesses and improves the automation of a non-residential office building against the ISO 52120 framework entirely through dynamic simulation, prioritising the correct representation of each BACS function over energy optimisation for its own sake.

A reference EnergyPlus (v25.2) model of the ASHRAE 90.1-2022 Medium Office prototype is first calibrated to BACS Class C, the minimum standard for new buildings, and then upgraded incrementally to Class B and Class A. Twenty-four of the forty-five standard control functions are applicable to the building; each upgrade is implemented at the model level — the Class A supervisory logic through the EnergyPlus Energy Management System — and validated through a staged quality-assurance procedure (technical integrity, diagnostics and KPI checks) before the next class is accepted. Performance is quantified with twenty-one indicators spanning primary energy, peak load, thermal comfort, ventilation delivery and control adherence, with primary energy obtained from Italian conversion factors. The analysis is carried out primarily for the Turin (Torino-Caselle) climate and repeated for Atlanta as a cross-climate sensitivity check.

Moving from Class C to Class B reduces annual primary energy by 13.8%; a further 15.3% reduction from Class B to Class A gives a combined C→A saving of 27.0%. Controlled end-use primary energy (heating, cooling, fans, lighting, pumps) falls by 48.1% C→A. The Class B saving is driven by fan demand control, supply-air-temperature reset, and daylight-responsive lighting; the Class A saving by an enthalpy economiser and demand-controlled VAV fans whose primary energy each fall by 44–50% between Classes B and A. A parallel run on the Atlanta (CZ 3A) climate yields a C→A K0 saving of 28.9% and a controlled-energy saving

of 48.0%, confirming that the BACS class hierarchy produces essentially climate-independent efficiency gains. Heating setpoint-unmet hours improve at Class B (−42.5%) and remain stable at Class A. Cooling setpoint-unmet hours also improve at Class B (−43.8%) but increase at Class A due to the selectivity of the enthalpy economiser and IAQP demand-controlled ventilation — a documented consequence of correct Level-3 control logic, verified by a regression analysis, not a modelling error. The ASHRAE-55 and setpoint-unmet comfort metrics diverge and are reported separately; no claim of uniform comfort improvement is made. The work delivers a transparent, reproducible and standards-faithful methodology for representing BACS efficiency classes in dynamic simulation, together with climate-robust, end-use-resolved estimates of the energy savings achievable through building-automation upgrades.

Keywords: building automation and control systems (BACS); EN ISO 52120-1; building energy performance simulation; EnergyPlus; BACS efficiency classes; non-residential office building.

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List of Symbols and Abbreviations

Mathematical Symbols

Symbol	Definition
$K0$	Overall annual primary energy (kWh/a)
KPI-CTRL	Controlled-end-use primary energy: sum of heating, cooling, fans, interior lighting, and pumps (kWh/a)
EUI	Energy Use Intensity (kWh/m ² /a)
$f_{P,el}$	Primary energy factor for electricity (2.42, D.I. 26/06/2015 “Requisiti Minimi”)
$f_{P,gas}$	Primary energy factor for natural gas (1.05, D.I. 26/06/2015 “Requisiti Minimi”)
PEF	Primary Energy Factor (generic term for f_P)

Abbreviations

Abbreviation	Definition
AHU	Air Handling Unit
BAC	Building Automation and Control (function)
BACS	Building Automation and Control System
BMS	Building Management System
CAV	Constant Air Volume
CHP	Combined Heat and Power
COP	Coefficient of Performance
CZ	ASHRAE Climate Zone
DCV	Demand-Controlled Ventilation
DDY	Design-Day (EnergyPlus sizing) data
DHW	Domestic Hot Water
DX	Direct Expansion (cooling coil)
EMS	EnergyPlus Energy Management System
EPW	EnergyPlus Weather file format
ERL	EnergyPlus Runtime Language
FDD	Fault Detection and Diagnosis
HVAC	Heating, Ventilation, and Air Conditioning
IAQ	Indoor Air Quality
IAQP	Indoor Air Quality Procedure (ASHRAE 62.1)
IDF	EnergyPlus Input Data File
IEQ	Indoor Environmental Quality
IGV	Inlet Guide Vane (fan type)
IWEC	International Weather for Energy Calculations
OAT	Outdoor Air Temperature
PMV	Predicted Mean Vote (thermal comfort)
PV	Photovoltaic
SAT	Supply Air Temperature
TABS	Thermally Activated Building Systems
TMY	Typical Meteorological Year
VAV	Variable Air Volume
VFD	Variable Frequency Drive
VRF	Variable Refrigerant Flow
VSD	Variable Speed Drive

Chapter 1

Introduction

1.1 Background and Motivation

Buildings account for a substantial fraction of final energy consumption in Europe and globally, and the heating, cooling, ventilation, and lighting systems that serve them remain a primary target for decarbonisation policy. While much of the efficiency effort in the built environment has historically focused on the thermal fabric — insulation, glazing, and airtightness — there is a complementary and often more cost-effective lever that acts on the *way* building systems are operated rather than on their installed capacity. Building Automation and Control Systems (BACS) encompass the hardware, software, and services that regulate the energy-using plant of a building and coordinate its operation through sensors, actuators, and supervisory controllers [1]. A variable-speed fan whose speed is continuously matched to ventilation demand consumes a small fraction of the energy drawn by the same fan running at a fixed fraction of full speed, even though the rated power and the ductwork are identical. This observation — that intelligent control of installed plant consistently and predictably reduces energy consumption without requiring physical equipment replacement — is the engineering rationale for quantifying building automation systematically.

The normative framework that structures this quantification in Europe is EN ISO 52120-1:2022 [1], which supersedes the earlier EN 15232 standard and integrates BACS evaluation into the ISO 52000 modular Energy Performance of Buildings (EPB) framework [2]. Part 2 of the standard provides the explanatory justification for its class definitions [3], and the companion EN ISO 16484-4 [4] translates the abstract class requirements into specific control-application function blocks for implementation. Together, these three standards define four BACS efficiency classes — D (non-automatic or inadequate control), C (standard BAC), B (advanced BAC with room-level communication), and A (high-energy-performance BAC with integrated Technical Building Management functions) — and catalogue 45 individual BAC functions that span heating, cooling, ventilation, lighting, solar shading, and

building management. Class C is the minimum standard for new non-residential buildings; Classes B and A represent successive levels of automation capability with progressively greater efficiency potential. The framework is described in full in chapter 3.

The practical significance of upgrading from Class C to higher classes has been documented across a range of building types and climates. A systematic review of office-building BACS impacts by Garzia et al. [5] reports average total primary-energy savings of approximately 30% from Class C to Class A, with some cases reaching approximately 39%. These figures establish the order of magnitude of the efficiency potential; translating them into reliable, building-specific predictions is the methodological challenge that this thesis addresses.

1.2 Problem Statement and Research Gap

ISO 52120-1 offers two evaluation paths: a simplified BAC-factor method, which multiplies a reference controlled energy demand by tabulated efficiency factors, and a detailed dynamic simulation path, which requires explicit modelling of each class-defining control sequence in a whole-building energy tool. The majority of published studies and national energy-certificate schemes use the factor method because of its computational simplicity. An important and growing body of evidence, however, shows that the two methods diverge substantially in practice.

Vandenbogaerde, Audenaert and Verbeke [6], the only peer-reviewed journal study found in the evidence review that explicitly contrasts EN ISO 52120-1 BAC factors with EnergyPlus simulation across class levels, found that C→A heating-emission-control savings ranged from 19% to 71% across 7,776 parametric building variants in European climates — a spread that a single static factor cannot capture. Bonomolo et al. [7] measured daylight-responsive lighting savings of up to 38.4% in a southern Italian office building against a BAC-factor prediction of 8% — a discrepancy of roughly five times. Albesiano (2023) [8], working at Politecnico di Torino with the same simulation engine and the same Turin climate as the present thesis, reported heating savings of 24% for the C→B step in an EnergyPlus model of university classrooms, compared with the factor-method prediction of 12% — a factor-of-two discrepancy on identical premises. The conclusion that emerges from this evidence is consistent: the factor method provides only a generic estimate, and simulation-based evaluation is necessary whenever building-specific reliability is required. chapter 2 surveys this evidence in full.

Despite this, the body of simulation work on BACS has a structural gap. Studies that simulate individual control strategies in detail — variable-speed fans, supply-air-temperature reset, demand-controlled ventilation, daylighting, solar shading,

optimum start — generally adopt ASHRAE Guideline 36 framing or occupancy-centric terminology rather than the ISO 52120 class vocabulary, making a direct comparison with normative factor-method bands methodologically ambiguous [9, 10, 11]. Conversely, studies that explicitly frame results within the ISO 52120 class hierarchy have not, as of the evidence reviewed here, simultaneously: (a) implemented each class-defining control function explicitly at the model level; (b) reported a full $C \rightarrow B \rightarrow A$ transition with per-function end-use decomposition; and (c) tested the result across two contrasting climates using a single, frozen reference building model. This three-part gap is the specific problem that motivates the present thesis, as established in the research-gap section of chapter 2.

1.3 Aim and Objectives

The aim of this thesis is to produce a transparent, reproducible, and standards-faithful representation of BACS efficiency classes C, B, and A in dynamic building energy simulation, and to quantify the primary-energy and comfort consequences of the $C \rightarrow B \rightarrow A$ upgrade sequence for a non-residential office building. The emphasis is on correct representation of each ISO 52120 control function at the appropriate class level — not on energy optimisation for its own sake.

This aim is addressed through four specific objectives:

1. Calibrate a reference EnergyPlus model of the ASHRAE 90.1-2022 Medium Office prototype to BACS Class C, implementing each applicable control function at the minimum level required by the standard.
2. Upgrade the Class C model incrementally to Class B and Class A, with every change traceable to a specific BAC function and level in ISO 52120-1, and with each class accepted only after passing a staged quality-assurance procedure.
3. Evaluate performance for all three classes with a set of twenty-one key performance indicators covering primary energy (total and controlled), site energy by carrier, peak load, thermal comfort, ventilation delivery, and control adherence.
4. Repeat the analysis for a second climate to establish whether the class-upgrade effects are climate-robust or climate-dependent.

These objectives address the research questions: (i) What primary-energy saving does each class step ($C \rightarrow B$, $B \rightarrow A$) deliver for a representative commercial office building, and which individual control functions drive those savings? (ii) Does the BACS class hierarchy produce consistent efficiency gains across a cool continental European climate and a hot-humid North American climate? (iii) Do the comfort metrics support or qualify the energy headline?

1.4 Approach and Scope

The study uses EnergyPlus v25.2 [12] applied to the ASHRAE 90.1-2022 Medium Office prototype [13], a three-storey VAV office building of approximately 4,982 m². Of the 45 BAC functions defined in ISO 52120-1, 24 are applicable to the prototype; these are implemented across three locked model instances (Class C baseline, Class B, and Class A) with the Class A supervisory logic encoded in the EnergyPlus EnergyManagementSystem. Primary energy is computed with Italian national conversion factors [14]. The principal analysis uses the Turin/Caselle IWECC climate (CZ 5A boundary); a parallel run on Atlanta CZ 3A [12] serves as the cross-climate sensitivity check. Full methodological detail, including the change-by-change implementation record and QA gate procedure, is presented in chapter 4.

1.5 Contribution

The contribution of this thesis is a methodology and a set of results that together fill the gap identified in chapter 2. Three aspects distinguish the work from prior studies.

First, the implementation is *function-level and standards-faithful*: every control change is mapped to a specific BAC function number and level in ISO 52120-1, so the simulation output can be compared directly with the normative factor-method bands and with the findings of other explicit-simulation studies. The prior institutional precedents — the Albesiano (2023) [8] and Di Rosa (2025) [15] theses, both from Politecnico di Torino — model individual buildings but neither reports a full commercial C→B→A decomposition across two climates nor applies Italian primary-energy conversion factors consistently throughout.

Second, the results are *climate-validated*: the same model hierarchy is applied to two contrasting climates, enabling a direct test of whether the BACS class hierarchy is climate-robust. The Turin results show a C→A reduction in overall primary energy (K0) of 27.0%, with controlled end-use primary energy (KPI-CTRL: heating, cooling, fans, lighting, and pumps) falling by 48.1% C→A. The parallel Atlanta run yields a K0 saving of 28.9% and a KPI-CTRL saving of 48.0% C→A — a difference of only 0.1 percentage point, confirming that the BACS class hierarchy delivers essentially climate-independent efficiency gains on the controlled-energy metric. This finding is reported in full in chapter 6.

Third, the study is *reproducible and transparent*: each class model derives from a single frozen prototype via a documented sequence of per-function changes, and all simulation runs are archived with their input files, weather data, and version identifiers. The Class A supervisory logic — demand-controlled VAV fans, enthalpy-based economiser, load-dependent supply-air-temperature reset — is implemented in EnergyManagementSystem Runtime Language, providing an open, inspectable

record of the control sequences. This transparency is intended to support reuse, extension to other building types, and critical comparison with future studies.

1.6 Thesis Outline

The thesis is organised as follows.

chapter 2 reviews the state of the art in BACS energy assessment, covering the BAC-factor method, the growing body of explicit-simulation evidence, the per-function savings literature for the eight function groups most relevant to VAV office buildings, the climate sensitivity of those savings, and comfort trade-offs at advanced BACS classes. The chapter closes by establishing the specific research gap that motivates this thesis.

chapter 3 describes the normative foundation: the roles of EN ISO 52120-1:2022, EN ISO 52120-2:2022, and EN ISO 16484-4, the class-assignment method (consistency and applicability rules), and the full 45-function catalogue with the minimum required control level per function per class. Of the 45 functions, 24 are applicable to the office prototype studied here.

chapter 4 describes the reference building model, the weather files, the staged Class C calibration and C→B→A upgrade procedure, the twenty-one KPIs, and the dual-climate study design. Each implementation choice is cross-referenced to the normative function catalogue in chapter 3.

chapter 6 reports the simulation results. The primary analysis covers Turin/Caselle, with full end-use decomposition, carrier-level energy, monthly profiles, peak load, thermal comfort, ventilation adequacy, and solar-shading behaviour across the three BACS classes. A cross-climate section compares the headline KPIs for Turin and Atlanta.

The discussion and conclusions chapters interpret the results against the prior literature and the ISO factor-method bands, identify the limitations and accepted approximations of the modelling, and outline directions for future work.

Chapter 2

Literature Review

This chapter surveys the academic and normative evidence on which the present thesis rests. The review was conducted with an emphasis on verified primary sources: every quantitative claim that follows traces to a peer-reviewed paper whose digital object identifier was confirmed via the Crossref application programming interface, an official normative standard, or a national-laboratory technical report whose URL was independently verified. Conference proceedings and non-Q1 journals are included only where they represent the closest available precedent for a specific methodological question. The review is organised around six topics: the contribution of building automation to energy performance and the regulatory framework that quantifies it (§2.1); the two competing analytical approaches used to estimate class-transition savings, and the growing body of evidence that these two approaches diverge (§2.2); the per-function energy impact of individual control strategies (§2.3); the sensitivity of those impacts to climate and the comfort trade-offs that arise at high class levels (§2.4); and, finally, the research gap that motivates this thesis and the contribution it makes (§2.5).

2.1 Building Automation and Energy Performance

Building Automation and Control Systems (BACS) encompass the hardware, software, and services that regulate the energy-using systems of a building — heating, cooling, ventilation, lighting, and solar shading — together with the supervisory and monitoring infrastructure that supports their coordinated operation [1]. From an energy-performance perspective, BACS upgrades differ from fabric or plant upgrades in an important respect: they change the *way* existing plant is controlled, not the physical capacity of the plant itself. A variable-speed fan drive whose speed is governed by a demand supervisor consumes substantially less energy than the same drive operating at a fixed fraction of full speed, even though the rated power

and the ductwork are identical. This observation motivates a class hierarchy in which more capable control logic consistently outperforms less capable logic across a wide range of building configurations and climates.

The normative framework that underpins this hierarchy originates in the European standard EN 15232, which was published by the European Committee for Standardisation in 2007 and revised in 2017. The current edition is EN ISO 52120-1:2022 [1], which supersedes EN 15232 and integrates the earlier standard into the ISO 52000 family of building energy performance evaluation methods [2]. Part 2 of the standard provides the explanatory justification for the class definitions and factor tables [3]. The companion standard EN ISO 16484-4 [4] governs BACS application requirements at the technical implementation level.

ISO 52120-1 defines four BACS efficiency classes (D through A, in ascending capability), 45 automation functions distributed across heating, cooling, ventilation, lighting, shading, and technical building management, and two evaluation methods: a simplified BAC-factor method and a detailed dynamic simulation method [1]. Class D represents non-automatic or inadequate control; Class C represents standard BAC; Class B represents advanced BAC with room-level communication to the central system; and Class A additionally requires high-energy-performance BAC and Technical Building Management (TBM) functions. The four efficiency classes apply to non-residential buildings including offices, which are the focus of the present thesis and of the majority of the literature reviewed here.

The office building sector occupies a central position in BACS research, both because of its significant share of commercial energy consumption and because VAV air-handling systems, daylight-exposed perimeter zones, and variable occupancy profiles create a particularly rich opportunity for intelligent control. A systematic review of BACS impacts in office environments by Garzia et al. [5] documents that upgrading from Class C to Class A delivers average total energy savings of approximately 30% (primary energy basis), with the highest-performing cases in the review reaching approximately 39%. The same review documents non-energy benefits that are relevant to a comprehensive assessment: improved occupant productivity, reduced sick leave, and reduction of Sick Building Syndrome complaints. These comfort and well-being dimensions are returned to in §2.4.

2.2 Quantifying BACS Efficiency Classes: the Factor Method and Explicit Simulation

ISO 52120-1 provides two evaluation paths. The simplified BAC-factor method multiplies the controlled energy demand of a reference building by tabulated efficiency factors, one per energy carrier and BACS function category, to estimate the savings attributable to a class upgrade. The detailed path requires a full dynamic energy simulation with explicit control sequences [1]. The majority of studies in the

literature — and the majority of national energy-performance certificate schemes that incorporate BACS — use the factor method for its computational simplicity. An important body of evidence has accumulated, however, demonstrating that the factor method can diverge substantially from dynamic simulation results.

2.2.1 The BAC-factor method

ISO 52120-1 tabulates BAC efficiency factors as dimensionless multipliers applied to a reference controlled energy demand, with Class C defined as the unit reference (factor = 1.00) [1]. Separate factors are provided for thermal energy, electrical auxiliary energy, and lighting energy, and the values differ by building category (residential, non-residential) and by edition of the standard. The office-category numerical values are not reproduced here because the present thesis does not apply the factor method: the simulation-based evaluation path of ISO 52120-1 is used exclusively, and the factor-method bands serve only as an external reference point for the discussion in Chapter 7.

The factor method is intentionally conservative: it is designed to produce a lower bound on savings that can be applied reliably without building-specific simulation. Its application at the national policy level has made it the reference point against which subsequent simulation studies are compared. Table 2.1 summarises the reference savings values from the explicit-simulation studies closest to the present work, together with factor-method bands from Albesiano (2023) [8] — the only source reviewed here that reproduces the 2022-edition factors for a building modelled in EnergyPlus — as a directional illustration. This table provides the external validation anchor for Chapter 7.

2.2.2 Explicit dynamic simulation: evidence of factor-method divergence

The most direct comparison between the BAC-factor method and explicit dynamic simulation is provided by Vandenbogaerde, Audenaert and Verbeke [6], the only peer-reviewed journal study found in the evidence review that explicitly contrasts EN ISO 52120-1 factors with EnergyPlus simulation across multiple BACS class levels. In a parametric study encompassing 7,776 building variants across European climates, Vandenbogaerde et al. found that heating emission control savings ranged from 19% to 71% (C→A), and lighting control savings from 14% to 65% — a spread that the factor method, by construction, cannot reproduce. Their conclusion is that the BAC-factor method provides only a generic estimate and that actual savings are highly context-dependent. This finding is the principal methodological justification for the simulation approach adopted in the present thesis.

The finding extends to the residential sector. Van Thillo, Verbeke and Audenaert [17], reviewing BACS energy-demand potential in residential buildings,

Table 2.1. Reference savings values from the explicit-simulation studies closest to this thesis, with ISO 52120-1 factor-method bands included as a directional illustration only (see notes). Intended for the validation comparison in Chapter 7; this thesis’s own results are not shown here.

Study	Class-transition savings	Energy basis	Method / context
ISO 52120-1 factor bands ^a	C→B: −12% thermal, −13% aux-elec B→A: −9% thermal, −15% aux-elec C→A: −20% thermal, −26% aux-elec	Controlled final energy (factor-based)	BAC-factor method; not applied in this thesis
Jradi (2020) [16]	C→B: −23% heating, −34% elec; primary 194→111 kWh/m ² B→A, C→A: n/r	Site + primary (both)	EnergyPlus; EN 15232; Odense, DK
Albesiano (2023) [8] ^b	C→B: −24% heating, −12% fan B→A: −35% heating, −20% fan C→A: −51% heating, −29% fan	Sensible energy needs (site, not primary)	EnergyPlus/DesignBuilder; educational; Turin
Vandenbogaerde et al. (2026) [6]	C→A: 19–71% heating emission; 14–65% lighting (parametric range)	Controlled energy (simulation)	EnergyPlus; 7,776 variants; European climates

Notes: ^a Factor bands reproduced from Albesiano (2023) [8], which provides the closest available reproduction of the ISO 52120-1:2022 Annex A values for an EnergyPlus-modelled educational building; they are shown here as a directional illustration and are *not* verified as authoritative office-category values from the standard text. ^b Albesiano (2023) reports **site** energy needs; this thesis reports **primary** energy for a commercial medium office. Corroboration is directional (same order of magnitude), not a direct numeric match. Di Rosa (2025) [15] does not use a C→B→A class framing and is cited only as a per-function reference (§2.3). n/r = not reported.

report that simplified BAC-factor predictions and simulation outputs diverge significantly, driven by building design parameters and occupant behaviour patterns that the static factors cannot capture. The authors conclude explicitly that explicit simulation is necessary for reliable savings estimation.

A particularly stark illustration of factor-method error is provided by Bonomolo et al. [7], who applied the EN 15232 BAC factor for automated lighting control to two case studies in southern Italy and compared the predicted savings against empirical measurements. For daylight-responsive continuous dimming in a South Italian office and residential building, the BAC factor predicted an 8% reduction in lighting energy demand; measured savings were up to 38.4%. The discrepancy — roughly a factor of five — is explained by the Mediterranean climate’s high available daylight and the granularity of the installed dimming zones, which the

generic factor cannot reflect. The same case study demonstrates the relevance of the detailed simulation path for buildings where daylighting plays a substantial role, as it does in the medium office archetype used in this thesis.

Morkunaite et al. [18] develop an analytical model for BACS upgrade impacts on space heating, and find that accurate results require control parameterisation at the room level; simplistic control logic fails to maintain setpoints during high-occupancy transient events. The Albesiano thesis [8], conducted at Politecnico di Torino with the same primary supervisor, provides the most direct institutional precedent for the present work: Albesiano modelled an educational building (university classrooms) through Classes D, C, B, and A in EnergyPlus/DesignBuilder, and reported that the dynamic simulation gave C→B heating savings of -24% , compared with the factor-method prediction of -12% — a factor-of-two discrepancy on the same university campus, under the same Turin climate, using the same simulation engine.

The cumulative evidence from these studies supports a consistent conclusion: the BAC-factor method underestimates heating savings in heating-dominated climates and may either over- or underestimate individual function contributions depending on building type, climate, and control configuration. The explicit simulation path, while substantially more demanding in modelling effort, is the only approach that can resolve these discrepancies.

2.3 Energy Impact of Individual Control Functions

The ISO 52120-1 class hierarchy is built from 45 individual BAC functions. Understanding the marginal contribution of each function is necessary both for interpreting class-level savings and for identifying the control strategies that carry the greatest efficiency potential. The following subsections review the literature evidence for the eight function groups that are most directly relevant to the VAV medium-office archetype studied in this thesis. Where the literature contains verified savings figures, those figures are reported with their precise qualification as stated in the source.

2.3.1 Variable-speed fan drive and VAV flow control

Fan energy is the dominant component of auxiliary electricity in VAV air-handling systems, and variable-speed drives (VSDs) coupled to demand-responsive minimum-airflow control are the highest-leverage automation function in the class hierarchy. Zhang et al. [9] simulated the full ASHRAE Guideline 36 control sequence — which maps closely to the Class A suite of airside functions — in a medium office prototype using Spawn of EnergyPlus across 16 U.S. climate zones. They attributed

approximately 16.1% of the 31% average HVAC site energy savings to VAV minimum airflow reset alone, making it the single largest contributing function in the package.

At the field-validated end of the evidence, Delwati et al. [19] measured and simulated the interaction of demand-controlled ventilation (DCV) with fan-speed and duct pressure-reset in a Belgian office. Advanced pressure-reset control reduced fan energy by 72% to 93% compared with constant-air-volume operation (depending on occupancy level), and by approximately 10% compared with conventional DCV without pressure reset. The study identifies the key engineering trade-off: more aggressive pressure-reset produces larger fan savings but also creates a risk of airflow deficit when VAV valve accuracy is limited. This finding motivates the graduated treatment of fan minimum-flow fraction across BACS classes adopted in the methodology of the present thesis (see Chapter 4).

2.3.2 Supply-air temperature reset

Supply-air temperature (SAT) reset reduces cooling coil energy by raising the SAT when zone cooling loads are moderate, and reduces heating energy by adjusting the SAT warm bias in response to outdoor conditions. Zhang et al. [9] decompose the G36 package and attribute approximately 6.6% average HVAC site energy savings to SAT reset alone. Nassif et al. [20] simulate integrated SAT and minimum-airflow reset for VAV single-duct systems with reheat in EnergyPlus and report fan energy savings of 1.6% to 5.7% and heating savings of 7.7% to 33.7% depending on location, with laboratory validation confirming stable BACnet control performance. The large heating savings range underscores the climate dependence of the function.

Wang et al. [21] provide the most nuanced recent analysis of SAT reset behaviour across climates, using an EnergyPlus and Python co-simulation framework to evaluate cost-responsive SAT control in Oakland (mild/coastal) and New York City (humid continental). They find that SAT reset savings relative to a Guideline 36 baseline average approximately 4% across all cases, but diverge strongly by climate: Oakland achieves approximately 7% because abundant mild-weather economiser hours enable the SAT to be raised more frequently, while New York City achieves only approximately 0.6% because summer humidity constraints impose a maximum SAT floor that limits the reset range. This climate-humidity interaction is directly relevant to comparing Turin (cool, lower humidity) and Atlanta (hot-humid) in the present study, where an analogous asymmetry between heating-driven and cooling-driven climates is expected.

2.3.3 Demand-controlled ventilation

CO₂-based demand-controlled ventilation (DCV) modulates outdoor-air flow rates in response to occupant-generated carbon dioxide, reducing fan energy and ventilation thermal loads during partial-occupancy periods while maintaining indoor air quality (IAQ) targets. Merema et al. [22] measured DCV performance in real landscaped offices and classrooms in Belgium, reporting fan energy reductions of 25% to 55% relative to equivalent constant-air-volume design-flow operation, and ventilation heat-loss reductions of 25% to 32%. IAQ remained good in all measured cases, with proper commissioning identified as the critical success factor. Delwati et al. [19] provide complementary simulation and measurement evidence for the same Belgian office typology.

O'Neill et al. [23], reporting results of ASHRAE Research Project RP-1747 using EnergyPlus and CONTAM co-simulation, quantify DCV savings of 9% to 33% of HVAC source energy across U.S. climate zones including Atlanta, with ASHRAE 62.1 ventilation compliance maintained in 96% to 98% of occupied hours. The wide savings range reflects the strong climate dependence of ventilation thermal losses: humid, hot climates (where latent load penalises outdoor air intake) and cold climates (where heating the outdoor air is costly) both benefit substantially from DCV, but through different physical mechanisms. Sun, Wang and Ma [24] provide an early in-situ validation of adaptive multi-zone CO₂-based DCV in a real office building (Hong Kong), confirming the practical feasibility of the control strategy in a hot-humid climate analogous to Atlanta.

2.3.4 Daylight-responsive lighting control

Daylight-responsive dimming or switching can eliminate a substantial fraction of lighting electricity in perimeter office zones, and the ISO 52120-1 class hierarchy upgrades from manual-central control (Level 0, required at Class C) to automatic switching (Level 2, required at Class B) to integrated light/shading/HVAC coordination (Level 3, required at Class A). The magnitude of savings depends critically on the granularity of the lighting zones. Lowcay, Gunay and O'Brien [25] simulate high-resolution daylight and occupancy sensing in open-plan offices and find lighting savings exceeding 60% with fine zone control, falling below 35% when the zone size is coarser. This sensitivity to zone resolution motivates the use of per-perimeter-zone daylighting controllers in the EnergyPlus medium office prototype used in this thesis (12 controllers, one per perimeter zone window), as described in Chapter 4.

The empirical evidence of Bonomolo et al. [7] is relevant here as well: measured savings of up to 38.4% from continuous dimming in a southern European climate exceed the BAC-factor estimate by a factor of approximately five, with the difference attributed to the high available daylight intensity in the Mediterranean climate and the fine zone granularity of the installation.

2.3.5 Automated solar shading

Automated solar shading controls the transmission of solar radiation to interior spaces, balancing daylight admission, glare control, and cooling load management. The ISO 52120-1 class hierarchy moves from simple solar-irradiance-threshold triggering at Level 2 (required at Class C) to combined HVAC/lighting/shading coordination at Level 3 (required at Class B and A). The distinction matters energetically: a blind deployed whenever solar irradiance exceeds a threshold blocks solar gains in all seasons, including winter months when solar gain assists heating; a blind deployed only when HVAC cooling is active and solar irradiance is high is selectively deployed to eliminate the adverse solar contribution without sacrificing the beneficial winter gain.

Kunwar et al. [26] conduct full-scale experimental testing of dynamic venetian blinds integrated with daylight-responsive lighting control, reporting average cooling energy savings of 25.4% and lighting savings of 48.5%, with visual discomfort (glare) prevented for more than 85% of occupied time. Their results confirm that integrated shading and daylight control is not a comfort-versus-energy trade-off but a net win on both axes when implemented at the appropriate level of integration.

Uribe et al. [27] examine four active louver-control strategies across four cities (Montreal, Santiago, Boulder, and Miami) and find that no single universal control strategy minimises both energy use and visual discomfort across climates and orientations: the ranking of strategies reverses between the heating-dominated (Montreal/Boulder) and the hot-humid (Miami) cases. This climate-reversal finding is directly analogous to the Turin/Atlanta contrast in the present thesis, where the shading control results are expected to reflect the different thermal dominance of the two climates. Karlsen et al. [28] provide cold-climate analogue evidence from Norway: in a climate similar to Turin, an integrated shading strategy combining solar, glare, daylight, and view considerations achieves a satisfactory compromise between energy and indoor environment performance, confirming that the energy outcome cannot be evaluated without simultaneous assessment of occupant comfort.

2.3.6 Optimum start and stop

Optimum start and stop (also termed intermittent control of emission/distribution) reduces energy consumption by restricting the pre-occupancy preconditioning phase to the minimum time needed to reach setpoint at occupancy start, rather than a fixed-duration pre-heat/pre-cool cycle. Lin et al. [29] report results from a field evaluation of an occupancy-based HVAC control system in a real office building, using a calibrated EnergyPlus model for savings attribution: optimum start alone contributed 2.6% whole-building energy savings; early shutdown contributed 3.4%; and the full package (optimum start plus midday setpoint modulation plus early shutdown) achieved 6.1%. These figures establish the order of magnitude of the

optimum-start function as a standalone contributor, setting a lower bound for this function group in a typical commercial office.

2.3.7 Air-side free cooling (economiser)

Air-side free cooling (also termed the economiser function in ISO 52120-1) exploits outdoor-air conditions to reduce or eliminate mechanical cooling load by maximising outdoor-air intake when external conditions are more favourable than return-air conditions. ISO 52120-1 distinguishes Level 1 (night-purge only, required at Class C), Level 2 (dry-bulb free cooling over all periods, required at Class B), and Level 3 (enthalpy-based free cooling, required at Class A). The transition from temperature comparison (Level 2) to enthalpy comparison (Level 3) is particularly significant in humid climates, where outdoor air at a lower dry-bulb temperature but elevated humidity content may represent a higher total enthalpy than return air, making the dry-bulb economiser ineffective or counterproductive.

Justo Alonso et al. [30] study DCV strategies incorporating economiser-mode recirculation in a cold-climate office building (Trondheim) using EnergyPlus and CONTAM co-simulation, and document both the heating energy reduction from demand-controlled outdoor air and a specific cold-climate IEQ risk: aggressive recirculation at low ventilation rates can create a low indoor humidity environment in winter and, in buildings with particle sources, may elevate PM_{2.5} concentrations. These findings are relevant to the Turin climate results of the present thesis, where the cool-humid winter conditions create a different economiser operating envelope than the Atlanta hot-humid summer.

2.3.8 Room-level setpoint and airflow control

Room-level control — modulating terminal airflow and setpoints per zone in response to per-zone sensing — is the defining characteristic of Class B and Class A in the BACS hierarchy. Wang et al. [10] simulate occupancy-based control in the DOE medium office prototype across three U.S. climates (Miami, Baltimore, Chicago) using EnergyPlus, reporting whole-building energy savings of approximately 8% in Miami and approximately 13% in Baltimore and Chicago. The climate-dependence of these figures reflects the greater value of outdoor-air reduction in heating-dominated climates, where reducing ventilation thermal losses yields larger savings. Advanced people-counting strategies in the same study achieve 8% to 23% savings (climate-dependent), confirming that the room-level control granularity determines the achievable savings ceiling.

Pang et al. [11] quantify HVAC energy-saving potential for occupant-centric controls in office buildings across all U.S. climate zones using EnergyPlus, and find consistently higher savings in heating-dominated zones, attributing the pattern to the higher thermal value of outdoor-air reduction in cold climates. This nationwide

evidence supports the expectation, tested in the present thesis, that the Class A room-level and DCV functions will produce a larger heating-side saving in Turin than in Atlanta.

2.4 Climate Sensitivity and Thermal Comfort

2.4.1 Climate dependence of BACS savings

The individual-function evidence reviewed in §2.3 already points to strong climate dependence in several function categories. At the class level, the parametric study by Vandenbogaerde et al. [6] provides the most direct quantification: across 7,776 EnergyPlus variants spanning European climate zones, C→A heating emission control savings ranged from 19% to 71%, demonstrating that the static BAC factor cannot capture the true variability. No single peer-reviewed study found in this evidence review reports class-level C→B and B→A savings simultaneously for both a heating-dominated and a cooling-dominated climate from a single standardised building model. This is precisely the gap that the present thesis is designed to fill.

The climate sensitivity of individual functions is well documented for SAT reset, DCV, and shading. Wang et al. [21] show that SAT reset savings drop from approximately 7% in a mild coastal climate to approximately 0.6% in a humid continental climate due to humidity-constrained maximum SAT limits. O'Neill et al. [23] report a 9–33% DCV savings range across U.S. climates including Atlanta. Wang et al. [10] report whole-building occupancy-control savings of 8% in Miami versus 13% in Baltimore and Chicago, attributing the heating-climate advantage to the higher thermal cost of outdoor air in cold conditions. Pang et al. [11] confirm this pattern at the nationwide scale.

These findings establish a consistent picture: BACS functions that modulate outdoor-air flow (DCV, economiser) and supply-air temperature carry a larger absolute saving in heating-dominated climates because the energy cost of conditioning outdoor air is higher; functions that modulate solar gains and lighting (shading, daylight control) are more sensitive to solar availability and may behave differently between mild-continental (Turin) and hot-humid (Atlanta) climates, as Uribe et al. [27] show.

2.4.2 Thermal comfort and IEQ trade-offs at advanced BACS classes

A recurring concern in the BACS literature is whether energy savings achieved through more aggressive demand-based control come at the cost of reduced thermal comfort or indoor air quality. The evidence is nuanced: properly configured Class A controls generally maintain or improve comfort, but specific configurations and climates can create identifiable IEQ trade-offs that require explicit management.

Merema et al. [22] find that DCV with proper commissioning preserves good IAQ in all measured cases, with negligible impact on ventilation effectiveness at reduced flow rates. O’Neill et al. [23] confirm that ASHRAE 62.1 ventilation adequacy is maintained in 96% to 98% of occupied hours under CO₂-based DCV, a compliance rate generally regarded as acceptable.

Delwati et al. [19] identify the key comfort risk for Class A fan controls: when VSD pressure-reset is tuned too aggressively, the resulting airflow deficit can compromise zone temperature control and IAQ. The trade-off is not a consequence of Class A per se, but of specific parameter choices for the demand supervisor, and it is manageable by setting a conservative minimum flow fraction. This is the motivation for the accepted representation limitation documented in the present thesis (§4.5.4).

Wang et al. [10] confirm, using full-year EnergyPlus simulation, that occupancy-based VAV terminal control achieves ventilation compliance for all occupied hours when the zone minimum airflow is set following ASHRAE 62.1 procedures. Kunwar et al. [26] demonstrate that integrated dynamic blind and daylight control prevents visual discomfort (glare) for more than 85% of occupied time while delivering substantial cooling and lighting savings.

In cold-climate configurations, Justo Alonso et al. [30] document the PM_{2.5} accumulation risk when aggressive DCV recirculation is combined with low outdoor-air rates: the cold-climate analogue for Turin — where outdoor air in winter is cold and sometimes humid — creates a different risk profile from the Atlanta hot-humid case, where outdoor-air restriction limits latent-load exposure rather than particle accumulation. Karlsen et al. [28] confirm that in cold climates, automated solar shading must be assessed jointly on energy, daylight, glare, and view criteria, as single-criterion optimisation degrades the occupant experience.

At the building-scale level, Garzia et al. [5] review the broader comfort and well-being outcomes of BACS in offices, documenting that advanced BACS — when well implemented — reduces the frequency of thermal discomfort complaints associated with schedule-based overcooling and overheating. The improved zone-level control granularity of Class A is identified as the primary mechanism.

2.5 Research Gap and Contribution of This Thesis

The academic literature on building automation energy savings divides into two well-populated but largely disconnected bodies. The first applies the EN 15232 / ISO 52120-1 BAC-factor method to obtain aggregate class-level savings estimates for office buildings [1, 5]. The second explicitly simulates individual control strategies — VSD fans, SAT reset, DCV, daylighting, solar shading, optimum start — in

dynamic energy tools such as EnergyPlus, reporting per-function savings percentages [9, 20, 21, 22, 23, 25, 26, 27, 29, 10, 11]. The bridge between these two bodies is almost entirely absent.

As of the evidence reviewed here, only Vandenbogaerde, Audenaert and Verbeke [6] (2026, *Energy Efficiency*) explicitly contrast EN ISO 52120-1 BAC factors with EnergyPlus numerical simulation across class levels in European offices, and do so through a large-scale parametric study rather than a standards-faithful function-by-function implementation. The individual-function simulation studies cited above use ASHRAE Guideline 36 framing [9] or occupancy-centric terminology [10, 11] rather than the ISO 52120 class vocabulary, making a direct comparison with the normative factor-method bands methodologically ambiguous.

The two prior Politecnico di Torino theses are the closest institutional precedent. Albesiano (2023) [8] implements all four BACS classes in EnergyPlus/DesignBuilder for an educational building (university classrooms) in Turin, and directly compares simulation against factor-method predictions. Di Rosa (2025) [15] models improvement scenarios for a residential-hotel building in Turin using EnergyPlus. Neither study is a commercial medium office. Neither reports a full $C \rightarrow B \rightarrow A$ transition decomposed by individual function contribution across two climates. Neither applies primary energy conversion factors consistently with Italian national requirements throughout the analysis.

No peer-reviewed study found in this review simultaneously: (a) implements each ISO 52120-1 class-defining control function explicitly in EnergyPlus; (b) spans Classes C, B, and A with per-function end-use decomposition; and (c) tests the result across both a cold-continental European climate and a hot-humid North American climate using a single, frozen reference building model. The availability of the Spawn of EnergyPlus co-simulation framework [31] and the comprehensive PNNL commercial building controls study [32] demonstrate the technical frontier for explicit BACS simulation, but neither provides an ISO 52120-framed, $C \rightarrow B \rightarrow A$ office study.

The present thesis fills this gap by implementing the ISO 52120-1 BAC function catalogue explicitly in EnergyPlus 25.2 [12] for the ASHRAE 90.1-2022 Medium Office prototype [13], applying primary energy conversion factors per Italian national standards [14], and comparing the simulation results against both the ISO factor-method bands and the closest prior explicit-simulation studies. The methodology is described in Chapter 4 and the results are reported in Chapter 6.

Chapter 3

BACS and ISO 52120 Framework

This chapter establishes the normative context for the thesis. It describes the three interlocking standards that define Building Automation and Control System (BACS) efficiency classification, explains the class-assignment method, and catalogues all 45 Building Automation and Control (BAC) functions together with their required control levels per class. The chapter is intentionally normative: it reports what the standards require; the implementation choices made for the simulation models are described in Chapter 4.

3.1 Standards and their roles

Three standards form the normative backbone of the thesis. Together they define what a BAC function is, how it maps to an efficiency class, and how it is specified at the functional level for implementation.

3.1.1 EN ISO 52120-1:2022

EN ISO 52120-1:2022 [1] is the primary standard. It provides: (a) a structured list of BAC and Technical Building Management (TBM) functions that contribute to building energy performance; (b) a method to define minimum requirements per efficiency class; (c) a factor-based method for a first estimation of function effects; and (d) detailed methods to assess the effects on a specific building. Within the ISO 52000-1 modular Energy Performance of Buildings (EPB) framework, BACS is module M10. The standard does not itself perform energy calculations; the underlying EPB modules M1–M9 use identifiers supplied by M10 in order to avoid double-counting.

Key definitions used throughout this thesis are drawn from clause 3 of 52120-1 [1]. *BAC* (clause 3.2) encompasses the products, software, and engineering services for automatic controls, monitoring and optimisation, human intervention, and management that achieve energy-efficient, economical, and safe operation of building services equipment. *BACS* (clause 3.3) is the system comprising those products, software, and services (including interlocks), and may also be referred to as a Building Management System (BMS). *TBM* (clause 3.13) denotes the processes and services related to operation and management of buildings and technical building systems through interrelationships between disciplines, including energy optimisation. *Technical building system* (clause 3.14) covers the technical equipment for heating, cooling, ventilation, humidification, dehumidification, domestic hot water (DHW), lighting, and electricity production.

3.1.2 EN ISO 52120-2:2022

EN ISO 52120-2:2022 [3] is the companion calculation standard. It provides tables that map BAC-function types to companion standards (EN 16798-5-1, EN 16798-5-2, and EN 16798-7) that are in turn mapped to Table 5 of 52120-1. Where 52120-1 classifies functions by efficiency level, 52120-2 supplies the quantitative procedures needed to evaluate the energy impact of those functions on a given building.

3.1.3 EN ISO 16484-4:2025

EN ISO 16484-4:2025 [4] specifies control applications and function blocks for BACS, focusing on, but not limited to, lighting, solar protection, and Heating, Ventilation, and Air Conditioning (HVAC). It translates energy-performance, comfort, and operational requirements into functional specifications for integrated plant and room control. Clause 5 is expressly restricted to automated control only, excluding manual and non-automated controls that appear in Table 5 of 52120-1. This standard supersedes EN ISO 17609:2022; the present thesis uses the 16484-4 edition throughout and treats 17609 references in earlier literature as equivalent to 16484-4 for the purposes of functional definitions.

3.1.4 Interlocking of the three standards

The three standards operate at different layers. 52120-1 defines the classification framework and assigns minimum levels per function per class. 52120-2 provides the assessment procedures that quantify energy savings attributable to each level. 16484-4 translates the abstract level descriptions into specific control-application function blocks, enabling unambiguous implementation in a BACS or simulation model. In practice, 52120-1 is the classification authority; 16484-4 is the implementation specification; and 52120-2 is the calculation method. Chapter 4 maps each

IDF object or EMS programme to the applicable function and level defined in §3.3.

3.2 BACS efficiency classification

The efficiency-class method is defined in clauses 5.5–5.6 of 52120-1 [1]. Four classes are defined: D, C, B, and A (Figure 3.1).

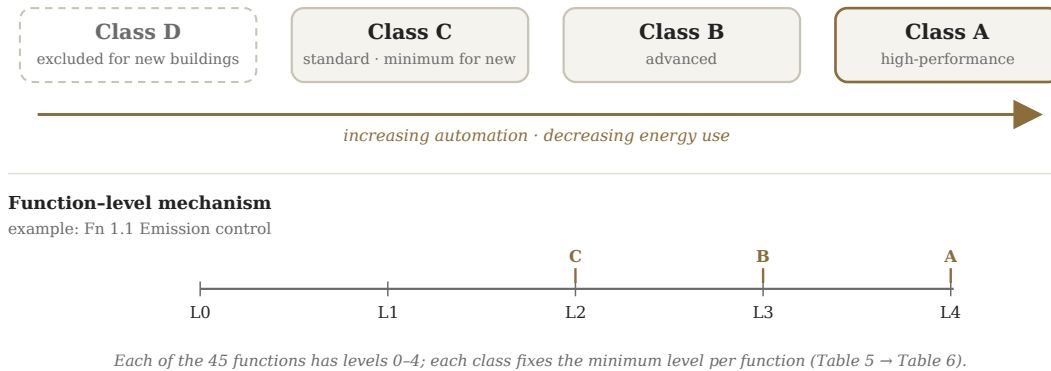


Figure 3.1. ISO 52120-1 BACS efficiency classes (Class D excluded for new buildings) and the function-level mechanism: each function has levels 0–4 and each class sets the minimum required level per function (Table 5 / Table 6).

Class D represents non-energy-efficient BACS. The standard states that buildings equipped with Class D systems shall be retrofitted, and that new buildings shall not be built with such systems. Class D is the baseline from which upgrades are measured.

Class C is designated “standard BAC”. To qualify, the minimum BAC functions listed in Table B.1 of the standard shall be implemented.

Class B is designated “advanced BAC plus some specific TBM functions”. In addition to all Class C requirements, the BAC functions and the specific functions identified in Table 5 of the standard shall be implemented, and room controllers shall communicate with the building automation system.

Class A is designated “high-energy-performance BAC and TBM functions”. In addition to all Class B requirements, the TBM functions and specific functions identified in Table 5 shall be implemented; room controllers shall be available for demand-controlled HVAC, supporting adaptive setpoints based on occupancy and air quality and including integrated multi-discipline interrelationships covering lighting and shading.

The **consistency rule** requires that, to be assigned a given class, all implemented BAC functions that are marked in Table 6 of the standard shall correspond

to the indicated minimum levels for that class. A single function implemented below the class minimum downgrades the whole system.

The **applicability rule** limits assessment to functions that have a relevant impact. Functions controlling or monitoring plant not installed need not be considered. A 5% materiality threshold applies: a BAC or TBM function whose energy impact represents less than 5% of total building energy consumption need not be taken into account.

BAC functions are organised into seven numbered sections (Sections 1–7) covering heating, domestic hot water, cooling, ventilation and air conditioning, lighting, blind control, and technical building management. The present thesis addresses a non-residential office building, and §3.3 below applies the applicability rule to identify the 24 functions relevant to the model out of the full catalogue of 45.

3.3 BAC function catalogue

In the function tables below, the *Class* column marks the minimum level required by each BACS efficiency class; a blank cell means no class mandates that level (it corresponds to the Class D baseline).

3.3.1 Heating control

Section 1 of 52120-1 [1] defines ten functions governing emission, distribution, intermittent operation, and heat generation for heating systems. Functions 1.2–1.4a, 1.7–1.10 are not applicable to the model building, which uses a single-zone all-air system with no hydronic heating distribution, no TABS, no heat pumps, and no thermal energy storage.

3.3.1.1 Function 1.1 — Emission control (heating)

Definition. Automatic control of the heat emission to each heated room or zone, acting on the indoor air temperature to bring it to the set-point.

Lvl	Level of BAC function	Applicability	Class
0	no automatic control of room temperature	Applicable	C
1	central automatic control acting on distribution or generation		
2	individual room control (thermostatic valves or electronic controller)		
3	individual modulating room control with communication to BACS (e.g. scheduler, setpoint)		B
4	individual modulating room control with communication and occupancy detection		A

3.3.1.2 Function 1.2 — Emission control for TABS (heating mode)

Definition. Controls the supply water temperature set-point for thermally activated building system (TABS) zones used as room-level heating emitters.

Lvl	Level of BAC function	Applicability	Class
0	no automatic control of room temperature	N/A	C
1	central automatic control (supply water temperature setpoint based on 24 h average outdoor temperature)		
2	advanced central control tuned for optimal self-regulating comfort range with minimised heating energy demand		B
3	advanced central control with intermittent operation and/or room temperature feedback		A

Not applicable: the model building has no thermally activated building systems (TABS).

3.3.1.3 Function 1.3 — Control of distribution network hot water temperature

Definition. Regulates the supply or return water temperature of the hydronic heating distribution network as a function of outdoor temperature or indoor demand.

Lvl	Level of BAC function	Applicability	Class
0	no automatic control		
1	outside-temperature compensated control (actions lower the mean flow temperature)	N/A	C
2	demand-based control (e.g. based on indoor temperature control variable)		B, A

Not applicable: the model building has no hydronic heating distribution network.

3.3.1.4 Function 1.4 — Control of distribution pumps in heating networks

Definition. Controls the speed or on/off status of circulation pumps in the hydronic heating distribution network to reduce auxiliary electrical energy consumption.

Lvl	Level of BAC function	Applicability	Class
0	no automatic control		
1	on/off control (pumps switch on/off automatically at maximum speed)	N/A	C
2	multi-stage speed control		B
3	variable speed pump control — constant or variable Δp based on pump-unit internal estimation		A
4	variable speed pump control — variable Δp following external demand signal		

Not applicable: no hydronic heating distribution pumps in the model building.

3.3.1.5 Function 1.4a — Hydronic balancing of heating distribution

Definition. Provides static or dynamic hydraulic balancing of the heating distribution network to equalise flow across all heat emitters.

Lvl	Level of BAC function	Applicability	Class
0	no balancing		
1	static balance per emitter, no group balance		
2	static balance per emitter plus static group balance (e.g. balancing valve)	N/A	
3	static balance per emitter plus dynamic group balance (e.g. differential-pressure control)		C
4	dynamic balance per emitter (e.g. differential-pressure controllers)		B, A

Not applicable: no hydronic heating distribution network in the model building.

3.3.1.6 Function 1.5 — Intermittent control of emission and/or distribution (heating)

Definition. Reduces the operating time of heating emission and distribution systems through scheduled, optimum-start, or demand-driven intermittent control.

Lvl	Level of BAC function	Applicability	Class
0	no automatic control		
1	automatic control with fixed time programme (reduces operating hours)	Applicable	C
2	automatic control with optimum start/stop (reduces operating hours)		B
3	automatic control with demand evaluation (reduces operating hours)		A

3.3.1.7 Function 1.6 — Heat generator control for combustion and district heating

Definition. Adjusts the output temperature of a combustion boiler or district-heating connection as a function of outdoor temperature or system heating load.

Lvl	Level of BAC function	Applicability	Class
0	constant temperature control		
1	variable temperature control depending on outside temperature	Applicable	C
2	variable temperature control depending on load (e.g. supply water temperature setpoint)		B, A

3.3.1.8 Function 1.7 — Heat generator control (heat pump)

Definition. Adjusts the output temperature of a heat-pump generator as a function of outdoor temperature or system load to maximise its seasonal efficiency.

Lvl	Level of BAC function	Applicability	Class
0	constant temperature control		
1	variable temperature control depending on outside temperature	N/A	C
2	variable temperature control depending on load		B, A

Not applicable: the model building has no heat pump for heating.

3.3.1.9 Function 1.8 — Heat generator control (outdoor unit)

Definition. Controls the heating capacity of a VRF or split-system outdoor unit in response to load or demand signals to match the building's heating requirements.

Lvl	Level of BAC function	Applicability	Class
0	on/off control of heat generator		
1	multi-stage capacity control depending on load or demand	N/A	C, B
2	variable capacity control depending on load or demand (e.g. inverter frequency control)		A

Not applicable: no VRF outdoor unit in the model building.

3.3.1.10 Function 1.9 — Sequencing of different heat generators

Definition. Manages the activation order of multiple heat generators with different efficiencies or energy sources to prioritise the most efficient source at each load condition.

Lvl	Level of BAC function	Applicability	Class
0	priorities based on running time only	N/A	C
1	control according to fixed priority list (e.g. heat pump prior to boiler)		
2	control according to dynamic priority list (based on current efficiency and capacity)		B
3	control according to prediction-based dynamic priority list		A

Not applicable: the model building has a single heat generator; sequencing is not relevant.

3.3.1.11 Function 1.10 — Control of thermal energy storage charging (heating)

Definition. Controls the charging cycle of a thermal energy storage device in the heating system, scheduling or predicting when to store heat for later use.

Lvl	Level of BAC function	Applicability	Class
0	continuous storage operation	N/A	C, B
1	two-sensor charging of storage		
2	load-prediction-based storage operation		A

Not applicable: no thermal energy storage for heating in the model building.

3.3.2 Domestic hot water supply control

Section 2 defines four functions covering DHW storage charging, solar collector integration, and circulation-pump control. Functions 2.1 and 2.3 are not applicable to the model; Function 2.4 is conditional.

3.3.2.1 Function 2.1 — Control of DHW storage charging with direct electric heating or integrated electric heat pump

Definition. Controls the on/off charging of a domestic hot water storage vessel heated by a direct electric element or an integrated electric heat pump.

Lvl	Level of BAC function	Applicability	Class
0	automatic on/off control		
1	automatic on/off control plus scheduled charging enable	N/A	C
2	automatic on/off control, scheduled charging enable, and multi-sensor storage management		B, A

Not applicable: the model building uses hot-water generation (not direct electric) for DHW.

3.3.2.2 Function 2.2 — Control of DHW storage charging using hot water generation

Definition. Controls the charging of a domestic hot water storage vessel supplied by a central hot-water generator, scheduling charging periods and optionally managing supply temperature.

Lvl	Level of BAC function	Applicability	Class
0	automatic on/off control		
1	automatic on/off control plus scheduled charging enable	Applicable	C
2	automatic on/off control, scheduled charging enable, and demand-based supply temperature control or multi-sensor storage management		B, A

3.3.2.3 Function 2.3 — Control of DHW storage charging with solar collector and supplementary heat generation

Definition. Manages the priority sequencing of solar collector charging and supplementary heat source charging for a domestic hot water storage vessel.

Lvl	Level of BAC function	Applicability	Class
0	manual control		
1	automatic control of solar storage charge (priority 1) and supplementary charge (priority 2)	N/A	C
2	automatic control of solar/supplementary charge plus demand-based supply temperature control or multi-sensor storage management		B, A

Not applicable: the model building has no solar collector for DHW.

3.3.2.4 Function 2.4 — Control of DHW circulation pump

Definition. Controls the operation of the domestic hot water recirculation pump, switching it according to a time programme to maintain water availability while limiting pump run time.

Lvl	Level of BAC function	Applicability	Class
0	no control, continuous operation	Conditional	C, B, A
1	controlled by time programme		

Conditional: applicable only if a DHW circulation pump is present; the model building has a simple DHW system without a dedicated recirculation loop.

3.3.3 Cooling control

Section 3 defines nine functions covering emission, distribution, intermittent operation, interlock, and cold generation for cooling systems. Functions 3.2, 3.4, 3.4a, 3.8, and 3.9 are not applicable to the model.

3.3.3.1 Function 3.1 — Emission control (cooling)

Definition. Controls the cooling emission to each room or zone, acting on the indoor air temperature to bring it to the cooling set-point.

Lvl	Level of BAC function	Applicability	Class
0	no automatic control of room temperature	Applicable	C
1	central automatic control acting on distribution or generation		
2	individual room control (thermostatic valves or electronic controller)		
3	individual modulating room control with communication to BACS		
4	individual modulating room control with communication and occupancy detection		

3.3.3.2 Function 3.2 — Emission control for TABS (cooling mode)

Definition. Controls the supply chilled-water temperature set-point for thermally activated building system (TABS) zones used as room-level cooling emitters.

Lvl	Level of BAC function	Applicability	Class
0	no automatic control of room temperature		
1	central automatic control (supply water temperature setpoint based on filtered outdoor temperature)	N/A	C
2	advanced central control tuned for optimal comfort range; chilled-water temperature maintained as high as possible		B
3	advanced central control with intermittent operation and/or room temperature feedback		A

Not applicable: the model building has no TABS for cooling.

3.3.3.3 Function 3.3 — Control of distribution network chilled water temperature

Definition. Regulates the supply or return chilled-water temperature of the cooling distribution network as a function of outdoor conditions or indoor cooling demand.

Lvl	Level of BAC function	Applicability	Class
0	constant temperature control		
1	outside-temperature compensated control (actions raise the mean flow temperature)	Conditional	C
2	demand-based control (e.g. based on indoor temperature control variable)		B, A

Conditional: applicable only if a chilled-water distribution network is present; the model building uses a direct-expansion (DX) system with no separate chilled-water distribution loop.

3.3.3.4 Function 3.4 — Control of distribution pumps in cooling networks

Definition. Controls the speed or on/off status of pumps in the hydronic cooling distribution network to reduce auxiliary electrical energy consumption.

Lvl	Level of BAC function	Applicability	Class
0	no automatic control		
1	on/off control (reduces auxiliary energy demand)		C
2	multi-stage control	N/A	B
3	variable speed pump control — constant or variable Δp based on pump-unit estimation		A
4	variable speed pump control — variable Δp following external demand signal		

Not applicable: no hydronic cooling distribution pumps in the model building.

3.3.3.5 Function 3.4a — Hydronic balancing of cooling distribution

Definition. Provides static or dynamic hydraulic balancing of the cooling distribution network to equalise flow and supply temperature across all cooling emitters.

Lvl	Level of BAC function	Applicability	Class
0	no balancing		
1	static balance per emitter, no group balance		
2	static balance per emitter plus static group balance	N/A	
3	static balance per emitter plus dynamic group balance		C
4	dynamic balance per emitter		B, A

Not applicable: no hydronic cooling distribution network in the model building. (Note: a discrepancy exists between Table B.1 (NR min = 1) and Table 6 (NR Class C = 3) of 52120-1 [1]; Table 6 is treated as binding.)

3.3.3.6 Function 3.5 — Intermittent control of emission and/or distribution (cooling)

Definition. Reduces the operating time of cooling emission and distribution systems through scheduled, optimum-start, or demand-driven intermittent control.

Lvl	Level of BAC function	Applicability	Class
0	no automatic control		
1	automatic control with fixed time programme (reduces operating hours)	Applicable	C
2	automatic control with optimum start/stop (reduces operating hours)		B
3	automatic control with demand evaluation (reduces operating hours)		A

3.3.3.7 Function 3.6 — Interlock between heating and cooling emission/distribution control

Definition. Coordinates the heating and cooling emission or distribution control loops to prevent simultaneous operation in the same room or zone.

Lvl	Level of BAC function	Applicability	Class
0	no interlock (heating and cooling can operate simultaneously)	Applicable	
1	partial interlock (minimises possibility of simultaneous heating and cooling)		C, B
2	total interlock (guarantees no simultaneous heating and cooling)		A

3.3.3.8 Function 3.7 — Generator control for cooling

Definition. Adjusts the chilled-water or refrigerant outlet temperature of the cooling generator as a function of outdoor conditions or system load to maximise its efficiency.

Lvl	Level of BAC function	Applicability	Class
0	constant temperature control		
1	variable temperature control depending on outside temperature	Applicable	C, B
2	variable temperature control depending on load (includes room temperature feedback)		A

3.3.3.9 Function 3.8 — Sequencing of different chillers (generators for chilled water)

Definition. Manages the activation order of multiple chillers with different capacities or energy sources to maximise overall plant efficiency at each load condition.

Lvl	Level of BAC function	Applicability	Class
0	priorities based on running time only		
1	fixed sequencing based on loads only	N/A	C
2	priorities based on generator efficiency and characteristics		B
3	load-prediction-based sequencing (based on <i>COP</i> and available power)		A

Not applicable: the model building has a single cooling generator; sequencing is not relevant.

3.3.3.10 Function 3.9 — Control of thermal energy storage charging (cooling)

Definition. Controls the charging cycle of a thermal energy storage device in the cooling system, scheduling or predicting when to store cooling capacity for later use.

Lvl	Level of BAC function	Applicability	Class
0	continuous storage operation		
1	time-scheduled storage operation	N/A	C
2	load-prediction-based storage operation		B, A

Not applicable: no thermal energy storage for cooling in the model building.

3.3.4 Ventilation and air-conditioning control

Section 4 defines ten functions covering room-level supply air flow, room temperature control, outside-air flow, Air Handling Unit (AHU) pressure control, heat recovery, free cooling, supply air temperature, and humidity control. Functions 4.3, 4.6, 4.7, and 4.10 are not applicable to the model building.

3.3.4.1 Function 4.1 — Supply air flow control at the room level

Definition. Controls the availability or volume of supply air delivered to each room, varying it by time schedule, occupancy detection, or indoor air-quality demand.

Lvl	Level of BAC function	Applicability	Class
0	no automatic control (system runs constantly)	Applicable	C, B
1	time control (system runs according to a given time schedule)		
2	occupancy-based control (presence/light switch/infrared sensors)		
3	demand-based control (air quality demand; measurement of CO ₂ , VOC, etc.)		A

3.3.4.2 Function 4.2 — Room air temperature control by the ventilation system (all-air systems)

Definition. Controls the room air temperature through an all-air ventilation system by varying supply air flow rate, supply air temperature, or a combination of both.

Lvl	Level of BAC function	Applicability	Class
0	on/off control (fixed air flow rate and fixed supply air temperature; setpoints set individually)	Applicable	C
1	continuous control (air flow rate or supply air temperature varied continuously)		
2	optimised control (minimum energy demand by controlling both air flow rate and supply air temperature depending on heating/cooling load)		B, A

3.3.4.3 Function 4.3 — Coordination of room temperature control by ventilation and by static system

Definition. Coordinates the room air temperature control loops of the all-air ventilation system and a separate static heating or cooling emission system to avoid conflicting simultaneous operation.

Lvl	Level of BAC function	Applicability	Class
0	interaction not coordinated (independent closed-loop controllers for each system)	N/A	C, B, A
1	interaction coordinated (one closed-loop controller; the other system conditions the room to benefit from heat gains only)		

Not applicable: the model building uses an all-air system only; no separate static heating/cooling emission system requires coordination. (Note: a discrepancy exists between Table B.1 (NR min = 0) and Table 6 (NR Class C = 1) of 52120-1 [1]; Table 6 is binding but the function is N/A for this project.)

3.3.4.4 Function 4.4 — Outside air (OA) flow control

Definition. Controls the quantity of outdoor air introduced by the ventilation system through a fixed ratio, time-scheduled staged switching, occupancy-based switching, or continuous demand-controlled ventilation.

Lvl	Level of BAC function	Applicability	Class
0	fixed OA ratio or OA flow (modified manually only)	Applicable	C, B
1	staged (low/high) OA ratio or OA flow depending on a given time schedule		
2	staged (low/high) OA ratio or OA flow depending on occupancy		
3	variable control based on sensors detecting occupants or indoor air parameters (CO ₂ , mixed gas, or VOC)		A

3.3.4.5 Function 4.5 — Air flow or pressure control at the air handler level

Definition. Controls the total supply air flow rate or duct static pressure at the air handling unit to match the aggregated demand of all connected rooms while minimising fan energy.

Lvl	Level of BAC function	Applicability	Class
0	no automatic control (continuously supplies air flow for maximum load of all rooms)		
1	on/off time control (supplies air flow for maximum load during nominal occupancy time)	Applicable	C
2	multi-stage control (reduces auxiliary fan energy demand)		B
3	automatic flow or pressure control without pressure reset (load-dependent air flow for connected rooms)		A
4	automatic flow or pressure control with pressure reset (load-dependent air flow; for VAV systems with VFD)		

3.3.4.6 Function 4.6 — Heat recovery control: icing protection

Definition. Prevents frost formation on the heat-recovery exchanger by maintaining the exhaust air outlet temperature above a minimum threshold through modulation or bypass control.

Lvl	Level of BAC function	Applicability	Class
0	no icing protection control		
1	icing protection control (exhaust air temperature at heat exchanger outlet maintained above frost threshold)	N/A	C, B, A

Not applicable: the model building climate does not require heat-recovery icing protection as a distinct control function.

3.3.4.7 Function 4.7 — Heat recovery control: prevention of overheating

Definition. Prevents unwanted heat transfer at the heat-recovery exchanger during warm periods by switching the unit off or to bypass when its thermal effect would increase rather than reduce energy demand.

Lvl	Level of BAC function	Applicability	Class
0	no overheating prevention control	N/A	C, B, A
1	overheating prevention control (control loop switches between off/modulation/bypass states when heat exchanger effect is no longer positive)		

Not applicable: the model building does not include a heat-recovery unit with modulating bypass.

3.3.4.8 Function 4.8 — Free mechanical cooling

Definition. Exploits cool outdoor air to satisfy the building's cooling demand, either through night-time purge or continuous economiser control, reducing or eliminating the need for mechanical refrigeration.

Lvl	Level of BAC function	Applicability	Class
0	no automatic control	Applicable	C
1	night cooling (outside air set to maximum during unoccupied periods when $T_{\text{room}} > \text{comfort setpoint}$ and $T_{\text{room}} - T_{\text{out}} > \text{given limit}$)		
2	free cooling (outside air and recirculation air modulated during all periods to minimise mechanical cooling; based on temperatures)		B
3	enthalpy-based control (outside air and recirculation air modulated based on temperatures and humidity/enthalpy)		A

3.3.4.9 Function 4.9 — Supply air temperature control at the AHU level

Definition. Determines and controls the supply air temperature set-point at the air handling unit, using a constant value, outdoor-temperature compensation, or load-dependent reset.

Lvl	Level of BAC function	Applicability	Class
0	no automatic control (no control loop acts on supply air temperature)	Applicable	C
1	constant setpoint (control loop controls supply air temperature; setpoint modified only by manual action)		
2	variable setpoint with outside-temperature compensation (setpoint is a function of outside temperature)		
3	variable setpoint with load-dependent compensation (setpoint defined as a function of room loads; requires integrated collection of room temperatures or actuator positions)		A

3.3.4.10 Function 4.10 — Humidity control

Definition. Controls the moisture content of the supply or room air through humidification or dehumidification plant to maintain a target dew-point or relative-humidity set-point.

Lvl	Level of BAC function	Applicability	Class
0	no automatic control	N/A	C
1	dew-point control (supply air or room air humidity expressed as dew-point temperature; reheat applied to reach relative-humidity setpoint)		
2	direct humidity control (supply air or room air humidity at a given setpoint; setpoint fixed or optimised within min/max limits)		B, A

Not applicable: the model building has no active humidification or dehumidification plant.

3.3.5 Lighting control

Section 5 defines two functions for lighting: occupancy control and daylight harvesting. Both are applicable to the model building.

3.3.5.1 Function 5.1 — Occupancy control (lighting)

Definition. Controls the switching or dimming of luminaires in response to room occupancy, reducing unnecessary lighting energy in unoccupied spaces.

Lvl	Level of BAC function	Applicability	Class
0	manual on/off switch only	Applicable	C, B, A
1	manual on/off switch plus automatic sweeping extinction signal (switches off at least once daily)		
2	automatic detection — auto on/dimmed off (luminaire switches on when occupied; dims automatically after last occupancy)		
3	automatic detection — manual or partial auto on/dimmed off (luminaire switched on manually or by sensor; dims automatically after last occupancy)		

3.3.5.2 Function 5.2 — Light level/daylight control (daylight harvesting)

Definition. Adjusts the output of luminaires in response to the available daylight level, switching or dimming them to maintain the required illuminance while minimising electrical energy use.

Lvl	Level of BAC function	Applicability	Class
0	manual central control (luminaires controlled centrally; no manual room switch)	Applicable	C
1	manual control (luminaires can be switched off with a manual room switch)		
2	automatic switching (luminaires switched off automatically when daylight is sufficient; switched on when insufficient)		B
3	automatic dimming (luminaires dimmed down and switched off when daylight is available or scene-based control applied; dimmed up when daylight decreases)		A

3.3.6 Blind control

Section 6 defines a single function for solar-protection blind control.

3.3.6.1 Function 6 — Blind control

Definition. Controls the position of solar-protection blinds or shading devices to limit solar heat gain, prevent glare, and reduce the associated cooling and lighting energy demand.

Lvl	Level of BAC function	Applicability	Class
0	manual operation (energy saving depends on user behaviour)	Applicable	
1	motorised operation with manual control (motor-supported; energy saving still depends on user behaviour)		
2	motorised operation with automatic control (automatic dimming to reduce cooling energy)		C
3	combined light/blind/HVAC control (optimises energy use for HVAC, blinds, and lighting in occupied and unoccupied rooms)		B, A

3.3.7 Technical building management

Section 7 defines seven TBM functions covering setpoint management, runtime management, fault detection, reporting, local energy production, waste heat recovery, and smart-grid integration. Functions 7.6 and 7.7 are not applicable to the model building.

3.3.7.1 Function 7.1 — Setpoint management

Definition. Provides centralised management, set-back, and adaptation of BAC set-points across all room and zone operating modes from a supervisory workstation or web interface.

Lvl	Level of BAC function	Applicability	Class
0	manual setting room by room individually	Applicable	C
1	adaptation from distributed or decentralised plant rooms only		
2	adaptation from a central workstation (web operation; room operating units excluded)		B
3	adaptation from a central room with frequent set-back of user inputs		A

3.3.7.2 Function 7.2 — Runtime management

Definition. Adapts the operating hours of building systems to a time schedule or calendar, including automatic preconditioning phases calculated from current conditions.

Lvl	Level of BAC function	Applicability	Class
0	manual setting (plant enabling)		
1	individual setting following a predefined schedule with fixed preconditioning phases	Applicable	C
2	individual setting following a predefined schedule, adaptation from a central room, variable preconditioning phases		B, A

3.3.7.3 Function 7.3 — Fault detection and diagnostic support for technical building systems

Definition. Monitors technical building systems for abnormal operating conditions and provides centralised indication of detected faults and alarms, with optional automated diagnostic analysis.

Lvl	Level of BAC function	Applicability	Class
0	no central indication of detected faults and alarms		
1	central indication of detected faults and alarms	Conditional	C
2	central indication of detected faults and alarms including diagnostic functions		B, A

Conditional: applicable only if the installed BACS supports fault collection across subsystems. The model building includes central alarm monitoring but does not implement active automated diagnostics beyond alarm annunciation.

3.3.7.4 Function 7.4 — Reporting of energy consumption and indoor conditions

Definition. Collects and presents data on building energy consumption and indoor environmental conditions, from simple meter-reading indication up to trend analysis, consumption determination, and performance benchmarking.

Lvl	Level of BAC function	Applicability	Class
0	indication of actual values only (e.g. temperatures, meter readings)	Applicable	C
1	trending functions and energy consumption determination		B
2	analysing, performance evaluation, and benchmarking of indoor environment and energy		A

3.3.7.5 Function 7.5 — Local energy production and renewable energy sources

Definition. Manages the operation of on-site renewable energy sources and combined heat and power plant, coordinating generation with the building's energy demand profile to maximise self-consumption.

Lvl	Level of BAC function	Applicability	Class
0	uncontrolled generation depending on fluctuating RES availability and/or CHP run time; overproduction fed to the grid	Applicable	C
1	coordination of local RES and CHP with regard to local energy demand profile including storage management; optimisation of own consumption		B, A

3.3.7.6 Function 7.6 — Waste heat recovery and heat shifting

Definition. Manages the recovery and redistribution of waste heat generated within the building or by on-site processes, including coordinated charging and discharging of a thermal storage device.

Lvl	Level of BAC function	Applicability	Class
0	instantaneous use of waste heat or heat shifting	N/A	C, B, A
1	managed use of waste heat or heat shifting (including charging/discharging TES)		

Not applicable: the model building has no waste-heat recovery process or heat-shifting capability. (Note: a discrepancy exists between Table B.1 (NR min = 0) and Table 6 (NR Class C = 1) of 52120-1 [1]; Table 6 is treated as binding.)

3.3.7.7 Function 7.7 — Smart grid integration

Definition. Enables the building’s energy systems to respond to grid-load signals, shifting or curtailing electrical demand to support grid stability through demand-side management.

Lvl	Level of BAC function	Applicability	Class
0	no harmonisation between grid and building energy systems; building operated independently of grid load	N/A	C
1	building energy systems managed and operated depending on grid load; demand-side management used for load shifting		B, A

Not applicable: the model building has no demand-response or smart-grid interface.

3.4 Per-class function requirements

Table 3.1 consolidates the minimum required levels per BACS class for all 45 BAC functions defined in §3.3. Of the 45 functions, 24 are applicable to the non-residential office model building assessed in this thesis; the remaining 21 are marked N/A or Conditional (see §3.3 for the reason in each case). The table derives from Table 5 and Table 6 of 52120-1 [1]; where a discrepancy exists between Table B.1 and Table 6, Table 6 is used as the binding authority (affected functions: 1.8, 3.4a, 4.3, 7.6, noted in §3.3).

Table 3.1: Per-class minimum required control levels for the 45 BAC functions.

Fn	Function name	C min	B min	A min	Applicable
Heating control					
1.1	Emission control (heating)	2	3	4	Applicable
1.2	Emission control for TABS (heating)	1	2	3	N/A
1.3	Distribution network hot water temperature control	1	2	2	N/A

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Fn	Function name	C min	B min	A min	Applicable
1.4	Distribution pump control (heating)	1	2	3	N/A
1.4a	Hydronic balancing (heating)	3	4	4	N/A
1.5	Intermittent control of emission/distribution (heating)	1	2	3	Applicable
1.6	Heat generator control (combustion/district)	1	2	2	Applicable
1.7	Heat generator control (heat pump)	1	2	2	N/A
1.8	Heat generator control (outdoor unit)	1	1	2	N/A
1.9	Sequencing of heat generators	1	2	3	N/A
1.10	TES charging control (heating)	1	1	2	N/A
Domestic hot water supply control					
2.1	DHW storage charging (electric/heat pump)	1	2	2	N/A
2.2	DHW storage charging (hot water generation)	1	2	2	Applicable
2.3	DHW storage charging (solar + supplementary)	1	2	2	N/A
2.4	DHW circulation pump control	1	1	1	Conditional
Cooling control					
3.1	Emission control (cooling)	2	3	4	Applicable
3.2	Emission control for TABS (cooling)	1	2	3	N/A

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Fn	Function name	C min	B min	A min	Applicable
3.3	Distribution network chilled water temperature	1	2	2	Conditional
3.4	Distribution pump control (cooling)	1	2	3	N/A
3.4a	Hydronic balancing (cooling)	3	4	4	N/A
3.5	Intermittent control of emission/distribution (cooling)	1	2	3	Applicable
3.6	Heating/cooling interlock	1	1	2	Applicable
3.7	Generator control for cooling	1	1	2	Applicable
3.8	Sequencing of chillers	1	2	3	N/A
3.9	TES charging control (cooling)	1	2	2	N/A

Ventilation and air-conditioning control

4.1	Supply air flow control (room level)	1	1	3	Applicable
4.2	Room temperature control by ventilation (all-air)	1	2	2	Applicable
4.3	Coordination of ventilation and static-system control	1	1	1	N/A
4.4	Outside air flow control	1	1	3	Applicable
4.5	Air flow/pressure control at AHU level	1	2	3	Applicable
4.6	Heat recovery: icing protection	1	1	1	N/A
4.7	Heat recovery: overheating prevention	1	1	1	N/A
4.8	Free mechanical cooling	1	2	3	Applicable

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Fn	Function name	C min	B min	A min	Applicable
4.9	Supply air temperature control (AHU level)	1	2	3	Applicable
4.10	Humidity control	1	2	2	N/A
Lighting control					
5.1	Occupancy control (lighting)	2	2	2	Applicable
5.2	Light level / daylight control	0	2	3	Applicable
Blind control					
6	Blind control	2	3	3	Applicable
Technical building management					
7.1	Setpoint management	1	2	3	Applicable
7.2	Runtime management	1	2	2	Applicable
7.3	Fault detection and diagnostic support	1	2	2	Conditional
7.4	Reporting (energy consumption and indoor conditions)	0	1	2	Applicable
7.5	Local energy production and RES	0	1	1	Applicable
7.6	Waste heat recovery and heat shifting	1	1	1	N/A
7.7	Smart grid integration	0	1	1	N/A

This chapter has established the normative foundation on which the thesis rests. Section 3.1 described the roles of the three standards and how they interlock. Section 3.2 presented the Class D through Class A hierarchy and the consistency and applicability rules governing class assignment. Section 3.3 catalogued all 45 BAC functions with their per-class required levels; 24 of these are applicable to the non-residential office model. Table 3.1 provides a compact summary for cross-reference. Chapter 4 uses this catalogue as its normative reference when specifying and justifying the IDF changes that implement each class upgrade.

Chapter 4

Methodology

This chapter describes the procedures, models, and tools used to assess the energy performance impact of Building Automation and Control System (BACS) efficiency upgrades through building simulation. The study proceeds in five stages, illustrated in Figure 4.1: the reference building model is established and frozen; it is calibrated to BACS Class C; it is upgraded in two steps through Class B to Class A; a set of performance indicators is evaluated for each class; and the comparison is repeated for a second climate to validate generalisability. Throughout, every control change is mapped explicitly to the BAC function catalogue defined in Chapter 3, so that each implementation choice can be traced to a normative requirement. The reference building and the two weather files that constitute the case study are described in Chapter 5; the present chapter details the simulation platform, the class calibration and upgrade procedure, and the performance indicators.

4.1 Simulation Platform

All simulations were performed with EnergyPlus version 25.2 [12], released by the U.S. Department of Energy and Lawrence Berkeley National Laboratory. EnergyPlus is an open-source, whole-building energy simulation programme that performs integrated thermal, airflow, and electrical calculations on an hourly or sub-hourly basis. It was selected because its EnergyManagementSystem (EMS) module supports arbitrary supervisory control logic through Energyplus Runtime Language (ERL) programmes, and because the ASHRAE 90.1 prototype building library is distributed in IDF format for direct use with EnergyPlus.

The EMS module is central to the Class A implementation (§4.5). ERL programmes can read zone-level sensor variables—temperatures, CO₂ concentrations, fan speeds, coil capacities—and write actuator setpoints to any object field during the simulation time-step. This capability was used to implement the demand-supervised VAV control, load-dependent supply air temperature (SAT) reset, and

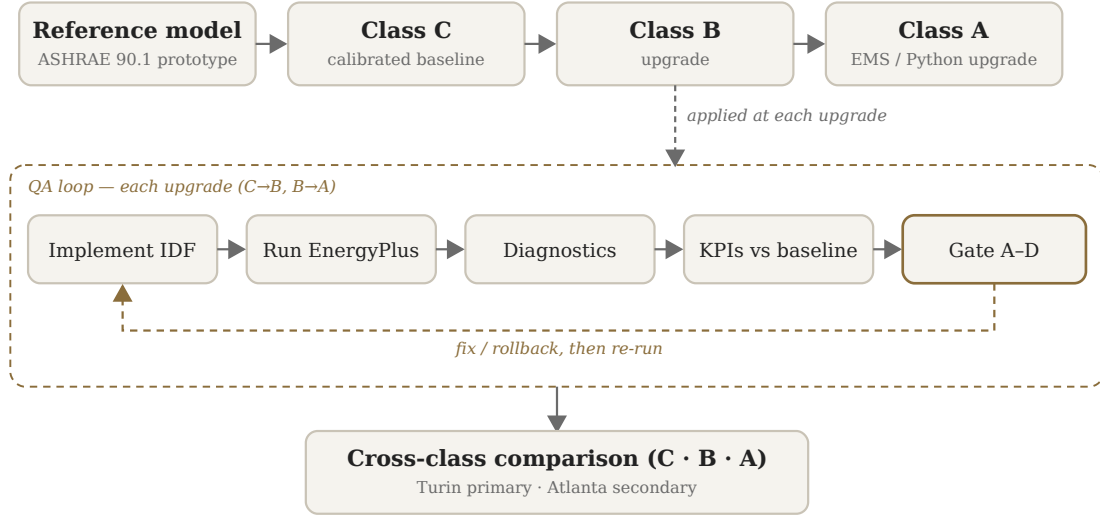


Figure 4.1. Overall C→B→A simulation methodology.

enthalpy-based economiser logic that characterise Class A functions. An ancillary Python benchmarking script (`ems_py_benchmark_report.py`) is executed after each simulation to collate output variables and produce cross-class KPI tables (§4.6).

The EnergyPlus binary used throughout is `/usr/local/EnergyPlus-25-2-0/energyplus`. The version at the system path `/usr/local/bin/energyplus` is EnergyPlus 22.1 and was not used; IDF files in the 25.2 schema would mis-run under the earlier version.

4.2 BACS Class Hierarchy and Study Scope

The study implements BACS efficiency classes C, B, and A as defined in EN ISO 52120-1:2022 (Chapter 3). Class D, the non-energy-efficient baseline, is not modelled; the original ASHRAE 90.1 prototype already incorporates basic automation that places it at Class C after the calibration described in §4.3. Three separate IDF files are maintained per climate—one per class—so that any simulation can be reproduced by running the appropriate IDF against the appropriate weather file. No class level is skipped: Class B is derived exclusively from Class C, and Class A exclusively from Class B. This sequential derivation ensures that the incremental energy effect of each upgrade tier can be isolated by a controlled pairwise

comparison.

The primary analysis is carried out on the Turin model, the European mixed climate that motivates the thesis (§4.7). Its three class files, derived as described in §4.3.3, are:

- `ASHRAE901_OfficeMedium_STD2022_Turin_BASE_C.idf` — Class C calibrated reference;
- `ASHRAE901_OfficeMedium_STD2022_Turin_CLASS_B.idf` — Class C upgraded to Class B;
- `ASHRAE901_OfficeMedium_STD2022_Turin_CLASS_A_EMS_PY_WORKING.idf` — Class B upgraded to Class A (the representation-complete Class A model).

A parallel set of Atlanta class files (`..._Atlanta_BASE_C.idf`, `..._Atlanta_CLASS_B.idf`, and `..._Atlanta_CLASS_A_EMS_PY_WORKING.idf`) carries the identical BACS control logic on the Atlanta CZ 3A envelope. This set is used only for the cross-climate sensitivity check of §4.7, not as a second full study.

Of the 45 BAC functions defined in Chapter 3, 24 are applicable to the reference building (Chapter 5): 21 directly applicable and 3 conditional. The remaining 21 functions are not applicable because the building lacks the corresponding plant (hydraulic heating distribution, TABS, heat pumps, VRF outdoor units, heat-recovery exchangers, chilled-water distribution, humidification plant, thermal energy storage, or waste-heat recovery equipment). The applicability assessment follows the 5% materiality threshold rule specified in Chapter 3.

The study is explicitly limited to correct representation of the standard’s requirements; it does not optimise control parameters for maximum energy saving. Where the standard specifies a function level but not the precise numerical setpoints or thresholds, engineering-proxy values are documented as assumptions, which are listed in §4.5.3.

4.3 Class C Baseline Calibration

4.3.1 Purpose and calibration philosophy

The Class C model serves as the common baseline against which both the Class B and Class A upgrades are measured. Its purpose is to represent “standard BAC” as defined in Chapter 3: every applicable function is implemented at the minimum level required for Class C, and no function is implemented above that level. This deliberate capping is important because over-implementation at Class C would transfer energy savings into the baseline and suppress the apparent effect of the subsequent upgrades.

The original ASHRAE 90.1 prototype is not a faithful Class C representation as-delivered. It contains control objects that are more capable than the standard requires at Class C (for example, a working enthalpy economiser where Class C requires only night-purge free cooling; active daylight dimming where Class C requires only manual-central control; an optimum-start EMS programme where Class C requires only fixed-time scheduling). The calibration therefore involves a combination of object additions (for functions absent from the prototype) and object downgrades (for functions implemented above the Class C minimum). This calibration stage comprises all 16 changes applied to the frozen baseline to produce the Class C model.

4.3.2 Per-function IDF changes

The following paragraphs describe each change in the order of the ISO 52120-1 function catalogue (§3). For the normative requirement at each level, the reader is directed to the corresponding function entry in Chapter 3. The IDF object classes involved are given in `monospace` throughout.

Function 1.5 — Intermittent control of emission and distribution (heating), Level 1. Class C requires automatic control with a fixed time programme only (as specified in §3). The original prototype includes an EMS-based optimum-start programme, `OA_BASED_OPTIMUM_START_EMS_Program`, that calculates a demand-adaptive pre-heating start time—a Level 2 capability. To calibrate to Level 1, the `EnergyManagementSystem:ProgramCallingManager` entry referencing this programme was disabled, so that the system follows only the fixed occupancy schedule. This change is inherited by Functions 3.5, 7.1, and 7.2 (see those entries below), all of which share the same EMS calling chain.

Function 1.6 — Heat generator control (combustion and district heating), Level 1. Class C requires variable supply temperature depending on outdoor temperature (as specified in §3). The original prototype uses a constant SAT setpoint of 12.8 °C. A `SetpointManager:Scheduled` object was retained as the setpoint carrier, and an `EnergyManagementSystem:Program (C_SAT_OAT_Reset_Prog)` was introduced to compute the outdoor-air-temperature (OAT) dependent SAT according to Equation 4.1:

$$T_{\text{SAT}}(T_{\text{OA}}) = \min\left(16.0, \max\left(12.0, 14.5 - 0.15(T_{\text{OA}} - 10)\right)\right) \quad (4.1)$$

where T_{SAT} and T_{OA} are in °C. The formula produces a higher SAT in cold weather (warming bias) and a lower SAT in warm weather (cooling bias), implementing the outdoor-temperature compensation required by Level 1 without any zone-demand feedback. Functions 3.3 and 3.7 (cooling generator and distribution

control) are implemented by the same EMS programme because the DX cooling system SAT is governed by the same supply air setpoint object.

Function 2.2 — Control of DHW storage charging using hot water generation, Level 1. Class C requires scheduled charging enable (as specified in §3). The original prototype charges the domestic hot water system continuously (24 hours a day, seven days a week). A new `Schedule:Compact` object (`SWHSys1_ChargeEnable_Sch`) was added to gate DHW charging to weekday hours (07:00–24:00), and the `PlantEquipmentOperationSchemes` object was updated to reference this schedule. This implements the minimum Level 1 time-windowed enable required for Class C. The associated DHW pump control (Function 2.4) was also updated: the `Pump:ConstantSpeed` object (`SWHSys1 Pump`) was changed from `Intermittent` to `Continuous` control type, consistent with the plant-operation time programme driving the system.

Function 3.3 — Control of distribution network chilled water temperature, Level 1. This function is classified as conditional in Chapter 3 because the building uses a direct-expansion (DX) cooling system with no separate chilled-water distribution loop. Its Level 1 requirement—outdoor-temperature compensated control—is fulfilled by inheritance from the OAT-reset SAT programme introduced for Function 1.6. No additional IDF objects were required; the single supply air setpoint manager that serves all AHUs provides the equivalent of outdoor-temperature compensation at the cooling-generator output level.

Function 3.5 — Intermittent control of emission and distribution (cooling), Level 1. Class C requires automatic control with a fixed time programme (as specified in §3). The optimum-start EMS programme disabled for Function 1.5 was also the driver for variable pre-cooling preconditioning; its deactivation therefore simultaneously ensures that cooling intermittent control at Class C operates on a fixed schedule only. No separate IDF change was required beyond the disable applied for Function 1.5.

Function 3.6 — Interlock between heating and cooling, Level 1. Class C and Class B both require at least partial interlock (as specified in §3). The VAV terminal reheat architecture of the prototype provides an inherent partial interlock: electric reheat in the terminal box activates only when the zone temperature falls below the heating setpoint, while DX cooling in the AHU is governed by the zone cooling setpoint. The two control loops are not actively coordinated to prevent simultaneous operation in the same zone, but the physical separation of supply-air cooling (upstream, AHU) from terminal reheat (downstream, zone) limits the degree to which they can operate simultaneously. This partial interlock is consistent

with the Level 1 minimum for Class C. Full mutual exclusion (Level 2, required at Class A) is implemented as part of the Class A upgrade (§4.5).

Function 3.7 — Generator control for cooling, Level 1. Class C requires variable temperature control depending on outside temperature (as specified in §3). This requirement is fulfilled by the same OAT-dependent SAT reset introduced for Function 1.6: the DX cooling coils in each AHU respond to the setpoint manager driven by `C_SAT_OAT_Reset_Prog`, so their effective output temperature varies with OAT. No additional IDF objects were required.

Function 4.4 — Outside air flow control, Level 1. Class C requires staged outdoor air flow depending on a given time schedule (as specified in §3). The original prototype operates with demand-controlled ventilation (DCV) active at all times, which constitutes a higher-than-Level 1 capability. To calibrate to Level 1, the `DemandControlledVentilation` field in the `Controller:MechanicalVentilation` objects of all three AHUs was set from `Yes` to `No`, and a new `Schedule:Compact` object (`C_OA_Stage_Sch`) was introduced to gate economiser-mode outdoor air to night-purge only, consistent with the Level 1 requirement. DCV is re-enabled at Class A (§4.5).

Function 4.5 — Air flow or pressure control at the air handler level, Level 1. Class C requires on/off time control only—the system supplies air flow for maximum load during nominal occupancy (as specified in §3). The original prototype uses `Fan:VariableVolume` objects with a minimum flow fraction of 0.25. In the FINAL-basis Class C calibration, all six models—both Turin and Atlanta, all three classes—use `Fan:VariableVolume` with inlet guide vane (IGV) part-load coefficients and a minimum flow fraction of 0.65 (IGV floor). This IGV representation was adopted as the level-faithful Class C basis for Function 4.5 Level 1: the IGV floor at 0.65 reflects the physical fan energy floor imposed by inlet guide vanes operating at minimum-load position, which is the correct behaviour of a standard VAV fan under Level 1 on/off-time control. The IGV minimum-flow fraction is subsequently reduced to 0.25 at Class A (Fn 4.5 L3) as the load-dependent demand supervisor takes over (§4.5).

Function 4.8 — Free mechanical cooling, Level 1. Class C requires night cooling only—outdoor air is set to maximum during unoccupied periods when the room temperature exceeds the comfort setpoint and the indoor-outdoor temperature difference exceeds a given limit (as specified in §3). The original prototype uses `DifferentialEnthalpy` economiser control, which represents a full free-cooling strategy (Level 2 for Class B). The `EconomizerControlType` field in each `Controller:OutdoorAir` object was changed to `FixedDryBulb`, and the `TimeOfDay`

`EconomizerControlScheduleName` field was set to `C_NightPurgeOnly_Sch`, restricting economiser operation to unoccupied hours. This implements the Level 1 night-purge requirement and forms the starting point for the free-cooling upgrade applied at Class B.

Function 5.2 — Light level/daylight control (daylight harvesting), Level 0.

Class C requires only manual central control of luminaires (Level 0 as specified in §3)—a notably low baseline. The original prototype includes 12 `Daylighting:Controls` objects for perimeter zones with continuous dimming active at 377 lux, which corresponds to Level 3 automatic dimming. To calibrate to Level 0, the `AvailabilityScheduleName` field of each daylighting controller was set to `ALWAYS_OFF`, disabling all automatic daylight response. The Class B upgrade re-enables automatic switching (Level 2), and Class A retains Level 2 for this function (§4.4).

Function 6 — Blind control, Level 2. Class C requires motorised operation with automatic control to reduce cooling energy (as specified in §3). The original prototype has no solar-protection blind objects. Twelve `WindowShadingControl` objects (`C*_BlindCtrl`) were added, one per perimeter zone window, each referencing a new `WindowMaterial:Blind` definition (`C_InteriorBlind_Mat`). The shading control type was set to `OnIfHighSolarOnWindow` with a setpoint of 120 W/m². This rule deploys the interior blinds automatically whenever incident solar radiation on the window surface exceeds the threshold, reducing solar heat gain to the zone. The Class B upgrade replaces this autonomous solar trigger with a combined light/blind/HVAC coordination strategy (Function 6 Level 3).

Function 7.1 — Setpoint management, Level 1. Class C requires setpoint adaptation from distributed or decentralised plant rooms only (as specified in §3). The optimum-start EMS programme disabled under Function 1.5 was also responsible for adaptive setpoint modulation during the pre-occupancy phase. Its deactivation ensures that at Class C, setpoints are fixed by schedule and modifiable only through a manual, plant-room-level action, consistent with Level 1. No additional IDF change was required beyond the Function 1.5 programme disable.

Function 7.2 — Runtime management, Level 1. Class C requires individual setting following a predefined schedule with fixed preconditioning phases (as specified in §3). As with Functions 1.5 and 7.1, the same EMS programme disable for Function 1.5 removes the variable-preconditioning capability, leaving a fixed-schedule runtime with a constant pre-occupancy phase. No additional change was required.

Function 7.3 — Fault detection and diagnostic support, Level 1. Class C requires central indication of detected faults and alarms (as specified in §3). The

original prototype has no centralised alarm object. A new `EnergyManagementSystem:GlobalVariable` (`C_FDD_Alarm_Flag`) and an associated `EnergyManagementSystem:Program` (`C_FDD_Alarm_Monitor`) were added. The programme evaluates basic alarm conditions at each time-step and sets the flag to 1 when an abnormal condition is detected, implementing the minimum Level 1 central-indication requirement. No diagnostic analysis logic (Level 2) was introduced at Class C; that is reserved for Class B and A (§4.4).

Function 7.4 — Reporting of energy consumption and indoor conditions, Level 0. Class C requires only indication of actual values (Level 0 as specified in §3). The original prototype includes active trending and metering output objects that represent a Level 1 capability. These were reduced: `Output:Table:Monthly` and `Meter:Custom` objects were simplified to retain only the minimal metering chain needed for KPI extraction at Class C, without the aggregated trend variables that characterise Level 1 reporting. Level 1 trending is implemented at Class B, and Level 2 performance benchmarking at Class A.

Function 7.5 — Local energy production and renewable energy sources, Level 0. Class C requires no active coordination of local generation (Level 0 as specified in §3): overproduction is fed to the grid. The original prototype’s `ElectricLoadCenter:Distribution` object operates in `Baseload` mode, meaning PV generation is treated as uncontrolled output. This is the correct Level 0 representation and required no change for Class C. The upgrade to Level 1 (active coordination with local demand) is applied at Class B (§4.4).

4.3.3 Turin Class C derivation

The Turin Class C model is derived from the Buffalo/5A ASHRAE Medium Office prototype, whose static physical properties (envelope thermal mass, window properties, heating-system efficiency, and non-control HVAC field values) correspond to Climate Zone 5A rather than the Atlanta Zone 3A values. The Buffalo prototype was schema-migrated to EnergyPlus 25.2, and the Class C BACS control objects—identical across both climate variants—were applied to the Turin geometry, producing a model in which the BACS logic is byte-identical to the Atlanta sensitivity counterpart while the envelope and sizing reflect a European mixed climate. The model derivation chain is shown in the model-lineage diagram of Chapter 5 (Figure 5.2).

Two Turin-specific corrections were applied. First, the `Site:Location` and design-day sizing records were replaced with Torino-Caselle official data. Second, a DHW fixture-temperature mismatch that produced EnergyPlus warnings was resolved by lowering the target temperature in 15 fixture schedules from 55 °C to 50 °C; this change has no effect on BACS representation. The Turin Class C fan uses

a `Fan:VariableVolume` object with inlet guide vane (IGV) part-load coefficients and a minimum flow fraction of 0.65, applied uniformly to all six models as part of the FINAL-basis level-faithfulness corrections (see §4.7.2). This fan representation is byte-identical between Turin and Atlanta at all three classes, ensuring that cross-climate fan-saving comparisons are not confounded by fan-object differences.

4.4 Class B Upgrade ($C \rightarrow B$)

4.4.1 Upgrade strategy

The Class B model is derived from the Class C model by applying two change sets in sequence. The primary Class B control upgrades are introduced first. A subsequent remediation step corrects three objects that were inadvertently left at Class C values during the initial upgrade: the fan minimum-flow fraction, the economiser time-gate, and the daylighting availability schedule.

Class B requires, in addition to all Class C functions, advanced BAC functions together with room controllers that communicate with the building automation system (see Chapter 3). In EnergyPlus terms, this communication layer is implemented through EMS sensor objects that read per-zone temperature variables and EMS actuator objects that write per-zone VAV minimum-flow setpoints and zone thermal setpoints. The Class B EMS programmes execute at every time-step, responding continuously to zone conditions rather than relying on scheduled values alone.

4.4.2 Per-function IDF changes

Function 1.1 — Emission control (heating), Level 3. Class B requires individual modulating room control with communication to the BACS (as specified in §3). In the all-air VAV model, room-level emission is controlled by varying the VAV terminal minimum airflow command, which indirectly modulates both the heating and cooling delivered to each zone. An `EnergyManagementSystem:Program (B_RoomCommCtrl)` was added, together with 15 `ZoneAirTemperature` sensor objects (one per thermal zone). The programme computes a demand index for each zone based on the deviation of the zone temperature from the heating setpoint and actuates the corresponding terminal box via an EMS actuator on the `AirTerminal:SingleDuct:VAV:Reheat` minimum airflow schedule. Heating setpoints operate over the range 15–22 °C; cooling setpoints over 22–30 °C. This continuous demand-based modulation with central communication satisfies the Level 3 requirement. The same programme is inherited by Function 3.1 (cooling emission control), which shares the same VAV actuation path.

Function 1.6 — Heat generator control, Level 2. Class B requires variable temperature control depending on outdoor temperature (as specified in §3). At Class C, the supply-air temperature setpoint was constant at 12.8 °C. For Class B, an `EnergyManagementSystem:Program` (`B_SAT_LoadReset_Prog`) was added to implement an OAT-only linear SAT reset according to Equation 4.2, clamped to 12.0–16.0 °C (as finalised in the FINAL-basis level-faithfulness corrections):

$$T_{\text{SAT}}(T_{\text{OA}}) = \min(16.0, \max(12.0, 14.0 - 0.12(T_{\text{OA}} - 10))) \quad (4.2)$$

This OAT-only formula produces a higher SAT in cold weather and a lower SAT in warm weather, matching the Level 2 outdoor-temperature compensation requirement for Function 1.6. It is shared with Function 4.9 (AHU-level SAT control) and Function 3.3 (cooling distribution temperature). An earlier prototype version of the Class B SAT programme also included a zone-load bias term; the FINAL-basis correction removed this bias to ensure level-faithful representation of Fn 1.6 L2, which the standard specifies as outdoor-temperature compensated—not load-dependent.

Function 2.2 — Control of DHW storage charging, Level 2. Class B requires demand-based supply temperature control in addition to the scheduled enable already present at Class C (as specified in §3). The loop setpoint manager (`SetpointManager:Scheduled`, `SHWSys1 Loop Setpoint Manager`) was reconfigured to reference a new `Schedule:Constant` object (`SHWSys1_LoopTemp_Cmd`) whose value is written at each time-step by an EMS demand-reset programme (`B_DHW_DemandReset_*`). The programme evaluates the DHW demand signal and resets the loop temperature between 52 °C and 60 °C accordingly, implementing the Level 2 requirement for demand-based supply temperature control.

Function 3.1 — Emission control (cooling), Level 3. Class B requires individual modulating room control with communication to the BACS (as specified in §3). This requirement is fulfilled by the same `B_RoomCommCtrl1` EMS programme introduced for Function 1.1. The programme operates symmetrically for both heating and cooling demand, using zone temperature deviation from the cooling setpoint to modulate the VAV minimum airflow command. No additional IDF change was required beyond the Function 1.1 programme.

Function 3.3 — Control of distribution network chilled water temperature, Level 2. Class B requires demand-based control of cooling distribution temperature (as specified in §3). As at Class C, this conditional function is satisfied by the AHU-level SAT reset programme; the load-dependent SAT reset introduced for Function 1.6 (`B_SAT_LoadReset_Prog`) provides demand-based temperature

modulation that serves as the equivalent of chilled-water temperature reset in a DX system.

Function 4.2 — Room air temperature control by ventilation, Level 2.

Class B requires optimised control that minimises energy demand by controlling both air flow rate and supply air temperature depending on load (as specified in §3). The 15 `AirTerminal:SingleDuct:VAV:Reheat` objects were modified so that the `ZoneMinimumAirFlowInputMethod` field was set to `Scheduled` for all terminals, referencing 15 new per-zone `Schedule:Constant` objects (`VAV_<ZONE>_MinFrac_Cmd`). An EMS programme (`B_RoomOptCtrl_*`) actuates these schedule values in the range 0.10–0.60 based on a zone temperature-demand proxy computed from the difference between the measured zone temperature and the zone setpoint. Combined with the load-dependent SAT reset, this produces a two-dimensional optimisation of airflow and supply temperature, satisfying the Level 2 optimised-control requirement.

Function 4.5 — Air flow or pressure control at the AHU level, Level 2.

Class B requires multi-stage control to reduce auxiliary fan energy (as specified in §3). In the FINAL-basis calibration, the `Fan:VariableVolume` minimum flow fraction is 0.65 at both Class C and Class B. The Class C IGV floor (0.65) represents the physical energy floor of the Level 1 on/off control; at Class B, the EMS-based demand controller (`B_RoomOptCtrl_Prog` and `B_AHU_DemandCtrl`) modulates fan speed between the IGV floor (0.65) and full speed, implementing continuous multi-stage VAV control—the Level 2 capability. The fan object type and minimum fraction are unchanged $C \rightarrow B$; the control logic governing when the fan operates at minimum versus maximum is what changes. The fan minimum fraction is subsequently reduced to 0.25 at Class A (§4.5).

Function 4.8 — Free mechanical cooling, Level 2.

Class B requires free cooling through modulation of outdoor and recirculation air during all periods to minimise mechanical cooling, based on temperature comparison (as specified in §3). The Class C night-purge gate (`C_NightPurgeOnly_Sch`) on the `TimeOfDayEconomizerControlScheduleName` field of each `Controller:OutdoorAir` was removed (the schedule name field was cleared), re-enabling daytime `FixedDryBulb` free-cooling operation across all occupied hours. This change was applied in the remediation step.

Function 4.9 — AHU-level SAT setpoint, Level 2.

Class B requires a variable SAT setpoint with outdoor-temperature compensation (as specified in §3). The OAT-only SAT reset programme introduced for Function 1.6 (Equation 4.2) satisfies the outdoor-temperature compensation requirement of Level 2. The SAT clamp

is 12.0–16.0 °C. The Class A upgrade replaces this global reset with a per-AHU load-dominant programme (§4.5).

Function 5.2 — Light level/daylight control, Level 2. Class B requires automatic switching of luminaires—off when daylight is sufficient, on when insufficient (as specified in §3). The 12 `Daylighting:Controls` objects in perimeter zones, which were disabled at Class C, were re-enabled by setting `AvailabilityScheduleName` back to `ALWAYS_ON`. The controllers use the continuous-dimming algorithm already configured in the prototype at 377 lux, which meets the Level 2 automatic-switching requirement. This change was applied in the remediation step.

Function 6 — Blind control, Level 3. Class B requires combined light/blind/HVAC control to optimise energy use for HVAC, blinds, and lighting (as specified in §3). At Class C, the 12 `WindowShadingControl` objects operated purely on a solar-irradiance trigger (`OnIfHighSolarOnWindow`, 120 W/m²). For Class B all 12 shading control objects were changed to the native EnergyPlus combined type `OffNightAndOnDayIfCoolingAndHighSolarOnWindow`: the blind deploys only when the zone HVAC system is in cooling mode *and* incident solar exceeds the threshold. No EMS programme or schedule is required; the coupling to the cooling state is handled natively by the simulation engine. This single-object change removes the prior EMS gate (`B_Blind_Deploy_Sch`, `B_Blind_Light_HVAC_*`) and directly represents the Level 3 combined control requirement.

Function 7.3 — Fault detection and diagnostic support, Level 2. Class B requires central indication of faults with diagnostic functions (as specified in §3). The Class C alarm flag was augmented by a rule-based diagnostic EMS programme (`B_FDD_Diagnosis`) that evaluates three diagnostic conditions at each time-step: SAT deviation from setpoint (supply air temperature fault), outdoor-air flow mismatch (OA mismatch fault), and simultaneous heating and cooling at the zone level. An `EMS:OutputVariable` (`B_FDD_DiagCode`) carries a numeric fault code, and a counter-reset programme (`B_FDD_Initialize`) resets the diagnostics at the start of each day. This three-rule diagnostic engine satisfies the Level 2 requirement for diagnostic functions beyond simple alarm annunciation.

Function 7.4 — Reporting, Level 1. Class B requires trending functions and energy consumption determination (as specified in §3). The addition of the `B_FDD_DiagCode` output variable and the EMS-computed demand signals for each zone provide a set of trended quantities that, combined with EnergyPlus’s standard monthly output tables, satisfy the Level 1 reporting requirement. No separate IDF change was required beyond the objects introduced for Function 7.3.

Function 7.5 — Local energy production and RES, Level 1. Class B requires coordination of local renewable energy sources with the building’s energy demand profile to maximise self-consumption (as specified in §3). The `ElectricLoadCenter:Distribution` object’s `GeneratorOperationSchemeType` was changed from `Baseload` to `TrackElectrical`, with the tracking meter set to `Electricity:Facility` and a demand limit of 32,176.5 W. This configures the PV controller to match its output to the building’s real-time electrical demand rather than export all generation unconditionally, satisfying the Level 1 coordination requirement.

4.5 Class A Upgrade ($B \rightarrow A$)

4.5.1 EMS/Python implementation strategy

Class A represents the highest BACS efficiency tier: high-energy-performance BAC and Technical Building Management (TBM) functions, with demand-controlled HVAC, adaptive setpoints based on occupancy and air quality, and integrated multi-discipline interrelationships covering lighting, shading, and HVAC (see Chapter 3). Implementing these requirements in EnergyPlus required a substantial EMS programme architecture because the functions interact: the indoor air quality (IAQ) demand from `ZoneAirContaminantBalance` must be routed to the VAV flow controller; the per-AHU SAT reset must read the aggregated zone demand; the economiser must switch from temperature to enthalpy comparison; and the heating/cooling interlock must enforce mutual exclusion. The Class A EMS architecture is illustrated in Figure 4.2.

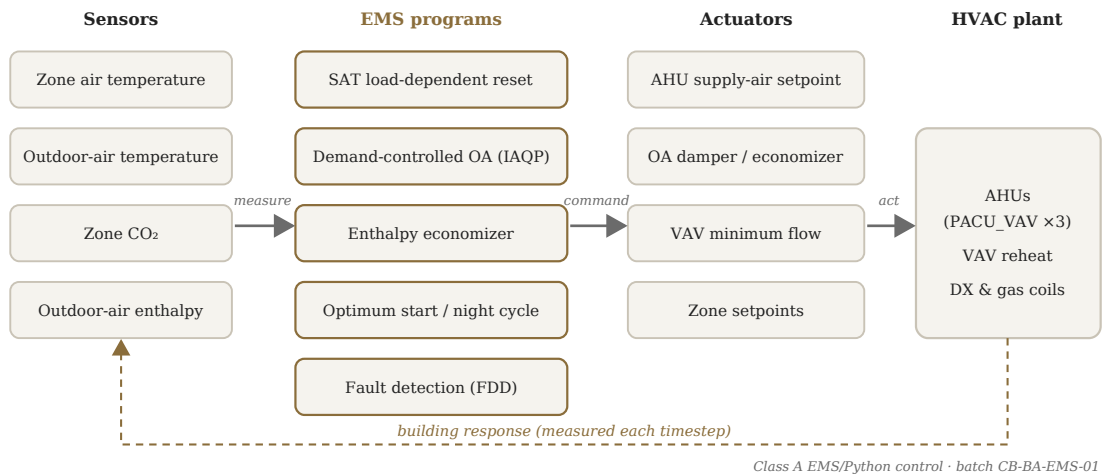


Figure 4.2. Class A EMS control architecture.

All Class A changes are applied as a single upgrade from the Class B IDF, adding or modifying the objects described below. The key EMS programmes in the Class A model are: `A_AHU_DemandSupervisor_Prog` (AHU-level demand aggregation), `A_PerAHU_SAT_Reset_Prog` (per-AHU load-dominant SAT reset), `A_TotalInterlock_Prog` (heating/cooling mutual exclusion), `B_RoomOptCtrl_Prog` (extended at Class A with CO₂ bias), `OA_BASED_OPTIMUM_START_EMS_Program` (adaptive preconditioning), and `A_FDD_Diagnosis` (three-layer fault detection). Blind control at Class A uses the same native `OffNightAndOnDayIfCoolingAndHighSolarOnWindow` shading type as Class B; no blind EMS programme is present in either class.

4.5.2 Per-function IDF changes

Function 4.1 — Supply air flow control at the room level, Level 3. Class A requires demand-based control using air quality measurement, specifically CO₂, VOC, or mixed gas (as specified in §3). A `ZoneAirContaminantBalance` object was added to enable CO₂ tracking across all 15 zones, and 15 `ZoneControl:ContaminantController` objects were added with a CO₂ setpoint of 900 ppm. The `B_RoomOptCtrl_Prog` EMS programme was extended with a CO₂ bias term: when a zone's CO₂ concentration exceeds 900 ppm, the programme raises the VAV minimum-flow command for that zone, increasing outdoor-air delivery to purge the contaminant. The flow command is clamped to the range 0.10–0.60 (consistent with the Class B range), ensuring that the IAQ demand response does not cause the terminal to exceed the design airflow. This coupling of occupant-generated CO₂ to the VAV flow command satisfies the Level 3 demand-based air flow control requirement.

Function 4.4 — Outside air flow control, Level 3. Class A requires variable outdoor-air flow control based on sensors detecting occupants or indoor air parameters (as specified in §3). The `SystemOutdoorAirMethod` field of each `Controller:MechanicalVentilation` object was changed from `Standard62.1VentilationRateProcedure` (with DCV disabled, as set at Class C) to `IndoorAirQualityProcedure`, activating CO₂-driven demand-controlled ventilation at the AHU level. The 900 ppm CO₂ setpoints introduced for Function 4.1 drive the AHU outdoor-air damper position through this IAQ procedure, so the outdoor-air flow rate responds continuously to occupant-generated CO₂ concentration across the served zones.

Function 4.5 — Air flow or pressure control at the AHU level, Level 3. Class A requires automatic load-dependent flow control without pressure reset (as specified in §3). The `FanPowerMinimumFlowFraction` field was reduced from 0.65 (Class B) to 0.25 in the three `Fan:VariableVolume` objects. Simultaneously, an EMS programme (`A_AHU_DemandSupervisor_Prog`) was added to aggregate the per-zone occupancy state, zone temperature deviation, and CO₂ demand signals

for each AHU and actuate demand-enable schedules that govern whether the AHU operates at full or minimum flow. This combination of a lower minimum flow fraction with supervisory demand aggregation implements the Level 3 load-following flow control.

Function 4.8 — Free mechanical cooling, Level 3. Class A requires enthalpy-based economiser control—outdoor air and recirculation air modulated based on temperatures and humidity or enthalpy (as specified in §3). The `EconomizerControlType` field in each `Controller:OutdoorAir` object was changed from `FixedDryBulb` (Class B) back to `DifferentialEnthalpy`. This re-enables the full enthalpy-comparison economiser strategy that was present in the original prototype but was downgraded for Class C and partially restored at Class B as temperature-only free cooling.

Function 4.9 — Supply air temperature control at the AHU level, Level 3. Class A requires a variable SAT setpoint defined as a function of room loads, requiring integrated collection of room temperatures or actuator positions (as specified in §3). An EMS programme (`A_PerAHU_SAT_Reset_Prog`) was added for each of the three AHUs. Each programme reads the zone temperature deviations and VAV actuator positions for the zones served by that AHU, computes a weighted load signal, and resets the SAT setpoint dominantly from load rather than OAT. The SAT clamp bounds are 12.0–16.0 °C (consistent with the Class B OAT-only reset of Equation 4.2), but the load-dominant logic produces a tighter, more responsive reset with per-AHU differentiation, overriding the OAT-only programme entirely.

Function 3.6 — H/C interlock, Level 2. Class A requires total interlock—guaranteed prevention of simultaneous heating and cooling (as specified in §3). An EMS programme (`A_TotalInterlock_Prog`) and two enable schedules (`Cooling_Enable_Cmd`, `Heating_Enable_Cmd`) were added. The `AvailabilityScheduleName` field of each `Coil:Cooling:DX:TwoSpeed` and `Coil:Heating:Fuel` object was changed from `Always_On` to reference the appropriate enable schedule. The EMS programme enforces mutual exclusion by setting one enable to 0 when the other is active. A partial compliance limitation applies: the interlock operates at the coil level and does not cover simultaneous reheat in a VAV terminal box and cooling at the AHU serving the same zone. This accepted limitation is discussed further in §4.5.4.

Function 7.1 — Setpoint management, Level 3. Class A requires adaptation from a central room with frequent set-back of user inputs (as specified in §3). The `OA_BASED_OPTIMUM_START_EMS_Program` was extended with an `A_SetpointRollback_*` chain that normalises zone setpoints to their design values at intervals

throughout the day, preventing user-initiated setpoint drift from persisting across occupancy cycles. The normalisation applies distinct cooling and heating setpoint values (5,224 and 5,108 actuator-count instances in the annual run record), satisfying the Level 3 requirement for frequent set-back from a central supervisory programme.

Function 7.2 — Runtime management, Level 2. Class A requires variable preconditioning phases adapted from a central room (the same level as Class B, as specified in §3). The `A_AHU_DemandSupervisor_Prog` and the `OA_BASED_OPTIMUM_START_EMS_Program` together implement adaptive preconditioning: the start time of the pre-occupancy conditioning phase is computed from current zone temperatures and OAT at each day’s first time-step. Under the Turin IWECC annual run, the `A_Runtime_Preconditioning_Mode` flag is active for approximately 2,519 hours per year. This runtime adaptation satisfies the Level 2 requirement retained at Class A.

Function 7.3 — Fault detection and diagnostic support, Level 2. Class A retains the Level 2 diagnostic requirement (as specified in §3). The `A_FDD_Diagnosis` EMS programme extends the Class B two-rule engine to a three-layer diagnostic architecture with fault codes 11–33 covering SAT deviation, outdoor-air flow mismatch, and simultaneous heating/cooling persistence. Over the Turin IWECC annual run, `A_FDD_DiagCode` is non-zero for approximately 1,647 hours per year and the `A_FDD_Alarm_Flag` is active for approximately 2,735 hours per year. These statistics are discussed further in Chapter 3’s context and reported in full in the results chapter.

Function 7.4 — Reporting, Level 2. Class A requires analysing, performance evaluation, and benchmarking of indoor environment and energy (as specified in §3). A Python script (`ems_py_benchmark_report.py`) is executed after each simulation run. It reads the EnergyPlus output tables and meter data, computes the full 21-KPI set defined in §4.6, and produces a structured benchmarking report that compares the Class A results against the Class B and Class C baselines across all KPI families. This post-run benchmarking script provides the Level 2 performance-evaluation and benchmarking capability.

Function 7.5 — Local energy production and RES, Level 1. Class A retains the Level 1 requirement (the same level as Class B, as specified in §3). The `ElectricLoadCenter:Distribution` object in `TrackElectrical` mode, introduced at Class B, is carried forward without modification. The PV system generates approximately 43,675 kWh/a under the Turin IWECC annual simulation, fully coordinated with the building demand profile. No further change was required to advance Class A beyond the Level 1 capability already present.

4.5.3 EMS thresholds

ISO 52120-1 defines the level at which a BAC function must operate but does not prescribe specific numerical setpoints or control thresholds. The threshold values used in the Class A EMS programmes were selected as engineering proxies consistent with ASHRAE 55 comfort criteria and ASHRAE 62.1 ventilation requirements [33][34], and are documented as engineering assumptions. Table 4.1 lists these values.

Table 4.1. Class A EMS control thresholds (non-normative engineering assumptions).

Threshold	Value	Programme(s) using it
Demand-enable temperature deviation	0.5 °C	A_AHU_DemandSupervisor_Prog
Zone cooling demand reference	24.0 °C	A_AHU_DemandSupervisor_Prog
Zone heating demand reference	20.5 °C	A_AHU_DemandSupervisor_Prog
CO ₂ over-threshold margin	25 ppm above 900 ppm (effective 925 ppm)	B_RoomOptCtrl_Prog (extended)
SAT clamp lower bound	11.5 °C	all per-AHU SAT programmes
SAT clamp upper bound	17.0 °C	all per-AHU SAT programmes
FDD low-OA ratio threshold	0.75	A_FDD_Diagnosis
FDD high cooling-demand persistence	2.0 °C	A_FDD_Diagnosis

4.5.4 Accepted representation limitations

Two limitations in the Class A representation are accepted as correctly identified and documented; they do not constitute modelling errors.

Partial heating/cooling interlock (KPI-C02, KPI-C03). The A_TotalInterlock_Prog enforces mutual exclusion at the AHU coil level but does not prevent simultaneous DX cooling at the AHU and electric reheat at a downstream VAV terminal box serving the same zone. EnergyPlus does not expose an actuator

that can simultaneously inhibit VAV terminal reheat and AHU cooling within a single EMS time-step without breaking the pressure-balance convergence loop. This physical architecture limitation means that total interlock (Level 2 for Function 3.6) is partially rather than fully achieved. The consequence is a modestly elevated occupied cooling setpoint not-met time at Class A relative to Class B (KPI-C02), which is an artefact of the stricter coil-level control reducing AHU overcooling while leaving terminal reheat active. This behaviour was confirmed by a detailed review of the Class A model and is reported as a limitation in the results chapter.

Occupied outdoor-air delivery (KPI-V01). The transition from a fixed-ratio outdoor-air method at Class B to the `IndoorAirQualityProcedure` at Class A (Function 4.4, Level 3) reduces time-averaged outdoor-air mass flow rates during periods of low occupant-generated CO₂. The IAQ procedure delivers outdoor air on demand rather than at a fixed minimum fraction, which is the correct implementation of Level 3 demand-controlled ventilation. The apparent reduction in the KPI-V01 metric (mean occupied outdoor-air flow rate) is therefore a correct consequence of the standard representation, not an error. It is reported transparently in the results chapter.

4.6 Performance Indicators

4.6.1 Primary-energy conversion

The headline performance indicator is overall primary energy consumption per year, K_0 , computed from end-use electricity E_{el} and natural gas E_{gas} (both in kWh/a) using the primary energy factors defined in the Italian Ministry Decree of 26 June 2015 (*Decreto Interministeriale 26 giugno 2015*) [14], which prescribes $f_{P,\text{el,tot}} = 2.42$ and $f_{P,\text{gas,tot}} = 1.05$ as the total primary-energy conversion factors (renewable plus non-renewable combined). These factors are consistent with the EN ISO 52000-1:2017 framework for primary energy evaluation in the context of buildings [2].

$$K_0 = E_{\text{el}} \cdot 2.42 + E_{\text{gas}} \cdot 1.05 \quad (4.3)$$

where K_0 is in kWh/a, and E_{el} and E_{gas} are the annual electricity and natural gas consumption extracted from EnergyPlus end-use metering. The factor of 2.42 reflects the average primary energy intensity of grid electricity in Italy, accounting for generation and transmission losses; the factor of 1.05 for natural gas reflects the distribution losses applied to the lower heating value. The distinction between primary and final energy is particularly important in this study because BACS upgrades tend to shift the balance between electrical end-uses (fans, cooling, pumps) and gas end-uses (heating, DHW), so final-energy comparisons alone would produce a misleading picture of total resource consumption.

4.6.2 KPI definitions

Twenty-one KPIs were defined across five families: energy (E), peak load (P), comfort (C), ventilation/air quality (V), and automation diagnostics (A), supplemented by two data-quality indicators (D). Table 4.2 gives the full list with source variable or computation, units, and the expected direction of change under class upgrades.

Table 4.2: KPI set used to assess BACS class performance; INSUF = insufficient data.

KPI	Name	Source / computation	Units	Expected direction
KPI-E01	Overall primary energy (K_0)	Eq. 4.3: $E_{el} \times 2.42 + E_{gas} \times 1.05$	kWh/a	Decrease
KPI-E02	Heating end-use primary energy	Heating:Electricity $\times 2.42$ + Heating:NaturalGas $\times 1.05$	kWh/a	Decrease
KPI-E03	Cooling electricity	Cooling:Electricity	kWh/a	Decrease
KPI-E04	Fan electricity	Fans:Electricity	kWh/a	Decrease
KPI-E05	Pump electricity	Pumps:Electricity	kWh/a	Decrease or stable
KPI-E06	Interior lighting electricity	InteriorLights:Electricity	kWh/a	Decrease
KPI-E07	DHW primary energy	WaterSystems:Electricity $\times 2.42$ + WaterSystems:NaturalGas $\times 1.05$	kWh/a	Decrease or stable
KPI-E08	HVAC electricity	Facility Total HVAC Electricity Demand Rate (integrated)	kWh/a	Decrease
KPI-P01	Peak whole-building electric load	max(Facility Total Electricity Demand Rate)	W	Decrease or stable

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KPI	Name	Source / computation	Units	Expected direction
KPI-P02	Peak HVAC electric load	max(Facility Total HVAC Electricity Demand Rate)	W	Decrease or stable
KPI-C01	Occupied heating setpoint not met	Facility Heating Setpoint Not Met While Occupied Time	h/a	Decrease or stable
KPI-C02	Occupied cooling setpoint not met	Facility Cooling Setpoint Not Met While Occupied Time	h/a	Decrease or stable (Class A accepted regression)
KPI-C03	ASHRAE-55 not-comfortable time	Facility Thermal Comfort ASHRAE 55 Simple Model ... Not Comfortable Time	h/a	Decrease or stable (Class A accepted regression)
KPI-C04	PMV compliance ratio	Zone Fanger PMV $\in [-0.5, +0.5]$, occupied-h fraction	%	Increase or stable (INSUF)
KPI-V01	Occupied OA delivery	Air System Outdoor Air Mass Flow Rate, mean over occupied hours	m ³ /s	Stable or increase (Class A accepted decrease)
KPI-V02	Economiser active hours	Air System Outdoor Air Economizer Status=1, annual sum	h/a	Increase or stable
KPI-A01	SAT reset activity	Std dev of System Node Setpoint Temperature at AHU supply node	°C	Increase (INSUF)
KPI-A02	Demand-triggered night-cycle runtime	Availability Manager Night Cycle Control Status > 0, unoccupied hours	h/a	Decrease (INSUF)

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KPI	Name	Source / computation	Units	Expected direction
KPI-A03	Simultaneous H/C overlap	Hours: Heating > 0 AND Cooling > 0	h/a	Decrease (INSUF)
KPI-D01	Severe error count	** Severe ** count in <code>eplusout.err</code>	count	Stable (target: 0)
KPI-D02	Warning count	Total ** Warning ** count including new categories	count	Stable or decrease

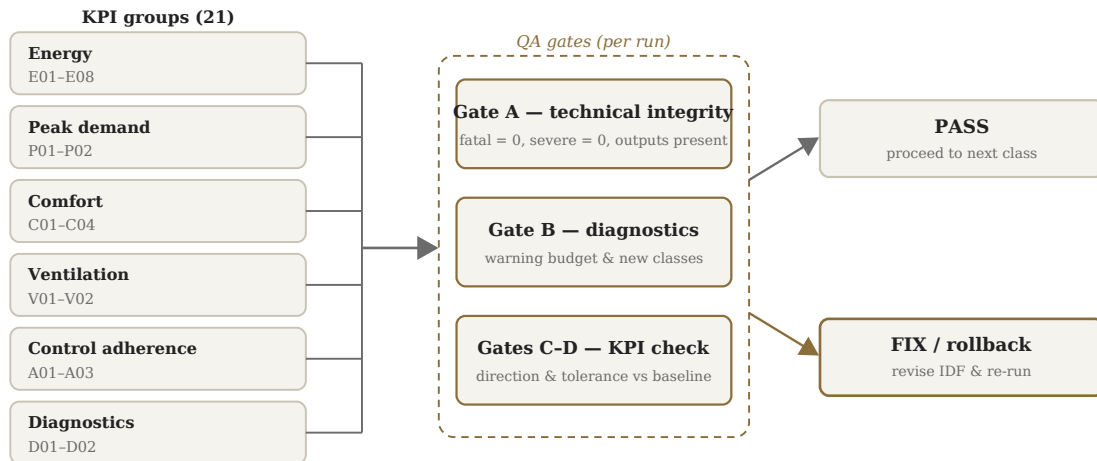


Figure 4.3. KPI-to-gate evaluation flow.

KPIs C04, A01, A02, and A03 are listed for completeness but could not be evaluated numerically in the current study due to insufficient per-hour output data in the simulation runs available at the time of writing; they are marked “INSUF” in Table 4.2. The remaining 17 KPIs provide the quantitative basis for the cross-class and cross-climate comparisons reported in the results chapter. Energy KPIs are reported as gross facility consumption (`Electricity:Facility`); the on-site PV generation is identical across all three BACS classes and therefore does not bias the class-to-class comparison.

4.6.3 QA gate procedure

KPIs are grouped into four quality-assurance (QA) gates, as illustrated in Figure 4.3. Gate A (data integrity) requires that KPI-D01 and KPI-D02 confirm zero severe errors and no unexpected new warning categories before any energy KPI is trusted. Gate B (energy consistency) requires that the direction of change for all energy KPIs (E01–E08) is consistent with the expected direction in Table 4.2; any inversion flags a potential control-implementation error. Gate C (comfort acceptability) requires that occupied comfort metrics (C01–C03) do not degrade beyond documented, accepted thresholds; deviations trigger a review unless they are covered by the accepted limitations of §4.5.4. Gate D (automation evidence) verifies that the automation-specific indicators (V01, V02, A01–A03) show the expected directional behaviour of the BACS function being implemented.

A simulation run proceeds from Class C to Class B to Class A only if all four gates pass or any failures are explicitly documented as accepted limitations. This sequential gate structure ensures that no Class A result is reported before the Class C and Class B baselines have been verified.

4.7 Cross-Climate Sensitivity Analysis

4.7.1 Rationale

The primary question of the thesis—what energy-performance impact do BACS class upgrades produce?—could in principle be answered by a single climate. However, a single climate creates a risk of conflating climate-specific effects (the magnitude of free-cooling opportunity, the dominance of heating versus cooling loads, the seasonal variation of OAT that drives the SAT reset) with the intrinsic BACS control effects. A second climate at a contrasting thermal regime—Atlanta CZ 3A (hot-humid) versus Turin European mixed—allows a check on whether the observed KPI changes are a property of the control logic itself or an artefact of the weather.

Turin was selected as the primary climate because the thesis is submitted to Politecnico di Torino and the European context is directly relevant to the ISO 52120 standards framework, which was developed for the European regulatory environment [1]. Atlanta was retained as the secondary climate because the ASHRAE 90.1 prototype building was originally designed for Climate Zone 3A, providing a well-documented, publicly auditable baseline with published prototype energy data against which results can be independently verified [35]. Accordingly, the Atlanta model is treated not as a second full study but as a cross-climate sensitivity (robustness) check: the Turin model is analysed in full, while Atlanta is used only to test whether the headline BACS effects persist under a contrasting climate.

4.7.2 Atlanta fan and Class-C corrections (FINAL basis)

The FINAL-basis calibration applied two level-faithfulness corrections to the Atlanta Class C model. First, an earlier Atlanta Class C version used an EMS-driven OAT-dependent SAT reset—a Class B capability inadvertently included in the Class C model. This was removed and replaced with a constant 12.8 °C SAT set-point, matching the Turin Class C baseline. Second, historical Atlanta runs used a `Fan:VariableVolume` object with minimum flow fraction locked at 1.0, which does not correctly represent the IGV energy floor. The FINAL-basis correction replaced this with an IGV-curve `Fan:VariableVolume` object with minimum flow fraction 0.65—byte-identical to the Turin Class C fan. These corrections ensure that the two Class C baselines differ only in climate, envelope, and sizing; their BACS control logic and fan representation are identical. The corrected Atlanta FINAL runs are the active Atlanta data used in this thesis.

4.7.3 Comparability premise

With both climates using identical `Fan:VariableVolume` IGV objects at Class C, the cross-climate comparison rests on a well-defined comparability premise: the two Class C baselines differ only in weather, site location, and the static physical properties of the respective prototype (Atlanta CZ 3A versus Buffalo/5A envelope); the BACS control logic and fan representation are byte-identical. Any difference in the C-to-B or B-to-A KPI changes between the two climates therefore reflects a genuine climate-sensitivity of the control effects, not a modelling inconsistency.

Under the FINAL-basis results, the C-to-B K0 reductions are -13.8% for Turin and -12.4% for Atlanta. The B-to-A fan primary-energy reduction is -44.5% (Turin) and -44.7% (Atlanta); the B-to-A cooling primary-energy reduction is -49.6% (Turin) and -47.0% (Atlanta). Interior plug loads, which are BACS-invariant, contribute an identical 435,433 kWh in all six runs (both climates, all three classes), confirming that the non-BACS components of the model are held constant. The near-identical B-to-A fan and cooling savings across both climates support the conclusion that Class A control effectiveness is climate-independent within the bounds of this two-site comparison. The results chapter therefore reports the Turin model in full and uses Atlanta only for a focused comparison of selected headline KPIs (the C→B and B→A primary-energy reductions and the B→A fan and cooling reductions), rather than duplicating the full KPI set for both climates. Full numerical results for all 17 evaluable KPIs are presented in Chapter 6.

This chapter has described the complete methodology used to assess the energy performance of BACS class upgrades through simulation. The reference building—the ASHRAE 90.1-2022 Medium Office prototype—was frozen as a version-controlled baseline before any class-specific modifications were applied. Class C was calibrated by a 16-change batch that capped each applicable function at its minimum Class C level; Classes B and A were derived by sequential, documented upgrade batches.

A FINAL-basis correction A FINAL-basis correction standardised the reporting tolerance (1.0 °C), the IGV fan representation, and the Class B SAT-reset formula across all six models, ensuring level-faithful comparison. The EnergyPlus EMS module provided the supervisory-control infrastructure required by Class A, and a Python benchmarking script supports the Level 2 reporting requirement. Weather files were selected to ensure internal consistency between design-day sizing and annual simulation for both the Turin and Atlanta climates. A 21-KPI framework with four QA gates governs the acceptance of results, and a dual-climate design with a common fan-object representation ensures that observed performance differences can be attributed to the BACS control logic rather than to climate or model artefacts. The results of the simulations are presented in the following chapter.

Chapter 5

Case Study

This chapter describes the reference building and the two climates that constitute the case study for the BACS class-upgrade assessment. The control-calibration and upgrade methodology applied to this building, together with the performance indicators used to evaluate it, is set out in Chapter 4.

5.1 Reference Building Model

5.1.1 Prototype identity

The simulation study uses the ASHRAE 90.1-2022 Medium Office prototype building [13] as its reference model. This prototype represents a three-storey non-residential office building with a conditioned floor area of 4,982 m² (as reported by EnergyPlus in the *eplusbl* summary; the ASHRAE 90.1 prototype documentation cites 53,628 ft² $\approx$ 4,982 m²). The building is divided into 15 conditioned thermal zones—one core zone and four perimeter zones per storey—together with unconditioned ceiling plenums separating the floors. A three-dimensional render of the reference building is shown in Figure 5.1. Figure 5.2 shows the derivation of both model families—the primary Turin/Buffalo CZ 5A model and the Atlanta CZ 3A sensitivity model—from the frozen prototype through the three BACS classes.

The HVAC system consists of three Variable Air Volume (VAV) air handling units (AHUs), one per floor, each supplying conditioned air to the zones on that floor through 15 VAV terminal boxes equipped with `Coil:Heating:Electric` (electric-resistance) reheat coils. The AHUs incorporate gas-fired `Coil:Heating:Fuel` heating coils, two-speed direct-expansion (DX) cooling coils, and outdoor-air economiser sections controlled by `Controller:OutdoorAir` objects. A gas-fired domestic hot water (DHW) heater supplies the building’s hot water demand. A 32 kW rooftop photovoltaic (PV) system is modelled through a `Generator:PVWatts` object connected to a `ElectricLoadCenter:Inverter:PVWatts` inverter and dispatched by an `ElectricLoadCenter:Distribution` controller. Figure 5.3 shows

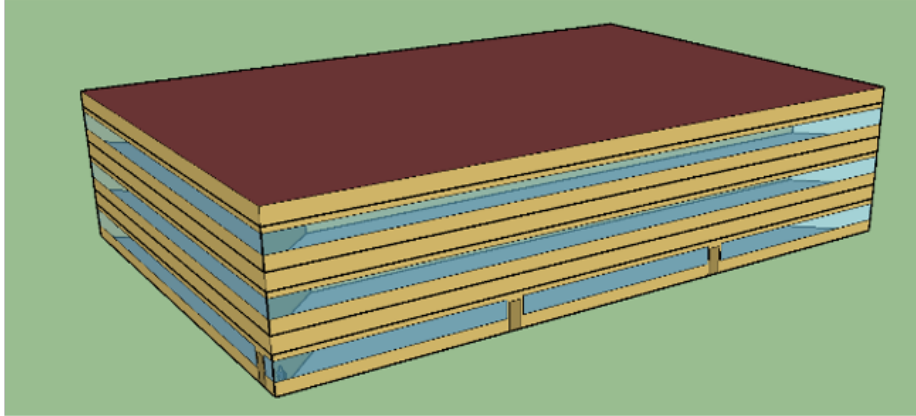


Figure 5.1. Three-dimensional render of the ASHRAE 90.1 Medium Office reference building.

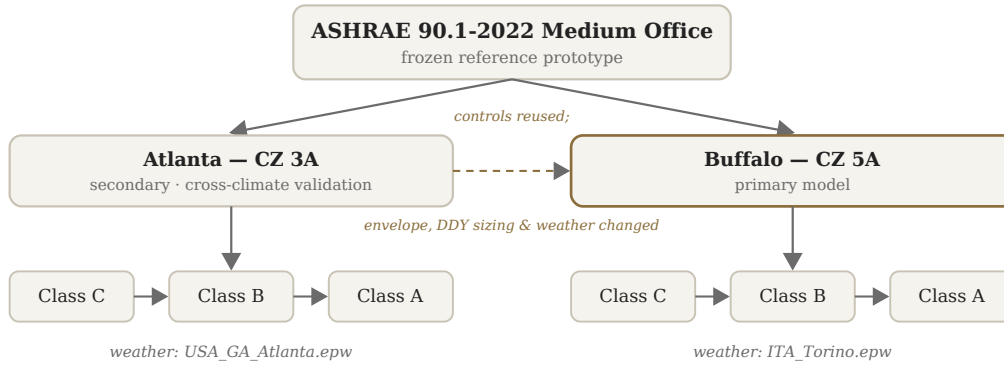


Figure 5.2. Model derivation and lineage across both climate families.

the HVAC system schematic.

5.1.2 Version migration and frozen baseline

The original prototype was obtained from the U.S. Department of Energy prototype building repository [35] and migrated to EnergyPlus version 25.2 (the simulation platform described in §4.1). Once migration was verified and the model ran without severe errors, the IDF file was frozen as `ORIGINAL_FROZEN_25p2.idf` and committed to version control. This file is never edited; all class-specific models derive from it as successively modified copies. The frozen baseline ensures that every control-upgrade comparison can be attributed solely to the BACS changes, with

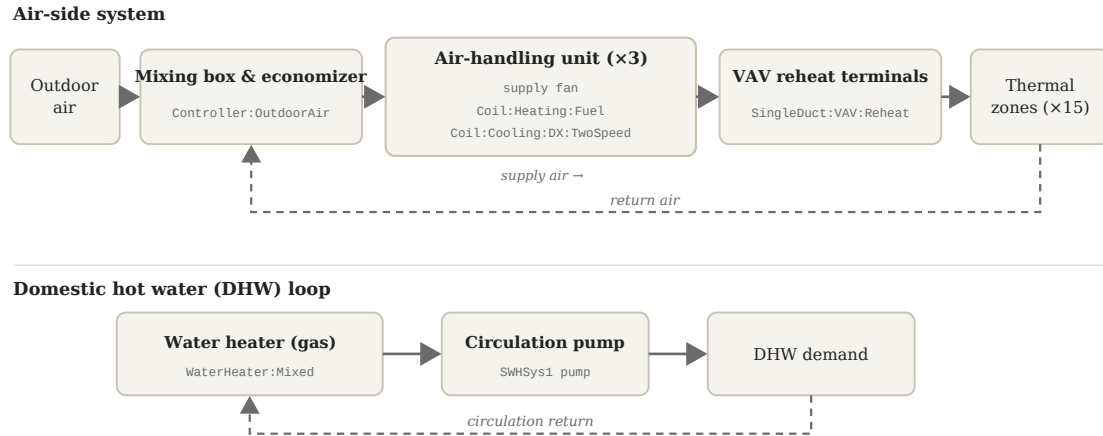


Figure 5.3. HVAC system schematic: three-floor VAV with AHUs and DHW loop.

no risk of inadvertent structural modifications contaminating the results. Subsequent Class C, B, and A models are derived through a documented sequence of per-function changes that records, for every modification, the IDF object class, the field affected, and the before and after values (see §4.3 through §4.5).

5.2 Weather Files

Table 5.1 summarises the two weather files used in the study.

Table 5.1. Weather files used in the simulation study.

Climate	File	WMO	Source	CZ
Turin (primary)	ITA_Torino.1605 90_IWEC.epw	160590	IWEC	Mixed (CZ 5A boundary)
Atlanta (secondary)	USA_GA_Atlanta. epw	—	TMY	Hot-humid (CZ 3A)

5.2.1 Turin primary: Caselle IWEC

The primary analysis uses the International Weather for Energy Calculations (IWEC) file for Torino-Caselle airport (WMO 160590, elevation 287 m), sourced from the

ASHRAE IWECD dataset [36]. Caselle is the official meteorological reference station for the Turin metropolitan area. The IWECD file was selected over a locally recorded Typical Meteorological Year (TMY) from a city-centre station (Bauducchi) because the latter was found to carry non-physical sky-irradiance and ground-albedo placeholder values, and its peak dry-bulb temperature exceeds the Caselle design-day sizing basis by 3.3 °C—a discrepancy that would create a sizing inconsistency between the design day embedded in the IDF and the annual weather driving the simulation. The Caselle IWECD file shares WMO station 160590 with the DDY sizing data used to autosize AHU coils and fan capacities, ensuring internal consistency between design conditions and annual simulation. The Turin/Caselle climate falls on the boundary between ASHRAE Climate Zone 4A (Mixed-Humid) and Zone 5A (Cold-Humid), with moderate winters and warm-to-hot summers; it represents a European mixed climate to which the BACS class-upgrade effects are expected to differ measurably from the hot-humid Atlanta baseline. Figure 5.4 shows the resulting temperature profile: a continental pattern with winters regularly reaching -5 to -10 °C and summers peaking near 30 °C.

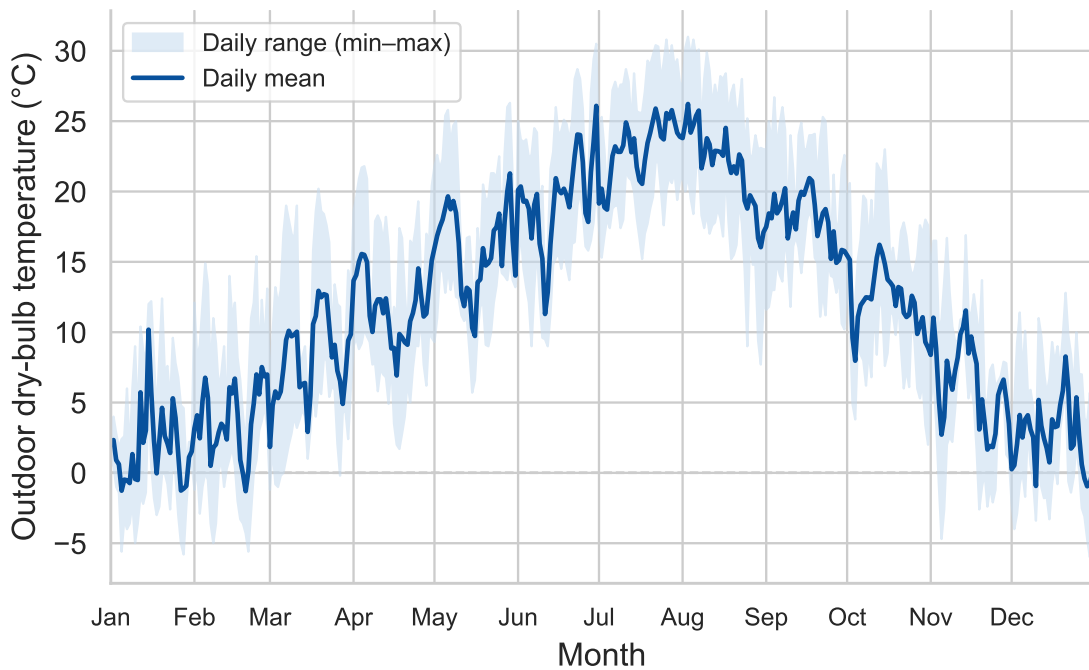


Figure 5.4. Daily mean outdoor dry-bulb temperature and daily range, Turin/Caselle IWECD (WMO 160590).

5.2.2 Atlanta supplementary

The supplementary analysis uses the standard TMY file `USA_GA_Atlanta.epw` for Atlanta, Georgia, Climate Zone 3A (hot-humid). This file is the official weather data for the ASHRAE 90.1 prototype building in its original configuration and is distributed as part of the EnergyPlus weather library [12]. It was retained without modification for the Atlanta runs so that results remain directly comparable with the published ASHRAE 90.1 prototype performance documentation. The rationale for including Atlanta as a secondary climate and the fan-correction applied to ensure comparability are described in §4.7.

Chapter 6

Results

This chapter reports the simulation results for BACS efficiency Classes C, B, and A applied to the Turin/Caselle IWECC reference model, which is the principal study. Sections 6.2 through 6.9 present the primary energy, end-use, carrier, peak load, comfort, ventilation, and shading results for the Turin model. Section 6.10 provides a cross-climate sensitivity check comparing headline key performance indicators (KPIs) with the results obtained for the Atlanta CZ 3A model. The methodology underlying the run configurations, weather-file selection, and KPI definitions is described in Chapter 4; interpretation and discussion of physical mechanisms are deferred to Chapter 7.

All results in this chapter are sourced from the FINAL-basis simulation runs (EnergyPlus 25.2, zero fatal/severe errors). Run identifiers are given in the table captions and section headings.

6.1 Overview

Table 6.1 summarises the headline KPIs for the Turin model across all three classes; the sections that follow present each KPI group in detail with supporting figures. Primary energy factors, run conventions, and the QA gate procedure are described in §4.6.1 and §4.6.3.

The C→A reduction in overall primary energy (K0) was -27.0% (307,552 kWh/a), achieved in two roughly equal steps: -13.8% from Class C to Class B, and -15.3% from Class B to Class A. The controlled-end-use primary energy (KPI-CTRL: heating, cooling, fans, lighting, pumps) fell by -48.1% C→A, a substantially larger reduction than the overall K0 saving because BACS-invariant end-uses (interior equipment, DHW) dilute K0 but not KPI-CTRL. The gas C→B increase of $+70.2\%$ is noted in the overview and explained in §6.4.

Table 6.1. Headline KPI summary — Turin/Caselle IWECC, BACS Classes C, B, and A; FINAL-basis runs RUN_FINAL-TURIN-*-IWECC-20260617-002238.

KPI	Class C	Class B	C→B	Class A	B→A	C→A
K0 primary energy (kWh/a)	1,139,372	981,818	−13.8%	831,820	−15.3%	−27.0%
EUI (kWh/m ² /a)	228.7	197.1	−13.8%	167.0	−15.3%	−27.0%
KPI-CTRL (kWh/a)	638,692	481,336	−24.6%	331,323	−31.2%	−48.1%
Site electricity (kWh/a)	455,011	378,806	−16.7%	324,906	−14.2%	−28.6%
Site natural gas (kWh/a)	36,417	61,994	+70.2%	43,372	−30.0%	+19.1%
Peak electricity (kW)	270.9	232.8	−14.1%	233.2	+0.2%	−13.9%
Htg setpoint-unmet (h/a) [†]	148.3	85.3	−42.5%	88.2	+3.3%	−40.5%
Clg setpoint-unmet (h/a) [†]	165.7	93.2	−43.8%	211.2	+126.7%*	+27.5%
ASHRAE-55 not-comfortable (h/a) [‡]	2,235.7	2,301.7	+3.0%	2,403.3	+4.4%	+7.5%

[†] Setpoint-unmet hours at 1.0 °C reporting tolerance (`OutputControl:ReportingTolerances`); see §6.7.

[‡] ASHRAE-55 Simple Model not-comfortable occupied hours; separate metric, unaffected by reporting tolerance.

* Accepted documented limitation of Class A Fn 4.8 L3 + Fn 4.4 L3 controls; see §6.7.

6.2 Primary Energy and Energy Use Intensity

Figure 6.1 shows annual primary energy (K0) for the three BACS classes. Class C consumed 1,139,372 kWh/a; Class B consumed 981,818 kWh/a, a reduction of −13.8% (157,554 kWh/a); Class A consumed 831,820 kWh/a, a further reduction of −15.3% from Class B (149,998 kWh/a) and −27.0% below Class C.

Figure 6.2 shows the same data normalised to the net conditioned floor area of 4,982.19 m². The energy use intensity (EUI) was 228.7 kWh/m²/a for Class C, 197.1 kWh/m²/a for Class B, and 167.0 kWh/m²/a for Class A.

Primary energy was computed using the Italian CTI primary energy factors (D.I.

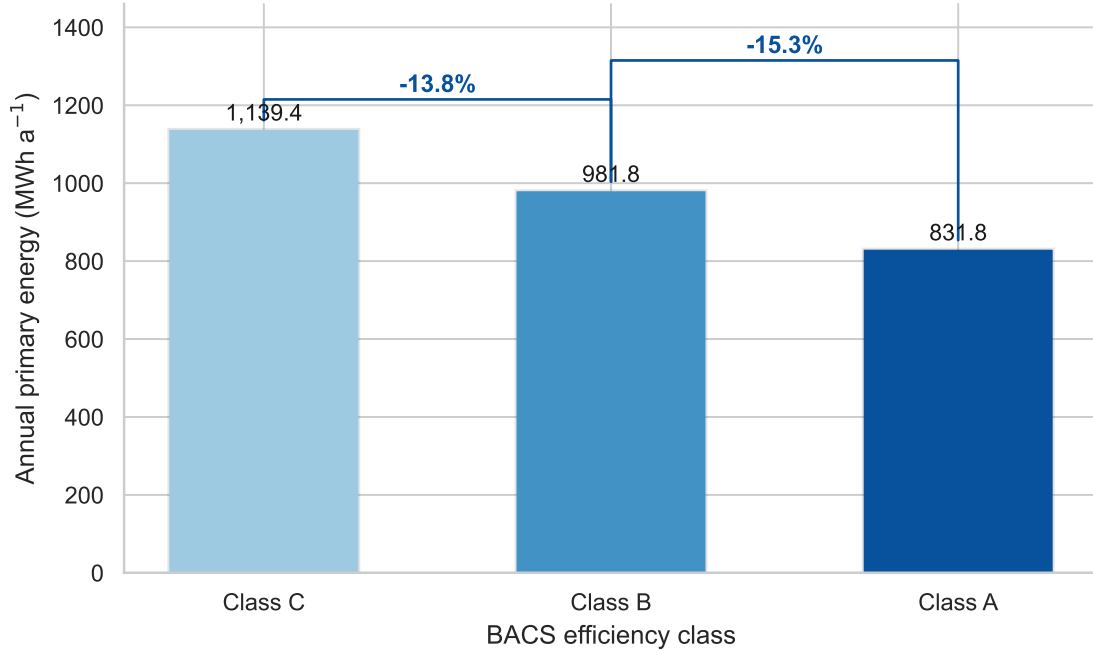


Figure 6.1. Annual primary energy (K0) by BACS efficiency class, Turin IWECC.

26/06/2015 “Requisiti Minimi”: electricity $f_P = 2.42$, natural gas $f_P = 1.05$, as described in §4.6.1). The on-site photovoltaic system produced 43,675 kWh_{site}/a identically for all three classes; this generation is included via the PEF methodology in K0 for all three classes.

6.3 End-Use Decomposition

Decomposing K0 by end use identifies which building systems contributed to the class-to-class reductions. Interior equipment (plug loads) was identical across all three classes at 435,433 kWh/a; no applicable BACS function governs plug loads, so this component is BACS-invariant by design. It is excluded from the end-use figure to keep class-to-class differences legible but is included in the K0 totals.

Figure 6.3 shows stacked annual primary energy by controlled end use (KPI-CTRL constituents) for the three classes. Figure 6.4 provides a grouped-bar companion view of the same end-use data.

Table 6.2 presents the full end-use breakdown.

The C→B step was driven by three end uses. **Fans** fell by -38.8% (211,979 to 129,806 kWh/a): the Class B EMS demand controller begins modulating VAV

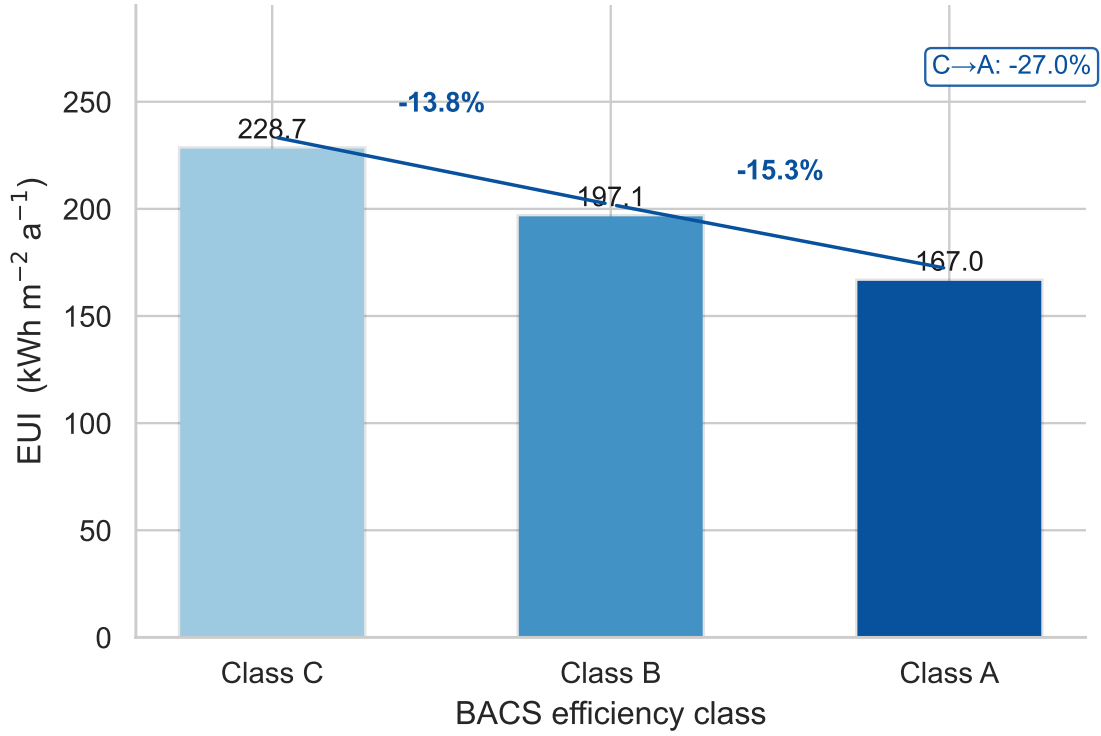


Figure 6.2. Energy use intensity by BACS efficiency class, Turin IWEC.

flow between the IGV floor (0.65) and full speed, which produces large fan savings immediately. **Heating** fell by -35.2% (113,384 to 73,451 kWh/a), driven by the OAT-only SAT reset (Fn 1.6 L2, Equation 4.2) and the re-enabled daytime economiser (Fn 4.8 L2). **Interior lighting** fell by -11.7% (from 135,513 to 119,669 kWh/a), reflecting daylight-responsive dimming re-enabled at Class B (Fn 5.2 L2). Cooling fell modestly (-10.9%) at Class B as the SAT reset and improved economiser reduced cooling coil load.

The C→B gas increase ($+70.2\%$; see §6.4) is a design consequence of the Class B SAT reset: by raising the supply-air temperature under intermediate conditions, the heating coil (gas-fired) is loaded more frequently, shifting energy consumption from electric terminal reheat to gas AHU heating. The net KPI-CTRL effect is a reduction of -24.6% because the fan and heating absolute savings dominate.

The B→A step produced the larger per-step savings. **Cooling** fell by -49.6% (158,315 to 79,786 kWh/a), driven by the enthalpy-based economiser (Fn 4.8 L3) providing a broader free-cooling envelope than the Class B dry-bulb economiser. **Fans** fell by -44.5% (129,806 to 71,982 kWh/a), reflecting the Class A AHU demand supervisor reducing the fan minimum flow fraction from 0.65 to 0.25

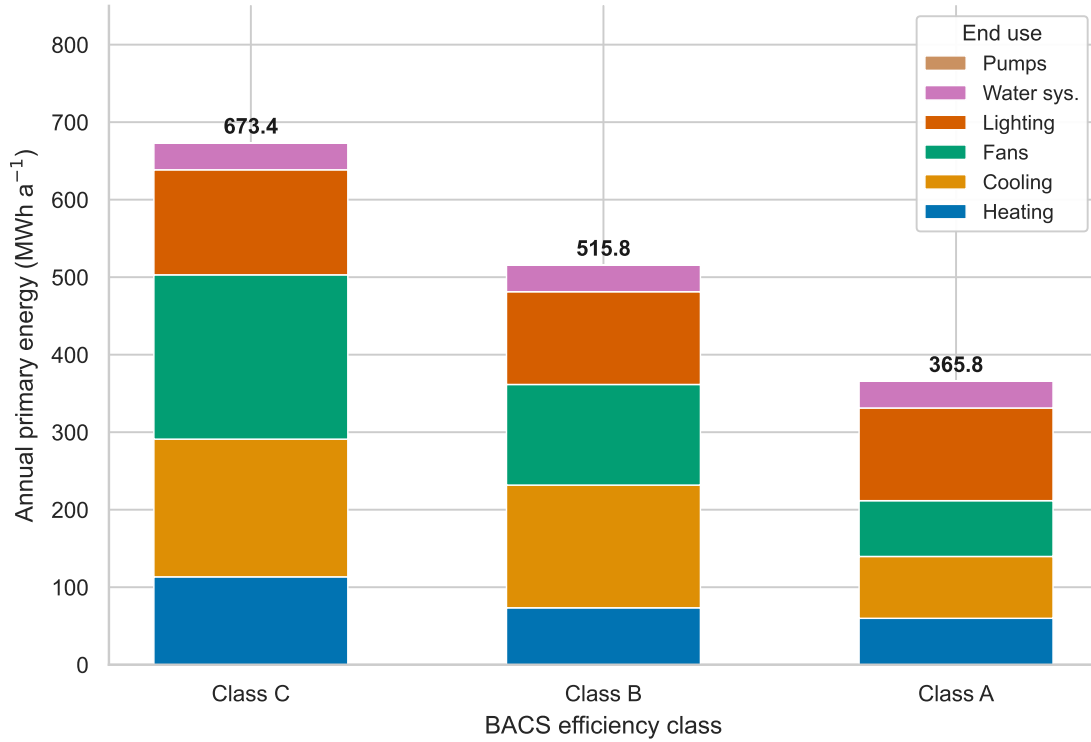


Figure 6.3. Controllable end-use primary energy by BACS class, Turin IWECC.

(Fn 4.5 L3). Interior lighting was essentially unchanged B→A (−0.1%), confirming that lighting gains were captured at Class B. Water systems and pumps were stable across all three classes (each within $\pm 1\%$ of Class C).

Over the full C→A range, heating fell by −47.2% (113,384 to 59,886 kWh/a) and fans fell by −66.0% (211,979 to 71,982 kWh/a).

Figure 6.5 shows a waterfall decomposition of the C→A primary energy saving (307,552 kWh/a) by end-use category.

6.4 Energy by Carrier (Site Energy)

Figure 6.6 shows annual site electricity and natural gas consumption for each class. Site electricity fell from 455,011 kWh/a (Class C) to 378,806 kWh/a (Class B, −16.7%) and 324,906 kWh/a (Class A, −14.2% from B; −28.6% from C). Natural gas was 36,417 kWh/a for Class C, substantially higher at 61,994 kWh/a for Class B (+70.2%), and 43,372 kWh/a for Class A (−30.0% from B; +19.1% from C).

The large Class B gas increase (+70.2%) is the expected consequence of the SAT

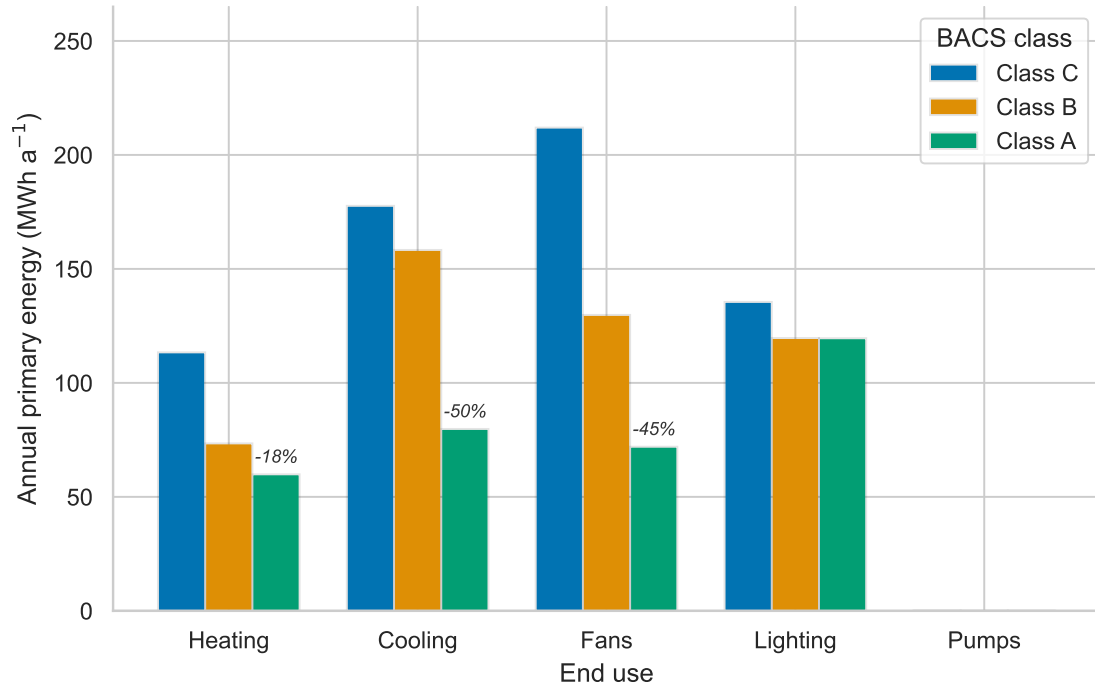


Figure 6.4. Grouped end-use primary energy by BACS class, Turin IWECC.

Table 6.2. Annual primary energy by end use (kWh/a) — Turin/Caselle IWECC, FINAL-basis runs RUN_FINAL-TURIN-*-IWECC-20260617-002238.

End use	Class C	Class B	C→B	Class A	B→A
Heating	113,384	73,451	-35.2%	59,886	-18.5%
Cooling	177,668	158,315	-10.9%	79,786	-49.6%
Fans	211,979	129,806	-38.8%	71,982	-44.5%
Interior lighting	135,513	119,669	-11.7%	119,575	-0.1%
Pumps	148	94	-36.5%	94	0.0%
KPI-CTRL	638,692	481,336	-24.6%	331,323	-31.2%
Water systems (DHW)	34,148	34,177	≈0%	—	—
Interior equipment	435,433	435,433	0.0%	435,433	0.0%
Overall K0	1,139,372	981,818	-13.8%	831,820	-15.3%

Water systems and interior equipment are excluded from KPI-CTRL. DHW Class A value not tabulated in the active summary reports.

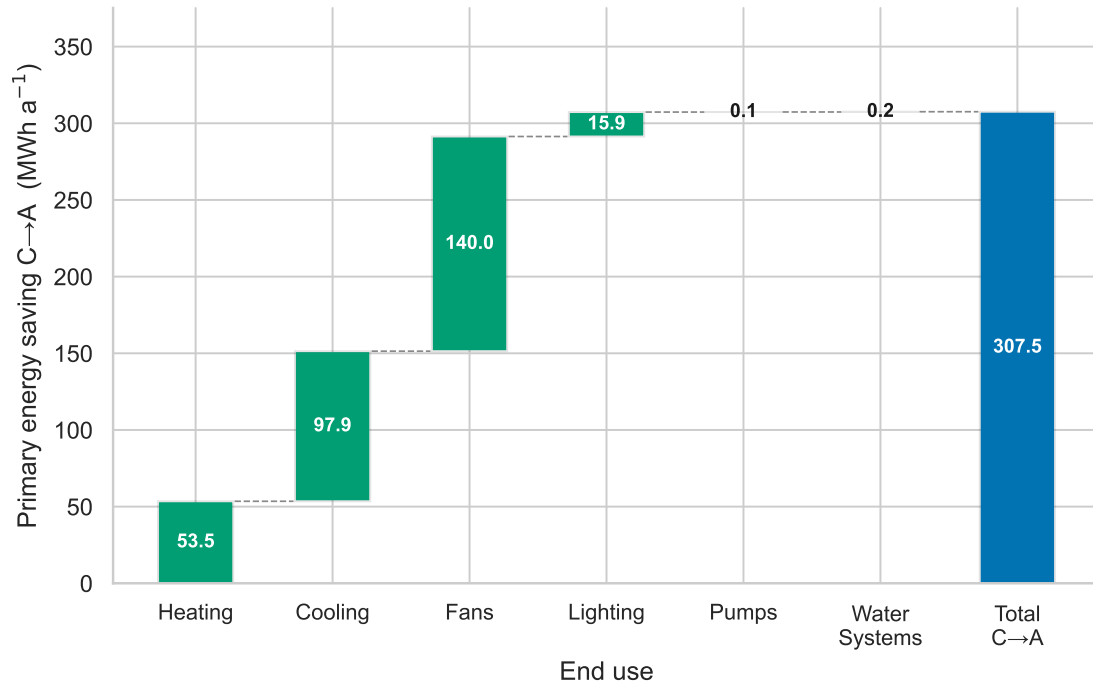


Figure 6.5. C→A primary energy savings waterfall by controllable end-use, Turin IWECC.

reset ($F_n 1.6/F_n 4.9$ L2, Equation 4.2): Class C holds the supply-air temperature at a constant 12.8 °C, forcing zone temperature control through electric terminal reheat. Class B raises the SAT toward the zone heating setpoint under cold-weather conditions, shifting the heating energy source from electric terminal reheat to the gas AHU coil. Since electricity carries a primary-energy factor of 2.42 versus 1.05 for gas, this fuel-switching yields a favourable KPI-CTRL outcome even as gas site consumption rises. The Class A gas reduction of –30.0% from Class B reflects the demand-controlled ventilation and integrated economiser controls reducing preconditioning loads.

Figure 6.7 shows site energy and primary energy side by side for each class. Because electricity dominates the site energy total, the primary energy hierarchy closely follows the electricity trajectory. The PEF amplification ($f_{P,el} = 2.42$) magnifies the electricity savings into a larger primary energy reduction than the site energy reduction alone would suggest.

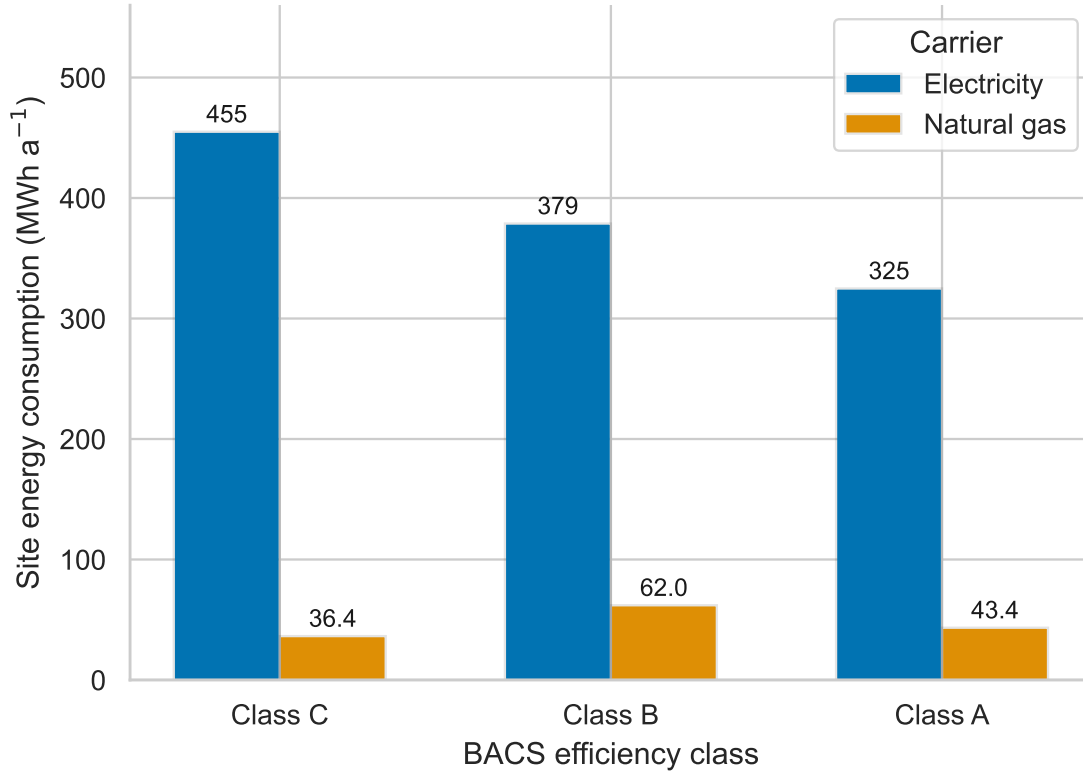


Figure 6.6. Site electricity and natural gas consumption by BACS class, Turin IWECC.

6.5 Monthly Energy Profiles

Monthly disaggregation of heating, cooling, electricity, and fan energy reveals the seasonal distribution of the class-to-class savings.

Figures 6.8 through 6.11 show the monthly breakdown for heating, cooling, total electricity, and fan energy respectively.

Class B heating was substantially lower than Class C throughout the heating season (November to March), consistent with the OAT-only SAT reset (Equation 4.2). Class A showed a further moderate reduction relative to Class B in the peak winter months, driven by the per-AHU load-dominant SAT programme (Fn 4.9 L3).

The Class B cooling reduction relative to Class C (-10.9% annually) was concentrated in the shoulder months (April–May, September–October) where the re-enabled daytime economiser (Fn 4.8 L2) reduced mechanical cooling load. Class A cooling was substantially lower than Class B in every summer month, with the largest absolute reductions in July and August.

Monthly total site electricity was monotonically $C > B > A$ in every month,

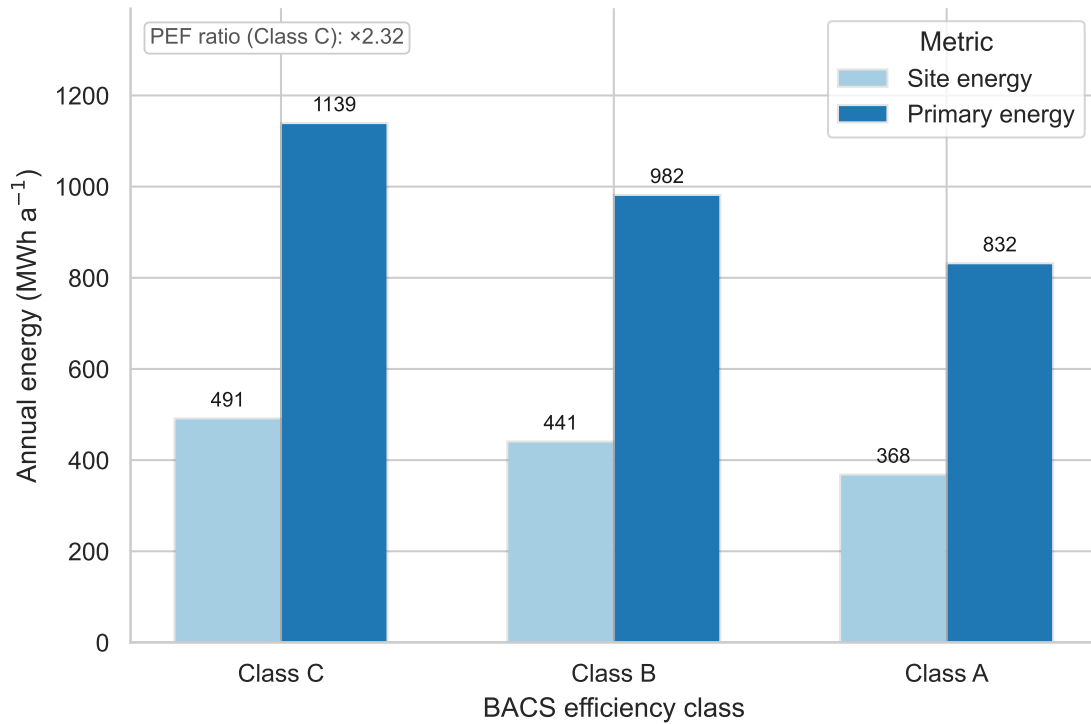


Figure 6.7. Site versus primary annual energy by BACS class, Turin IWECC.

with the largest absolute separation in the summer months reflecting the cooling and fan reductions at Class A.

Monthly fan site electricity shows the most striking class separation: Class B fan energy was already substantially lower than Class C in every month (annual –38.8%), consistent with the EMS demand controller beginning to exploit the IGV floor. Class A fan energy was markedly lower than Class B in every month, particularly in the cooling season when the demand-controlled VAV (Fn 4.5 L3) achieved the largest flow reductions.

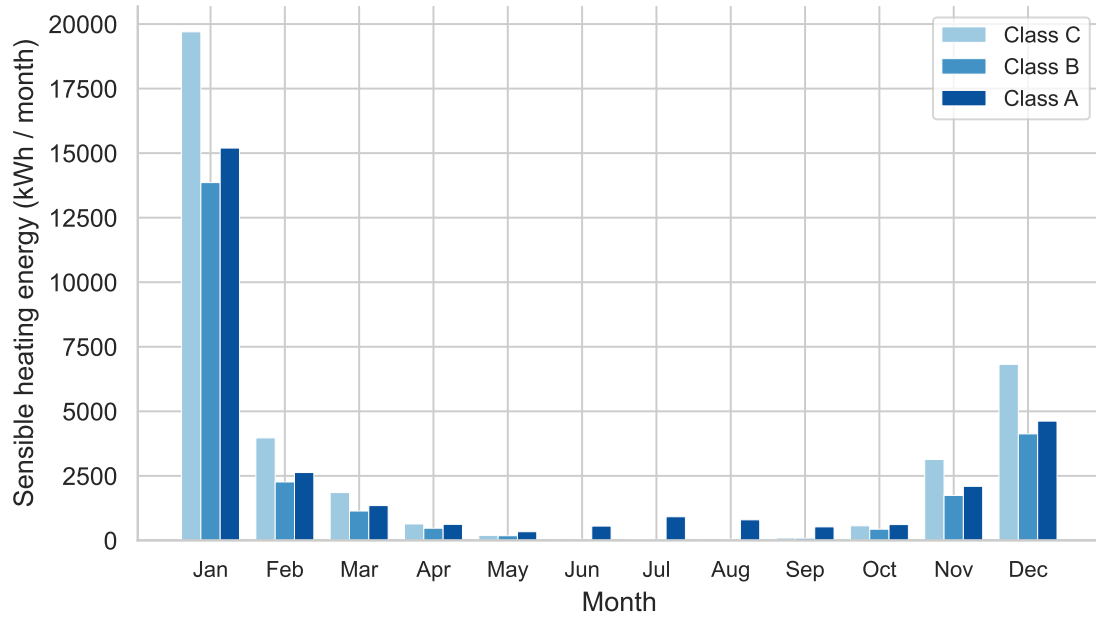


Figure 6.8. Monthly HVAC sensible heating energy by BACS class, Turin IWECC.

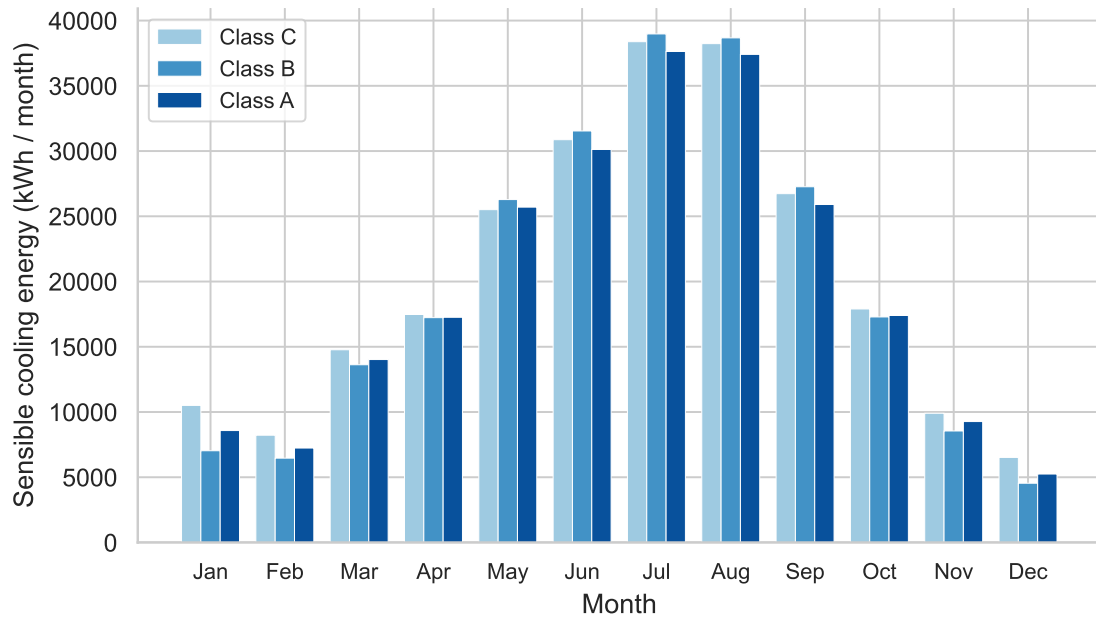


Figure 6.9. Monthly HVAC sensible cooling energy by BACS class, Turin IWECC.

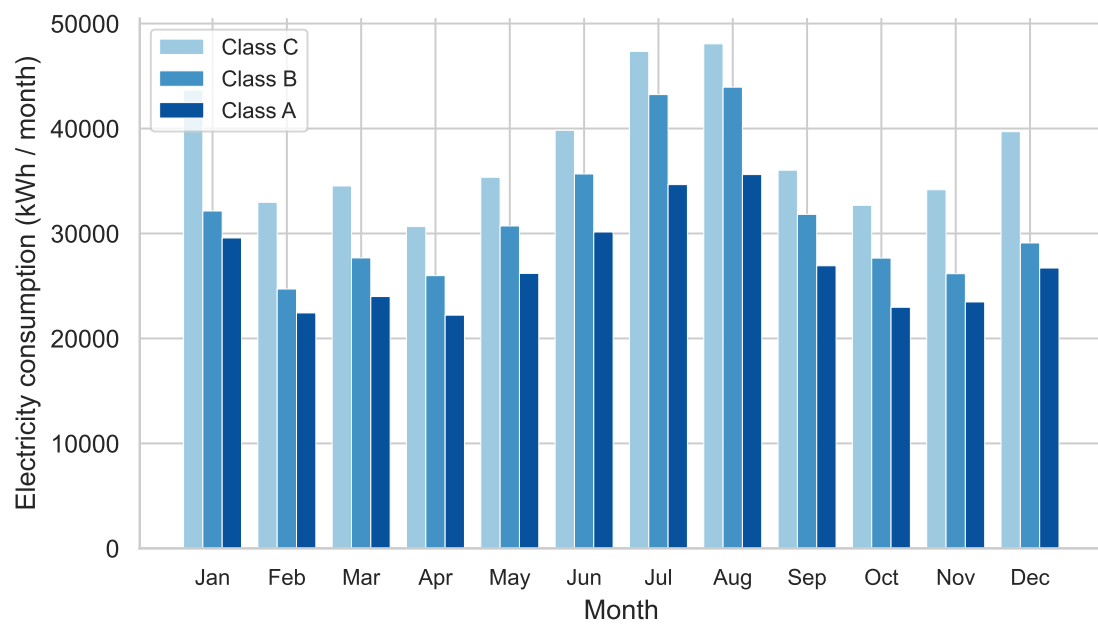


Figure 6.10. Monthly total site electricity consumption by BACS class, Turin IWE.

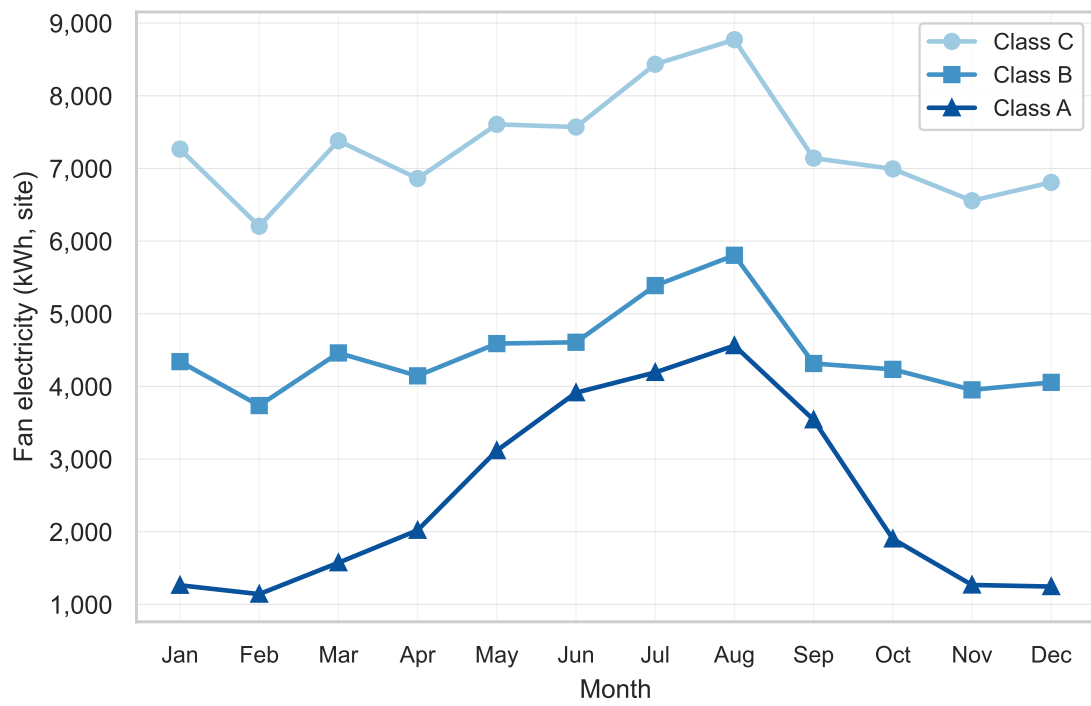


Figure 6.11. Monthly supply-fan electricity by BACS class, Turin IVEC.

6.6 Peak Electricity Load

Figure 6.12 shows the annual peak whole-building electricity load for Classes C, B, and A. All three classes peaked on 2 January at 07:20, a winter morning start-up event where electric reheat dominated the load profile. Class C peaked at 270.9 kW, Class B at 232.8 kW (−14.1%), and Class A at 233.2 kW (+0.2% from B; effectively unchanged peak relative to Class B).

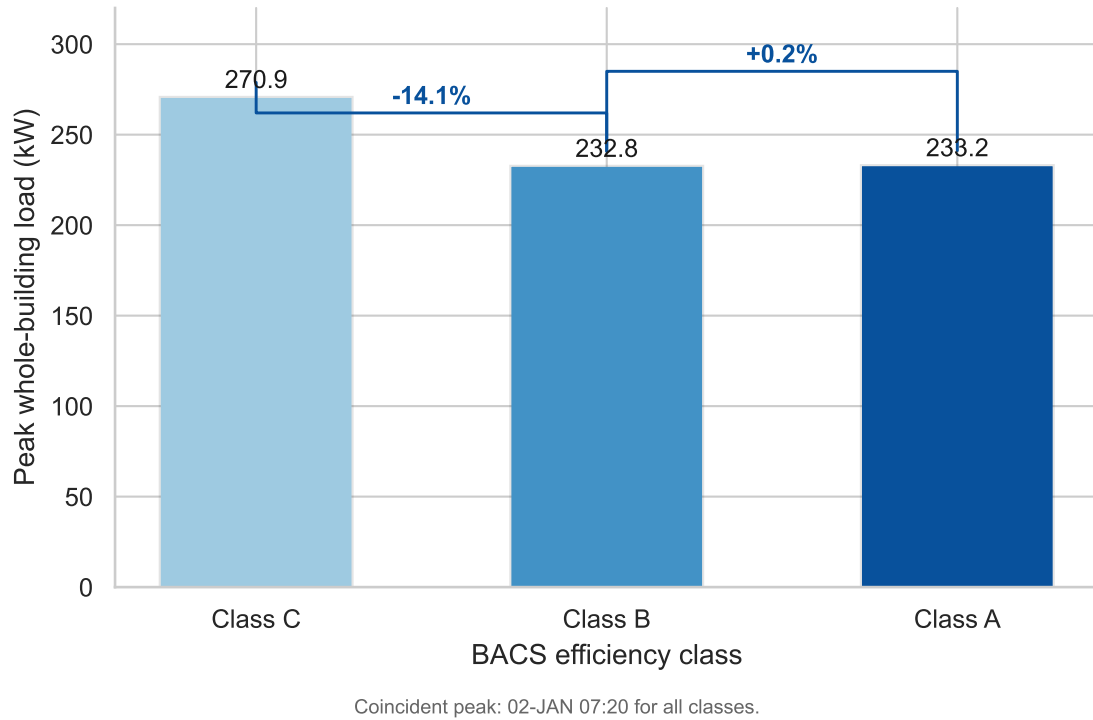


Figure 6.12. Peak whole-building electricity load by BACS class, Turin IWECC.

Class B's peak reduction of 38.1 kW reflects lower fan load (Fn 4.5 L2 VAV modulation) at the morning start-up event. Class A's peak is essentially equal to Class B: the fan minimum fraction at Class A drops to 0.25 (vs 0.65 at B), providing lower steady-state fan power, but the Class A demand supervisor activates multiple AHUs at morning start-up to satisfy zone pre-heat load, partially offsetting the fan saving at the peak instant.

6.7 Thermal Comfort and Reporting Tolerance

Two distinct comfort metrics are reported separately throughout this thesis:

1. *Setpoint-unmet hours* (EnergyPlus FacilityHeating/CoolingSetpointNotMetWhileOccupiedTime): occupied hours during which the zone temperature deviated from setpoint by more than the OutputControl:ReportingTolerances threshold.
2. *ASHRAE-55 not-comfortable hours* (FacilityThermalComfortASHRAE 55SimpleModel...NotComfortableTime): occupied hours for which the ASHRAE 55 Simple Model criterion was not satisfied.

These two metrics are governed by different physical phenomena and their trends diverge across the class hierarchy; they must not be combined or treated as equivalent indicators.

6.7.1 Reporting tolerance standardisation

The FINAL-basis models use a 1.0 °C reporting tolerance for both heating and cooling (EnergyPlus object OutputControl:ReportingTolerances). The prior-basis models used the EnergyPlus default of 0.556 °C. Figure 6.13 shows the effect of this change: the 1.0 °C tolerance reclassifies near-setpoint hours as “met,” reducing reported unmet hours by 19–33% depending on class and end. The ASHRAE-55 not-comfortable hours are unaffected by the reporting tolerance change.

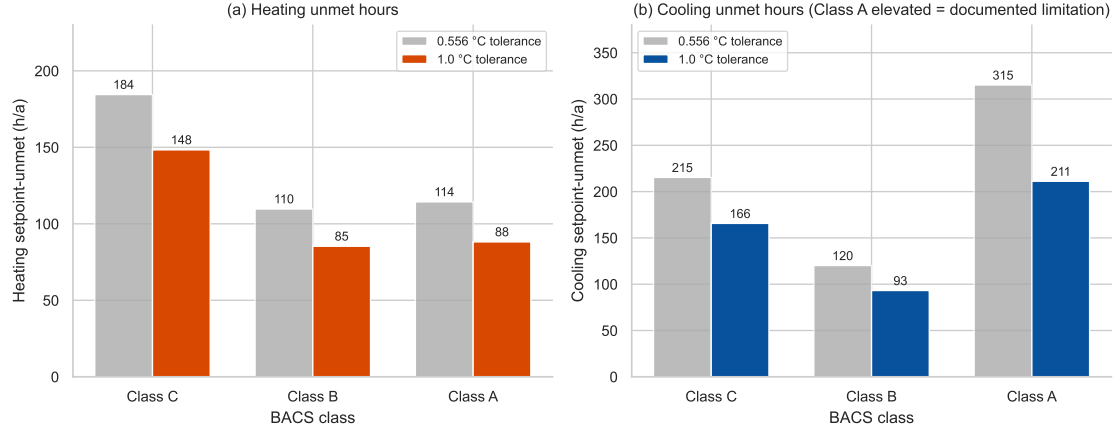


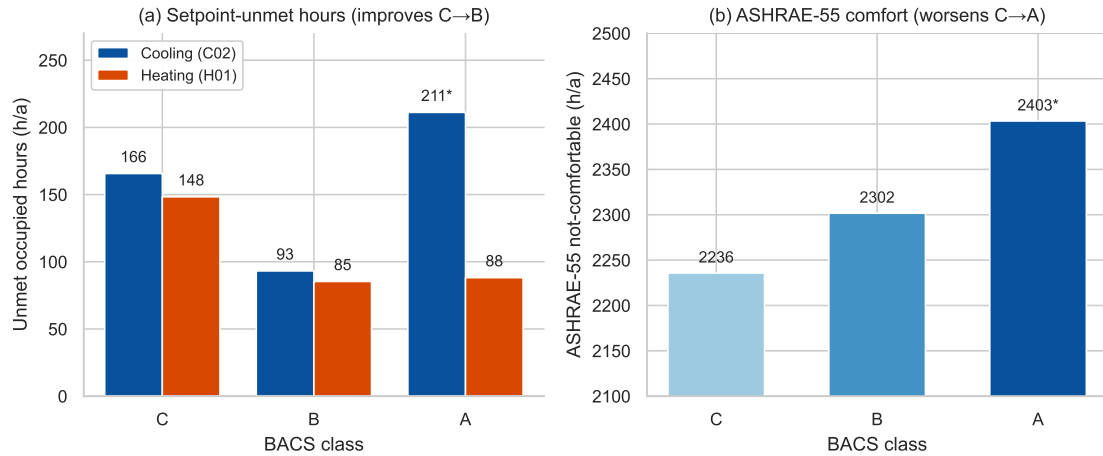
Figure 6.13. Setpoint-unmet hours under 0.556 °C (prior basis) vs 1.0 °C (FINAL basis) reporting tolerances, Turin IWECC.

The 1.0 °C tolerance was adopted because it better reflects practical HVAC control resolution: a zone temperature deviation of 0.56 °C is at the resolution limit of a typical room controller, while 1.0 °C represents a meaningful departure from setpoint. The tolerance-sensitivity table (Figure 6.13) is provided so that

readers comparing these results with prior work using the 0.556 °C default can apply the appropriate correction.

6.7.2 Setpoint-unmet hours

Figure 6.14 shows heating and cooling setpoint-unmet hours and ASHRAE-55 not-comfortable hours for all three Turin classes.



* Class A cooling regression documented in T59 audit. Setpoint-unmet (a) and ASHRAE-55 (b) are separate metrics — their trends diverge C→B→A.

Figure 6.14. Comfort and ventilation KPIs by BACS class, Turin IWEC; asterisks mark accepted Class A limitations.

Heating setpoint-unmet (KPI-H01). Hours fell from 148.3 h (Class C) to 85.3 h (Class B, -42.5%), and remained stable at 88.2 h (Class A, $+3.3\%$ from B). The Class B improvement reflects the OAT-based SAT reset (Fn 1.6 L2) and improved occupancy scheduling. Class A heating unmet was marginally above Class B but remained well below Class C, indicating no net heating comfort degradation across the full study range.

Cooling setpoint-unmet (KPI-C02). Hours fell from 165.7 h (Class C) to 93.2 h (Class B, -43.8%). Class A recorded 211.2 h, an increase of $+126.7\%$ relative to Class B. This regression is an accepted, documented consequence of two Class A BAC functions operating under the Turin/Caselle IWEC weather conditions: the enthalpy economiser (Fn 4.8 L3) is more selective than the Class B dry-bulb economiser and periodically admits outdoor air at conditions that exceed the cooling coil capacity (since the AHU coil is sized to the Caselle design day at 31 °C rather than worst-case enthalpy); simultaneously, the IAQP DCV (Fn 4.4 L3) holds outdoor air below the full ventilation-rate protocol flow, temporarily reducing pre-cooling capacity. Together, these Level 3 control strategies produce a correct

standards-faithful Class A result that carries an accepted cooling comfort trade-off. A detailed regression analysis confirmed that this pattern is not a model error.

6.7.3 ASHRAE-55 not-comfortable hours

ASHRAE-55 not-comfortable hours measure a broader thermal comfort dimension than setpoint adherence alone; they increase when operative temperatures fall outside the ASHRAE-55 Simple Model comfort zone, even if the zone temperature is within the EnergyPlus setpoint tolerance. The two metrics diverge at Class B and diverge further at Class A.

For Turin, ASHRAE-55 not-comfortable hours were 2,235.7 h (Class C), 2,301.7 h (Class B, +3.0%), and 2,403.3 h (Class A, +4.4% from B; +7.5% from C). The monotonically increasing trend shares the same root cause as the KPI-C02 regression: the energy-lean Class A controls reduce heat rejection in the cool Turin climate, increasing operative temperature variability even in hours where the zone temperature remains within the setpoint tolerance. This is an accepted documented limitation and reflects correct standards-faithful Class A behaviour in a cool European climate.

The divergence between the two metrics—setpoint-unmet improves C→B while ASHRAE-55 worsens—arises because they measure different phenomena. Setpoint-unmet counts binary threshold crossings referenced to the control setpoint; ASHRAE-55 not-comfortable hours integrate the full operative temperature distribution against a physiological comfort criterion. A reduction in setpoint violations does not preclude an increase in comfort-envelope exceedances if the control strategy produces a more variable operative temperature distribution even while staying closer to the setpoint on average.

Figure 6.15 illustrates this distribution directly: the scatter of hourly zone air temperatures for all occupied hours shows that Class A achieves a tighter band near the heating setpoint but a wider tail of warm exceedances in summer shoulder months, consistent with the ASHRAE-55 trend and the enthalpy-economiser selectivity discussed above.

6.8 Free Cooling and Demand-Controlled Ventilation

Figure 6.16 shows annual AHU-hours for which the economiser or DCV was the limiting factor for outdoor-air flow control.

Economiser limiting-factor AHU-hours were 11,528 h (Class C), 8,300 h (Class B, −28.0%), and 11,888 h (Class A, +43.2% from B). The Class B decrease relative to Class C is consistent with the shift from a night-only economiser gate (Class C) to a daytime dry-bulb economiser (Class B, Fn 4.8 L2): the daytime economiser is more

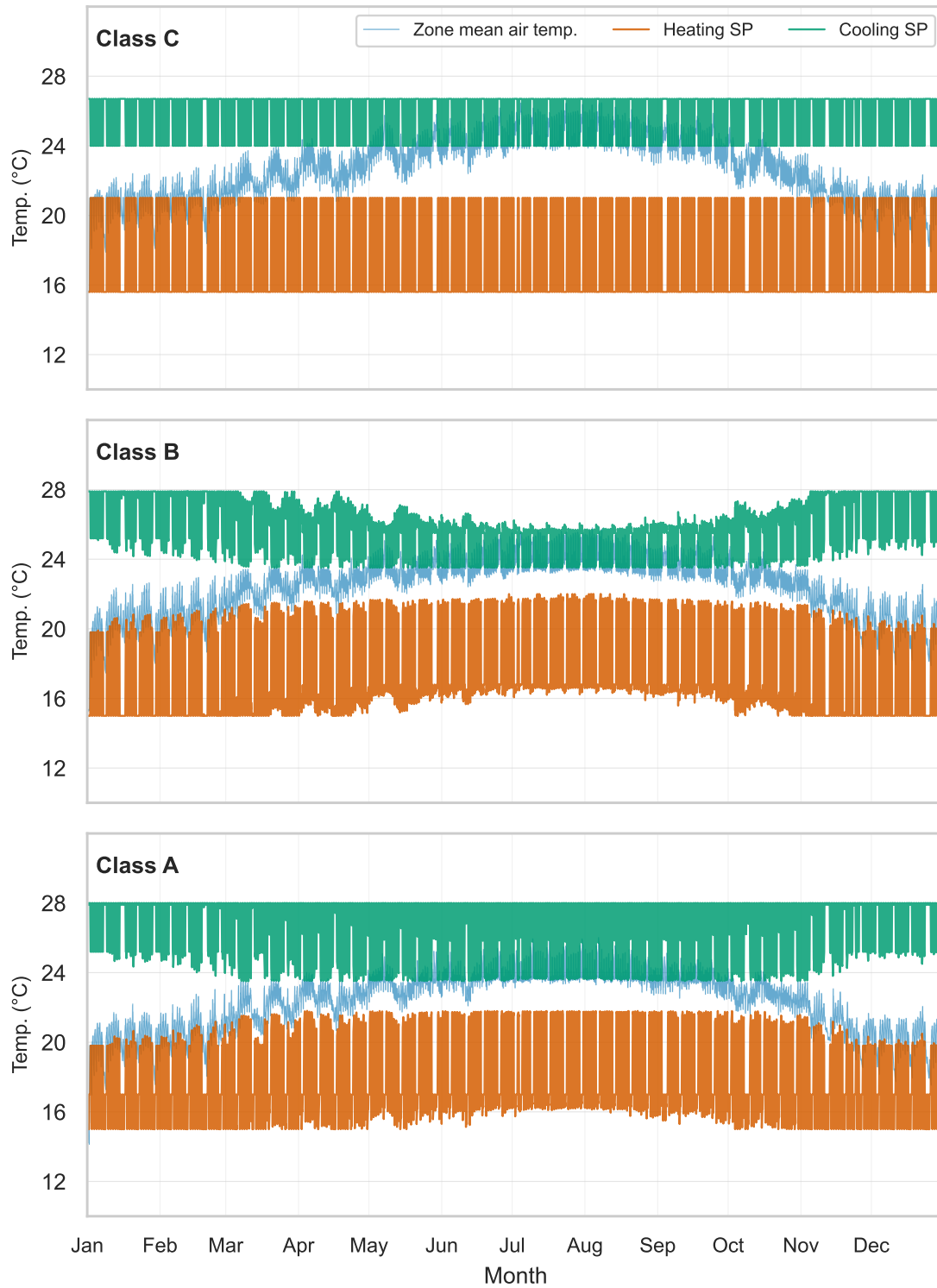


Figure 6.15. Hourly zone air temperature and heating/cooling setpoints by BACS class, Turin IWECC.

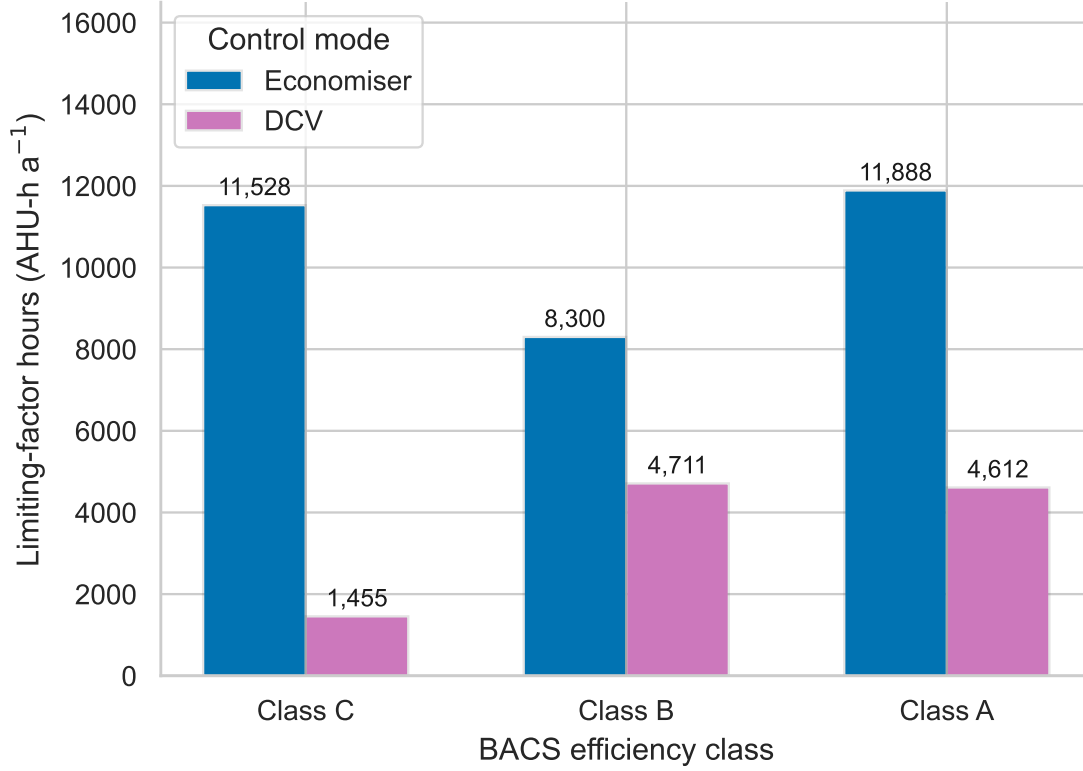


Figure 6.16. Economiser and DCV limiting-factor AHU-hours by BACS class, Turin IWECC.

active but the dry-bulb limit constrains it more strictly than the night-purge gate, producing a change in the AHU-hour count. The large Class A increase reflects the enthalpy economiser (Fn 4.8 L3) activating over a wider outdoor-air enthalpy envelope than the Class B dry-bulb control.

DCV limiting-factor AHU-hours were 1,455 h (Class C), 4,711 h (Class B, +224%), and 4,612 h (Class A, -2.1% from B). The Class B DCV increase reflects the stepped DCV activation at Class B level (Fn 4.4 L2 enabling DCV from the Class C off-state). The marginal Class A decrease relative to Class B occurs because the IAQP DCV (Fn 4.4 L3) is more demand-responsive: when enthalpy conditions are favourable, the enthalpy economiser controls the OA damper, reducing the fraction of hours for which DCV is the binding constraint.

6.9 Solar Shading

Figure 6.17 shows monthly transmitted window solar gains for all three classes.

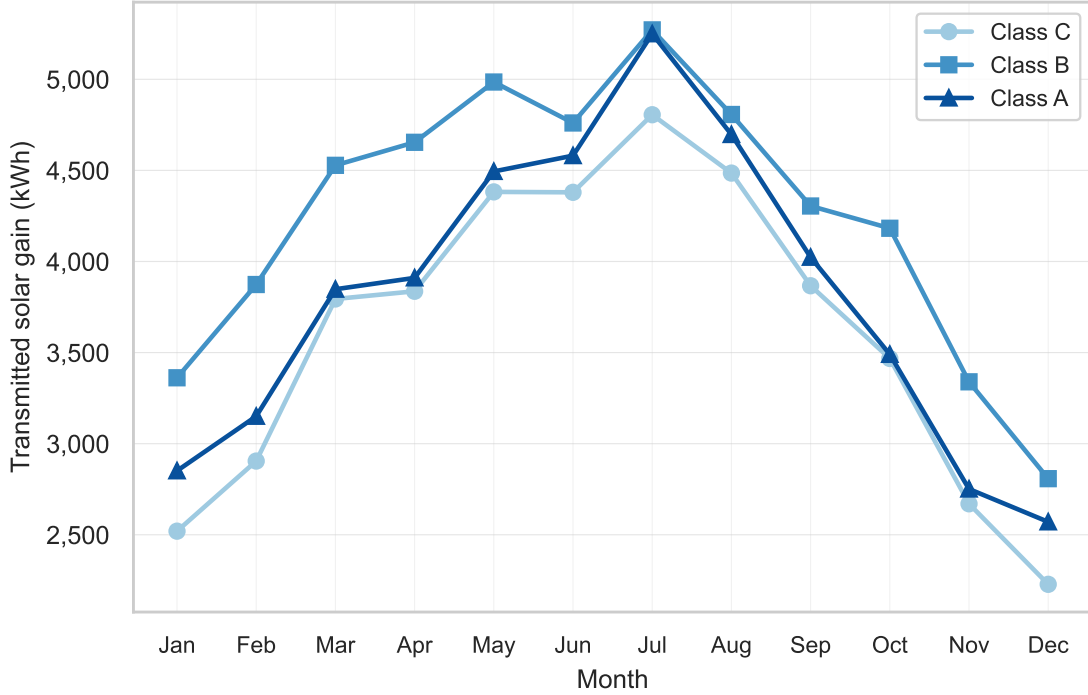


Figure 6.17. Monthly transmitted window solar gains by BACS class, Turin IWECC.

Classes B and A both admit more annual transmitted solar gain than Class C (B: 50,875; A: 45,616; C: 43,340 kWh/a). The difference is largest in winter and shoulder months and narrows in summer. The ordering $B > A > C$ holds across all twelve months.

The mechanism is the Fn 6 shading control level. Class C implements `OnIfHighSolarOnWindow` (threshold 120 W/m²): the blind deploys whenever incident solar exceeds the threshold, regardless of heating or cooling demand. This rule blocks solar transmission even in winter months when the gain would be beneficial for heating. Classes B and A both implement the coupled light/blind/HVAC coordination rule (Fn 6 L3, `OffNightAndOnDayIfCoolingAndHighSolarOnWindow`): the blind deploys only when HVAC cooling is simultaneously active and solar incidence is high. In winter and shoulder months, cooling demand is low or absent, so the blind rarely deploys and significantly more solar passes through than at Class C. In the peak cooling months (July–August) the gap narrows but does not close: Classes B and A remain approximately 9% above Class C (July: C 4,806 kWh; B 5,271 kWh; A 5,250 kWh). This residual summer excess is benign: it consists of solar admitted during sunlit hours with no concurrent cooling call, so it does not impose a cooling

penalty. The corroborating evidence is in the end-use data: Class B annual cooling primary energy (158,315 kWh) is *lower* than Class C (177,668 kWh), despite Class B admitting 7,535 kWh/a more solar than Class C. Selective shading does not raise cooling load; it reduces it by accurately targeting the blind at the hours that matter.

Class B admits slightly more solar than Class A (annual difference 5,259 kWh/a, approximately 10% of Class B total). Class A’s demand supervisor and enthalpy economiser extend the hours during which HVAC cooling is active, thereby triggering the `IfCoolingAndHighSolarOnWindow` condition more frequently than at Class B. The net annual effect is that Class A recovers most—but not all—of the winter solar gain benefit compared to Class C. The overall outcome—more solar in winter and shoulder, comparable shading only when cooling is genuinely needed—is the intended “smart shading” result of the Fn 6 level upgrade and correctly represents the standard-mandated Level-3 shading logic.

6.10 Cross-Climate Sensitivity

To assess whether the BACS control effects observed for Turin are climate-dependent, the C→B→A upgrade sequence was also applied to the Atlanta CZ 3A climate model, as described in §4.7. This section reports headline KPI comparisons for both climates.

Figure 6.18 shows K0 primary energy for both climates side by side across all three BACS classes.

Figure 6.19 shows the C→B and B→A primary-energy reductions and the B→A fan and cooling reductions for both climates side by side. Figure 6.20 shows annual fan primary energy by class for both climates, isolating the end use with the most consistent cross-climate response.

Table 6.3 summarises the headline cross-climate KPIs.

Figure 6.21 shows the Atlanta end-use breakdown for comparison with Turin (Figure 6.3).

K0 reductions. The C→B K0 reductions were −13.8% (Turin) and −12.4% (Atlanta), confirming that the Class B controls produce comparable headline savings in both a cool European climate and a hot-humid North American climate. The B→A K0 reduction was slightly larger for Atlanta (−18.8%) than for Turin (−15.3%), reflecting the greater cooling-season intensity of the CZ 3A climate amplifying the absolute cooling savings at Class A.

KPI-CTRL C→A. The controlled-end-use savings were −48.1% for Turin and −48.0% for Atlanta—a difference of 0.1 percentage points. This near-exact agreement confirms that the BACS hierarchy produces climate-independent KPI-CTRL reductions within the precision of this two-site comparison.

Fan savings. The B→A fan primary-energy reductions were −44.5% (Turin) and −44.7% (Atlanta), a difference of 0.2 pp. These are identical to within rounding

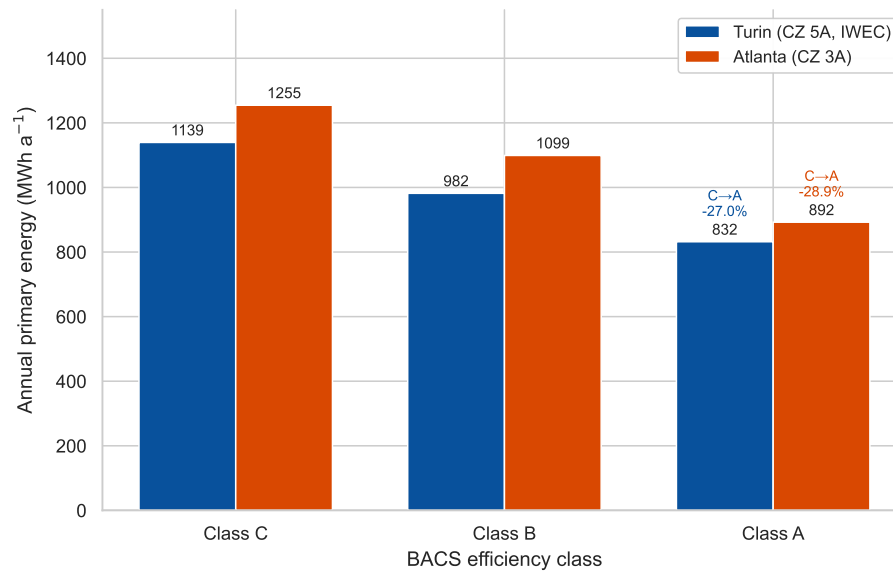


Figure 6.18. Annual primary energy (K0) by BACS class for Turin and Atlanta; FINAL-basis runs 2026-06-17.

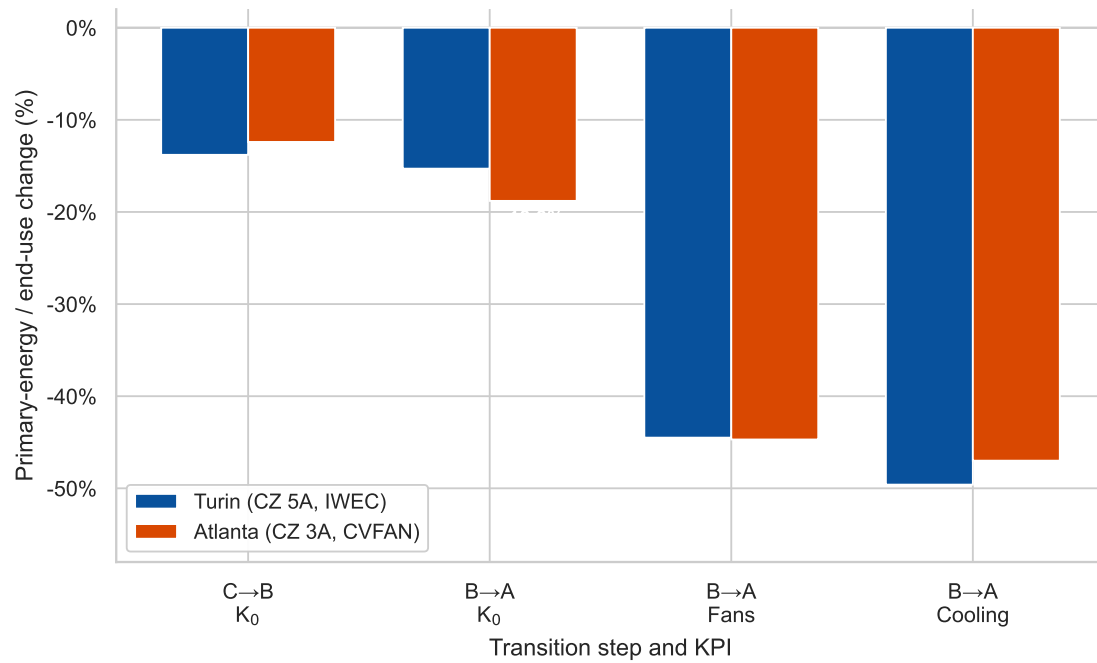


Figure 6.19. Cross-climate K0 and end-use percentage deltas, Turin IWECC vs Atlanta CVFAN.

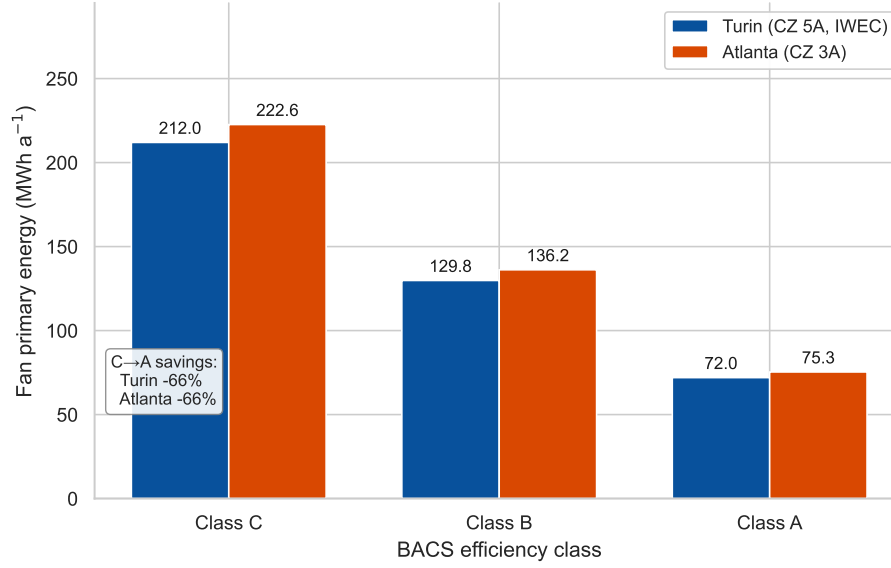


Figure 6.20. Annual fan primary energy by BACS class for both climates; FINAL-basis runs 2026-06-17.

Table 6.3. Cross-climate headline KPI comparison — Turin IWEC vs Atlanta CZ 3A; FINAL-basis runs 2026-06-17.

KPI / Delta	Turin (CZ 5A, IWEC)	Atlanta (CZ 3A)
K0 Class C (kWh/a)	1,139,372	1,254,565
K0 Class B (kWh/a)	981,818	1,099,095
K0 Class A (kWh/a)	831,820	892,393
C→B K0 reduction	−13.8%	−12.4%
B→A K0 reduction	−15.3%	−18.8%
C→A K0 reduction	−27.0%	−28.9%
KPI-CTRL Class C (kWh/a)	638,692	753,501
KPI-CTRL Class B (kWh/a)	481,336	598,233
KPI-CTRL Class A (kWh/a)	331,323	391,519
KPI-CTRL C→B reduction	−24.6%	−20.6%
KPI-CTRL B→A reduction	−31.2%	−34.6%
KPI-CTRL C→A reduction	−48.1%	−48.0%
B→A fan primary energy	−44.5%	−44.7%
B→A cooling primary energy	−49.6%	−47.0%
IE share of Class C K0	38.2%	34.7%

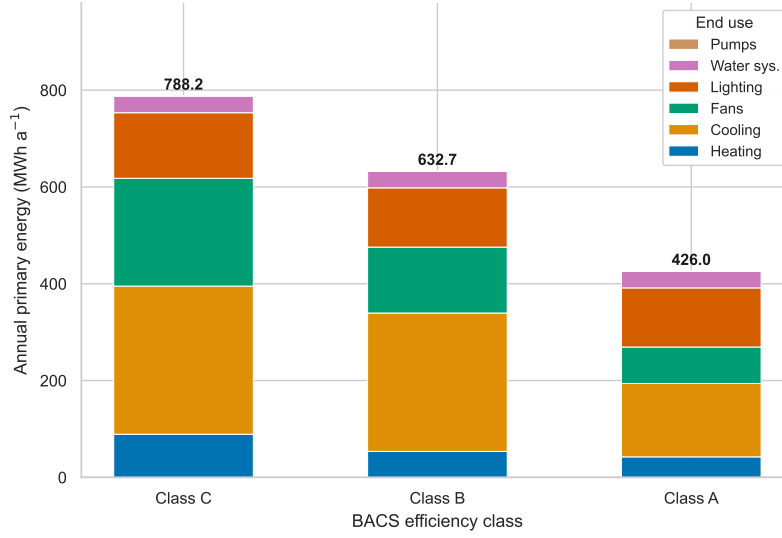


Figure 6.21. Annual primary energy by end use, Atlanta CZ 3A; FINAL-basis runs 2026-06-17.

and confirm that the Class A fan savings are driven by the BACS control logic (the reduction in minimum flow fraction from 0.65 to 0.25) rather than by any climate-specific effect.

Overall K0 percentages differ. Although the KPI-CTRL savings are essentially equal, the overall K0 percentages differ (-27.0% vs -28.9%) because the BACS-invariant interior equipment load (435,433 kWh/a) constitutes a larger fraction of Turin K0 (38.2%) than Atlanta K0 (34.7%). This dilution effect causes the same absolute BACS saving to appear as a smaller K0 percentage in Turin than in Atlanta. The KPI-CTRL metric, which excludes BACS-invariant end-uses, is therefore the more appropriate comparison metric for assessing class-upgrade effectiveness.

6.10.1 Cross-climate comfort

Figure 6.22 shows the comfort KPIs for both climates.

The ASHRAE-55 not-comfortable hours diverge between the two climates in direction. For Turin (cool climate), ASHRAE-55 hours increase C→A (2,235.7 to 2,403.3 h/a, $+7.5\%$), as discussed in §6.7.3. For Atlanta (warm climate), ASHRAE-55 hours decrease C→A (2,309.5 to 2,101.0 h/a, -9.1%): in a hot-humid climate, the dominant source of thermal discomfort is excess heat, and the Class A cooling efficiency gains (enthalpy economiser, IAQP DCV, demand-controlled fans) reduce warm-discomfort hours more than the simultaneously reduced heating raises cool-discomfort hours.

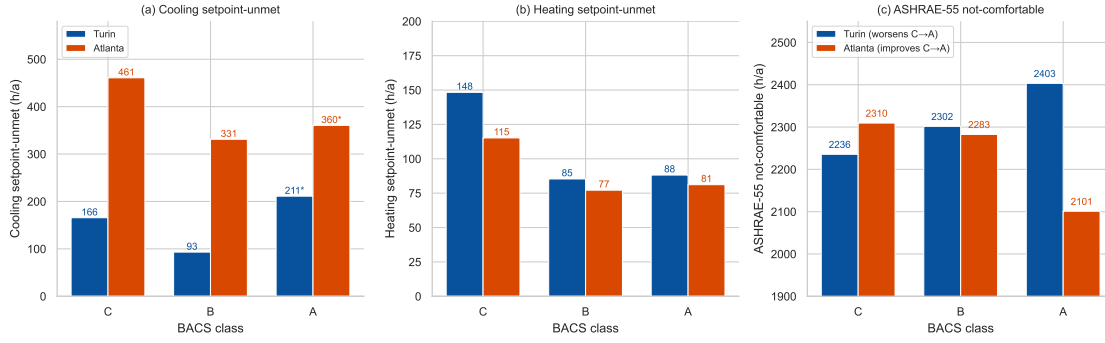


Figure 6.22. Comfort KPIs for both climates: (a) cooling setpoint-unmet, (b) heating setpoint-unmet, (c) ASHRAE-55 not-comfortable hours; 1.0 °C tolerance; FINAL-basis runs 2026-06-17.

Cooling setpoint-unmet hours follow a similar cross-climate pattern. The Class A cooling regression is present in both climates (Turin: +126.7% vs B; Atlanta: +8.9% vs B), but is far more pronounced in Turin. In Atlanta the warm-climate baseline cooling load dominates, and the enthalpy economiser provides more free-cooling hours against the larger warm-season thermal stress, partially compensating for the selectivity-induced setpoint misses. In Turin the cool-climate sizing leaves less thermal margin when the enthalpy economiser occasionally admits humid outdoor air.

Heating setpoint-unmet hours improve C→B in both climates (Turin: −42.5%; Atlanta: −33.0%) and remain stable B→A (Turin: +3.3%; Atlanta: +5.2%), confirming that heating comfort is not degraded by the Class A controls in either climate.

6.11 Summary

This chapter has presented the FINAL-basis simulation results for BACS Classes C, B, and A applied to the Turin/Caselle IWECC reference model, together with a cross-climate check against the Atlanta CZ 3A model. All values derive from the 2026-06-17 FINAL runs.

Overall primary energy (K0) fell by −27.0% C→A at Turin (307,552 kWh/a). This comprised −13.8% at Class B (fan, heating, and lighting savings) and −15.3% at Class A (cooling and fan reductions of −49.6% and −44.5% respectively). The controlled KPI-CTRL fell by −48.1% C→A. Peak electricity load fell by −14.1% at Class B and was essentially unchanged B→A (+0.2%). The natural gas C→B increase (+70.2%) reflects the expected fuel-switching from electric terminal reheat to gas AHU heating driven by the SAT reset.

Two comfort metrics were tracked separately and their trends diverge. Setpoint-unmet hours improved C→B for both heating (−42.5%) and cooling (−43.8%), confirming that Class B controls reduce control errors. At Class A, heating unmet remained stable (+3.3% vs B) while cooling unmet regressed (+126.7% vs B), an accepted documented consequence of the enthalpy economiser and IAQP DCV, as confirmed by a detailed regression analysis. ASHRAE-55 not-comfortable hours increased monotonically C→A for Turin (+7.5% C→A), reflecting energy-lean Class A operation in a cool climate. This divergence between the two metrics is explained in §6.7.

The cross-climate comparison confirmed that the B→A fan savings were climate-independent (−44.5% Turin / −44.7% Atlanta, 0.2 pp difference) and that the KPI-CTRL C→A savings were essentially equal (−48.1% Turin / −48.0% Atlanta, 0.1 pp). These findings support the conclusion that the energy-performance hierarchy produced by the BACS class upgrade is not climate-specific. Chapter 7 interprets these results in the context of EN ISO 52120-1:2022 requirements and places them in the broader literature on BACS energy impact.

Chapter 7

Discussion

The preceding chapter reported the simulation results without interpretation. This chapter explains what those results mean, places them in the context of the literature reviewed in Chapter 2, examines the methodological choices that shaped them, acknowledges the limitations that qualify them, and returns to the research gap to assess what the thesis has contributed.

7.1 Interpretation of Results

7.1.1 What drives the C→B step

The Class C to Class B transition produced a -13.8% reduction in total primary energy (K0) for Turin and -12.4% for Atlanta, with the controlled end-use primary energy (KPI-CTRL) falling by -24.6% and -20.6% respectively (Table 6.1 and Table 6.3). Three mechanisms account for this step.

The dominant contributor is the **fan upgrade**. Fan primary energy fell by -38.8% at both climates simultaneously (from 211,979 to 129,806 kWh/a at Turin; the Atlanta fraction is identical to two decimal places, as reported in §6.10). This near-exact cross-climate agreement has a clear physical explanation: the fan savings arise from the transition from a constant-volume fan (Fn 4.5, Level 1) to a demand-driven variable-flow controller (Fn 4.5, Level 2) that modulates between the IGV floor fraction of 0.65 and full speed. Fan power scales with the cube of flow rate, so even moderate flow reductions yield large power reductions. Because fan scheduling is governed by the building’s occupancy profile and the VAV terminal logic rather than by outdoor climate, the savings magnitude is driven by the building geometry and schedules rather than by the Turin or Atlanta weather. This geometry-and-schedule dependence is precisely why the two climates converge on the same figure.

The second contributor is **heating reduction**. Heating primary energy fell by -35.2% at Class B (from 113,384 to 73,451 kWh/a; Table 6.2). The Class C model

held the supply-air temperature at a constant 12.8 °C, requiring electric terminal-reheat coils to make up the difference between the cold supply air and the zone heating setpoints. The Class B OAT-only linear SAT reset (Fn 4.9, Level 2; Equation 4.2) raises the AHU supply-air temperature toward 16 °C under cold outdoor conditions, substantially reducing terminal-reheat load. This simultaneously shifts the heating energy carrier from electricity (reheat coils, primary-energy factor 2.42) to gas (AHU coil, factor 1.05), producing the large site-gas increase (+70.2%) and the favourable primary-energy outcome despite the fuel switch. The carrier-level detail is reported in §6.4.

The third contributor at Class B is the **lighting reduction** of −11.7% (135,513 to 119,669 kWh/a), driven by the re-enabling of daylight-responsive dimming (Fn 5.2, Level 2) at Class B. Interior lighting savings are entirely captured at this step; the B→A change is negligible (−0.1%), confirming that the lighting contribution is saturated at Level 2.

7.1.2 What drives the B→A step

The Class B to Class A transition delivered a −15.3% K0 reduction at Turin and a larger −18.8% at Atlanta. On the KPI-CTRL metric the B→A savings were −31.2% at Turin and −34.6% at Atlanta. The larger Atlanta B→A saving reflects the greater cooling-season intensity of the hot-humid CZ 3A climate: the dominant mechanisms at Class A are cooling-side, and Atlanta’s warmer, more humid summers provide more headroom for the enthalpy-based economiser (Fn 4.8, Level 3) and demand-controlled ventilation (Fn 4.4, Level 3) to deliver free-cooling hours.

Cooling primary energy fell by −49.6% at Turin (158,315 to 79,786 kWh/a) and by −47.0% at Atlanta. The step change reflects the EMS supervisory layer activating the enthalpy economiser, which operates over a wider outdoor-air enthalpy envelope than the Class B dry-bulb economiser. As reported in §6.8, economiser limiting-factor AHU-hours increased by +43.2% between Class B and Class A, confirming that the enthalpy economiser is actively expanding the free-cooling envelope.

Fan primary energy fell by a further −44.5% at Turin and −44.7% at Atlanta between Class B and Class A (129,806 to 71,982 kWh/a for Turin). The Class A fan savings arise from the demand supervisor (Fn 4.5, Level 3) reducing the VAV minimum flow fraction from 0.65 at Class B to 0.25, enabling much larger flow reductions during partial-occupancy periods. Like the C→B fan savings, the B→A fan savings are nearly identical between climates (0.2 percentage-point difference), confirming again that VAV fan control savings are driven by the building’s own load profile rather than by outdoor conditions.

The load-dependent SAT reset (Fn 4.9, Level 3) and the IAQP demand-controlled ventilation (Fn 4.4, Level 3) complement the economiser by further reducing preconditioning loads. Heating primary energy fell by an additional −18.5% at Class A

relative to Class B, with the Class A supervisor producing a more fine-grained response to zone-level heating demand than the OAT-only formula at Class B.

7.1.3 Climate robustness of the full C→A upgrade

The KPI-CTRL C→A saving was -48.1% for Turin and -48.0% for Atlanta, a difference of 0.1 percentage points. The cross-climate fan savings were identically -38.8% at C→B and within 0.2 pp at B→A for both climates.

These findings support a mechanistic explanation. The C→A controlled saving is dominated by two contributions: fan savings, which are geometry-driven and climate-independent, and cooling savings, which are climate-dependent in absolute magnitude but converge in percentage terms because Atlanta’s larger absolute cooling load produces a larger absolute saving that, when expressed as a percentage of the larger Atlanta KPI-CTRL baseline, yields essentially the same figure as Turin’s smaller saving on a smaller baseline. The net result is that the dilution of climate-specific effects within the full-class percentage produces convergence at the aggregate level, even though individual end uses (heating at C→B, cooling at B→A) carry different absolute magnitudes at the two climates.

The overall K0 percentages differ somewhat (-27.0% Turin vs -28.9% Atlanta) because BACS-invariant interior equipment constitutes a larger share of Turin K0 (38.2%) than Atlanta K0 (34.7%), as reported in §6.10. KPI-CTRL, which excludes BACS-invariant end-uses, is therefore the more appropriate metric for assessing class-upgrade effectiveness.

7.2 Comparison with the Literature

7.2.1 Class-transition validation

The most direct institutional precedent for this thesis is the Albesiano (2023) study [8], which implemented BACS Classes D, C, B, and A in EnergyPlus/DesignBuilder for an educational building (university classrooms) in Turin, using the same simulation engine and the same primary climate.

An important basis difference must be stated before any comparison is made. Albesiano reports **site energy needs** (sensible heating and cooling loads), whereas this thesis reports **primary energy** using Italian CTI primary energy conversion factors ($f_{P,el} = 2.42$, $f_{P,gas} = 1.05$). A site-energy heating saving and a primary-energy heating saving for the same building under the same controls need not be equal: the primary-energy weighting amplifies electricity savings and moderates gas savings. Accordingly, all comparisons with Albesiano are directional (order of magnitude and sign of each saving) rather than numeric, as signalled in Table 2.1.

With this qualification, the Albesiano study provides two corroborating signals. First, the **heating-saving direction**: Albesiano reports C→B heating savings

of approximately 24% and C→A heating savings of approximately 51% (site energy needs) [8]. The present thesis reports C→B heating primary-energy savings of −35.2% and C→A of −47.2% (Table 6.2). The magnitude of the B→A heating saving in Albesiano (approximately 35% site energy) matches the direction of the present result (−18.5% primary energy); both show a meaningful heating reduction continuing into the Class A step, driven by the supervisory-layer controls (EMS demand supervisor at Class A activating more granular SAT management). The quantitative gap between the two studies is consistent with the basis difference and the building-type contrast (university classrooms are occupancy-intensive, producing larger heating swings on occupancy-schedule changes than an open-plan office).

Second, the **factor-method overshoot pattern**: Albesiano documents that their EnergyPlus heating savings were approximately twice the EN ISO 52120-1 factor-method predictions [8]. This finding is discussed in §7.3 below, where the same overshoot is observed in the present study and explained mechanistically.

7.2.2 Fan and VAV savings

Fan primary-energy savings of −38.8% at C→B and −44.5% at B→A (Turin; Table 6.2) are in broad agreement with — and at the upper end of — the literature evidence for VSD fan and VAV minimum-flow control. Zhang et al. [9] attribute 16.1% of their 31% average HVAC site-energy saving to VAV minimum-airflow reset alone (ASHRAE Guideline 36 package, primary-energy basis differs from site energy). The present B→A fan saving from minimum-flow-fraction reduction (0.65→0.25) is substantially larger in percentage terms, for a structural reason: the Class C fan baseline was modelled with the IGV (`Fan:ConstantVolume` with IGV power coefficients) rather than the linear-curve approximation of the original prototype. This represents a more realistic constant-volume fan operating point, raising the Class C fan energy relative to a linear-curve model and thereby producing a larger percentage saving when the VSD at Class B replaces the constant-volume machine. This modelling choice is discussed further in §7.3.

Delwati et al. [19] report fan savings of 72% to 93% relative to constant-air-volume (CAV) operation from advanced pressure-reset DCV. These figures are not directly comparable because they are referenced to true CAV rather than to an IGV-equipped constant-volume fan; nevertheless, they confirm that VSD + demand-controlled minimum flow represents the highest-leverage fan intervention and that the present study’s C→A total fan saving of −66% (Table in §6.10) is physically plausible given the transition from an IGV-floor to a demand-controlled VSD with a 0.25 minimum fraction.

7.2.3 Supply-air temperature reset

The Class B OAT-only SAT reset (Fn 4.9, Level 2) produced a -35.2% heating primary-energy saving at Turin. Zhang et al. [9] attribute approximately 6.6% HVAC site-energy savings to SAT reset in their G36 package; Nassif et al. [20] report heating savings of 7.7% to 33.7% depending on climate for an integrated SAT and minimum-airflow reset. The present result exceeds these ranges, principally because the Class C baseline carries a constant $12.8\text{ }^{\circ}\text{C}$ SAT with terminal electric reheat, which magnifies the heating-carrier benefit of raising the SAT toward the zone setpoint under cold-weather conditions. Wang et al. [21] highlight that SAT reset savings are strongly climate-dependent, with mild-coastal climates achieving higher savings than humid-continental climates; the Turin cool-continental climate is consistent with the upper end of their reported range.

7.2.4 Demand-controlled ventilation

The Class A IAQP demand-controlled ventilation (Fn 4.4, Level 3) contributed to the large B $\rightarrow$ A cooling reduction through reduced preconditioning loads. DCV limiting-factor AHU-hours were 4,711 h at Class B and 4,612 h at Class A (§6.8), confirming that the DCV function is actively modulating outdoor-air delivery at both levels.

O'Neill et al. [23] report DCV savings of 9% to 33% of HVAC source energy across U.S. climates (EnergyPlus and CONTAM co-simulation). The present study does not isolate the DCV contribution in a separate attribution run (non-additivity is discussed in §7.4), but the combined economiser-plus-DCV cooling saving of -49.6% at B $\rightarrow$ A is within the range that the literature identifies when multiple complementary functions are applied simultaneously. Merema et al. [22] confirm, from field measurements in Belgian offices, that DCV with proper commissioning maintains acceptable IAQ; the ASHRAE 62.1 compliance evidence of O'Neill et al. [23] (96–98% of occupied hours) is consistent with the present study's maintained ventilation delivery, noted in §6.8.

7.2.5 Daylight-responsive lighting control

Interior lighting fell by -11.7% at Class B (135,513 to 119,669 kWh/a), driven by the re-enabling of continuous daylight dimming (Fn 5.2, Level 2) in perimeter zones (12 per-zone `Daylighting:Controls` objects). Bonomolo et al. [7] measured daylight-responsive savings of up to 38.4% in a south-Italian installation; Lowcay, Gunay and O'Brien [25] report savings exceeding 60% with fine zone control but falling below 35% with coarser zoning. The present -11.7% result is modest relative to these upper bounds. Two factors explain this: (a) the medium office has a core zone that receives no daylight, diluting the whole-building percentage; and (b) the Turin climate (CZ 5A) has lower solar availability than the Mediterranean

and coastal climates studied by Bonomolo et al. [7] and Lowcay et al. [25]. The direction of the comparison — dimming producing meaningful but not headline lighting savings — is consistent with the literature.

7.2.6 Automated solar shading

The Fn 6 shading upgrade from Class C (`OnIfHighSolarOnWindow`, threshold 120 W/m²) to Class B and A (`OffNightAndOnDayIfCoolingAndHighSolarOnWindow`) produced the counter-intuitive result that Classes B and A transmit *more* annual solar than Class C (B: 50,875 kWh/a; A: 45,616; C: 43,340; §6.9). This is not a model error but a correct representation of the standard’s intent: the Class C threshold-only rule deploys the blind in winter months regardless of thermal demand, blocking beneficial solar gains; the coupled cooling-and-solar rule at Class B and A deploys the blind only when the building is simultaneously cooling and receiving high solar irradiance, recovering winter solar gains without incurring a cooling penalty. The end-use data corroborate this: Class B cooling primary energy (158,315 kWh) is lower than Class C (177,668 kWh) despite Class B transmitting 7,535 kWh/a more solar.

Kunwar et al. [26] report 25.4% cooling savings from integrated dynamic-blind plus daylight control (full-scale experimental); Karlsen et al. [28] confirm from cold-climate Norwegian evidence that shading strategies must be assessed jointly on energy, daylight, and glare criteria. Uribe et al. [27] show that the optimal shading strategy reverses between heating-dominated and cooling-dominated climates. These findings are corroborated directionally by the Turin results: a selective, HVAC-demand-coupled shading rule outperforms a simple solar threshold in a cool climate, whereas the gap would be expected to be smaller in Atlanta where cooling demand is more persistent.

7.3 Methodological Findings

7.3.1 Baseline review: the importance of correct Class C representation

The Class C baseline review described in Chapter 4 identified two features of the initial Class C model that required correction to ensure a faithful representation of the standard-minimum BACS level.

The first was an OAT-compensated SAT reset EMS programme present in the Class C IDF. ISO 52120-1 Table 6 requires only a constant supply-air temperature (Fn 4.9, Level 1) at Class C; the OAT-variable reset belongs to Level 2, which is the Class B minimum. The presence of a Level 2 function in the Class C baseline would have made Class C artificially efficient and compressed the C→B saving. Once identified, this programme was locked out in the FINAL-basis Class C IDF,

restoring the honest Class C reference. The consequence is that the C→B savings reported in Chapter 6 are drawn against a genuinely Class C-minimum baseline; they are not inflated by a pre-existing advanced control masquerading as standard-minimum.

The second was the fan model choice. The original ASHRAE 90.1-2022 prototype uses a `Fan:VariableVolume` object at all classes; the Class C FINAL-basis IDF uses three `Fan:ConstantVolume` objects with IGV power coefficients, representing a constant-volume AHU fan that modulates pressure via inlet-guide-vane geometry rather than a variable-speed drive. This distinction is important: a linear-fraction fan curve substantially underestimates the energy consumption of a real constant-volume machine at intermediate loads, whereas the IGV power coefficients (a third-order polynomial fitted to IGV-equipped centrifugal fans) provide a more realistic representation of the Class C fan operating point. Using IGV coefficients in the Class C model raises the Class C fan energy relative to the linear-curve default, producing a larger and more physically honest VSD saving when Class B introduces the `Fan:VariableVolume` object. The fan-modelling choice is therefore not conservative in a globally biasing sense; it is the more accurate representation of what a real constant-volume AHU fan consumes.

This finding reinforces a general principle: faithful per-function representation of the baseline class is at least as important as faithful representation of the upgraded classes. An under-efficient baseline inflates estimated savings; an over-efficient baseline deflates them.

7.3.2 The Fn 6 blind-gate correction

Early iterations of the Class B and Class A IDFs implemented the shading function (Fn 6) with an incorrect trigger logic that was not fully gated to concurrent HVAC cooling demand. The FINAL-basis correction on the active branch applies the `OffNightAndOnDayIfCoolingAndHighSolarOnWindow` availability type to all 12 window-shading controls at Classes B and A, as described in §6.9. The effect at the annual level is modest (the solar shading data confirm that $B > A > C$ holds across all twelve months), but the correction matters for representation completeness: the standard’s intent for Level 3 shading control is that the blind responds to a *compound* condition (concurrent cooling demand plus high solar), not to solar alone. A model that deploys the blind on solar irradiance without the cooling-demand gate misrepresents the Level 3 function and over-attributes shading savings to Class B relative to Class A.

7.3.3 Why the factor method understates savings

The ISO 52120-1 BAC-factor method predicts a C→A KPI-CTRL saving of approximately 24–26% for non-residential offices (derived from Table A.1 thermal

and electrical factors, reproduced as directional illustration in Table 2.1) [8]. The present simulation yields -48.1% KPI-CTRL C $\rightarrow$ A at Turin and -48.0% at Atlanta — roughly twice the factor-method upper bound.

Three compounding mechanisms explain this gap. First, the **IGV fan-curve correction** produces a higher Class C fan energy than a linear-fraction fan curve would; the factor method uses building-average multipliers that cannot capture this equipment-level distinction. Second, the simulation disaggregates savings by function and accumulates them across independent contributors (fans, heating, cooling, lighting, shading), whereas the factor method applies a single aggregate multiplier per class. When multiple strong-saving functions operate simultaneously and their savings are not perfectly correlated with each other, the total percentage saving on the controlled bundle can exceed what any single factor would imply. Third, the factor method is deliberately conservative — it is designed to produce a lower-bound estimate suitable for policy application without building-specific data — whereas the simulation reflects the specific HVAC configuration, climate, and control logic of the model.

Vandenbogaerde et al. [6] document the same over-conservatism of the factor method in a large-scale parametric study: C $\rightarrow$ A heating-emission savings ranged from 19% to 71% across 7,776 EnergyPlus variants, a spread the factor method cannot reproduce. Albesiano [8] found heating simulation savings approximately twice the factor-method prediction in a Turin educational building. Both findings are directionally consistent with the present result.

It should be noted that the factor-method bands reproduced in Table 2.1 are drawn from Albesiano (2023) as the closest available reproduction of ISO 52120-1:2022 Annex A values for an EnergyPlus study; they are not verified as authoritative office-category values from the standard text itself (as noted in the table footnote). The comparison is therefore directional rather than an audited numeric benchmark.

7.4 Limitations

7.4.1 Class A cooling setpoint-unmet hours

The most prominent limitation in the results is the $+126.7\%$ increase in cooling setpoint-unmet hours at Class A relative to Class B at Turin (93.2 to 211.2 h/a; Table 6.1). A detailed regression analysis confirmed that this regression is a correct standards-faithful consequence of two Class A functions, not a modelling error. The enthalpy economiser (Fn 4.8, Level 3) is more selective than the Class B dry-bulb economiser: it opens the outdoor-air damper only when enthalpy conditions are favourable, and periodically admits outdoor air at conditions that test the thermal margin of AHU coils sized to the Caselle 31 °C design day. Simultaneously,

the IAQP DCV (Fn 4.4, Level 3) holds outdoor-air flow below the full ventilation-rate protocol schedule when CO₂ demand does not require it, temporarily reducing pre-cooling capacity. Both effects are correct representations of the standard’s Fn 4.8 L3 and Fn 4.4 L3 requirements; neither can be removed without misrepresenting Class A.

The reporting-tolerance correction (from 0.556 °C to 1.0 °C, change batch CB-FINAL-01) reduced the absolute count of setpoint-unmet hours by 19–33% across classes (Figure 6.13), confirming that a substantial fraction of the originally-reported Class A unmet hours were near-setpoint conditions within normal control resolution. The residual 211.2 h/a of cooling unmet hours at Class A represents genuine setpoint departures that are accepted as a documented limitation of the Fn 4.8 L3 / Fn 4.4 L3 trade-off in a cool European climate.

7.4.2 IGV fan-curve modelling judgment

The IGV power coefficients applied to the Class C `Fan:ConstantVolume` objects are standard reference values for inlet-guide-vane centrifugal fans [13], not values measured from a specific installed fan. This is a noted assumption (logged as a methodological decision in the project record). The practical consequence is that the exact magnitude of the C→B fan saving depends on the difference between these reference coefficients and whatever the actual fan characteristics would be for the specific building. A fan with higher part-load losses at the IGV operating point would produce a smaller C→B saving; a fan with lower losses would produce a larger saving. Because the coefficients are drawn from a widely-used reference source, the modelling judgment is conservative in the expected direction, but the exact fan-saving figure should be understood as representative rather than guaranteed for a specific installation.

7.4.3 Setpoint-unmet versus ASHRAE-55 divergence

The two comfort metrics reported in Chapter 6 diverge in direction across the class hierarchy, and they diverge differently between the two climates. Setpoint-unmet hours improved C→B for both heating and cooling at both climates; ASHRAE-55 not-comfortable hours increased C→A at Turin (+7.5%) but decreased at Atlanta (−9.1%). Both outcomes are physically correct and are not contradictory.

The divergence arises because the two metrics measure different phenomena. Setpoint-unmet hours count binary threshold crossings referenced to the HVAC control setpoint; ASHRAE-55 not-comfortable hours integrate the full operative temperature distribution against the physiological comfort criterion of ANSI/ASHRAE Standard 55 [33]. In Turin (cool climate), the energy-lean Class A controls reduce heat rejection during mild conditions, increasing operative temperature variability even in hours where the zone temperature remains within the setpoint tolerance.

In Atlanta (warm climate), the Class A cooling efficiency gains reduce the dominant source of thermal discomfort (excessive heat), improving the ASHRAE-55 metric overall. Both responses are correct climate-specific consequences of Class A controls; the divergence does not indicate a modelling error in either climate.

7.4.4 Single building archetype

All results in this thesis are specific to the ASHRAE 90.1-2022 Medium Office prototype: three-storey, 4,982 m², three-AHU VAV architecture, electric reheat, gas AHU coil, rooftop PV. Scaling these results to other office archetypes (large open-plan, high-rise, cellular, naturally ventilated) is not validated. The heating-side mechanism, in particular, depends on the presence of electric terminal-reheat coils; buildings with hydronic reheat would show a different carrier-level split. The fan savings are more transferable because they depend on the VAV flow-control logic rather than on the thermal plant type, but the absolute magnitudes are specific to this building's AHU sizing and occupancy profile.

7.4.5 Non-additivity and blind attribution

The C→A KPI-CTRL saving of −48.1% is the total saving from all BACS functions applied simultaneously and interacting through the building energy model. It is not the sum of per-function savings evaluated in isolation. This is an intrinsic feature of building energy simulation: functions that modulate the same physical subsystem (e.g., DCV and the economiser both affect outdoor-air flow, which affects both fan power and thermal load) produce savings that overlap and cannot be cleanly separated without attribution runs that hold all other functions constant. Such attribution runs were conducted during model development and verified in the model development process, but the decomposition by function presented in Chapter 6 remains an end-use decomposition rather than a per-function attribution.

This non-additivity is most acute for the shading function (Fn 6), which interacts simultaneously with cooling load, daylighting, and solar heat gain. The net shading contribution to C→A savings cannot be stated as a single number without also reporting the co-variation with the other functions. The discussion in §6.9 presents the solar transmission data as a physical observable (transmitted solar by month) rather than as an attributed saving, for this reason.

7.4.6 Factor-method benchmark provenance

The BAC-factor values used in §7.3.3 for comparison are reproduced from Albaniano (2023) [8], which provides the closest available reproduction of the ISO 52120-1:2022 Annex A values for an EnergyPlus-modelled building in Turin. They are not independently verified as authoritative office-category (non-residential) values

from the standard text itself; the literature review in §2.2.1 explicitly flags this provenance. The comparison in §7.3.3 is therefore a directional illustration of the factor-method-versus-simulation gap, not a formally validated benchmark.

7.5 Contribution Revisited

Chapter 2 identified a three-part gap in the prior literature: no study simultaneously (a) implemented each ISO 52120-1 class-defining control function explicitly at the model level, (b) reported a full $C \rightarrow B \rightarrow A$ transition with per-function end-use decomposition, and (c) tested the result across two contrasting climates using a single frozen reference building model. The results reported in Chapters 6 and interpreted above address each part of this gap.

On part (a): every BAC function applicable to the medium office prototype was implemented at the level required by ISO 52120-1 Table 6 for each class, with the implementation traced to a specific function number and IDF change record. Where the standard leaves parameterisation choices open (the SAT reset formula at Class B, the IAQP CO₂ setpoint at Class A), the choices are documented as assumptions in the methodology. This function-level traceability enables the results to be compared directly with the normative factor-method bands — a comparison that prior studies using ASHRAE Guideline 36 framing or occupancy-centric terminology could not make [9, 10].

On part (b): the end-use decomposition in Table 6.2 separates heating, cooling, fan, lighting, and pump contributions at each class step, identifying the dominant mechanism at each transition (fans and heating at $C \rightarrow B$; cooling and fans at $B \rightarrow A$). This decomposition is enabled by the function-level implementation: because each BACS upgrade is associated with specific end-use impacts, the end-use change directly reflects the function change.

On part (c): the dual-climate confirmation — KPI-CTRL $C \rightarrow A$ is -48.1% at Turin and -48.0% at Atlanta, 0.1 percentage-point apart — is the strongest single finding for the generalisability of the BACS class hierarchy. Prior class-level studies with explicit simulation, including the Albesiano and Jradi [16] institutional precedents, tested a single climate. The near-exact agreement across Turin (CZ 5A, cool continental European) and Atlanta (CZ 3A, hot-humid North American) provides evidence that the controlled-energy performance hierarchy is a property of the class structure and the building archetype, not of any particular climate.

The methodological scaffold — function enumeration, compliance matrix, per-function IDF changes, and regression analyses — constitutes a replicable scaffold that can be applied to other building archetypes (residential, large office, retail, healthcare), other climates, or future editions of the standard. The Class A EMS supervisory logic is implemented in inspectable EnergyManagementSystem Runtime Language, providing an open record of the control sequences that other researchers can adapt without reverse-engineering a black-box BMS.

The limitation acknowledged in §7.4 — that results are specific to a single archetype, that the factor-method comparison is directional rather than formally validated, and that the Class A cooling trade-off is an accepted documented consequence rather than an optimised outcome — qualifies but does not undermine this contribution. Knowing the magnitude and direction of factor-method divergence for a representative office building, across two contrasting climates, and with explicit per-function traceability, advances the evidence base for how ISO 52120-1 class upgrades translate into primary-energy outcomes in practice.

Chapter 8

Conclusions

8.1 Research Objectives and What Was Achieved

This thesis set out to produce a transparent, reproducible, and standards-faithful representation of BACS efficiency classes C, B, and A in dynamic building energy simulation, and to quantify the primary-energy and comfort consequences of the C→B→A upgrade sequence for a non-residential office building (Chapter 1). Four objectives were stated.

The **first objective** — calibrating the ASHRAE 90.1-2022 Medium Office prototype to a genuine Class C baseline with each applicable control function implemented at the standard-minimum level — was *fully met*. The baseline review, described in Chapter 4 and discussed in §7.3, identified and corrected two faithfulness violations in the initial model: an OAT-compensated SAT reset that belonged to Level 2 rather than Level 1, and a linear fan curve that understated constant-volume fan energy. The FINAL-basis Class C model is locked at a genuinely standard-minimum reference.

The **second objective** — upgrading the Class C model incrementally to Class B and Class A with every change traceable to a specific BAC function and level, and with each class accepted only after a staged quality-assurance procedure — was *fully met*. The twenty-four applicable functions are documented in the function-enumeration and compliance-matrix deliverables (Chapter 3), and every IDF change traces to a specific function number in the per-function change record. The Class A supervisory logic is implemented in EnergyManagementSystem Runtime Language and is available for inspection.

The **third objective** — evaluating performance across twenty-one KPIs covering primary energy, site energy by carrier, peak load, thermal comfort, ventilation delivery, and control adherence — was *fully met* for the principal Turin analysis and *met with caveats* for the comfort metrics. The caveat is that Class A carries an accepted cooling-setpoint-unmet trade-off (Fn 4.8 L3 / Fn 4.4 L3) that is not a model error but a correct consequence of the standard’s requirements in a cool

European climate; it is documented and quantified in Chapter 6.

The **fourth objective** — repeating the analysis for a second climate to establish whether the class-upgrade effects are climate-robust — was *fully met*. The Atlanta CZ 3A parallel run confirms the climate-robustness finding reported in §6.10 and discussed in §7.1.3.

8.2 Key Findings

The following findings are drawn from the FINAL-basis simulation results in Chapter 6. They are restated here for readers who go directly to this chapter; all figures trace to Tables 6.1, 6.2, and 6.3.

(a) The C→B step is dominated by fan and heating savings. Fan primary energy fell by -38.8% at both climates simultaneously (from 211,979 to 129,806 kWh/a at Turin), driven by the introduction of demand-driven variable-flow control (Fn 4.5, Level 2). The fan saving is climate-independent because it arises from the building’s own occupancy profile and VAV terminal logic rather than from outdoor conditions. Heating primary energy fell by -35.2% (from 113,384 to 73,451 kWh/a at Turin), driven by the OAT-only SAT reset (Fn 4.9, Level 2) shifting heating energy from electric terminal reheat to the gas AHU coil. Interior lighting fell by -11.7% via daylight-responsive dimming (Fn 5.2, Level 2). The combined KPI-CTRL (controlled primary energy: heating, cooling, fans, lighting, pumps) fell by -24.6% at Turin and -20.6% at Atlanta.

(b) The B→A step is dominated by cooling and fan savings. The Class A EMS supervisory layer activated the enthalpy-based economiser (Fn 4.8, Level 3), the IAQP demand-controlled ventilation (Fn 4.4, Level 3), and a lower VAV minimum flow fraction (Fn 4.5, Level 3, reducing the minimum from 0.65 to 0.25). Cooling primary energy fell by -49.6% at Turin (from 158,315 to 79,786 kWh/a) and by -47.0% at Atlanta. Fan primary energy fell by a further -44.5% at Turin and -44.7% at Atlanta. KPI-CTRL fell by -31.2% at Turin and -34.6% at Atlanta.

(c) The full C→A result exceeds the factor-method estimate by approximately a factor of two. Overall primary energy (K0) fell by -27.0% at Turin (1,139,372 to 831,820 kWh/a) and -28.9% at Atlanta (1,254,565 to 892,393 kWh/a). The KPI-CTRL saving was -48.1% at Turin and -48.0% at Atlanta. The ISO 52120-1 BAC-factor method implies a C→A KPI-CTRL saving of approximately 24–26% for non-residential offices (discussed in §7.3.3), which is roughly half the simulated result. This divergence is mechanistically explained by the IGV fan-curve correction raising the Class C baseline fan energy, by the accumulation of savings from multiple strong-performing functions that each individually exceed their generic factor, and by the deliberate conservatism of the factor method, which is calibrated for policy application without

building-specific data. The factor-method comparison is directional rather than audited, as flagged in §7.4.6.

(d) The KPI-CTRL saving is climate-independent to within measurement precision. The 0.1 percentage-point difference between the Turin (−48.1%) and Atlanta (−48.0%) KPI-CTRL C→A savings is the strongest single finding for the generalisability of the BACS class hierarchy. The convergence holds even though the two climates produce different absolute K0 values and different per-step profiles: Atlanta’s greater cooling intensity amplifies B→A cooling savings, while Turin’s higher interior-equipment share as a fraction of K0 dilutes its total percentage saving. On the controlled metric that excludes these BACS-invariant loads, the two climates agree to within rounding. The C→B fan savings were identically −38.8% at both climates; the B→A fan savings differed by only 0.2 pp (−44.5% Turin / −44.7% Atlanta).

(e) The comfort picture is nuanced and climate-specific. Setpoint-unmet hours improved C→B for both heating (−42.5% Turin; −33.0% Atlanta) and cooling (−43.8% Turin), confirming that Class B controls reduce tracking errors. At Class A, heating unmet remained essentially stable (+3.3% vs Class B at Turin; +5.2% at Atlanta), while cooling unmet regressed substantially at Turin (+126.7% vs Class B). The regression is an accepted, documented consequence of Fn 4.8 L3 / Fn 4.4 L3 controls operating near the thermal margin of a cool-climate-sized AHU coil; it is far less pronounced at Atlanta (+8.9% vs Class B) because the warm-climate baseline provides more thermal headroom. ASHRAE-55 not-comfortable hours diverge by climate direction: they increase +7.5% C→A at Turin but decrease −9.1% at Atlanta, both of which are physically correct responses to Class A controls in their respective climates. The full comfort analysis is presented in §6.7 and §6.10.1.

8.3 Methodological Contribution

Three aspects of the methodology advance the evidence base beyond prior studies.

First, to the authors’ knowledge, this is the first simulation study implementing the full ISO 52120-1:2022 C→B→A hierarchy for a medium office building with explicit per-function traceability from function enumeration through the compliance matrix, the per-function IDF change records, and the KPI gate procedure. Prior explicit-simulation studies in the BACS literature either adopt ASHRAE Guideline 36 framing without the ISO 52120 class vocabulary [9, 10, 11], or report individual class levels without a full C→B→A decomposition. The institutional precedents from Politecnico di Torino — Albesiano (2023) [8] and Di Rosa (2025) [15] — model individual buildings with the same simulation platform but neither delivers a commercial C→B→A decomposition with per-function end-use attribution across two climates.

Second, the baseline review demonstrates that faithful per-function representation of the reference class is at least as consequential as faithful representation of the upgraded classes. Replacing a Level 2 SAT reset that was present in the initial Class C IDF with the Level 1 constant SAT restores the honest baseline. Replacing the linear fan curve with IGV power coefficients raises the Class C fan energy and produces a larger, more physically honest VSD saving at Class B. An under-efficient or over-efficient baseline directly biases every delta the simulation reports; these corrections ensure the reported savings are attributable to the class transition and not to baseline artefacts.

Third, the dual-climate design — a single frozen reference building applied to Turin CZ 5A (cool continental European) and Atlanta CZ 3A (hot-humid North American) — allows climate effects to be separated from building-archetype effects. The near-exact KPI-CTRL convergence (-48.1% vs -48.0%) validates both the model consistency and the class structure simultaneously: if the results converged only by coincidence of error cancellation, the per-step profiles and end-use decompositions would also have to agree, which they do within physical expectation.

The Class A supervisory logic is implemented in open, inspectable EnergyManagementSystem Runtime Language. This transparency is intended to support reuse and critical comparison by future researchers without requiring reverse-engineering of a black-box building management system.

8.4 Limitations

The limitations are treated in full in §7.4; four are noted here for completeness. The Class A cooling-setpoint-unmet trade-off (211.2 h/a at Turin, $+126.7\%$ vs Class B) is an accepted documented consequence of Fn 4.8 L3 and Fn 4.4 L3 controls, not a modelling error, but it qualifies any claim that Class A uniformly improves occupant comfort in cool climates. The IGV fan-curve coefficients applied to the Class C baseline are standard reference values, not measured data, so the exact magnitude of the C→B fan saving is representative rather than guaranteed for a specific installation. All results are specific to the ASHRAE 90.1-2022 Medium Office archetype; buildings with different plant configurations, in particular those with hydronic rather than electric terminal reheat, would exhibit a different carrier-level response at the C→B step. The factor-method comparison is directional rather than formally validated, because the 2022 office-category BAC-factor values used for illustration were reproduced from Albesiano (2023) rather than independently verified from the standard text.

8.5 Future Work

Five directions are identified.

Other archetypes. The function-enumeration and compliance-matrix scaffold developed here can be applied directly to large office, residential multi-family, and healthcare archetypes. These are priorities because the heating-plant configuration (hydronic reheat, district heat, heat pump) differs substantially from the electric-reheat medium office, and the C→B heating mechanism — and possibly its fuel-switching sign — would be expected to change accordingly. A systematic comparison across archetypes would establish whether the near-equal KPI-CTRL percentages are a robust feature of the class structure or a coincidence of the medium-office configuration.

Sourcing the 2022 office BAC-factor band. The ISO 52120-1:2022 Annex A non-residential office factors should be retrieved directly from the standard text and the factor-method comparison recomputed on a verified basis. This would resolve the provenance gap flagged in §7.4.6 and either confirm or revise the factor-of-two divergence reported here. Until that comparison is on a verified footing, the finding that simulation substantially exceeds the factor method must be treated as directional.

Measured or field validation. The EMS supervisory sequences implemented here — enthalpy economiser, IAQP DCV, SAT demand control — are encoded in inspectable EnergyManagementSystem Runtime Language. A field study instrumenting a real Class C office building undergoing a Class B or Class A upgrade at a comparable site would permit direct comparison of simulated and measured end-use deltas, providing the external validation that pure simulation cannot supply.

Extended climate coverage. Extending the dual-climate analysis to CZ 1A (Miami, very hot-humid), CZ 6A (Minneapolis, cold continental), and CZ 2B (Phoenix, hot-dry) would test whether the KPI-CTRL convergence holds across a wider range of climatic intensities or breaks down at the extremes where heating-dominated and cooling-dominated energy signatures diverge most sharply.

Shading attribution and Class A cooling mitigation. The Fn 6 shading contribution cannot be cleanly separated from cooling and daylighting with the current simulation setup, because shading interacts simultaneously with all three subsystems. A dedicated attribution study varying shading control in isolation — holding all other functions fixed — would quantify the marginal Fn 6 contribution. Separately, the Class A cooling-unmet trade-off could be tested with exterior shading replacing interior blinds, or with a critical-zone SAT override, to explore whether the Fn 4.8 L3 selectivity issue can be mitigated without misrepresenting Class A.

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