Ventilation in Adaptive Reuse

Reducing uncertainty in concept-stage decisions

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LICENTIATE DISSERTATION

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This thesis develops a framework for retaining or adapting ventilation in conversion projects, providing structured decision support to reduce uncertainty at the conceptual stage. The thesis comprises three strands. First, a building stock strand reconstructs pre- and post-conversion building pairs from national Energy Performance Certificates (EPCs). This is done to identify conversion pathways and describe the dominant ventilation concept, as well as the declared airflow. Second, a feasibility strand compares ventilation requirements from earlier and current Swedish building regulations. This strand also uses interview data to capture practitioners' perspectives on when reuse is acceptable and how responsibilities are allocated. Third, a design-science strand develops a ventilation-aligned, low-intervention design (VALID) sequence that screens functional programme-layout compatibility, aligns high-demand rooms with existing supply terminals, and assesses consequences through scenario-based LCC and LCA limited to stages A1–A5.

Three results follow. Stock-scale conversions concentrate on office-to-residential and retail-linked pathways. Within these, EPCs tend to indicate retention of the ventilation concept, and where paired changes in declared airflow are detectable, reductions dominate. The feasibility strand suggests that office-to-apartment, school-to-apartment, and school-to-office pairs may meet contemporary outdoor air requirements without altering the ventilation concept. Practitioners state that reuse is acceptable when performance, cleanliness, airtightness, origin and documentation of the ventilation systems can be verified. Applying the screen-align-appraise method to an office-to-residential case enables a large portion of the existing ventilation system to be retained, resulting in reductions in carbon emissions (stages A1–A5) and construction costs compared to full replacement. A workshop-based screening of a pre-school-to-elderly care case led to rejecting the conversion because the required functional divisions and adjacencies could not be accommodated within the as-found layout.

The primary contribution of this thesis is the reduction of concept-stage uncertainty in adaptive reuse projects with a focus on ventilation. This is achieved by establishing a national baseline for conversion pathways and ventilation characteristics within these pathways, developing a feasibility framework that translates regulations and acceptance procedures into project-level conditions for reuse, and conceptualising a low-intervention conversion method that focuses on preserving existing supply-air systems and reporting ranges of environmental and cost outcomes. This approach can support lower-intervention conversions where hygiene, airtightness and documentation requirements are met.

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To my family and friends

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"Cities need old buildings so badly it is probably impossible for vigorous streets and districts to grow without them.... for really new ideas of any kind—no matter how ultimately profitable or otherwise successful some of them might prove to be—there is no leeway for such chancy trial, error and experimentation in the high-overhead economy of new construction. Old ideas can sometimes use new buildings. New ideas must use old buildings"

Jane Jacobs, The Death and Life of Great American Cities (1961)

This thesis explores the art of making the most of what already exists. It has likewise been built from what already existed around me: patient supervision, generous colleagues, engaged practitioners, supportive institutions, and steady personal encouragement. I could not have produced this work alone; it is a collective result. Many people and institutions created the leeway for trial, error and refinement; I thank them here.

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If this work seeks to build upon what exists, it is because others have made space for it to happen.

Lund, Sweden, 30 October 2025

Ilia Iarkov

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Abstract

Decarbonisation of the built environment requires alternatives to the prevailing practice of demolition followed by new construction. The new production of buildings adds upfront embodied emissions, while much of the non-residential stock remains underutilised, and housing demand remains high. Adaptive reuse, the practice of converting existing buildings for new functions, preserves the building's envelope and structural frame, and may retain its building services, thereby avoiding embodied emissions and capital costs. Ventilation equipment can be reused or adapted; however, concept-stage planning often defaults to full replacement of it. Early design decisions, therefore, determine whether reuse is seen as viable and what material and cost consequences follow.

This thesis develops a framework for retaining or adapting ventilation in conversion projects, providing structured decision support to reduce uncertainty at the conceptual stage. The thesis comprises three strands. First, a building stock strand reconstructs pre- and post-conversion building pairs from national Energy Performance Certificates (EPCs). This is done to identify conversion pathways and describe the dominant ventilation concept, as well as the declared airflow. Second, a feasibility strand compares ventilation requirements from earlier and current Swedish building regulations. This strand also uses interview data to capture practitioners' perspectives on when reuse is acceptable and how responsibilities are allocated. Third, a design-science strand develops a ventilation-aligned, low-intervention design (VALID) sequence that screens functional programme-layout compatibility, aligns high-demand rooms with existing supply terminals, and assesses consequences through scenario-based LCC and LCA limited to stages A1–A5.

Three results follow. Stock-scale conversions concentrate on office-to-residential and retail-linked pathways. Within these, EPCs tend to indicate retention of the ventilation concept, and where paired changes in declared airflow are detectable, reductions dominate. The feasibility strand suggests that office-to-apartment, school-to-apartment, and school-to-office pairs may meet contemporary outdoor air requirements without altering the ventilation concept. Practitioners state that reuse is acceptable when performance, cleanliness, airtightness, origin and documentation of the ventilation systems can be verified. Applying the screen-align-appraise method to an office-to-residential case enables a large portion of the existing

ventilation system to be retained, resulting in reductions in carbon emissions (stages A1–A5) and construction costs compared to full replacement. A workshop-based screening of a pre-school-to-elderly care case led to rejecting the conversion because the required functional divisions and adjacencies could not be accommodated within the as-found layout.

The primary contribution of this thesis is the reduction of concept-stage uncertainty in adaptive reuse projects with a focus on ventilation. This is achieved by establishing a national baseline for conversion pathways and ventilation characteristics within these pathways, developing a feasibility framework that translates regulations and acceptance procedures into project-level conditions for reuse, and conceptualising a low-intervention conversion method that focuses on preserving existing supply-air systems and reporting ranges of environmental and cost outcomes. This approach can support lower-intervention conversions where hygiene, airtightness and documentation requirements are met.

Sammanfattning

För att minska och försöka eliminera utsläppen av koldioxid från byggsektorn krävs alternativ till dagens metod att skapa önskad funktion genom att riva befintliga byggnader följt av nyproduktion. Nyproduktion av byggnader medför stora klimatbelastande utsläpp kopplade till framställning av nya produkter och material, men även kopplat till rivnings- och nybyggnadsprocessen. Samtidigt är en del av lokalbeståndet underutnyttjat och bostadsefterfrågan stor. Ett alternativ för att lösa detta är konvertering, som innebär anpassning av en befintlig byggnad för att passa en ny typ av användning. Vid en konvertering kan den bärande stommen och klimatskalet bevaras men det möjliggör också återanvändning av delar av de installationstekniska systemen. Konvertering har potential att minska utsläppen knutna till produkt- och byggskedet och kan även vara en kostnadseffektiv lösning. Ventilationsaggregat och kanalsystem kan i många fall återanvändas eller anpassas, men i tidigt projekteringsskede väljs ofta detta alternativ bort till förmån för helt nya ventilationssystem utan att undersöka möjligheten till bevarande och återanvändning. Tidiga beslut avgör om återanvändning anses som ett rimligt alternativ och vilka resurs- och kostnadskonsekvenser som detta får.

I denna licentiatavhandling undersöks möjligheten för bevarande eller anpassning av ventilationssystem vid konvertering med Sverige som nationell avgränsning, samt utvecklas ett strukturerat beslutsstöd som minskar osäkerheten vid tidigt projekteringsskede för konvertering av byggnader. Licentiatavhandlingen omfattar tre delar. Först används svenska energideklarationer (EPC) för att på byggnadsbeståndsnivå beskriva konverteringspar, det vill säga par av samma byggnad ”före verksamhetsbyte” och ”efter”, i syfte att identifiera typiska konverteringsvägar. Efter detta analyseras dessa konverteringsvägars påverkan på deklarerad ventilationsprincip (F/FT/FTX) och deklarerat uteluftsflöde. Därefter jämförs svenska luftflödesbestämmelser från olika tiders normer med dagens normer på rums- och verksamhetsnivå. Dessutom inhämtas industrins bedömningar avseende villkor för när det för dem är acceptabelt att återanvända installationstekniska system. Vidare inkluderas industrins syn på ansvarsfördelning i konverteringsprojekt. Avslutningsvis redovisas en konverteringsmetod som baseras på att göra så liten åverkan på det befintliga ventilationssystemet som möjligt, genom att förpröva kompatibiliteten mellan den framtida verksamhetens krav och befintlig planlösning och att placera lokaler med höga uteluftsbehov där befintliga tilluftsdon och kanaler kan utnyttjas. Dessutom värderas följder med

scenariobaserad livscykelanalys (LCA) inom de standardiserade skedena A1–A5 (produkt- och byggskede) och livscykelkostnadsanalys (LCC).

Tre resultat framträder. För det första koncentreras konverteringar på byggnadsbeståndsnivå till att gå från kontor till bostäder samt konverteringar kopplade till handel/butikslokaler. Inom dessa par bibehålls ofta den angivna ventilationsprincipen. När det gäller deklarerade förändringar i dimensionerande uteluftsflöde dominerar minskningar. För det andra visar jämförelserna att flera par, exempelvis kontor → lägenheter samt skola → lägenheter eller skola → kontor, kan uppfylla dagens innemiljökrav utan att en ny ventilationsprincip måste föreskrivas. Industrin anger att acceptans för återanvändning förutsätter påvisbar renhet och lufttäthet i systemen, spårbar dokumentation (ursprung, underhåll och status) samt tydlig garanti- och ansvarsfördelning. Om dessa villkor uppfylls bedöms ventilationssystem ofta som återanvändbara. För det tredje visar tillämpningen av metoden att förpröva–placera–värdera i en konvertering från kontor till bostad att en stor del av tilluftskanalsystemet kan behållas, vilket jämfört med ett utbyte av hela systemet ger betydande potentiella minskningar av växthusgasutsläpp (A1–A5) samt lägre omedelbara kostnader i byggskedet. En workshop-baserad förprövning av en konvertering från förskola till äldreboende förkastade denna konvertering, eftersom kompatibiliteten inte kunde tillgodoses inom den befintliga planlösningen.

Denna licentiatavhandlings huvudsakliga bidrag är att minska osäkerheten i det tidiga projekteringsskedet vid konvertering av byggnader med fokus på ventilationssystem. Arbetet tydliggör ett nationellt underlag som redovisar genomförda konverteringar av byggnader i Sverige baserat på data insamlat via energideklarationer. Dessutom ger arbetet ett perspektiv på hur regelverket tolkas och att det, enligt detta underlag, inte föreligger några hinder för konvertering av befintliga byggnader i de tekniska delarna av byggreglerna. Arbetet inkluderar även industrins perspektiv på återanvändning av installationstekniska system och hinder för detta. Slutligen analyserades hur konvertering av en byggnad kan konceptualiseras, med speciellt fokus på bevarande av befintliga tilluftssystem.

Аннотация

Задача сокращения выбросов парниковых газов в строительном секторе требует альтернатив для преобладающей сейчас практики сноса зданий с последующим новым строительством. Новое строительство ведет к значительным выбросам парниковых газов, связанным с производством новых продуктов и материалов, а также с процессами демонтажа и возведения новых зданий. В то же время существенная часть нежилого фонда используется не в полной мере, тогда как спрос на жильё остаётся высоким. Смена функционального назначения существующего здания и его приспособление под новые нужды позволяет сохранить несущие и ограждающие конструкции и, в ряде случаев, повторно использовать элементы систем ОВиК. Это снижает капитальные затраты и дополнительные выбросы парниковых газов, связанные со стадиями продукции и строительства. Системы вентиляции, во многих случаях, могут быть использованы повторно или адаптированы. Однако нередко на ранней стадии по умолчанию принимается решение о полной замене этих систем без анализа возможностей их сохранения. Тем самым, именно ранние решения определяют, будет ли рассматриваться повторное использование систем ОВиК и каковы будут последствия этих решений.

В этой диссертации исследуется возможность сохранения или адаптации систем вентиляции при смене функционального назначения здания в национальном контексте Швеции и разрабатывается структурированная поддержка принятия решений для снижения неопределённости на предпроектной стадии. Работа включает три взаимосвязанных направления. По данным энергетических сертификатов (Energy Performance Certificates) строительного фонда изучаются реконструируемые здания по парам состояний одного и того же здания: «до изменения функции» и «после изменения». По этим же данным выявляются типовые траектории преобразований, а также фиксируются сведения о преобладающем типе системы вентиляции и о расчётном воздухообмене. Далее, в блоке нормативной выполнимости исторические шведские нормативные требования сопоставляются с современными требованиями на уровне помещений и функций. Кроме того, собираются мнения практикующих специалистов об условиях приемлемости повторного использования систем ОВиК и распределении ответственности за это. В проектно-прикладном

направлении разработана последовательность проектирования с минимальным объёмом вмешательства в существующую систему вентиляции. Предлагаемая схема: проверка совместимости новой планировки со старой — привязка помещений к существующим приточным терминалам — оценка последствий методом оценки жизненного цикла и анализа жизненных затрат в границах стадий A1–A5.

Получены три ключевых результата. На уровне строительного фонда преобразования зданий концентрируются по направлениям «офисы → жильё» и вариантам, связанным с торговыми площадями. При этом данные энергетических сертификатов чаще указывают на сохранение исходного типа системы вентиляции, а там, где удаётся отследить изменения расчётного воздухообмена, преобладают снижения. В блоке нормативной выполнимости сопоставления показывают, что ряд пар «офисы → жильё» и «школа → жильё/офисы» может удовлетворять современным требованиям к минимальному воздухообмену без смены типа вентиляции. Суждения практиков сходятся в том, что приемлемость повторного использования обусловлена чистотой и герметичностью систем, документацией происхождения и состояния оборудования, а также разграничением гарантийных обязательств и ответственности. При наличии таких подтверждений вентиляция обычно признается пригодной к повторному использованию. В проектно-прикладном направлении последовательность «проверка — привязка — оценка» в случае «офисы → жильё» позволяет сохранить значительную часть систем вентиляции и обеспечивает сокращение капитальных вложений и выбросов парниковых газов, связанных с производством материалов и новым строительством. В варианте «детский сад → дом престарелых» проверка привела к отклонению решения из-за невозможности соблюсти требования к соседству помещений в существующей планировке.

Основной вклад этой диссертации состоит в снижении неопределённости на предпроектной стадии при смене функционального назначения здания с акцентом на системы вентиляции. Это работа создает национальную базу преобразования зданий в Швеции на основе данных энергетических деклараций. Кроме того, эта работа даёт представление о том, как интерпретируется нормативная база, и указывает на то, что, согласно этим данным, в технических разделах строительных норм не выявляется препятствий для преобразования существующих зданий. В этой работе также отражена позиция отрасли в отношении повторного использования ОВиК и связанных с этим барьеров. Наконец, в этой работе описан подход для преобразования зданий с минимальным объёмом вмешательства при соблюдении требований к санитарной чистоте, герметичности и документации.

Popular science summary

Buildings use a significant amount of energy and materials. When we demolish and rebuild, we also “spend” the carbon already locked into concrete, steel and building services. At the same time, many offices stand partially empty while housing remains expensive. A practical question arises: could we convert existing buildings to new uses while retaining more of what is already installed, especially the ventilation system, so that projects may be quicker, cheaper, and lower in embodied carbon?

This thesis studies ventilation because it is often the limiting service in conversions. Ventilation is not only about mechanical components; it is also a web of shafts, main ducts, and ceiling branches that are fixed into the building. Changing where air is supplied and extracted can be invasive. Unlike electrical wiring or water pipes, ducts are bulky and hard to reroute. Design targets also change with building use: homes, classrooms and offices need different outdoor-air rates. These features mean ventilation could decide whether reuse is feasible.

The work combines three strands. First, it examines Sweden’s Energy Performance Certificate records to identify where conversions are reported and how declared ventilation concepts and design airflows are handled. Conversions appear to cluster into a few destinations, i.e., housing, offices and schools. Across many pathways, the dominant ventilation concept, for example, mechanical supply and exhaust with heat recovery, is more often retained than changed. Where paired changes in declared outdoor airflow per area are detectable, reductions are reported more frequently than increases. These are administrative signals rather than measurements, but they suggest that reusing parts of the air-side system could be possible in a non-trivial share of projects.

Second, the thesis examines historical and contemporary Swedish building regulations and asks practitioners how acceptance is built in real projects. Swedish regulations are performance-based: meeting outcomes (air quality, hygiene, noise) matters more than following a single prescribed system. Read in this way, many office-to-apartment, school-to-apartment and school-to-office pairs may meet today’s requirements without changing the ventilation concept. Interviews and a questionnaire provide the following information: ducts and air-handling units are considered to be the most reusable elements, while moving parts and water-related components are described as less suitable for reuse. Acceptance typically requires proof of various aspects, including cleanliness, leakage/airtightness checks, clear documentation, and a warranty. Barriers include the potential for polluting substances in insulation, unclear responsibilities, and the time and space required to dismantle, store, and reinstall components.

Third, the thesis develops and tests a planning method for early decisions. It works in three steps: (1) screen whether the target programme fits the donor building's functional divisions and adjacencies; (2) if it fits, arrange rooms so that high-demand spaces align with existing supply diffusers, minimising redistribution; (3) compare the material and construction-stage cost consequences of reuse versus replacement. This sequence is designed for the concept stage, when detailed simulations and commissioning data are not yet available.

A worked office-to-residential case illustrates the approach. By fixing the as-found supply ducting network and adding new exhaust, 92.25% of the existing supply ductwork was retained in its original location. Under a declared assessment scope limited to products and construction (excluding cleaning/testing and operation), full replacement was estimated at 10 887 kg CO_2-equivalent, while reuse scenarios ranged from about 21 kg CO_2-equivalent to 59 kg CO_2-equivalent. Immediate construction-phase costs were likewise lower for reuse (about 5 100 SEK–273 000 SEK) than for replacement (about 562 500 SEK), subject to assumptions about dismantling and reinstallation. A separate workshop demonstrated that the method also rejects poor fits: a preschool-to-elderly care case failed the division-level screen because the required unit count and adjacencies would likely trigger a major, impractical redesign.

The thesis proposes a method for determining, early and transparently, whether ventilation reuse is feasible in a given conversion. When donor and target outcomes align, and basic assurance checks are met, maintaining the supply-side backbone can lead to significant cost savings and prevent unnecessary disruptions. Where alignment fails, the screen may save time by signalling that extensive rerouting, and therefore replacement, is more realistic. The approach could help Sweden repurpose underused buildings for housing and other purposes while reducing their embodied environmental impacts and costs. However, applied studies on cleaning, certification, warranties, and in-use performance would strengthen confidence for wider adoption.

Nomenclature

Terminology

Adaptive reuse - Change of a building's primary function (use class) to another primary function (e.g., office–to–residential, school–to–office). It implies a functional change at the building (or clearly bounded premises) level and typically retains the building's envelope; it is not a reconfiguration within the same use.

Adjacency (rule) — Required direct spatial contiguity between functional divisions (e.g., living units ↔ shared rooms).

Conversion — A realised instance of adaptive reuse; used interchangeably with "adaptive reuse" in this thesis. Always denotes a change of primary function, not reconfiguration within the same function.

Dominant ventilation system type — Single building-level ventilation concept used for paired comparisons. It is assigned in the following hierarchy when multiple systems are declared: MV-HR > MV > MEV-HR > MEV > NV > None.

Donor/Target — Original (pre-conversion) building function / Intended (post-conversion) building function.

Functional division — An operational cluster of rooms serving one function (e.g., living unit, staff/service cluster, classroom cluster). Each division is specified by type, minimum area/size, and adjacency requirements to other division types; it is the unit used in the functional programme.

Functional programme — The set of required functional divisions for the target function, with their counts, sizes, and required adjacencies. It aggregates divisions and serves as the direct input to programme–layout screening.

Programme–layout screening — An early-stage check of whether the target functional programme could be realised within the donor building's as-found partitioning and circulation with minimal adjustments to non-load-bearing partitions and doors only.

Renovation — Interventions to fabric, services or layout that typically retain the primary function. In this thesis, the term also encompasses works carried out alongside a conversion that do not, in themselves, cause a change of use (e.g., façade upgrades during an office–to–residential project). When used without qualification, renovation refers to same-use upgrades.

System retention/concept retention — The post-adaptive reuse dominant ventilation concept is the same as the pre-adaptive reuse dominant ventilation concept (e.g., MV–HR–to–MV–HR). Does not imply component-level retention.

Abbreviations

AHU	Air-Handling Unit
BBR	Swedish Building Regulations (Boverkets byggregler)
CO_2 eq.	Carbon-dioxide equivalent
EPC	Energy Performance Certificate
HVAC	Heating, Ventilation and Air Conditioning
ISO	International Organization for Standardization
LCA	Life-Cycle Assessment
LCC	Life-Cycle Costing
MEV	Mechanical Exhaust Ventilation (Swedish F)
MEV-HR	Mechanical Exhaust with Heat Recovery (Swedish FX or FVP)
MV	Mechanical Supply and Exhaust (Swedish FT)
MV-HR	Mechanical Supply and Exhaust with Heat Recovery (Swedish FTX)
NV	Natural Ventilation (Swedish S)
RQ	Research Question
SEK	Swedish krona (SEK 1 = EUR 0.09157 as of 28 October 2025)
VALID	Ventilation-Aligned Low-Intervention Design

Latin letters

p	*p-value*: the probability, under the null hypothesis, of observing a test statistic at least as extreme as the one obtained.

List of publications

This thesis is synthesised from the following peer-reviewed publications, which constitute the appended papers and are cited in the text by Roman numerals:

Paper I

Building function, ownership, and space heating: Exploring adaptive reuse pathways in Swedish building stock.
Iarkov, I., Fransson, V., Johansson, D., Janson, U., & Davidsson, H.
Energy and Buildings. Elsevier Ltd. Volume 345, 15 October 2025, 116108
DOI: 10.1016/j.enbuild.2025.116108

Paper II

EPC-driven analysis of airflow capacity and ventilation-type conversions in Swedish adaptive reuse
Iarkov, I., Johansson, D., Fransson, V., Janson, U., & Davidsson, H.
Manuscript under review in *Building and Environment,* Elsevier Ltd

Paper III

Building services and adaptive reuse – an overview of the regulations and potential in Swedish context.
Iarkov, I., Johansson, D., Janson, U., Fransson, V., & Davidsson, H.
RoomVent 2024 – April 22-25 in Stockholm, Sweden
(Presented manuscript)

Paper IV

Adaptive reuse and building services: stakeholder perspectives on obstacles and pathways.
Iarkov, I., Sjöholm, M. J., & Rabie, S.
Journal of Physics: Conference Series. IOP Publishing Ltd. Volume 3140, 27 November 2025, 132018.
DOI: 10.1088/1742-6596/3140/13/132018

Paper V

A novel method for early-stage evaluation of adaptive reuse potential through functional division matching.
Iarkov, I., Janson, U., & Henriks, T.
In *Circularity in the Built Environment: Proceedings of the 2025 conference held in Tampere, Finland, September 16–18, 2025*
DOI: 10.5281/zenodo.17398143

Paper VI

Adaptive reuse and ventilation: a novel approach for reducing embodied environmental and economic impacts.
Rabie, S., Sjöholm, M. J., & **Iarkov, I.**
*Journal of Physics: Conference Serie*s. IOP Publishing Ltd. Volume 3140, 27 November 2025, 162002.
DOI: 10.1088/1742-6596/3140/16/162002

Author's contributions

Contributions made by the author to the appended papers are presented in Table 1. Roles are classified using the CRediT taxonomy

Table 1. Author's contributions to Papers I–VI (CRediT roles). An "X" indicates a contribution; "—" indicates no contribution; N/A indicates the role was not applicable to the paper.

Contributor role (CRediT)	Paper I	Paper II	Paper III	Paper IV	Paper V	Paper VI
Conceptualisation	X	X	X	X	X	X
Methodology	X	X	X	X	X	X
Software	X	X	N/A	N/A	N/A	—
Validation	X	X	X	N/A	X	X
Formal analysis	X	X	X	X	X	—
Investigation	X	X	X	—	X	—
Data curation	X	X	X	X	X	—
Writing – original draft	X	X	X	X	X	X
Writing – review & editing	X	X	X	X	X	X
Visualisation	X	X	X	X	—	X

1. Introduction

1.1 Background

The building sector may be considered a material and energy system whose operational and product-stage consequences remain central to climate policy. Recent assessments attribute a large share of final energy use and energy-related CO_2 emissions to buildings, even when the scope is limited to in-use activities [1]. When cradle-to-gate processes for materials and construction are included, the sector's contribution rises further, implying that attention to both operational and embodied emissions is required. Comparative syntheses suggest that embodied carbon can account for a substantial share of whole-life impacts. As operational energy use decreases in high-efficiency buildings, the share of embodied energy and carbon may approach or exceed 50% of the life-cycle total [2,3].

The future growth of the global building stock may lead to increased energy demand and emissions. Scenario and building stock-modelling studies report large additions to floor area through mid-century, with several sources forecasting that total floor area could nearly double by 2060 and that most growth will occur in lower- and middle-income regions [4,5]. Under prevailing practice, this growth would largely rely on demolition and subsequent new construction. In that case, it may reduce or stabilise future operational energy demand but result in substantial upfront greenhouse-gas emissions from new materials and construction processes. Approaches that reuse existing buildings and reduce the need for new construction materials should therefore be examined at both the city and project levels.

At the same time, several indicators of occupancy and floor-space utilisation suggest under-use in parts of the non-residential building stock. Empirical studies that investigate variation in remote-working intensity report reduced office demand, higher vacancy, and lower office construction activity in locations with persistent remote working. Effects vary by city, sub-market, and asset quality, but a recurring outcome is surplus capacity in several office segments [6]. This surplus, by itself, does not resolve housing constraints. It does, however, indicate donor–target combinations in which reallocating existing office floor area to residential use could enable the addition of dwellings without constructing new buildings, provided that technical feasibility and regulatory requirements are satisfied.

Housing affordability indicators show that pressure on lower-income tenants has remained high in several high-income countries. Comparative studies link housing-cost burdens to variations in housing institutions, such as rent regulation, social housing provision, and tax treatment, and demonstrate that low-income renters frequently allocate a substantial portion of their income to housing, with consequences including overcrowding or reduced spending on other basic needs [7]. These findings do not imply a direct link between surplus commercial space and affordable housing. They do, however, motivate attention to conversion routes that add dwellings in locations where buildings already exist, and where ventilation, structural, fire-safety, and other building services constraints can be met.

Within this context, adaptive reuse, understood as converting an existing building to a new primary function, offers a route to reduce upfront carbon emissions and initial capital investment by retaining the structural frames and envelopes. Comparative life-cycle assessments of refurbishment versus demolition followed by new construction tend to report lower greenhouse gas emissions for reuse across a range of cases, with reductions largely attributable to lower material-stage emissions and the avoided production and installation of new structural and envelope components [8,9]. Recent methodological work similarly presents renovation and reuse as credible strategies for reducing near-term emissions from the building stock [10]. Economic appraisals that move beyond initial costs toward life-cycle costing report that reuse may yield lower net present costs than rebuilding under realistic assumptions about service lives, discount rates, and maintenance profiles [11]. These results remain case-dependent, but they support a working proposition that adaptive reuse can be advantageous in both environmental and economic terms when the existing structure, geometry, and service zones can accommodate the intended new use without extensive alteration.

Despite this, building-services systems remain under-examined in many assessments of adaptive reuse. These systems mediate indoor environmental quality and provide the conditions for occupation; they also entail non-trivial embodied impacts and installation costs. Reviews of building life-cycle assessment (LCA) practice note that services are often modelled coarsely and that studies frequently simplify or omit end-of-life, reuse, and refurbishment scenarios for mechanical, electrical, and plumbing components [12]. This limits the usefulness of such studies for decision support. If services are not represented explicitly in the models, two things follow. First, replacing ducts, pipes, and air-handling units adds little or nothing to the reported impacts, because the extra materials and installation work are not accounted for. Second, options that keep existing ducts, shafts, pipework, and associated equipment in place appear, on paper, similar to options that install new systems, even though, in practice, options that preserve the existing equipment avoid additional material use, labour, and emissions.

Ventilation warrants specific attention within building services. The room function and occupant density determine the airflows and the placement of supply and exhaust terminals. A change in function, therefore, changes both the amount of outdoor air required and where it needs to be supplied and extracted [13]. At the same time, the distribution system is physically embedded in the building layout. Fans, main ducts, branches, and terminals are fixed to shafts, fire compartments, and ceiling grids. Rerouting these elements can be invasive, may trigger additional work on fire separation and building envelope, and may introduce hygiene, airtightness, and acoustic risks if not controlled. Commissioning activities, such as leakage testing, balancing, and verification that fans and terminals deliver the intended airflows, often apply to entire systems rather than isolated terminals, which raises transaction costs for small, local changes [14–16]. These properties distinguish ventilation from many electrical and water-side systems, which can often be recirculated or re-zoned with fewer dependencies. In practice, ventilation may become the constraining service in adaptive reuse, limiting what can be retained without relocating shafts, replacing main ducts, or redesigning most of the ventilation system.

Ventilation choices may also impact both energy and material costs. End-use studies and reviews classify HVAC, including ventilation, as a dominant or near-dominant contributor to delivered energy in many non-residential typologies, with the balance varying by climate, control strategy, internal loads, and hours of use [17]. For embodied impacts, case studies and synthesis papers report that mechanical, electrical, and plumbing services can account for a substantial share of whole-life greenhouse-gas emissions, and that this share tends to increase in buildings with better-insulated, more airtight envelopes and lower operational energy use [2,3,18]. On that basis, reducing the replacement and new installation of ventilation components may be important for both emissions and cost. Where the air-side distribution system can be retained or adapted in place, e.g., by keeping existing ducts, dampers, silencers, and AHUs, product- and construction-stage impacts and construction time could be reduced, provided that hygiene, leakage, noise, and regulatory requirements are still met. This expectation serves as a working assumption in this thesis, rather than a result established in the cited studies.

A further consideration is that empirical reuse decisions in Sweden are taken under performance-based regulation [19]. In this setting, meeting required outcomes, such as outdoor air rates, temperature control, noise limits, and hygiene, is the primary requirement. At the same time, the type of ventilation system itself is not prescribed. This may allow the retention of existing air-side infrastructure when performance can be demonstrated through commissioning evidence, such as cleanliness and leakage tests, as well as airflow verification. Where the existing system cannot meet target minima, e.g., too low airflow rates, or differs fundamentally from what is required, e.g., exhaust-only when balanced supply and exhaust with heat recovery is needed, the options narrow to partial or full replacement. In both situations, early screening that aligns the planned room layout for the new function with existing terminals and ducts may reduce uncertainty by clarifying, before design, how much of the distribution system would need to be moved or replaced.

The present thesis adopts this orientation. It treats ventilation as the primary building service for analysis in adaptive reuse, places decisions within Swedish performance-based regulation, and focuses on early-stage methods that may reduce the need to relocate or replace ducts, shafts, and air-handling units. This focus is motivated by three points from the literature. First, buildings account for a large share of energy use and greenhouse-gas emissions, and expected growth in floor area implies that both operational and embodied emissions require attention [1–5]. Second, evidence on underutilised offices and housing affordability suggests that donor–target pairs, particularly office-to-residential conversions, could create additional dwellings without constructing new buildings if building services constraints can be met [6,7]. Third, ventilation is closely tied to the building layout through shafts and ceiling zones, yet it is often treated implicitly or assumed to be fully replaced in comparative studies, even though choices to retain or replace air-side systems affect construction-stage impacts and delivery risks [8–12,14–18]. On this basis, a systematic treatment of ventilation in adaptive reuse is required.

Therefore, the aim of this research is threefold. First, it aims to shift attention in adaptive reuse from predominantly envelope-led practices to the treatment of building services, with ventilation as the focal system. Second, it aims to establish a framework by combining building stock evidence, regulatory analysis, and practitioner perspectives, thereby identifying conditions that may permit or prevent ventilation retention. Third, it develops and tests an integrated approach that (i) checks whether the target functional programme can be placed within the existing internal structure, (ii) arranges rooms so that key spaces align with existing supply terminals, and (iii) appraises reuse and replacement options through scenario-based LCA and life-cycle cost analysis (LCC). The study is undertaken in Sweden, which provides the empirical and regulatory context for all analyses.

1.2 Research aim

This thesis aims to establish a framework for retaining or adapting existing ventilation systems in Swedish adaptive reuse and to provide structured decision support that may reduce early-stage uncertainty for practitioners. This aim is pursued through the following three research questions.

- **RQ1:** What adaptive reuse patterns are observed in Sweden, and how do ventilation system types and declared airflows change with conversion?

The aim of this research question is to establish an empirical baseline by identifying where conversions occur and characterising reported changes in ventilation provision at the stock scale. This RQ is addressed in **Paper I**, which analyses national EPC records to quantify conversion incidence and attributes, and in **Paper II**, which uses EPC ventilation data to assess pre- and post-conversion system types and declared design airflows.

- **RQ2:** Which regulatory requirements and practical conditions may permit or prevent the retention or adaptation of ventilation systems?

The aim of this research question is to establish the feasibility framework by combining an analysis of the Swedish regulatory lineage with stakeholder perspectives on barriers, enablers and responsibilities. This RQ is addressed in **Paper III**, which reviews HVAC-relevant provisions across code eras, and in **Paper IV**, which reports a questionnaire- and interview-based study with practitioners, from which the industry perspective is derived.

- **RQ3:** Could an adaptive reuse method be designed to enable retention of existing ventilation systems, and what implications might follow?

The aim of this research question is to develop and appraise a screening method for spatial fit between the target functional programme and the donor building's existing partitioning and circulation (programme–layout compatibility). In a theoretical case study, the screening is then combined with diffuser-aligned planning, which anchors rooms to existing supply terminals and duct clusters to test ventilation retention and estimate potential carbon and cost implications through scenario analysis. This RQ is addressed in **Paper V**, which presents the screening method, and in **Paper VI**, which applies diffuser-aligned design and models outcomes using LCA and LCC.

The research process flow, which connects the overarching aim of the thesis to the three research questions, the six appended papers, and their principal outputs, is illustrated in Figure 1.

1.3 Structure of the dissertation

The thesis comprises a summary (kappa) and six appended papers (**Papers I–VI**). The summary is organised into five sections. **Section 1** introduces the problem context, states the research aim and three research questions, and outlines the structure of the work. **Section 2** sets out the methodological stance and research design, including the three empirical strands. **Section 3** reports the results from the stock-scale, feasibility, and design-science strands, organised by the research questions. **Section 4** presents the combined findings in the Swedish context and discusses their implications for decision-making and future research. **Section 5** presents the conclusions at the thesis level, notes key limitations, and identifies priorities for future work. The appended papers follow in full.

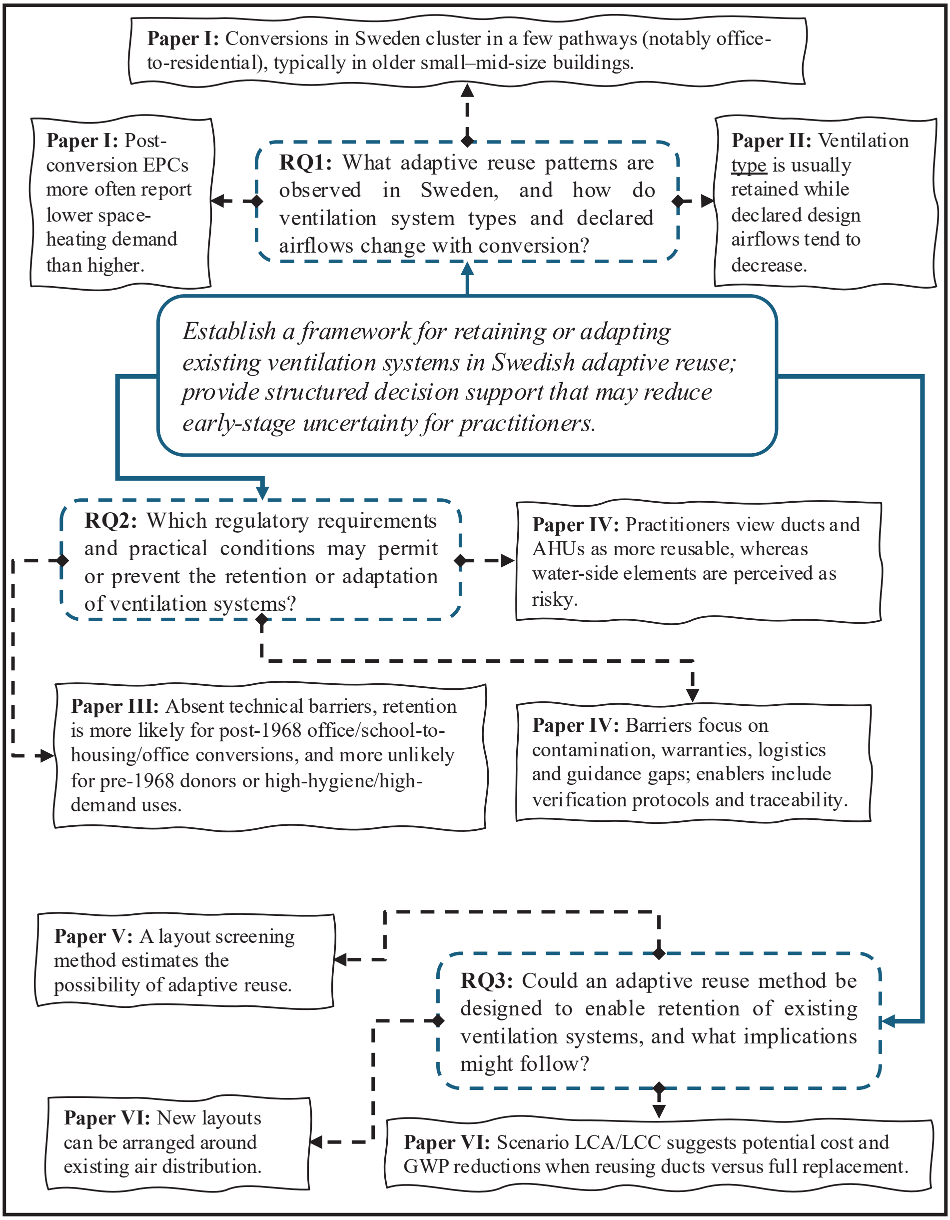

Figure 1. Research process flow linking the overarching aim, research questions, appended papers and main outputs.

2. Research methodology and methods

This section introduces the research philosophy that structures the thesis and explains how it informs the three strands and their associated methods. Methodology denotes the philosophical and logical basis of the research; methods are the concrete procedures and instruments used to generate and analyse evidence. The research design is structured to justify the selection of specific methods to address the Swedish challenge of adaptive reuse, with a focus on ventilation.

This thesis adopts a composite methodological stance, comprising a pragmatist orientation, a critical realist reading, and an abductive logic of inference. In the design-science sense, pragmatism views methods as tools for decision support under constraints; research in engineering and construction aims to yield useful artefacts, procedures, or "technological rules" [20,21]. *Pragmatism* here means that methods are chosen for their usefulness in addressing the decision problem, rather than for allegiance to a single explanatory model. A critical realist reading complements this stance [22]. *Critical realist* here means that claims are conditional on data quality, and that inference recognises the gap between mechanisms and indicators. Abductive reasoning is employed to transition from observed patterns to a usable design. When a recurring pattern is identified, a tentative design rule is proposed, e.g. placing high-demand rooms at existing diffusers to increase retention of ventilation components. The rule is implemented as a screening-and-planning tool and evaluated for its usefulness by comparing the retention of ventilation components and LCA/LCC results with simple baselines, and by ensuring compliance with Swedish regulatory constraints [23,24]. *Abductiv*e here means moving from the required function, via a plausible rule, to a design that could work under uncertainty. The choice of this philosophical triad over alternatives and its implications are argued in Section 2.1, with references to performance-based regulation in the built environment that further motivate the stance [25].

Within this orientation, the empirical work is implemented through three strands aligned with the research questions: a building stock-scale strand that constructs building-level Energy Performance Certificate (EPC) pairs to describe where conversions are reported and how declared ventilation descriptors differ across these conversion events; a feasibility strand that combines a comparative analysis of contemporary and historical Swedish building regulations with a practitioner enquiry to analyse acceptance pathways for retaining or adapting ventilation systems; and a design-science strand that constructs and evaluates a low-intervention, diffuser-aligned planning method and appraises consequences through LCA and LCC.

Section 2.2 summarises the research design; Sections 2.3, 2.4, and 2.5 present the methods specific to each strand; Section 2.6 argues coherence across strands; Section 2.7 states limitations consistent with the adopted philosophy.

2.1 Rationale for the stance and logic of inference

The rationale for the stance addresses a socio-technical decision problem in which physical mechanisms and institutional rules co-determine outcomes. Under a critical realist reading, claim strength is bounded: mechanisms relevant to ventilation reuse, e.g., occupant density shaping outdoor-air demand or the ventilation concept shaping air distribution and heat recovery potential, may be real even when the available indicators are proxy-based or administratively declared rather than measured. This pairing permits cautious inference from heterogeneous evidence [26–28]. Within the pragmatist orientation, a design-science approach is utilised. The aim is to produce a usable artefact for early planning under constraints rather than to maximise the explanatory power of a single predictive model. In this approach, artefacts and “technological rules” may constitute knowledge when the process of constructing and evaluating them is made explicit and situated in context [29,30]. The research proceeds abductively: observed regularities motivate the selection of a potential solution, which is then embodied in a procedure and checked for usefulness. Abductive design reasoning is well established as a movement from function to principle and then to form in innovative design [31,32].

Given the pragmatist–critical realist stance and abductive design logic outlined previously, integration is necessary. Technical performance interacts with organisational and regulatory constraints, so no single method is likely to yield decision support on its own. Mixed-methods integration is therefore employed across the three strands, with explicit joining principles derived from the applied mixed-methods literature [33,34]. This also aligns with a consequence-sensitive view of evidence: the adopted evidential policy should be judged by the quality of decisions it supports under uncertainty, which motivates integrating heterogeneous indicators when doing so improves decision consequences [35].

Alternative methodological stances were examined and not adopted because they could mis-specify the evidential situation. A positivist, hypothesis-testing design would presuppose unbiased measurement and strong control. In this domain, declared EPC variables and early-stage models may diverge from in-use performance, which weakens causal claims from declarations and supports descriptive, non-parametric treatment at the stock scale [36,37]. A physics-first, deterministic stance would privilege a single representation of the ventilation-and-space system, that is, one detailed physical model with one parameter set as arbiter of feasibility, and could under-specify how building regulations changed over time and how assurance/approval steps shape adoption; planning scholarship cautions that such one-model framings may be brittle where objectives are contested, and constraints are socio-technical [38]. A Bayesian causal strategy would require credible priors, i.e., explicit probability distributions for key effects, and a well-characterised data-generating process, i.e., how buildings enter conversion, or how EPC fields are produced. While EPC data are structured, selection into conversion is unobserved, and administrative production processes may introduce measurement and classification biases. Under such conditions, the identification of causal effects is doubtful, and narrow posteriors may reflect modelling assumptions or priors rather than information in the data [39]. An exclusively interpretivist/ethnographic research design could recover sense-making, i.e., how actors construct problems and make decisions, as well as transaction costs (including coordination, approvals, information, and procurement frictions). However, it would not establish a national baseline or yield a forward-looking tool under regulatory obligations. [40]. A purely doctrinal reading clarifies obligations and permissions but, alone, would not reveal spatial compatibility with existing terminals and ducts, nor the project-level assurance steps that shape adoption. It is therefore used here as an input to, rather than a substitute for, the design-science strand.

Section 2.2 outlines how building stock data, doctrinal analysis, and practitioner perspectives are connected and compared using shared criteria, and how the planning artefact (programme–layout screening followed by diffuser-aligned planning) is implemented and evaluated.

2.2 Research design in this work

The adopted philosophy motivates the selection of methods. Pragmatism requires methods that could deliver decision support at the concept stage. Critical realism requires that indicators be treated as fallible and that claims be bounded by what administrative and elicited evidence may warrant. Abduction requires a path from observed regularities to a provisional rule, its implementation, and appraisal against simple baselines. Mixed methods are employed because no single evidence stream can credibly span description, permissibility, acceptance, and consequence.

The stock-scale strand was required because, under critical realism, administrative registers must be used cautiously to describe regularities rather than to assert model-driven causal effects. Building-level pairing of EPCs is therefore used to recover before–and–after signals from declarations, rather than from unbiased metering of in-use operations. Where EPCs are issued at the property level, building-level records are reconstructed where possible. Plausibility filters remove obvious mismatches and anomalies, e.g., changes in the number of buildings and implausible shifts in the heated floor area. Under abduction, the resulting regularities supply mechanisms and parameter ranges that bound subsequent design moves. Under pragmatism, the output is a national descriptive baseline intended to inform early decisions without presuming a single predictive model.

The feasibility strand was required because, under pragmatism, decision support must state what could be done within prevailing obligations and routines. A doctrinal regulatory analysis of BBR across code eras compares historical regulations with a contemporary regulatory framework, enabling donor–target pairs to be consistently queried on the ventilation concept and outdoor air minimums. Within critical realism, these regulations are treated as institutional mechanisms that shape outcomes. A questionnaire- and interview-based study with practitioners complements the doctrinal analysis by making explicit the assurance routines and responsibility ordinarily sought in projects. Under abduction, these two inputs bound the design rules that may be attempted and the criteria used for appraisal. The result is a feasibility frame for early-stage briefing and planning.

The design-science strand was required because, under abduction, a provisional rule suggested by stock-scale signals and bounded by feasibility must be instantiated and exercised. Ventilation distribution is embedded in the geometry, i.e., shafts, main ducts, and terminal clusters constrain feasible room placement. Therefore, an architectural method, functional-division matching followed by diffuser-aligned placement, is used to test whether a target functional program can be arranged to utilise existing diffusers and ducts, thereby reducing rerouting and replacement. Under pragmatism, the aim is a usable procedure under low-intervention constraints. Under critical realism, evaluation targets effects that the indicators could support, i.e., expected retention of diffusers and main ducts and the extent of any new shafts or central-plant works, rather than idealised optimisation.

Consequence appraisal was required because pragmatism requires quantities that matter at the conceptual stage. LCA and LCC, therefore, compare orders of magnitude for alternative ventilation interventions, such as reuse in place, disassembly and reinstallation, and full replacement, under transparent assumptions and sensitivity ranges. Under critical realism, results are presented as ranges with declared data sources; operational outcomes are not modelled at this stage. Under abduction, the scenarios appraise the applied rule against simple baselines rather than aiming for exact numbers.

In this configuration, the stock-scale description motivates feasibility bounds and inputs; the feasibility work defines the permissible and routinely accepted space within which rules may be attempted; and the design-science with consequence steps implement and appraise the planning move. The literature review within each paper refines constructs, terminology, and boundary conditions; data assembly and cleaning follow a critical realist approach to indicators. The summary of the methods used in the appended papers is shown in Table 2.

Table 2. Methods used in the appended papers I-VI. Tags: [CR] critical realism — treat indicators as fallible; bound claims. [ABD] abduction — regularities → rule → artefact. [PRAG] pragmatism—decision-useful at concept stage. [INT] integration — explicit joining across evidence streams.

Methods used	Paper I	Paper II	Paper III	Paper IV	Paper V	Paper VI
Literature review [PRAG, ABD, INT]	X	X	X	X	X	X
Stock data assembly & pairing; descriptive summaries [CR, PRAG]	X	X	—	—	—	—
Non-parametric statistical testing [CR]	X	X	—	—	—	—
Doctrinal regulatory analysis [CR, PRAG]	—	—	X	—	—	—
Survey/interview study [PRAG, INT]	—	—	—	X	—	—
Design-science method [ABD, PRAG]	—	—	—	—	X	X
LCC and LCA (comparative A1-A5 scope) [PRAG]	—	—	—	—	—	X

2.3 Stock-scale strand: reconstructing administrative signals and restricting constructs (**RQ1**)

This strand was required to replace case-led inference with a national baseline of adaptive reuse that sets the inputs and limits for the later feasibility and design-science strands. It reports observed donor–target pathways, declared airflow ranges by function and era, and tendencies in system-type retention or change. EPCs are the only near-census, structured source that can be used to infer pre- and post-conversion states at scale in Sweden; however, they are administrative declarations rather than controlled measurements. Accordingly, the analysis is descriptive and distribution-aware, utilising building-level pre- and post-conversion pairing. It does not begin with a pre-specified causal model and attempt to infer parametric effects from administrative records. Pairing rules, property-to-building reconstruction, and plausibility checks are documented in the appended papers and are not repeated here.

The analysed variables were restricted to those that shape adaptive reuse and ventilation planning at the concept stage and are available in the dataset. **Paper I** examines space-heating energy use per area, derived from measured EPC fields, along with function, era, and ownership, to identify conversion pathways in the stock. **Paper II** examines declared ventilation descriptors, the dominant ventilation system type, and design airflow per area, to describe how ventilation provision is reported to change across conversion events. The dominant system type denotes a single classification per building, as EPCs can list multiple systems without providing area shares. It is assigned by a fixed hierarchy: MV-HR > MV > MEV-HR > MEV > NV > None, enabling paired pre- and post-conversion comparisons without combinatorial fragmentation. Systems with mechanical supply outrank exhaust-only because combined supply and exhaust ventilation constrains adaptive reuse more strongly. The heat-recovery variant outranks the non-recovery variant because it introduces additional embedded components and reuse constraints. This fixed precedence is required because EPCs do not report area shares by system; if such shares were available, an area-weighted assignment could be used instead.

Statistical procedures were chosen to respect the administrative provenance and the paired structure. In **Paper I**, directional change in space-heating use per area was tested with a one-sided binomial sign test at $p < 0.05$, which evaluates whether increases or decreases predominate without assuming a specific distribution of paired differences. This test is robust to skewness, heaping, and outliers, and it aligns with the aim of detecting stock-level regularities in the direction of change rather than estimating magnitudes of change due to adaptive reuse [41].

In **Paper II**, the non-normality of paired airflow differences was established using the Shapiro–Wilk test . Subsequently, paired changes were assessed using the Wilcoxon signed-rank test at $p < 0.05$, which tests for a median shift without requiring normality assumptions. Transitions in dominant ventilation system type were analysed with a chi-square test of independence at $p < 0.05$, supplemented by standardised Pearson residuals to identify over- and under-represented pathways. These choices are standard for heterogeneous, administratively declared data and for nominal transition tables where the objective is association rather than parameter estimation [41–43].

No sensitivity analysis was undertaken in this work. Robustness was instead supported by building-level pairing; explicit reconstruction and filtering rules, e.g., removing cases with conflicting identifiers between paired records, large unexplained shifts in conditioned floor area, or changes in the reported number of buildings on the estate; and distribution-free tests that are less sensitive to known reporting artefacts in EPC data, such as defaulted values, property-level aggregation across multi-building sites, or calculated rather than measured values. This placement is consistent with the critical realist constraint, which requires inference to remain descriptive and conditional on the quality of the data. Under pragmatism, the aim is a decision-useful baseline rather than model-driven precision.

Outputs from this strand serve two functions in the research design. First, they provide a national descriptive baseline on where conversions are reported and how the descriptors for measured heating and declared ventilation differ across events. Second, they supply inputs for abductive development, i.e., concrete donor–target pathways, declared airflow ranges, and observed tendencies for ventilation system-type retention or change.

2.4 Feasibility strand: regulatory lineage and practitioner perspectives (**RQ2**)

This strand addresses the step between stock-scale regularities and project-level planning by asking when retention or adaptation of existing ventilation may be permitted in principle and when it is likely to be accepted in practice. The restriction to the system concept, i.e., Swedish labels S, F, FT, FX, FTX, corresponding to NV, MEV, MEV-HR, MV, and MV-HR, and to the outdoor-air provision, i.e., airflow, follows directly from the stock signals and the early-programming focus of the thesis. These two descriptors drive preliminary planning, map-building code obligations, and design calculations. This strand's position and scope are consistent with the adopted philosophy: regulations and acceptance routines are treated as mechanisms that shape outcomes; pragmatism requires decision-useful guidance rather than exhaustive doctrine; and abductive reasoning uses stock-scale patterns to motivate the questions that the feasibility lens must answer.

The regulatory component constructs a cross-era similarity matrix that compares historical Swedish building regulations with current requirements at the room and use level. Historical regulations are read doctrinally and normalised to a contemporary frame so that donor–target pairs can be queried consistently on ventilation scheme similarity and outdoor-air minima. Preserving the Swedish concept nomenclature while mapping to the outcomes of the Swedish building code era allows for two feasibility tests for any pair: whether the target minima could be met without changing the ventilation system type and, if not, whether the era mandated a specific concept or left concept choice open. This instrument operationalises the performance orientation of modern Swedish regulation, where achieving outcomes is primary, and the choice of concepts is not prescribed. It turns heterogeneous historical texts into a project-facing lookup that can be used during the development of the functional programme for the target function. The details of the analysis are documented in **Paper III**. Outcome normalisation across eras in building control aligns with risk-informed, performance-based regulation in the built environment [44] and with socio-technical approaches to performance-based regulation [45].

The practitioner viewpoint complements the building regulation analysis with a purposive enquiry into acceptance. A structured questionnaire and semi-structured interviews with Swedish and Nordic stakeholders were used to explore how acceptance of ventilation reuse is viewed today. Responses were coded thematically into enablers, barriers, and responsibility allocations. Coding followed a simple Actor–Network rule: treat people, organisations, documents, and technical artefacts as potential actors that can enable or block reuse, without assuming that human actors dominate by default. Thematic analysis is appropriate where the aim is to highlight mechanisms, i.e. the practical reasons acceptance occurs or fails, and assurance routines, i.e. the checks and documentation used to provide evidence for those mechanisms, rather than to estimate frequencies, and it is established in construction research for rigorous coding and theme development [46,47]. **Paper IV** details the instrument, sampling, coding grammar and resulting acceptance taxonomy.

Integration with the preceding strand is direct. Stock-scale outputs provide the donor–target pathways and declared airflow ranges that require interpretation. The regulatory analysis converts these into permissibility judgments under Swedish rules. At the same time, the practitioner enquiry identifies the proofs typically required for the reuse of ventilation equipment in projects, such as airflow verification, leakage or cleanliness testing, provenance and documentation, and allocation of responsibility and warranty. Together, these readings form a feasibility framework for the development of a functional programme, which, in turn, provides decision rules and boundary conditions for the planning artefact in the next strand. This strand extends the stock-scale analysis by situating its administrative signals within outcome-based regulation and project acceptance, consistent with the pragmatist and abductive logic of this thesis.

2.5 Design-science strand: artefact logic, implementation and consequence appraisal (**RQ3**)

This strand implements the abductive logic in a concept-stage artefact designed for decision support under constraints, treating spatial constraints in ventilation as real while working with partial indicators, and moving from regularities and feasibility bounds to a workable planning procedure [48–50]. The artefact addresses the question posed by the preceding strands: given a donor building with a declared dominant ventilation type and airflow ranges, can a target functional programme be arranged so that key rooms utilise existing terminals and ducts rather than necessitating the complete replacement of the ventilation system?

Two coordinated moves are used. First, programme-led screening compares the target programme's divisions, room counts and sizes, as well as adjacency rules (e.g., living units adjacent to shared rooms), with the donor's as-found partitioning and circulation. It returns a reasoned feasibility judgement: whether the programme could be realised with local partition changes or would require a complete architectural redesign. This implements functional-division matching as an early feasibility check on spatial fit. Second, diffuser-aligned planning places high-demand rooms so that they coincide with existing supply diffusers, aiming to reduce the re-routing of existing branches and minimise the additional length of new ducts, and to avoid new ducts where possible. The screening step draws on the stock-scale outputs, i.e., donor-target pathways and declared airflow ranges, to select plausible pairs; the planning step adheres to the feasibility framework established by the regulatory analysis and practitioner perspectives. These steps are developed and exercised in **Papers V** and **VI**.

The focus is limited to product- and construction-stage evaluations of the ventilation interventions (A1–A5). Operational energy and operating costs are not modelled at the concept stage. Consequence appraisal is framed comparatively via LCA and LCC, reporting orders of magnitude under transparent assumptions and sensitivity ranges [51,52].

Dynamic energy simulation is not used at this stage. The decision problem is spatial compatibility under incomplete information, not annual performance prediction. Reviews of early-stage simulation show substantial data and calibration requirements unlikely to be available before design development, e.g., envelope thermal properties and airtightness, zoning and setpoints, HVAC efficiencies and control sequences, internal gains and schedules, infiltration, commissioning tolerances, and measured data for calibration, supporting deferral of calibrated simulation to later phases [36,53]. Recent work suggests that building services may contribute materially to embodied emissions yet remain underrepresented in whole-building inventories, which justifies the use of explicit ventilation modelling in conversion scenarios [54–56].

LCA and LCC are parameterised to compare only the ventilation intervention while holding the functional programme choice fixed. Scenarios include full replacement, reuse in place with limited adjustments, and disassembly and reinstallation within the same building. Inventories are constructed per metre of duct, including fittings. Swedish or Nordic data sources were preferred, and if unavailable, data from other countries were used. Reporting per reused metre of duct is adopted to improve transferability across geometries. This approach follows building-LCA practice in declaring results using assembly-level physical reference units when assessing specific interventions, rather than whole-building totals [18,57]. Cost analysis follows ISO 15686-5 logic for inclusion and discounting, with labour, handling, and storage explicitly treated where relevant [58]. LCA follows ISO 14040/14044 for comparative assessment of alternative air-side interventions, limited to the product and construction stages [59,60].

Evaluation follows the design-research convention, focusing on fitness-for-use in the specific case setting rather than statistical generalisation. Usefulness is judged by whether the screening reduces added duct length in the proposed layout and whether comparative LCA/LCC indicates differences of a magnitude that could matter at the concept stage. This form of contextual evaluation is consistent with established design-science guidance and construction-management research on artefact appraisal in applied, multi-disciplinary settings [48–50].

2.6 Coherence, validity and reproducibility

Coherence is treated as the alignment between constructs, data, and claims, so that each strand advances the overall aim of establishing a framework for retaining or adapting ventilation systems in Swedish adaptive reuse. The stock-scale strand provides administrative before–and–after signals on where conversions are reported and how declared ventilation descriptors differ by pathway; the feasibility strand translates those signals into permissibility and acceptance under Swedish rules and practice; the design-science strand operationalises a low-intervention planning tool and appraises the material and cost consequences. This sequencing remains consistent with the philosophical placement described above.

Validity is argued at the level of the research design as triangulation with declared uncertainties, rather than as internal validity in a narrow causal-identification sense. That is, stock data, doctrinal analysis, and practitioner perspectives are connected and compared using shared criteria, while limits and ranges are explicitly stated.

For the stock-scale strand, validity rests on transparent building-level pairing, stated reconstruction and filtering rules, and distribution-aware non-parametric paired tests (e.g., a one-sided binomial sign test for directional change, a Wilcoxon signed-rank test for paired airflow differences) that avoid normality and equal-variance assumptions unsuitable for administrative data [41]. Causal claims on metered in-use energy are not made; known gaps between declarations, predictions and in-use performance justify a descriptive approach [61]. For the feasibility strand, validity derives from doctrinal traceability, i.e., each regulation interpretation is linked to its source text, and from the credibility of thematically analysed practitioner perspectives that clarify acceptance proofs and barriers, e.g., required tests, documentation, and responsibility allocation, rather than estimate their prevalence. For the design-science strand, validity lies in procedural transparency and case-fit evaluation, with scenario parameters declared and varied within ranges, consistent with design-science evaluation guidance that prioritises fitness-for-use over statistical generalisation. [50,62].

Philosophical coherence is maintained by keeping claims conditional on the quality and scope of the data. Stock-scale adaptive reuse data is used to prompt and parameterise questions; regulatory lineage and practice testimony delimit what may be permissible and accepted; the artefact embodies a planning method that could exploit existing terminals and ducts; consequences are reported as ranges rather than points. This pattern reflects the separation of mechanisms and indicators characteristic of critical realism, the focus on decision support of pragmatism, and the logic of abduction, which involves a function-to-principle-to-form approach.

Reproducibility is addressed through artefact-level and strand-level transparency. For the stock-scale strand, a pairing and reconstruction protocol specifies the mapping from properties to buildings, the processing algorithm, the criteria for building-level pairs, and the exact non-parametric procedures used. For the feasibility strand, **Paper III** documents the sources and normalisation rules used to build the cross-era similarity matrix; Paper IV describes the questionnaire and interview protocol, sampling, and the step-by-step procedure for classifying responses into enablers, barriers, and responsibility allocations. For the design-science strand, decision rules for functional programme–layout screening and diffuser-aligned placement are specified so another team could apply them to a different donor–target pair; the LCA/LCC set-up states declared units, system boundaries, inventory sources and cost items in line with ISO transparency requirements, and methodological framing follows established LCA practice [52]. What is reproducible is the reasoning sequence, artefact procedure and statistical workflow, rather than any single numeric outcome bound to a particular dataset or donor building.

2.7 Methodological limitations

The research design supports three types of claims: descriptive claims about stock-scale patterns, feasibility claims about what may be permissible and acceptable at the concept stage, and comparative consequence claims about embodied greenhouse gas emissions and life-cycle costs. Other types, e.g., causal effects on metered operational energy or population-level prevalence of barriers and enablers, are outside its scope. The planning artefact is not presented as universally optimal; evaluation targets fitness-for-use in context rather than statistical generalisation, which is consistent with design-science evaluation [50,62].

Data and construct limitations constrain the descriptive strand. EPC variables are administrative declarations and may contain defaults or approximations. Mapping property-level EPC records to buildings and retaining only pairs that satisfy stated pairing rules and plausibility filters reduces, but cannot eliminate, misclassification. Non-parametric paired tests are used to summarise directions of change and associations, and should not be interpreted as estimates of causal effects or regression-type effect sizes [41]. No formal sensitivity analysis is undertaken in the stock strand; instead, robustness relies on the data filtering protocol and distribution-free procedures that may be appropriate for heterogeneous administrative data.

External validity is limited. The feasibility reading reflects Swedish regulations and practices, as well as those of the Nordic region. Application elsewhere may require re-evaluation of concepts, thresholds, and minimum outcome levels. Consequences from the design-science strand are scenario-dependent: the scope is limited to the product and construction stages of ventilation interventions, operational energy and operating costs are not modelled at the concept stage, and results may vary with the choice of background data, assumed service lives, labour rates, and handling and storage allowances. A preference for Swedish or Nordic emission factors is stated; where proxies from other contexts are used, these are clearly identified. Evidence that mechanical, electrical, and plumbing installations may contribute materially to embodied impacts motivates an explicit treatment of ventilation interventions, but also implies that results could vary across projects and supply chains [18,57].

The abductive structure itself is a limitation. Stock-scale regularities are used to prompt plausible mechanisms and parameter ranges. Regulatory lineage and practitioner perspectives define what may be permissible and acceptable. The artefact embodies a lightweight planning procedure, and LCA/LCC comparisons report consequence ranges rather than point estimates. This configuration is well-suited for concept-stage decision support under uncertainty. However, it may overlook factors that emerge during detailed design, procurement, and commissioning [63–65].

3. Results

This chapter presents the results from the appended papers, organised by the three research questions. It presents findings that are directly relevant to ventilation in adaptive reuse or that appeared noteworthy for early decision-making. Full statistical tables, instruments and supplementary figures are provided in **Papers I–VI**.

Section 3.1 summarises the observed conversion incidence and donor–target pathways in the paired EPC dataset, along with ventilation descriptors, including the declared dominant system type and declared design outdoor airflow per area. Section 3.2 presents the results from the feasibility strand, which includes an analysis of Swedish regulatory texts mapped to contemporary outdoor air regulations and practitioner perspectives gathered through a questionnaire and interviews. Section 3.3 presents outputs from the design-science strand, including functional-programme layout screening based on functional-division matching, outcomes from diffuser-aligned planning relative to conventional full replacement of the ventilation systems, and comparative LCA and LCC scoped to the product and construction stages of ventilation.

3.1 Stock-scale strand (**RQ1**)

This section reports national stock signals on functional conversions and ventilation. It first describes the conversions that occur between functions in the Swedish building stock by presenting, for each donor function, the distribution of realised donor–to–target conversion pathways and the corresponding within-donor shares of conversions to each target. Read together, these views indicate which target functions absorb most projects overall and which donor–to–target pathways recur most frequently once a donor type is present.

Ventilation is then examined at the same stock scale using two descriptors relevant at the concept stage: the dominant ventilation system type before and after conversion, and the direction of change in the declared design outdoor airflow per floor area. These two descriptors are presented jointly in intersection plots that link donor–to–target pathways, system-type transitions, and the majority direction of airflow change for each pathway, allowing pathway-specific patterns to be inspected without reprinting all intermediate tables, cross-tabulations, and test statistics. All ventilation variables are administratively declared EPC fields and are treated as indicative rather than metered performance. Reporting here is limited to conversion incidence, donor–to–target structure, ventilation concept retention or change, and direction of declared airflow change. A detailed analysis is provided in the appended **Papers I** and **II**.

Overall, the majority of conversions are concentrated in a small number of destination functions, as shown in Figure 2.

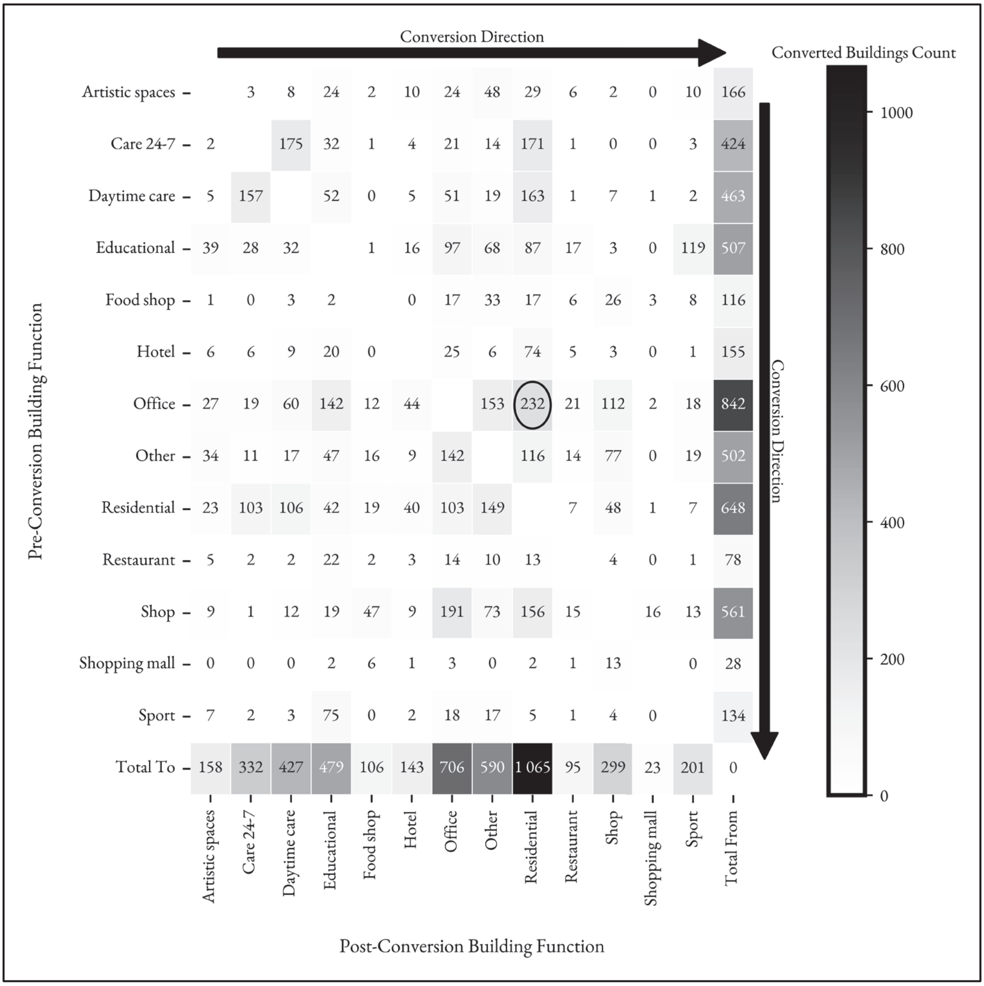

Figure 2. Building conversions by donor–to–target function (counts). Rows show donor function; columns present target function; cell labels show number of buildings; row and column marginals give donor and target totals. Dataset: paired EPC records after reconstruction and filtering (n = 4 624 converted buildings).

Residential receives 1 065 buildings and constitutes the largest single target column. The office received 706, the “others” category 590 and the educational 479. Within these destination columns, a few high-throughput flows are visible. Office–to–residential contributes 232 buildings and sits alongside two other sizeable office outflows: office-to-other at 153 and office-to-educational at 142. Shops contribute two triple-digit streams to the main destinations: 191 shop–to–office and 156 shop–to–residential. Care categories exchange in both directions at scale, with 175 care 24-7–to–daytime care and 157 daytime care–to–care 24-7, and also contribute directly to residential with 171 and 163 buildings, respectively. Residential itself supplies notable volumes to non-housing uses, including 149 residential–to–other and 103 residential–to–office. Additional recurrent movements include 75 sport–to–educational and 74 hotel–to–residential. Low-volume donors are also present; the shopping mall supplies 13 shopping mall–to–shop conversions and restaurant supplies 22 restaurant–to–educational conversions. The overall count structure is therefore many-to-few: diverse donors feed a compact set of destinations that absorb most recorded conversions.

The propensity view reorganises prominence by expressing each donor–to–target cell as a share of all EPC-registered buildings in the corresponding donor function in the national dataset, as shown in Figure 3. Several modest-volume pathways become visible as frequent resolutions within their donor categories. The shopping mall–to–shop ratio reaches 8.2%, involving 13 buildings, indicating a high share of shopping mall donors converting into shops, despite the small base. Hotel–to–residential reaches 6.9% with 74 buildings, signalling a frequent outcome for hotels that undergo adaptive reuse. Care facilities retain high propensities that mirror their volumes: care 24-7–to–daytime care is 7.0%, and daytime care–to–care 24-7 is 7.1%; care 24-7–to–residential is 6.8%, and daytime care–to–residential is 7.4%. These values indicate that, conditional on being in a care class, movement within the pair and into residential is comparatively common.

Retail-linked donors remain prominent on both views. Shop–to–office is 7.3% with 191 buildings, and shop–to–residential is 6.0% with 156 buildings, which couples high throughput with an elevated per-donor likelihood. Additional frequent donor-specific routes appear to shift toward educational purposes: sport–to–educational is 6.6% with 75 buildings, and restaurant–to–educational is 5.4% with 22 buildings. The “other” category allocated 142 buildings to office use and 116 to residential, simultaneously recording high propensities of 7.0% and 5.7%. This suggests that, once present in this donor class, conversion into these destinations is common.

Large donor classes show the converse pattern. Offices supply the largest total departures and the single biggest stream into residential in the numerical view. Nevertheless, donor-normalised propensities are lower due to the large denominator: office–to–residential is 3.4%, office–to–other is 2.2%, and office–to–educational is 2.1%. Residential, as a donor, behaves similarly: it contributes sizable departures to other and office in volume, yet exhibits low propensities across most targets, consistent with its prevalence in the non-converted stock.

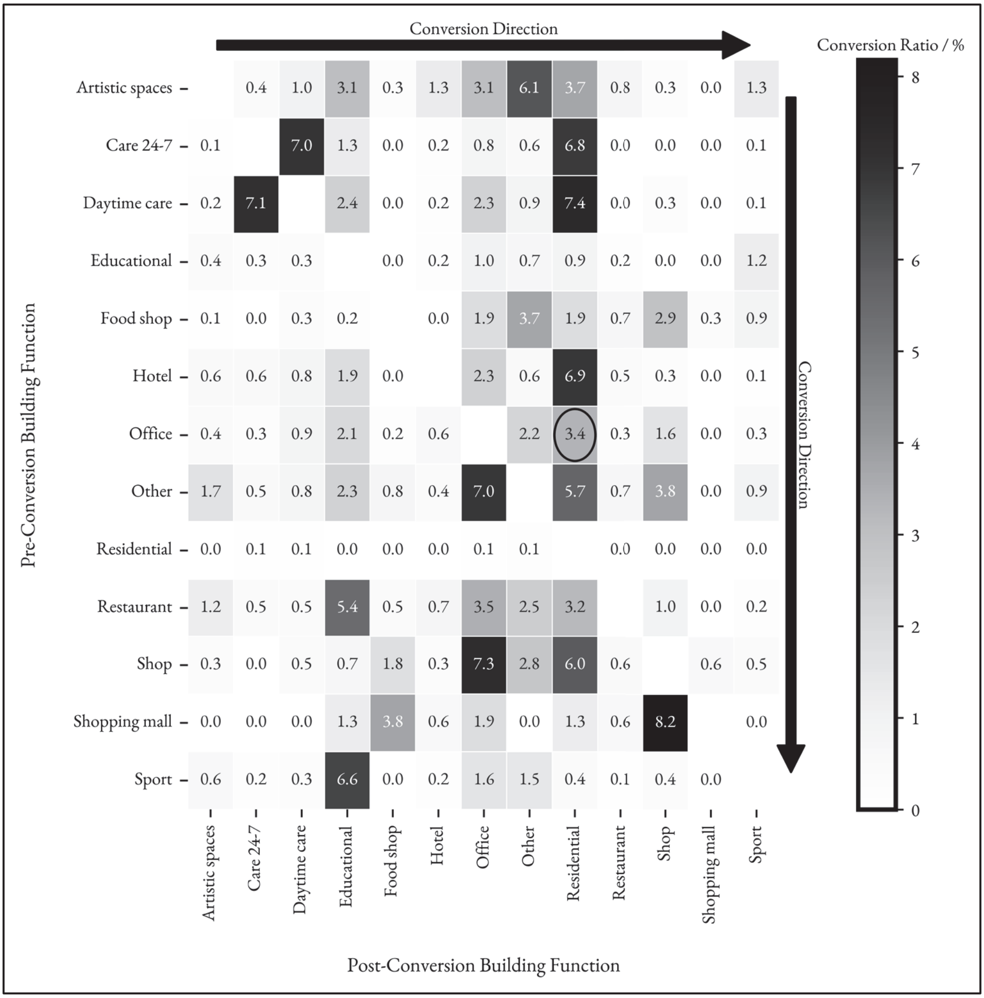

Figure 3. Donor-normalised conversion ratios. Rows show donors; columns show targets. Each cell represents the conversions from the donor to the target, divided by the number of buildings in the donor class, and is expressed as a percentage. Donor denominators correspond to the row totals in Figure 2; cells with small denominators should be read with caution.

Viewed as destination columns, the two figures together indicate that residential, office, educational, and "other" destinations not only have the largest arrival totals but also receive elevated propensities from specific donors. Residential is fed at high rates by the shop, hotel, and both care classes. The office receives a large share from the shop and the "other" category. The educational sector receives frequent inflows from the sport and restaurant sectors. The other sector receives frequent inflows from the care classes.

Ventilation outcomes are examined at the stock scale by intersecting donor–to–target functional pathways with two descriptors available in the EPC corpus: the dominant ventilation system type before and after conversion, and the prevailing direction of change in declared design outdoor airflow per area.

In the subset where paired airflow change is statistically detectable, shown in Figure 4, three regularities are visible.

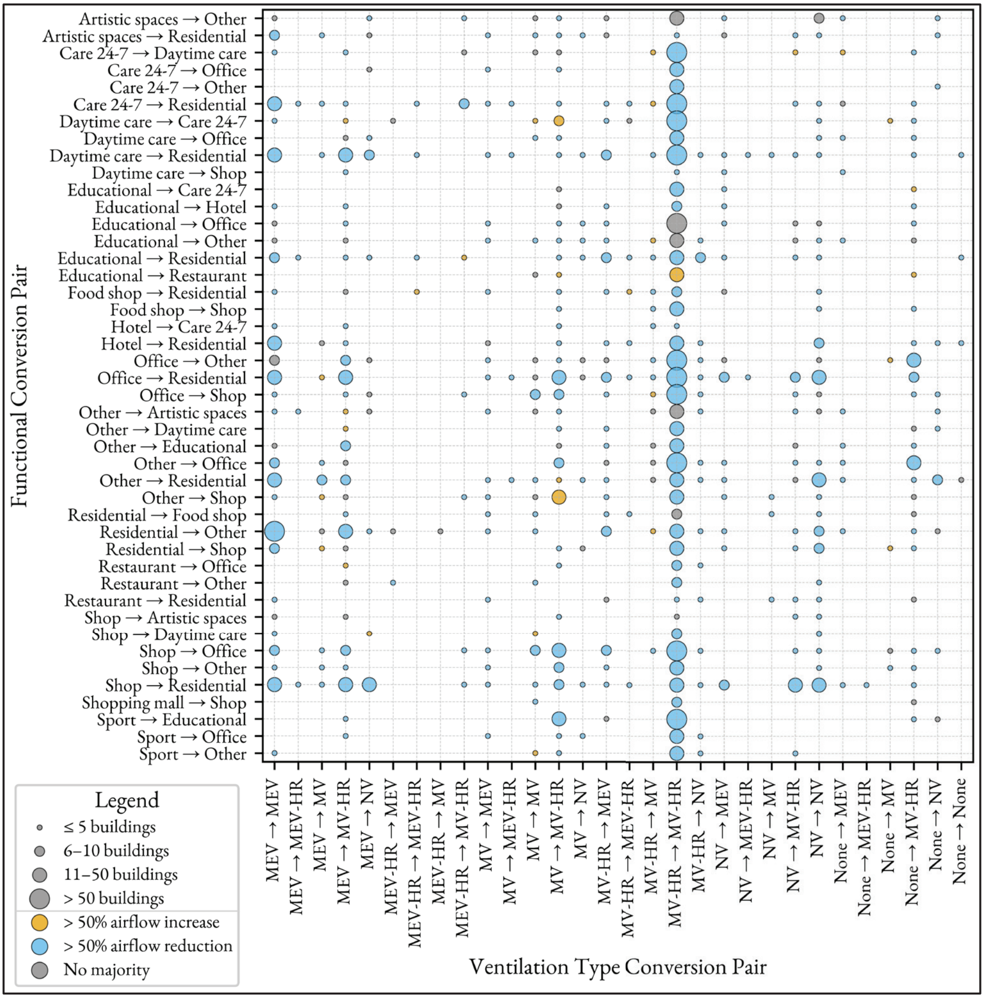

Figure 4. Intersection of donor–to–target pathway with ventilation-type transition for pairs with statistically significant change in design outdoor-airflow; columns show ventilation conversion pairs, rows show functional conversion pairs; the bubble size visualises the number of buildings; colour shows the majority direction of airflow change (reduction/increase/no majority).

Retention of MV-HR dominates across many high-throughput pathways, with large bubbles aligning with office–to–residential, shop–to–office, shop–to–residential, and care 24-7–to–daytime care exchanges, among other recurrent flows. Within these groups, the prevailing classification is a declared reduction in outdoor air provision, meaning that more than half of the buildings in each grouped pathway report lower declared design airflow after conversion. Mechanical exhaust-only appears mainly through MEV–to–MEV for pathways that end in residential use; these points are smaller than the MV-HR cluster and again tend to be reduction-shaded in the detectable-change set. Upgrades toward MV-HR from less controlled concepts are present but at lower counts, while NV-related transitions are sparse.

In the complementary subset where paired airflow change is not statistically detectable, the column structure remains centred on MV-HR–to–MV-HR, but the colouration is mixed, as visualised in Figure 5. Many grouped pathways show no clear majority direction in the airflow change. MEV–to–MV-HR appears more often here than in the detectable-change subset, including around flows that originate from residential donors and move into non-residential targets. MEV–to–MEV persists on residential-donor routes, although bubbles are generally smaller than in the detectable-change set. Transitions away from MV-HR are limited in size.

Read by destination, residential areas receive many pathways that sit under MV–HR–to–MV–HR, with a majority showing a detectable reduction, alongside a smaller band of MEV–to–MEV. The office again focuses on MV-HR retention, with scattered MEV–to–MV-HR points suggesting a selective concept tightening for some donors. The other categories are split between MV–HR–to–MV–HR and MEV–to–MEV, with reduction shading being common only in the significant-change plot. Read by the donor, shops moving to an office or a residential cluster under MV-HR retention. Offices that move to residential, educational, or “other” categories undergo the same process. Care donors are present in both MV-HR–to–MV-HR and MEV–to–MEV.

These signals are indicative rather than dispositive. Declared reductions in airflow may not correspond to realised reductions in commissioned airflow because EPC entries may contain default or assumed rather than measured values. Likewise, retention of the dominant system type indicates that the reported concept remains the same, not that the same air-handling units, diffusers, or branches are reused. Within these constraints, the combined pattern is still operationally relevant: if the dominant concept is typically retained and declared airflow tends to reduce where change is detectable, then reuse or partial reuse of existing ventilation infrastructure could be feasible in a substantial subset of pathways, subject to as-found hygiene, leakage, acoustic, and commissioning constraints. Where airflow changes are not detectable, the intersections still show widespread concept retention; however, the mixed directions in airflow classification should not be interpreted as evidence of stability in installed flow.

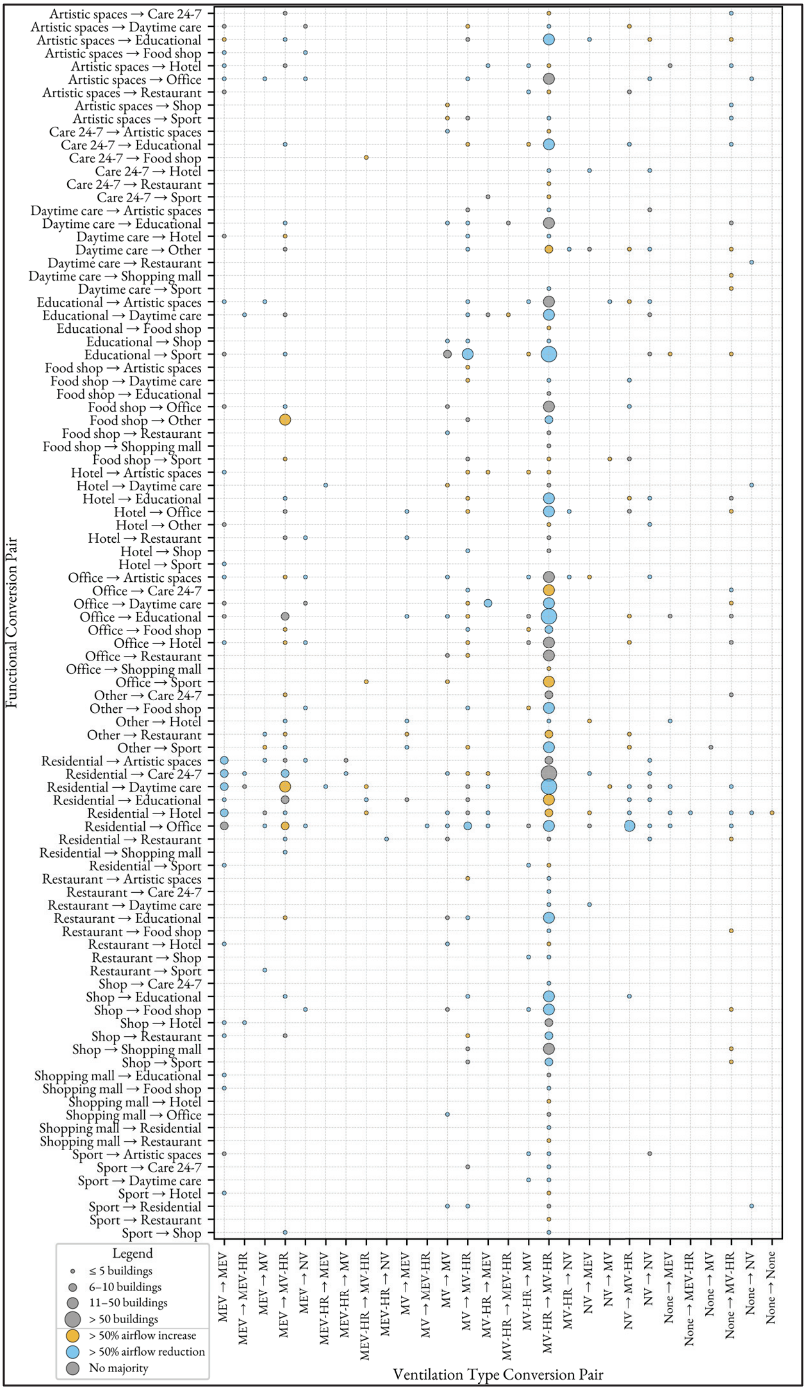

Figure 5. Intersection of donor–to–target pathway with ventilation-type transition for pairs without statistically detectable change in declared design outdoor-airflow; encodings as in Figure 4.

Therefore, RQ1 can be answered as follows: Swedish conversions appear concentrated into a small set of destinations, i.e., residential, office, educational and other, with recurrent flows such as office–to–residential and shop–to–office or to–residential, while donor-normalised propensities show that, conditional on being in smaller donor classes, e.g., hotels, shopping malls, care premises, conversions tend to run towards residential or shop uses. Within these pathways, EPC declarations indicate that the dominant ventilation concept is more often retained than changed. When paired changes in declared airflow rate are statistically significant, reductions predominate, whereas non-significant cases show mixed directions. Interpreted as indicative administrative signals, this pattern suggests that preservation of substantial portions of the ventilation equipment may be most plausible on pathways combining concept retention with reduced declared airflow, particularly office–to–residential, shop–to–office, shop–to–residential, and care 24-7 or daytime-care into residential/other, where AHUs, main ducts and terminal groups could remain in place or be adjusted, subject to hygiene, leakage class, and fire compartmentation relative to new room loads. Where the concept shifts, e.g., MEV–to–MV-HR, reuse may narrow to the selective retention of components rather than whole-system retention.

3.2 Feasibility strand (**RQ2**)

This section outlines the circumstances under which ventilation retention or adaptation may be permissible in principle and acceptable in practice. Two readings are combined: a cross-era regulatory analysis that maps historical building regulations to contemporary ones, and a practitioner's enquiry that compiles the acceptance routines typically sought in projects. Together, they form a feasibility framework designed for use at the concept stage. Full information is provided in the appended **Papers III** and **IV**.

The section is organised accordingly. First, a similarity matrix, as shown in Table 3, compares era–function donors with BBR 29 targets on three outcome descriptors: HC (heating/cooling setpoints), I (mechanical intake/supply), and E (mechanical exhaust/return). Each cell is classified using symbols:

- ≈ similar/planning equivalent to BBR 29,
- > exceeds BBR 29
- < below BBR 29
- ≠ far below BBR 29,
- ? no requirement/unclear.

Table 3. Regulatory similarity matrix. Donor era–function compared to BBR 29 targets (Apartment, Office, School) for heating/cooling setpoints (HC), mechanical intake (I) and exhaust (E). Symbols denote concept-stage planning equivalence.

		BBR 29								
		Apartment			Office			School		
		HC	I	E	HC	I	E	HC	I	E
BBR13-29	Apartment				≈	≠	≠	≈	≠	≠
	Office	≈	>	>				≈	≠	≠
	School	≈	>	>	≈	>	>			
BBR1-12	Apartment	≈	≈	≈	≈	≠	≠	≈	≠	≠
	Office	≈	≈	≈	≈	<	<	≈	≠	≠
	School	≈	>	>	≈	>	>	≈	<	<
NR1	Apartment	≈	>	>	≈	≠	≠	≈	≠	≠
	Office	≈	>	>	≈	<	<	≈	≠	≠
	School	≈	>	>	≈	>	>	≈	<	<
SBN75, 80	Apartment	≈	≈	≈	≈	≠	≠	≈	≠	≠
	Office	≈	≈	≈	≈	≠	≠	≈	≠	≠
	School	≈	>	>	≈	>	>	≈	<	<
SBN67	Apartment	>	≈	≈	?	≠	≠	>	≠	≠
	Office	?	≈	≈	?	≠	≠	?	≠	≠
	School	>	>	>	?	>	>	>	≠	≠
BABS 60	Apartment	?	?	≈	?	?	≈	?	≠	≠
	Office	?	≈	>	?	≈	≈	?	≠	≠
	School	?	?	>	?	?	≈	?	≠	≠
BABS 46,50	Apartment	?	?	>	?	?	≈	?	?	≠
	Office	?	?	≈	?	?	≠	?	?	≠
	School	?	?	>	?	?	>	?	?	≠

In terms of outcomes, heating and cooling setpoints converge after 1976. From SBN 75 onwards, apartments, offices, and schools are specified to be maintained at approximately 18–20 °C with central heating. Therefore, donor–target comparisons on heating and cooling generally yield similar results for post-1976 stock. SBN 67's 20 °C with central heating is treated similarly for screening purposes. Pre-1968 building codes lack explicit heating and cooling prescriptions for the three reference building functions.

For intake and exhaust ventilation, systematic differences appear by function. When donor offices are compared to the BBR 29 office, most historical eras are classified as being below or substantially different, reflecting tightened contemporary office minima. The same donors, compared to the BBR 29 apartment, frequently classify similar in ventilation requirements or exceed them. Donor schools are typically substantially different from the BBR 29 school because current school minima are high; however, several school eras classify similar or exceed the target for apartments (and, in some eras, offices). Donor apartments are generally similar within their own class, but are substantially different from the BBR 29 office/school, implying that a major intervention would be required. Read across the inserted table, three tendencies emerge: office–to–apartment often aligns with intake and exhaust ventilation; school–to–apartment or school–to–office may align depending on the era; apartment–to–office/school generally requires an increase in airflow.

Permissibility cues outside numeric minima also condition reuse routes. Air mixing is allowed under conditions in SBN 67 (preheating with odour/pollutant control), broadened in SBN 75/80 (including toilet air with low-quality air fraction ≤ 1:15), prohibited in high-quality air zones from NR1 through BBR 12, and re-allowed in BBR 13 provided mixed air returns to its premise of origin with odour/pollutant spread prevented. Shared ducts between apartments are permitted in early BABS periods for mechanical systems (not for natural ventilation), with later codes tightening segregation for hazardous or specialised occupancies. These lineage features do not prescribe a system concept; they indicate arrangements an approval authority might accept if outcomes are met.

Read as a permission map, the regulatory evidence suggests the following project-facing placements. Post-1968 office–to–apartment pairs often read similarly or exceed intake and exhaust rates, and similarly on heating/cooling setpoints, so concept retention could be arguable in principle, subject to spatial fit and later acceptance checks. School–to–apartmen or school–to–office may be arguable if the donor era is comparable or exceeds the target minimum; apartment–to–office/school would typically require uplift. Donors from before 1968 often exhibit no requirements or unclear baselines and may require additional investigation before any retention claim becomes credible.

Practitioner responses refine the permission map by indicating what may be reusable in practice, which proofs are ordinarily sought, and who is expected to carry a reuse claim. Components judged most suitable for reuse are shown in Figure 6 and anchor a consistent message in the testimony: respondents repeatedly prioritise air-side infrastructure.

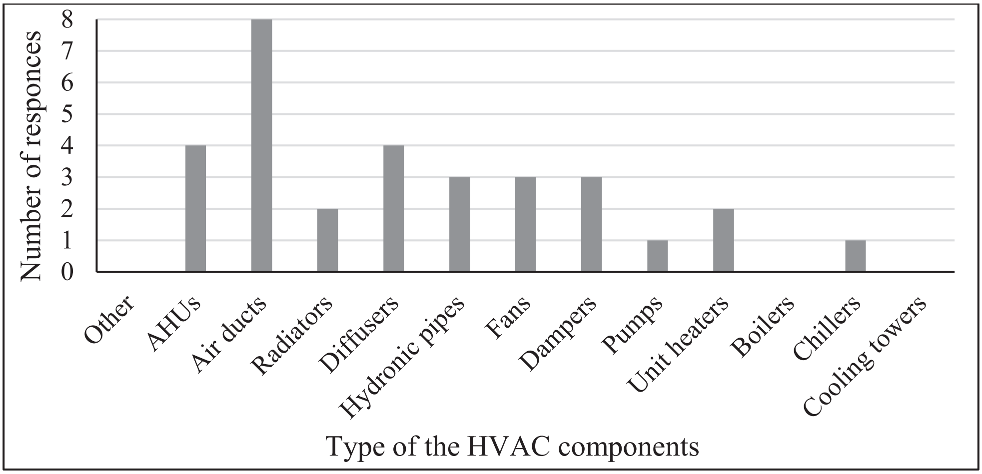

Figure 6. Reported suitability for reuse by HVAC component from survey respondents, counts per option.

One interviewee states, "*Air ducts are the most ideal. They are simple in design and take up the majority of space in HVAC designs.*" Another emphasises cleanliness pathways, "*Air ducts, specifically supply air ducts, as they tend to be cleaner.*" A building-side perspective aligns, "*Ducts, AHUS, Radiators. Not pipes because there could be a risk of rust and corrosion.*" Scope across assemblies is also raised, "*Essentially everything. From our company, it would be diffusers and AHUs… An AHU is a large component that can be refurbished by replacing fans and other electronic components.*"

Caution centres on moving parts and water-filled items, which several respondents describe as weak candidates for reuse: "*All moving parts, motors etc. will have a loss in effectivity after a while, all water connected products might have a corrosion problem. Who shall take the guarantee?*" and "*Electronic equipment, pumps and fans, would make no sense because the efficiencies could deteriorate over time.*" These views are consistent with the regulatory reading: where outcome minima can be met, retention may be argued in principle for ductwork and AHU shells, while items with wear, corrosion risk, or rapidly evolving efficiency baselines will attract higher scrutiny.

Acceptance is framed as conditional on simple, verifiable checks coupled with documentation. One interviewee summarises minimum assurance: "*The quality* *assurance would consist of cleaning and checking for leakage. Quality check would be a visual inspection.*" Another adds performance and logistics, "*Ensuring airtightness and energy efficiency. Cleaning before reusing and having a facility to store them.*" Liability appears central to owner acceptance: "*Owners are going to need a warranty on reused or refurbished components.*" These proofs map to the similarity matrix: where donor–target outcomes are similar or exceed intake and exhaust, a retained concept may be acceptable if the as-found installation is demonstrably clean, tight, and documented.

Five barriers recur and shape whether an otherwise permissible route will be accepted. Technical performance uncertainty is prominent: "*Reuse is not always allowed due to efficiency requirement updates in applicable codes… It is just more complex to both design for and implement reuse of existing equipment and infrastructure,*" and "*I would say that the option of reuse is most often erased when there is some uncertainty regarding the lowering of energy use or other type of performance.*" Environmental concerns focus on possible contamination and insulation, e.g., "*Toxic materials in HVAC are a big no. If such are detected, it is automatically impossible,*" and "*Old ducts from the 70s-80s have glass wool insulation which at the time had toxic materials in them.*" Legislation is described as both barrier and enabler, "*One of the biggest barriers that we have now is in reality we cannot really reuse. Because it really does not comply with the current building regulations and needs to be solved,*" alongside the warranty gap, "*Something I want to push is the warranty period on the product. That's a very big disadvantage and something our industry needs to sort out before companies feel safe to make reuse a standard.*" Economics and logistics appear together in many accounts: "*the cost of reuse, including the cost of storage, transportation, disassembling, and cleaning, could be roughly twice the cost of buying new,*" and, on handling, "*Yes, but the ducts would require large amounts of space for storage and transporting them could also pose a challenge,*" complemented by, "*The parts needs to be dismantled carefully, then stored somewhere (which costs money), and then be transported back and forth.*"

Responsibility focuses on planning competence and client intent, with regulation viewed as an enabling condition rather than the sole driver. This distribution is illustrated in Figure 7. One interviewee notes, "*It would start with good planning, i.e. the most important thing. That would be the mechanical engineers.*" Parallel signals are requested from policy and clients: "*Government regulations and demand from building owners would have to happen simultaneously.*" The market layer is explicit: "*A new business model, and new businesses in general, are needed. Incentives need to be established, primarily by the government, to create a market,*" and a project-delivery view compresses the allocation of influence: "*Money is talking, and laws are power.*"

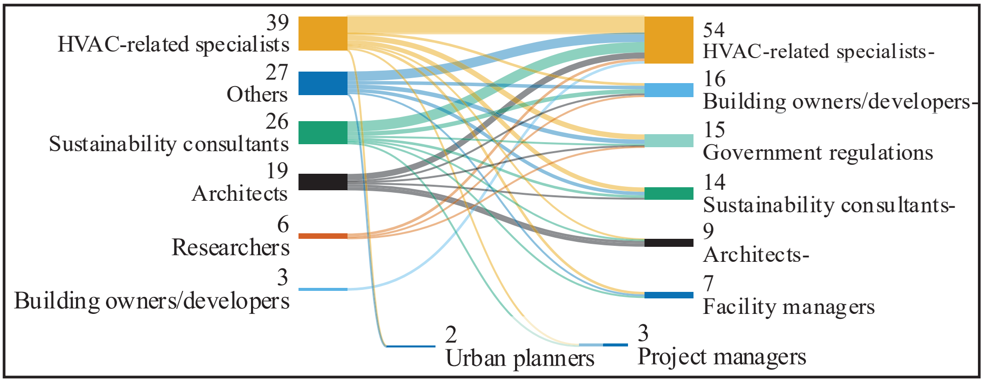

Figure 7. Parties identified by respondents as carrying primary responsibility for implementing and warranting HVAC reuse, counts per option. Left nodes group respondents by role. Right nodes list the party nominated as responsible for implementation. Link width is proportional to the number of nominations.

There is also convergence on where to begin and how to scope practice. One interviewee proposes, "*It is better to focus first on only residential and office buildings in the beginning since it is a new area,*" which aligns with the stock-scale pathways and the regulatory matrix, where office-to-apartment buildings often compare similarly or exceed one another in intake and exhaust airflow. Existing practice is reported for air-side items where condition allows: "*The reuse of HVAC components is already practised to some extent in my work. Some examples are ducts, dampers and silencers. Things can be reused as long as they have kept their performance level, and if it is not too hard to relocate or reuse from a practical standpoint.*" Two modes of implementation are repeatedly distinguished and map to different assurance sets: "*There are two types of reuse: (1) fixed reuse – keeping everything in place, no cleaning or leakage check. (2) demount reuse – disassemble, clean, and reconfigure for the new design needs.*" The first aligns with cases where the dominant concept is retained and declared airflow is reduced; the second requires storage, transport, and refurbishment capacity, as well as checks against contemporary minimums.

Respondents also describe an enabling layer that could reduce uncertainty. Design-for-disassembly and explicit reuse instructions are requested: "*You need to design for disassembly and choose products with high quality and where the manufacturer can guarantee long-term commitment,*" and "*All components need a reuse instruction. The design has to follow a reuse- guideline, that give clear rules about the installation, labelling, mounting and reuse instruction (what to clean, what to check, etc).*" A supplier-side role is envisaged for refurbishment and storage, with a clear performance proposition, "*the solution needs to be easy, and it needs to be better than just using recycled steel.*"

Read against the regulatory similarity map, these testimonies indicate that air-side retention may be acceptable when donor–target outcomes are similar or when the donor airflow exceeds the target airflow, provided the dominant concept remains the same, and when cleanliness, leakage, condition, and provenance can be demonstrated with warranty. Where donor outcomes are below or materially different, acceptance could still be considered for demount reuse if refurbishment improves performance and if hazardous-substance screening, documentation, and cost allocation are explicitly addressed. This placement operationalises the feasibility envelope for the planning artefact that follows.

Therefore, RQ2 can be answered as follows: under Swedish rules, retention or adaptation of ventilation may be permissible in principle where donor–target outcome requirements align on heating/cooling setpoints and on outdoor-air provision, and acceptable in practice when simple, verifiable proofs of condition and provenance are supplied. Outcome alignment is most evident post-1976, when apartments, offices, and schools converge on temperatures of 18 °C–20 °C with central heating, and when office–to–apartment, school–to–apartment, and school–to–office pairings compare similarly or exceed contemporary intake/exhaust minimums. Earlier frames contain allowances that could support retention if outcomes are met, including conditional air-mixing and shared-duct arrangements. In contrast, pre-1968 donors often lack clear baselines and may require reconstruction. Acceptance in projects appears to hinge on demonstrable cleanliness, airtightness/leakage, as well as documentation with a warranty. Moving parts and water-filled items require caution, while air-side infrastructure and AHUs are considered to be stronger candidates. Economic and logistical frictions, such as disassembly time, storage and transportation, refurbishment effort, as well as hazardous substance screening and responsibility allocation, may prevent reuse in the absence of an explicit business model and client intent. Two implementation modes are distinguished: fixed reuse in place and demount-and-refurbish with testing; each implies different proofs and costs.

Read together, the stock-scale signals from RQ1 and the feasibility readings for RQ2 are mutually reinforcing. Pathways that dominate the conversion backbone, i.e., office–to–residential, shop–to–office and shop–to–residential, and care–to–residential, are also those in which the dominant ventilation concept is commonly retained and declared outdoor-air design tends to reduce, conditions that the regulatory similarity map suggests could meet contemporary apartment or office minima without wholesale system replacement. Practitioner evidence then supplies the acceptance steps, i.e., cleanliness, leakage, provenance and warranty, that translate these permissible matches into workable routes, while also explaining why demount-and-refurbish will require storage, testing and clearer responsibility. This alignment suggests that ventilation reuse may be credible initially on office–to–residential and selected retail-linked pathways, and it motivates the design-science emphasis on diffuser-aligned planning and low-intervention scenarios in the next strand.

3.3 Design-science strand (**RQ3**)

This final part of the results synthesises the design-science outputs into a single sequence that treats ventilation as the binding service in conversion. The two case applications are used to assemble a coordinated procedure: an early functional-programme–layout screen to judge whether the target function can plausibly be accommodated within the donor's existing functional divisions and circulation structure; where that screen is passed, a diffuser-aligned planning step that adjusts the spatial arrangement of high-demand rooms to existing supply terminals and duct clusters, to limit rerouting and additional duct length; and a comparative appraisal of the resulting intervention set for embodied greenhouse gas emissions and construction-phase costs. Read together, these steps constitute a ventilation-aligned low-intervention design (VALID) sequence for concept-stage work. The cases did not exercise VALID end-to-end; rather, they supply the screened inputs and the diffuser-aligned and appraisal components from which the sequence is assembled. Full case-specific results and diagrams are reported in the appended **Papers V** and **VI**.

Functional-division matching, which underpins the functional-programme layout screen, is illustrated in Figure 8. Circles denote functional divisions, e.g., living units, shared spaces, staff and service zones; circle size approximates relative area; arrows indicate required direct adjacencies. Donor and target functional programmes are represented as clustered arrangements of such divisions, so that division counts, indicative areas, and adjacency structure can be compared without specifying a detailed room layout. The screen is constructed at the level of functional divisions and their adjacencies, rather than at the level of isolated rooms. Donor and target programmes are first decomposed into operationally linked clusters and adjacency rules; these are then overlaid to test whether the donor's existing internal partitioning and circulation (walls, cores, and main routes) can accommodate the number, size, and adjacency requirements of the target divisions without extensive reconfiguration of the spatial structure.

In the first case, a pre-school building was examined as a potential facility for elderly care. In the case context, stakeholders indicated that an elderly-care facility would need approximately 50 living units to be economically viable, given the staffing and operating-cost structures; a much smaller number of units would not justify conversion. The functional-division overlay indicated that the existing building could accommodate approximately 10 living units without major modifications to corridors and support spaces. Moreover, the adjacency graph for the full elderly-care programme could not be embedded in the donor layout without substantial rearrangement of divisions and circulation, because critical adjacencies between care rooms, shared rooms, and staff/service spaces could not be met simultaneously. Under the proposed screen, this donor–target pair is therefore judged unsuited at the division level: progressing into detailed design would likely trigger extensive re-partitioning, with knock-on implications for services that the existing geometry is poorly positioned to support. Where partial alignment exists, the same representation can identify reversible moves, such as alternative placements of shared rooms to match existing clusters, that preserve donor flexibility if functional requirements change.

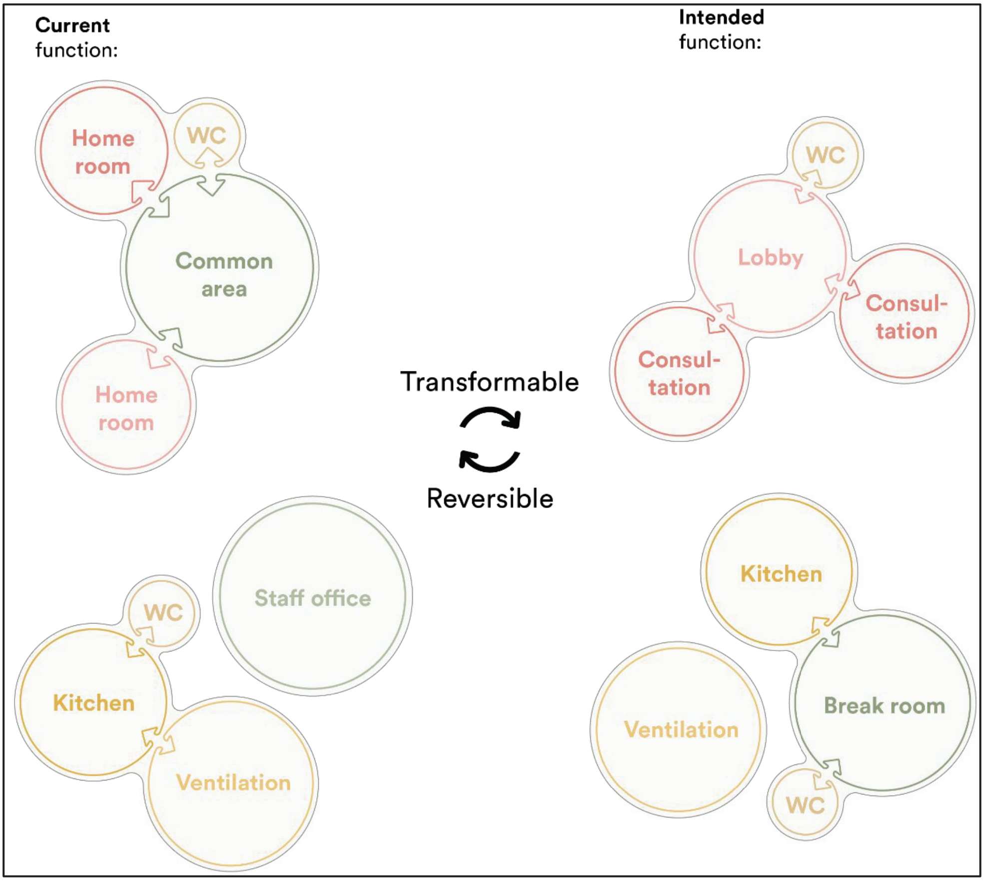

Figure 8. Functional-division matching of donor and target functional programmes. Circles denote functional divisions; circle size approximates relative area; arrows indicate required direct adjacencies. The clustered arrangements depict donor and target configurations used to assess alignment in division counts, sizes and adjacency structure.

Where the screen indicates that donor and target are compatible at the division level, the planning move treats the existing ventilation supply as fixed and aligns high-demand rooms to existing diffusers and ducts. The Malmö office-to-residential case operationalised this by treating the office air-handling units and supply distribution as anchors and designing the apartment layout around the as-found terminals; exhaust was provided anew due to contamination risk and hygiene requirements. Under these constraints, 92.25% of the office duct network was retained, and 7.75% was removed due to unavoidable conflicts. This arrangement yields an intervention set that is spatially feasible and bounded: local adjustments to branches and terminals occur, but full rerouting of ventilation and the creation of new shafts are avoided.

Absolute embodied greenhouse-gas emissions are shown in Figure 9, and construction-phase costs are presented in Figure 10. Consequences were assessed comparatively as a product- and construction-stage evaluation with defined scope limits. The baseline scenario comprised full replacement of the duct system. Two reuse scenarios were compared with the baseline: fixed-position reuse in place with minor adjustments, and disassembly–reinstallation in which ducts were removed, inspected, stored, and reinstated. The assessment covered A1–A5, included disassembly and reinstallation under B2, and included C2–C3. Cleaning, reusability testing, and operational energy were not included because standardised data were not available at the concept stage. Under this scope, the absolute disparities were substantial. The baseline replacement registered 10 887 kg CO_2 eq. Fixed-position reuse registered 21 kg CO_2 eq., while disassembly–reinstallation registered 59 kg CO_2 eq. The corresponding absolute reductions relative to baseline were therefore 10 866 kg CO_2 eq. for reuse in place and 10 828 kg CO_2 eq. for disassembly–reinstallation.

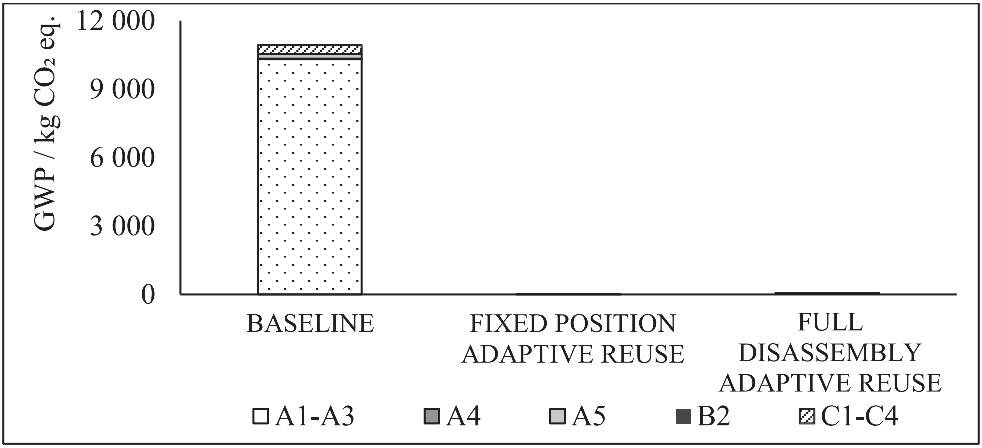

Figure 9. Absolute embodied greenhouse-gas emissions (kg CO_2 eq.) for ventilation interventions: baseline full replacement, reuse in place with minor adjustments, and disassembly–reinstallation with inspection and storage. Assessment scope: A1–A5 with B2 (disassembly/reinstallation) and C2–C3; cleaning, reusability testing and operational energy excluded.

Regarding costs, the baseline replacement was estimated at 562 500 SEK. Fixed-position reuse incurred approximately 5 100 SEK for limited removals and repositioning, while disassembly–reinstallation was estimated at 273 000 SEK, covering dismantling, inspection, and reinstallation under the stated assumptions. These values describe immediate construction-phase expenditures and exclude storage, cleaning, and longer-term maintenance.

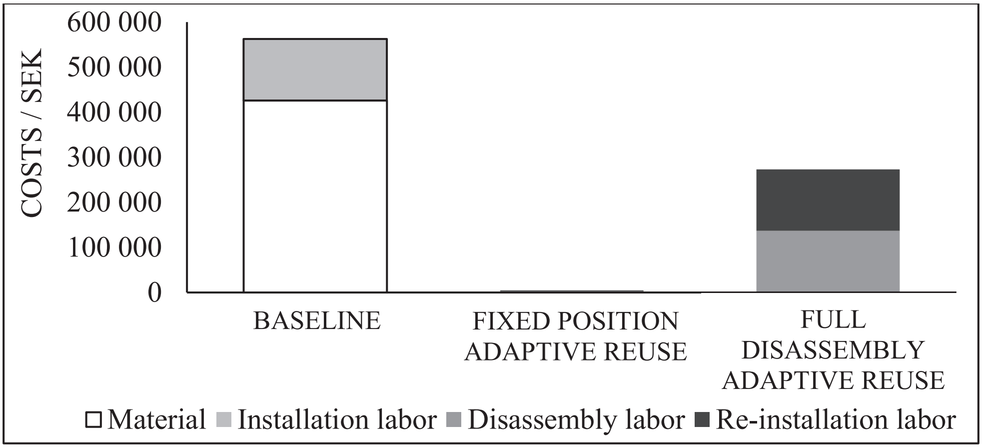

Figure 10. Construction-phase costs (SEK) for ventilation interventions: baseline full replacement, reuse in place with minor adjustments, and disassembly–reinstallation with inspection. Costing scope: immediate construction-phase expenditures, including disassembly/reinstallation and handling where applicable; storage, cleaning, reusability testing, and long-term maintenance excluded.

Synthesised across the two strands, these results support a three-step VALID sequence for concept-stage decision-making. First, a donor–target pair is screened at the level of functional divisions. This yields a structured feasibility judgement grounded in the number and size of divisions and their adjacency structure. In the workshop case, the screen indicated that roughly 50 care units would be required for viability, while only about 10 could be realised within the donor without major reconfiguration, and it identified the adjacency conflicts that would require new shafts and branch runs. In an industry setting, this step may prevent a project from advancing where the geometry is unlikely to support the brief without invasive work, and it may indicate where brief adjustments would create a compatible mapping. Second, where the screen returns a plausible mapping, room placement is revised to accommodate existing supply terminals and ducts. This diffuser-aligned step does not assume that all system elements are reusable; rather, it fixes the elements most difficult to relocate and arranges rooms around those elements so that redistribution is minimised. The Malmö case demonstrates that this move can retain the majority of the supply ventilation while meeting hygiene constraints by introducing new exhaust, thereby limiting the intervention. The result is a set of concrete quantities: which branches are retained, which are removed, and which terminals are added or relocated.

Third, the resulting intervention set is appraised in absolute terms for embodied emissions and construction-phase costs under a transparent scope. In the Malmö case, the absolute differences relative to baseline replacement were of the order of ten tonnes of CO_2 eq. avoided and several hundred thousand SEK avoided, conditional on scope and exclusions. Reporting absolute values rather than only proportional changes is useful for procurement and early budgeting. The declared scope allows exclusions to be addressed later if data becomes available. This step treats the early decision as a comparative choice among interventions of bounded extent rather than an optimisation of whole-building operation under uncertain loads.

In response to RQ3, the two studies indicate that an adaptive reuse method could be designed to retain existing ventilation systems at the concept stage. The resulting sequence, VALID, couples a functional programme layout screen at the level of functional divisions with diffuser-aligned placement of rooms to existing supply terminals and trunks, followed by comparative appraisal of the bounded intervention. Applied to an office-to-residential case, this sequence retained 92.25% of the existing duct network and avoided wholesale rerouting. At the same time, the comparative assessment, scoped to the product and construction stages with declared exclusions, yielded absolute embodied carbon outcomes of 21 kg CO_2 eq. – 59 kg CO_2 eq. for the reuse scenarios against 10 887 kg CO_2 eq. for full replacement and construction-phase costs of approximately 5 100 SEK – 273 000 SEK against 562 500 SEK for replacement. These values are case- and scope-dependent; nevertheless, they show that, where the screen is passed, and hygiene, leakage, and documentation constraints are met, the supply-side distribution can often be preserved. The material and cost consequences of the air-side intervention can fall by orders of magnitude. The pre-screen also delimits where reuse is unlikely to be credible, as illustrated by the pre-school-to-elderly-care workshop, where division counts, and adjacencies could not be reconciled without major reconfiguration.

The VALID sequence is grounded in and supported by the earlier strands. Stock-scale evidence showed that conversions concentrate on pathways such as office-to-residential and shop-to-office/shop-to-residential, that the dominant ventilation concept is commonly retained, and that declared outdoor-air design tends to reduce where change is detectable. These regularities motivated a supply-side anchoring rule and the focus on pathways where reuse might plausibly occur. The feasibility strand mapped legacy provisions to contemporary outcomes and, together with practitioner testimony, identified acceptance conditions centred on cleanliness, airtightness and provenance, with air-side infrastructure seen as the most reusable layer. These conditions influenced the design choices in the case application: the supply was retained in place, new exhaust was installed where hygiene required it, and consequence reporting was confined to the product and construction stages, with explicit exclusions. In turn, the case-level results support the earlier strands by demonstrating that, on a pathway highlighted by RQ1 and deemed permissible and acceptable by RQ2, high distribution retention rates and large absolute differences in A1–A5 impacts, as well as construction-phase costs, could follow. The negative screen in the workshop case is also consistent with the feasibility envelope, suggesting that the method may reject donor–target pairs in which spatial compatibility and outcome minima are unlikely to be met without invasive redistribution.

4. Discussion

This section discusses the results at the thesis level. The intention is to interpret the combined evidence across strands within the stated pragmatist, critical-realist and abductive stance, to place the findings in Swedish practice and regulation, and to indicate where the research could reduce uncertainty in concept-stage decisions.

A general limitation concerns the measurement system available for national-scale work on existing buildings. Administrative EPC records were not designed for research; ventilation fields may be coarse or defaulted; timestamps and commissioning states are not versioned, that is, changes over time are not recorded as distinct, auditable states; and ventilation concepts are reported at the building level without zone area shares. These features introduce errors that cannot be easily eliminated and may interact with selection into conversion and local reporting practices. Even with building-level pairing, plausibility filters, and distribution-aware tests, residual bias may remain, including ambiguity between planned and commissioned airflow and uneven portfolio coverage. Comparable gaps occur in permit systems and facility logs, where ventilation concept, leakage/cleanliness tests, and acceptance proofs are rarely recorded in machine-readable, versioned form. In Sweden, mandatory ventilation inspections (OVK) provide a partial parallel record; however, systematic cross-evaluation between these inspection reports and EPC data has not yet been implemented on a large scale. Consequently, stock signals can be described and compared, but should not be treated as measured performance. A constructive path could include persistent building identifiers across cadastral, EPC, permit, and inspection systems; event-level timestamps and versioned records; and a compact ventilation scheme (dominant concept with zone area shares; design outdoor-air rates by zone; commissioning status; most recent leakage/cleanliness results with dates; AHU state and major refurbishments; binary flags for contaminant findings and remediation). Attachments for certificates could support acceptance and warranty. In parallel, purposive audit studies linking declarations to site verifications and record-linkage procedures that explicitly account for measurement error and mismatch risk in summary estimates could enhance the conclusions that can be drawn from current registers while their underlying structures remain unchanged.

Within these bounds, the stock-scale signals and the feasibility framework are consistent with a plausible delivery behaviour. Administrative declarations tend to show retention of the dominant ventilation concept across conversions and a predominance of declared reductions in design outdoor airflow where paired changes are detectable. This may reflect a preference for low-disruption routes when projects face time and budget constraints, and approvals hinge on outcomes rather than prescribed concepts. The declarations do not demonstrate in-use flow or component retention; defaults and approximations remain possible. The pattern nevertheless aligns with acceptance accounts that picture ducts and AHUs as the comparatively reusable layer, with moving parts and water-side items attracting more scrutiny. On that reading, a planning move that fixes the ventilation supply and adjusts the functional-programme layout accordingly is a reasonable response to both the stock signals and the feasibility framework.

The operative barrier appears to be uncertainty rather than doctrine. The analysis of building codes indicates that Swedish performance-based regulation may permit retention when outcomes can be demonstrated. The interview and questionnaire materials indicate that reuse is frequently deterred by uncertainty about cleanliness, leakage, the equipment's history and documentation, and liability, rather than by explicit prohibitions. The contribution of this thesis may therefore be characterised as uncertainty reduction through structured, early decisions. VALID screens spatial compatibility at the level of functional divisions before commitments are made, aligns room placement with the most embedded supply elements that pass the screen, and reports bounded consequence ranges within a declared scope. This converts a general possibility into specific, checkable propositions that can be tested against hygiene and leakage proofs. It also returns a reasoned negative when division-level mismatches and adjacency conflicts indicate that preserving the existing supply network would require relocating shafts, replacing main ducts, and reconfiguring the entire ventilation system, i.e., introducing interventions comparable in extent to installing a new ventilation system.

Socio-economic implications of these adaptive reuse patterns should be drawn cautiously. Total renovations that replace services and the envelope may lead to or coincide with displacement pressures in constrained markets [66]. In contrast, low-intervention conversions that preserve embedded infrastructure could add units with lower immediate construction costs and lower product- and construction-stage impacts. The research design does not estimate social outcomes. It does, however, provide a decision route that could enable lower-capital additions, provided target functional programmes can be mapped to existing distributions and hygiene, acoustic, and acceptance checks are met. This is consistent with the observation that, in many contexts, the constraint is a shortage of timely, affordable housing rather than an absolute shortage of floor area [67,68]. Minimal-intervention conversion may be one mechanism to address this problem in specific pathways.

Reversibility and circularity provide a longer-horizon rationale for the proposed sequence. Demographic and market demands are uncertain in the long term, with potential rebalancing among schools, offices, elderly care premises, and housing. Recurrent demolition and replacement are unlikely to be environmentally or fiscally robust under such variability. Preserving both the air distribution system and the building envelope could enable reverse conversions and circularity by allowing future changes of use to be delivered primarily through partition changes aligned with existing diffusers and ducts, rather than through repeated strip-outs and full system replacement. VALID is consistent with this orientation because it reasons about functional programmes as sets of functional divisions, rather than fixed typologies, and preserves embedded elements that are costly to relocate. Design-for-disassembly and explicit reuse instructions for air-side elements could further reduce transaction costs in subsequent adaptations.

A related, largely unexplored aspect concerns the cultural-heritage value of building services. In older, culturally protected buildings, historic ventilation and heating components may form part of the site's technological and social history, alongside envelope and structural features. Preserving selected diffusers, fans, or pipework as visible artefacts, even when new systems are installed, could support interpretation of technological evolution and provide educational value. Future work might therefore examine when and how representative elements of historic services can be retained or integrated into adaptive reuse projects, without compromising hygiene, safety, and performance requirements, particularly in buildings already subject to heritage protection.

Ventilation’s position as a binding service follows from its multi-scale structure. Room-level requirements specify locations and magnitudes for outdoor-air provision, yet plants and many distribution elements operate at the building scale and are embedded in shafts, risers, and ceilings. Electrical and many water-side systems can often be recircuited or re-zoned with fewer invasive dependencies; ventilation generally cannot. The high cost and disruption of replacing vertical shafts, main ducts, and central units, rather than a preference for ventilation per se, may therefore constrain concept-stage options. Replacing these elements may entail intrusive demolition, penetrations through compartmentation and fire separations, ceiling reconstruction, and extensive recommissioning. At the concept stage, such works could dominate both cost and time risks. The Malmö case suggests that a planning move which fixes the existing ventilation supply and tests functional-programme compatibility against it may limit interventions in a manner that is advantageous for cost and embodied emissions at the conceptual stage.

A short extension beyond ventilation is warranted, but should remain conditional. The stock strand indicates that non-converted buildings tend to undergo renovation and that reported heating energy use per area reduces over time. This is consistent with the national and European emphasis on efficiency. It could suggest that parts of heating systems may be retained after envelope upgrades, provided the minimum requirements are still met and the systems are in good condition and documented for continued use. A countervailing constraint is the transition to low-temperature operation. Delivering comfort at lower supply temperatures generally requires larger radiators or higher volumetric flow rates, which may render old high-temperature systems, pumps, and terminal capacities insufficient without modification, unless space-heating demand is reduced through envelope improvements and, where applicable, heat recovery. In such cases, the existing piping and terminals might suffice at reduced supply temperatures. The reuse of heating distribution is therefore possible but contingent; hydraulic verification under the intended supply temperatures would be required, and in some cases, reuse may not be feasible even if the loads are reduced. The general principle remains to retain where outcomes can be met with credible assurance and to replace where they cannot, with explicit reasoning.

Indoor air quality and legacy pollutants remain substantive uncertainties. Asbestos, radon, and certain historic insulation binders, together with hygiene and duct leakage, may constrain reuse in ways that declarations cannot reveal. Project-credible protocols for screening, cleaning, refurbishment, and certification of ventilation elements in situ are not yet routine, and warranty structures remain limited. Without such protocols, acceptance risks remain high and the default to replacement persists. The economic and environmental thresholds at which cleaning and certification outperform replacement, or at which selective demolition becomes justified, also require better specification. While comparative appraisals confined to product-and-construction stages indicate large absolute differences under reuse scenarios in one case, whether those differences persist when cleaning, testing, and maintenance are included remains uncertain, and this requires applied studies that explicitly account for those activities.

The behavioural interpretation that concept retention and declared airflow reductions reflect a tendency towards the path of least resistance should be treated as conjecture. Alternative mechanisms include selective reporting, timing of declarations relative to commissioning, and the selection of donors for conversion with favourable plant and shaft configurations. Disentangling these possibilities would require improved administrative fields and purposive project-level audits. Pending such evidence, stock signals are best used to prioritise feasibility screening and to prompt verification rather than to infer in-use performance.

Two near-term research lines could extend the present work within the adopted stance. First, end-to-end applications of VALID on live projects, including cases that fail at screening, with documentation of acceptance proofs, hygiene and leakage results, transaction costs, and product- and construction-stage impacts. This could move from plausible logic to observed practice. Second, in-situ performance characterisation of reused air-side components and systems: stability of leakage class after cleaning, cleanliness outcomes by method, achievable fan duties and controllability after refurbishment, and any systematic efficiency drift.

Complementary work could include the development of contaminant screening and cleaning protocols with explicit acceptance criteria and warranty structures; incremental improvements to administrative records to capture ventilation concepts, equipment history, and basic commissioning status; bounded examinations of when heating and other services may be retained during low-temperature transitions without compromising outcomes; and, particularly in older or protected buildings, systematic assessment of when historic services should be documented or partially preserved as cultural heritage. Measurement of indoor-environment indicators after low-intervention adaptive reuse would add an occupant-facing dimension to material and cost comparisons.

The thesis-level contribution may be read as reducing early-stage uncertainty and providing a structured method for assessing ventilation reuse under Swedish performance-based regulation. The sequence screens functional-programme–layout compatibility at the division level, aligns room placement to supply-side elements where permissible and acceptable, and reports transparent consequence ranges. This does not resolve all uncertainties; however, it may offer a practicable approach to handling them in concept-stage decisions and provide a basis for applied studies that could strengthen acceptance and performance assurance over time.

5. Conclusions

This thesis examined ventilation in adaptive reuse in Sweden with the aim of establishing a framework for retaining or adapting existing systems and providing structured decision support that may reduce early-stage uncertainty. Three strands were integrated: stock-scale signals reconstructed from paired EPCs; a feasibility reading combining regulatory lineage with practitioner acceptance conditions; and a design-science artefact that screens functional programme–layout compatibility, aligns layouts to existing supply terminals and main ducts, and assesses product- and construction-stage consequences.

At the stock scale (**RQ1**), conversions appear concentrated on a compact set of pathways, notably office-to-residential and retail-linked routes. Within these, administrative declarations more often indicate retention of the dominant ventilation concept than change. Where paired changes in declared design outdoor airflow are statistically detectable, the prevailing direction is a reduction. These are indicative signals rather than metered performance, yet they motivate attention to pathways where ventilation preservation might be plausible under outcome-based regulation.

The feasibility reading (**RQ2**) suggests that Swedish performance-based rules may allow retention where outcomes can be demonstrated. Practitioner perspectives frame acceptance as conditional on verifiable cleanliness, leakage, and documentation, with warranty provisions. They repeatedly identify ductwork and AHUs as comparatively reusable, while moving parts and water-side items attract more caution. Together, these readings provide project-facing permissions and proofs that can be checked at the concept stage.

The design-science strand (**RQ3**) assembles a ventilation-aligned low-intervention design (VALID) sequence: screen the donor–target pair at the level of functional divisions and adjacencies; align room placement to existing supply terminals and main ducts where the screen is passed; and appraise embodied greenhouse-gas emissions and construction-phase costs under a transparent scope. In an office-to-residential case, this approach retained 92.25% of the supply-side distribution in place and, relative to full replacement, yielded large absolute differences in A1–A5 impacts (baseline 10 887 kg CO_2 eq.; reuse scenarios 21 kg CO_2 eq. – 59 kg CO_2 eq.) and immediate construction-phase costs (baseline 562 500 SEK; reuse scenarios ≈5 100 SEK – 273 000 SEK) under the stated exclusions. A workshop screen of a pre–school–to–elderly care case returned a reasoned negative, indicating that reuse is unlikely to be credible without invasive redistribution.

Read together, these strands support the following thesis-level conclusions. First, ventilation is frequently the binding service in conversion because room-level obligations are mediated through building-scale, spatially embedded infrastructure. A planning move that fixes the supply backbone and aligns the functional programme with it is, therefore, a practical response that meets outcomes and hygiene. Second, the primary contribution lies in uncertainty reduction. The work provides:

(i) A stock-scale baseline that constrains priors about where conversions occur and how ventilation descriptors behave.

(ii) A feasibility framework that translates regulation and acceptance routines into permissions and proofs.

(iii) A structured screen–align–appraise method that yields absolute, scope-declared quantities at the concept stage.

Third, the approach may enable lower-capital, lower product- and construction-stage interventions on specific pathways, although social outcomes are not estimated in this work.

Limitations are explicit. EPC variables are administrative declarations and may include default values and calculated, rather than measured values; claims are descriptive and conditional. Consequence appraisals are scoped to the product and construction stages of the air side and exclude cleaning, reusability testing, and operation. The readings are situated in Swedish regulation and practice.

Further work is needed along several lines. First, VALID should be applied end-to-end on live projects, including cases that fail at the screening stage, with systematic documentation of assurance steps, hygiene and leakage results, transaction costs, and impacts on both product and construction stages. Second, the in-situ performance of reused air-side components should be characterised, including the stability of the leakage class after cleaning, cleanliness by method, achievable fan duties, controllability after refurbishment, and any efficiency drift. Third, project-credible protocols for contaminant screening, cleaning, refurbishment, and certification of building services should be developed and tested, with explicit acceptance criteria, warranty structures, and indicative cost ranges. Fourth, administrative records should be improved by using stable building identifiers, versioned entries, and basic ventilation fields that cover the ventilation concept, airflow, equipment history, and commissioning status. Finally, future studies should examine when heating systems can be retained during transitions to low-temperature operation, how cultural heritage values of building services can be integrated into adaptive reuse, and how indoor environment conditions evolve after low-intervention conversions.

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Appended papers

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Building function, ownership, and space heating: Exploring adaptive reuse pathways in Swedish building stock☆

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ABSTRACT

Adaptive reuse, the conversion of existing buildings to new functions, offers a sustainable alternative to demolition and new construction by reducing environmental impact, conserving materials, and minimising costs. This study presents the first large-scale, systematic analysis of adaptive reuse in Sweden, using Energy Performance Certificates (EPCs) from 141 778 buildings issued between 2007 and 2023. EPCs provide measured data on building function, conditioned floor area, construction year, and space heating energy use—a dominant contributor to operational emissions in cold-climate regions. The study identifies common conversion pathways and examines how building characteristics and ownership influence reuse patterns. Conversions were most frequent in buildings sized 1 000–5 000 m^2 and constructed between the 1930s and 1970s. Office–to–residential conversions were most common in absolute terms, but normalised data revealed frequent reuse of care facilities and retail spaces. Ownership analysis showed that corporate and public actors are the primary initiators of reuse, while private and cooperative owners are underrepresented. Energy performance analysis revealed that 82 % of converted buildings were associated with reductions in space heating energy use, and 54 % outperformed their non-converted counterparts. The average reduction for converted buildings was 9.6 kWh/m^2·year, compared to 9.3 kWh/m^2·year for non-converted buildings; office–to–residential conversions achieved mean savings of up to 19 kWh/m^2·year. However, sign tests indicated that statistically significant trends were present in only a subset of conversion pairs, suggesting that the direction of energy use change is not uniformly robust. These differences likely reflect a combination of changes in building use intensity and renovation measures introduced during conversion. The findings demonstrate that adaptive reuse is physically feasible, broadly applicable, and, in some cases, associated with measurable energy efficiency gains. Although national in scope, the methodology is transferable to other regions with structured building energy datasets, and the results are relevant for countries with similar climatic conditions and ageing building stocks. This study provides an empirical basis for cautiously integrating adaptive reuse into energy efficiency policy, housing strategy, and long-term decarbonisation planning.

1. Introduction

The building sector accounts for 30 % of the global final energy use and 26 % of the global environmental impact during both the construction and operational phases [1]. Population growth and urbanisation have created increasing pressure to provide built spaces [2]. Simultaneously, many buildings remain underutilised due to industrial changes and evolving work patterns, particularly in the post-COVID-19 era, leaving a significant portion of the building stock vacant or partially occupied [3–6]. This contrast, between the growing demand for new spaces and widespread vacancy rates, raises concerns about the sustainability of addressing these needs through new construction, which increases energy use and accelerates resource depletion [7,8].

Adaptive reuse, the practice of converting existing buildings for new functions, offers a promising alternative to demolition and new construction. Adaptive reuse could reduce the need for new resource-intensive materials and conserve embodied energy already present in the building stock [9–12]. While adaptive reuse is gaining traction as a

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sustainable strategy, there is a gap in understanding its specific patterns and characteristics. Existing studies primarily focus on individual cases or decision-making techniques, and general data on building functions, sizes, ages, ownership, and energy performance in adaptive reuse projects remains limited [13–18]. One notable exception is a small-scale inventory of approximately 140 adaptive reuse projects, which provided valuable insights into conversions but did not identify broader trends or benchmark reuse projects against non-converted buildings [19]. To the authors' knowledge, no existing studies have systematically investigated adaptive reuse trends at a national scale using consistent building-level data.

This study addresses these gaps by offering the first national quantitative characterisation of adaptive reuse in Sweden, using the dataset covering over 141 000 buildings. It introduces a systematic method for tracking changes in building function using Energy Performance Certificates (EPCs), which are mandatory for most buildings in Sweden and provide detailed information on building function, energy use, and conditioned floor area [20]. Combined with Sweden's well-documented building stock and advanced energy performance regulations, these certificates could serve as a valuable data source for systematically examining adaptive reuse trends [21]. While this study focuses on Sweden, the methodology is transferable to other regions with structured EPC systems or building energy databases. The information regarding function-based conversion trends, ownership influences, and space heating performance offers valuable insight for countries with similar climatic conditions and ageing building stocks.

The following research questions are investigated:

- Which building functions in Sweden are most frequently converted through adaptive reuse?
- What are the typical conditioned floor areas and construction ages of buildings that undergo adaptive reuse?
- Which owners are most prone to initiate an adaptive reuse project?
- How does adaptive reuse affect space heating energy use across different conversions, and which conversions lead to the most substantial changes?

The novelty of this study lies in the structured application of existing national datasets—specifically Energy Performance Certificates (EPCs) and ownership registers—to produce a comprehensive statistical mapping of realised building conversions. The findings extend prior research by revealing national patterns in functional shifts, ownership dynamics, and energy performance outcomes, including comparisons against non-converted buildings. They provide a foundation for designing building-sector decarbonisation policies, including targeted reuse incentives and retrofit strategies that reflect actual patterns in building characteristics, ownership, and energy performance.

2. Methods

This section first describes the nature and purpose of EPCs, then elaborates on the dataset and used research methods. Finally, potential limitations and assumptions are discussed, outlining the sources of error and uncertainties that may affect the study's results.

2.1. EPC data and ownership integration

EPCs in Sweden provide data on a building's energy use and building functions, e.g. schools, offices, residential buildings, etc. These certificates are produced by certified energy experts [20]. They are required for most buildings, with an expiration date of ten years. EPCs include the building's primary function, energy use for space heating, domestic hot water, space cooling, and total conditioned floor area. However, EPC data is reported at the property level, which may encompass multiple buildings [20]. For this study, the property-based EPC data was converted to building-specific data to enable a more accurate analysis of adaptive reuse patterns, following the algorithm elaborated in Section 2.2. Dataset processing.

Several studies have highlighted issues related to the quality and consistency of EPC data [22,23]. Uncertainties in the EPC often arise from the methods used to derive the conditioned floor area and variations in how energy experts assess energy use and building characteristics. These inconsistencies can impact the accuracy of comparative studies and require consideration. Despite these limitations, previous research has successfully employed EPC data to assess building stocks and energy performance across different regions [24,25].

In this study, EPC data is employed to investigate trends in adaptive reuse by analysing the following elements:

- Building function: EPCs categorise buildings by their primary function, such as residential, office, or educational facilities. This categorisation helps to identify which buildings are most frequently repurposed through adaptive reuse.
- Building size: The total conditioned floor area is recorded in the EPCs, providing a basis for understanding the typical sizes of buildings undergoing conversion.
- Year of construction: The EPC data include each building's construction year, enabling an exploration of the age distribution of buildings most likely to undergo adaptive reuse.
- Space heating energy use: EPCs provide information on the measured space heating energy use, which is critical for assessing how adaptive reuse affects energy performance.

While EPCs provide detailed property-specific data, they do not include ownership information. To address this, data from Lantmäteriet, Sweden's national land survey authority [26], was merged with the EPC dataset using a property index linked to the municipality, a common identifier between EPC and the property register. Ownership data, updated with each change in ownership, was used to determine if there is a connection between conversion pathways and ownership, therefore creating a more complete profile of adaptive reuse trends.The selection of these variables was guided by their practical relevance to adaptive reuse processes. Given the descriptive nature of this study and the use of a full national dataset rather than a sample, the analysis focuses on identifying empirical trends rather than conducting formal significance testing.

The dataset used in this study spans from 2007, when Energy Performance Certificates (EPCs) were first introduced, to 2023, encompassing 410 573 declarations over sixteen years. The distribution of EPCs during this period is shown in Fig. 1, with two notable peaks observed. The first peak, between 2008 and 2010, aligns with the introduction of mandatory energy declarations under Swedish law [20], requiring residential buildings to be declared by 2008 and other building functions starting in 2009. The second peak, between 2017 and 2022, coincides with two key factors: the expiration of the initial ten-year declarations and the implementation of updated energy declaration requirements in 2020 [27].

2.2. Dataset processing

The resulting dataset described in Section 2.1 was processed using Jupyter Notebook software. The dataset contained properties with either one EPC, referred to as "Current," or two EPCs, referred to as "Previous" and "Current." For properties with two EPCs, the earlier EPC in chronological order was considered "Previous," while the later EPC was considered "Current." If a property had only one EPC, it was classified as "Current." Due to the relatively recent introduction of EPCs in Sweden, no properties in the dataset contained more than two EPCs. All properties were filtered based on the availability and completeness of their EPCs to ensure consistency and accuracy in the analysis. The filtering process used the following criteria (see Fig. 2 for an overview of this process):

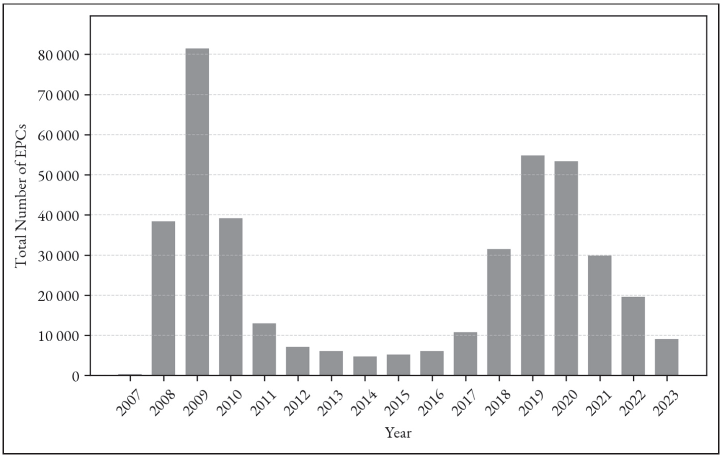

Fig. 1. The annual distribution of EPCs available in the dataset.

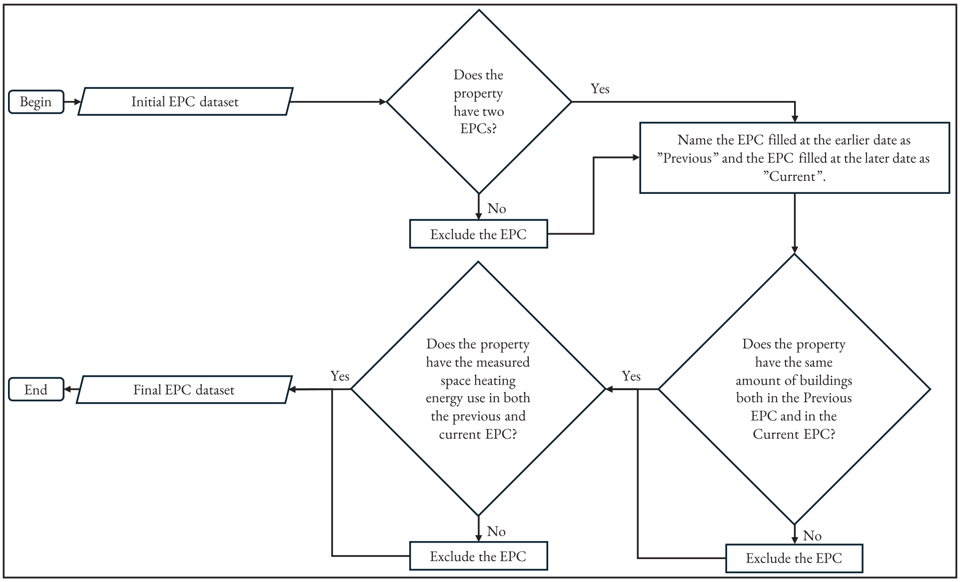

Fig. 2. EPC dataset filtering algorithm.

- **Inclusion of properties with two EPCs**: The analysis focused exclusively on properties with two EPCs. These entries allowed for a comparative evaluation of building characteristics and energy performance changes before and after adaptive reuse. Properties with only one EPC ("Current") were excluded, as they lacked sufficient data to track temporal changes.
- **Exclusion of inconsistent records:** Properties with discrepancies in the number of buildings between the "Previous" and "Current" EPCs were excluded. For example, if a property listed five buildings in the "Previous" EPC but nine in the "Current," such differences could indicate boundary changes or redevelopment activities. These inconsistencies posed challenges in accurately tracking building-specific characteristics over time and were excluded from the analysis.
- **Exclusion of calculated space heating energy use:** EPCs, where the space heating energy use was calculated rather than measured in either the "Previous" or the "Current" dataset, were excluded to maintain consistency. Calculated values could introduce variability not directly tied to building performance, making them unsuitable for a reliable analysis of space heating energy use changes.

After the initial filtering of the dataset, it was necessary to address the fact that EPCs represent properties that may contain multiple buildings. New entries were created for each building within properties that included more than one building to ensure accurate building-level analysis. Data regarding the function (e.g. residential or office), year of construction, number of buildings, ownership, conditioned floor area, and annual space heating energy use were provided at the property level. Properties with only one building were directly included in the final buildings' dataset without modification. Individual building entries were generated for properties containing multiple buildings to ensure proper representation. The number of new entries corresponded to the total number of buildings within the property. These entries were populated following the algorithm outlined in Fig. 3.

Each property in the dataset was categorised based on its primary function, determined by the largest area. For instance, a property with 80 % residential and 20 % shop area was classified as "Residential." While this method ensured consistency in building-level analysis, it introduced some limitations.

In mixed-use properties, the energy use of secondary functions might contribute disproportionately to the total, yet the total space heating energy use was still attributed to the primary function. This categorisation approach was also applied to properties where the largest area function comprised 50 % or less of the total, such as a property with 40 % residential, 30 % shop, and 30 % office areas. Such cases could lead to misinterpretations when analysing results, as the classification may not fully represent the diversity of uses within the property.

This study focused on converted buildings, i.e., buildings whose primary function changed between the two EPCs. However, non-converted buildings were also included where applicable to facilitate comparisons with the general Swedish building stock, helping to identify whether converted buildings exhibit specific characteristics distinct from the broader dataset. Twelve building functions were identified and classified using the original Swedish EPC designations. The additional "Other" category was used for the buildings that did not fit the predefined categories. The summary of these building functions are provided in Table 1.

In addition to categorising buildings based on their usage, ownership information was also used in the analysis. Ownership data was classified into five categories. The "Public Ownership" category included buildings owned by government or municipal entities, typically used for public purposes such as affordable housing or public services. The "Cooperative Housing Association Ownership" category included buildings owned by housing cooperatives, where residents collectively own and manage the building, commonly seen in multifamily residential buildings. The "Corporate/Partnership/Limited Partnership Ownership" category included commercial properties or buildings held for investment purposes. The "Private Ownership" category included the buildings owned by individuals or private entities and encompassed residential and commercial properties. The "Other" ownership category was used for buildings that did not fit the predefined ownership categories.

Several quantitative parameters were used to examine patterns of adaptive reuse. These parameters included the space heating energy use, selected as the primary focus due to its dominance in Sweden's heating-driven climate, and the changes in mean space heating energy use, reflecting the difference between pre- and post-conversion values, along with the mean building area and mean year of construction. To further validate the robustness of the observed changes in heating energy use, a one-sided binomial sign test was conducted for each conversion pair.

Table 1
Summary and explanation of building functions in the dataset.

Building use	Description
Artistic spaces	Included theatres, concert halls, cinema venues, and other gathering spaces.
Care 24–7	Included care homes and facilities providing continuous residential care.
Daytime care	Included buildings used for daytime care, such as serviced accommodation hairdressers and similar facilities.
Educational	Included educational buildings, ranging from preschools to universities.
Food shop	Included grocery stores and food storage facilities.
Hotel	Included hotels, boarding houses and student dormitories.
Office	Included office spaces and administrative centres.
Residential	Included primary residential spaces and secondary areas such as stairwells and conditioned basements.
Restaurant	Included restaurants.
Shop	Included retail shops and storage facilities associated with commercial activities.
Shopping mall	Included shopping malls, which housed multiple stores under a single roof.
Sport	Included bathing and sports facilities, excluding outdoor arenas.
Other	Included a wide range of functions that did not fit into the predefined categories (e.g. communal laundry areas, ecclesiastic buildings, etc).

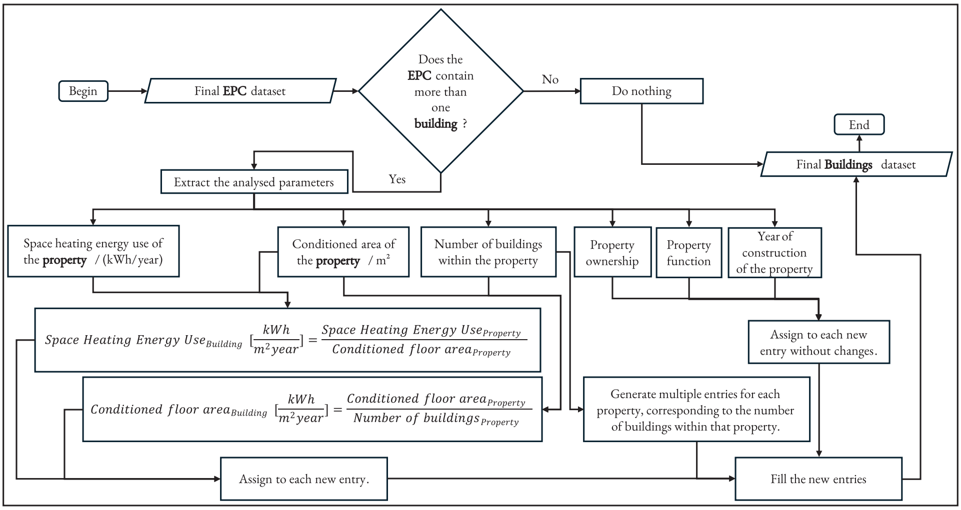

Fig. 3. Algorithm to convert property-level information into the building-level information.

This test evaluated whether the proportion of buildings with a reduction (or increase) in heating energy use exceeded 50 % within each pair, in the same direction as the mean value. Conversion pairs where the likelihood of observing such a majority purely by chance was less than 5 % ($p < 0.05$) were considered statistically significant.

Space heating energy use was extracted from the EPCs as an absolute value, representing each building's heating energy performance at the time of issuance. This focus was chosen because space heating typically represents the largest share of operational energy demand in Nordic countries [28] making it a critical indicator of energy performance. Total energy use was not used in the analysis because it is calculated from multiple components, such as property electricity, domestic hot water, and other energy uses, without specifying whether the underlying values are measured or calculated. In contrast, space heating energy use is reported separately and clearly marked as either measured or calculated in the EPCs. [20]. Therefore, only the buildings with measured space heating energy use in both pre- and post-conversion EPCs were included in the analysis, and all calculated entries were excluded to ensure consistency and reliability.

The mean area was calculated using the buildings' total conditioned floor area before conversion. The mean was chosen as it provides a measure for comparing the general size of converted buildings, accounting for the variation in building sizes across the dataset. This metric was chosen to highlight whether conversions are more common in smaller or larger buildings without overemphasising extreme cases.

The mean year of construction was used to summarise the age of buildings undergoing conversion. This approach allows for an understanding of the average age of buildings involved in adaptive reuse, helping to reveal any trends related to the age of converted buildings. The mean value smooths out variations caused by buildings from different construction periods, providing a generalised view of the dataset. An example of data processing and parameter aggregation is provided in Table 2.

2.3. Limitations

Several limitations should be acknowledged when interpreting the results of this study.

The analysis relied on Energy Performance Certificates (EPCs), issued at the property level and might not always accurately reflect building-specific details. EPCs may be completed by energy experts employed by property owners, which could introduce bias if property owners seek to downplay energy deficiencies. Additionally, industrial and agricultural buildings are exempt from EPC requirements, limiting the representation of certain building functions in the dataset. Furthermore, the variability in how different experts assess energy use, property usage, and conditioned floor area could affect the consistency of the dataset, potentially leading to discrepancies in the recorded data.

Certain building functions pose additional classification challenges due to their complex ownership structures. For example, homes for older people and care facilities may be owned and registered as homes, hospitals, or offices, complicating their categorisation in the analysis.

Table 2
Quantitative parameter aggregation example.

Office–to–residential conversions Parameter	Building 1	Building 2	Building N	Mean
Space heating energy use in the previous EPC /(kWh/m^2/y)	90	100	40	NaN
Space heating energy use in the current EPC / (kWh/m^2/y)	80	50	55	NaN
Space heating energy use change / (kWh/m^2/y)	−10	−50	15	−15
Year of construction / year	1932	1960	1970	1954
Conditioned floor area / m^2	2 546	5 236	3 534	3 772

Moreover, this study focused on the primary use of buildings for the analysis. It did not capture adaptive reuse cases where the primary use remained unchanged but secondary uses shifted. For example, if a shop within a large multifamily building was converted into an office but the building's overall classification remained residential, such conversions were not included in the analysis. Similarly, the dataset does not provide sufficient detail to distinguish between internal space reallocations and substantive functional changes in certain borderline cases, such as shopping mall–to–shop conversions. As a result, some conversions classified as adaptive reuse may involve limited or incremental changes rather than full transformations.

EPCs with discrepancies in the number of declared buildings between time points or those with incomplete or missing data were excluded. While this filtering ensured cleaner data, it may have excluded properties that could have provided additional insights into adaptive reuse.

As EPCs are provided at the property level, assumptions were required when distributing certain parameters, such as conditioned floor area and heating energy use, across multiple buildings on a property, as outlined in Section 2.2. Dataset processing. Although this step was necessary for the analysis, it introduces some uncertainty, particularly when different buildings on a single property may have had distinct energy profiles or characteristics. This simplification might obscure more granular trends.

Similarly, building typologies such as structural form, envelope characteristics, or HVAC system types could not be separately analysed, as these parameters are not included in EPC data. This led to a uniform treatment of building types despite the likely influence of such characteristics on energy use outcomes.

The dataset spans from 2007 to 2023, capturing trends in adaptive reuse during this period. However, this time frame may not fully reflect longer-term developments or degradation effects. Energy Performance Certificates are typically issued once every ten years, which limits the temporal resolution and precludes analysis of post-conversion energy performance beyond a single update cycle. As such, this study does not assess long-term operational outcomes following conversion.

The study also does not explicitly address the impact of regulatory frameworks, planning policies, or economic incentives on reuse activity. While these factors are undoubtedly relevant, their analysis falls outside the scope of this data-driven investigation and would require complementary qualitative or policy-focused methods.

These limitations should be considered when interpreting the findings. Future research could address these challenges by incorporating more granular building-level data, accounting for regional or structural factors, and expanding the scope to capture instances where secondary building uses have changed. Additionally, follow-up studies could combine longitudinal energy data with policy instruments to investigate adaptive reuse's regulatory and operational dynamics in greater detail.

3. Results

The following section presents the analysis results, focusing on patterns of adaptive reuse in the Swedish building stock. The analysis is divided into five subsections, addressing the following aspects:

- Dataset processing results, including the initial number of EPCs and buildings in the dataset, the number remaining after each filtering step, and a summary of building functions.
- The distribution of converted buildings, highlighting the direction of conversion, i.e. from the initial building use to the new one.
- Conditioned floor area and construction year of the converted buildings.
- Ownership.
- Changes in space heating energy use.

Each subsection provides a detailed examination of the data, supported by visualisations.

3.1. Dataset processing

Before applying any filtering, the initial dataset contained 144 091 EPCs classified as “Previous,” corresponding to 235 700 buildings, and 266 482 EPCs classified as “Current,” corresponding to 452 742 buildings.

- Properties with fewer than two EPCs, i.e., missing the “Previous” EPC, were excluded in the first filtering step. As a result, 122 391 EPCs were discarded, leaving 288 182 EPCs in the dataset. This number and subsequent EPC counts are evenly split between “Previous” and “Current” EPCs, with each property having two EPCs.
- Properties where the number of declared buildings differed between the “Previous” and “Current” EPCs were excluded in the second filtering step. This step removed 44 976 EPCs, leaving 243 206 EPCs in the dataset.
- Properties where the space heating energy use was calculated rather than measured in either EPC were excluded in the third filtering step. This step excluded 9 290 EPCs, resulting in a final dataset of 233 916 EPCs.

Of the remaining dataset, 225 574 EPCs corresponded to properties whose primary function remained the same, representing 137 154 buildings. Meanwhile, 8 342 EPCs corresponded to properties whose primary function changed, representing 4 624 buildings.

Among the EPCs for non-converted properties, 15 292 EPCs contained more than one building. Among the EPCs for converted properties, 546 EPCs contained more than one building.

Regarding multiple building functions within the same EPC, for converted properties, 2 026 buildings in the earlier period had more than one function, compared to 2 020 buildings in the later period. For non-converted properties, 44 824 buildings in the earlier period and 42 212 buildings in the later period had more than one function.

The number of buildings in the final dataset with a specific primary building function is presented in Table 3, including non-converted buildings and converted buildings, both before and after conversion. Residential buildings overwhelmingly dominate the dataset, accounting for over 75 % of non-converted buildings. However, while residential buildings are the most prevalent in the dataset, their conversion ratio is relatively low, with only 648 pre-conversion residential buildings being converted to other functions. Moreover, the table highlights that residential, restaurant, sport and “other” functions experience a net increase in numbers when comparing post-conversion to pre-conversion counts. This shows that these functions serve as popular recipient functions in adaptive reuse projects.

Table 3
Number of buildings in the dataset sorted by primary building function.

Primary building function	Non-converted buildings	Converted buildings	
		Pre-conversion	Post-conversion
Artistic spaces	615	166	158
Care 24–7	2 074	424	332
Daytime care	1 734	463	427
Educational	9 081	507	479
Food shop	770	116	106
Hotel	910	155	143
Office	6 075	842	706
Other	1 539	502	590
Residential	110 841	648	1 065
Restaurant	327	78	95
Shop	2 053	561	299
Shopping mall	131	28	23
Sport	1 004	134	201

3.2. Adaptive reuse pathways

The resulting conversion distribution is shown in Fig. 4. The matrix visualises the direction and number of conversions, with the vertical axis representing the original (pre-conversion) building function and the horizontal axis indicating the new (post-conversion) building function. Each cell in the matrix shows the number of buildings converted from one function to another, read from left to right and top to bottom, illustrating the conversion direction. For example, the number of conversions from the office function, represented on the vertical axis, to the residential function, represented on the horizontal axis, is 232 and is highlighted with a circle.

The colour coding highlights the number of conversions, where lighter shades represent fewer conversions and darker shades indicate more conversions. Totals for each building function are included as the last row and column of the matrix, summarising the total number of conversions from and to specific building functions. For example, the total number of conversions into the residential function is 1 065, while the total number of conversions from the office function is 842.

The results reveal that office buildings are the most commonly converted into a new function, followed by residential, shop, and educational functions. In terms of new functions, most buildings were converted into residential functions, followed by office, “other” and educational functions. The most frequent conversion pathway is from office to residential function.

Given that residential buildings constituted over 75 % of all buildings in the dataset, the absolute number of conversions alone does not provide a complete picture of adaptive reuse trends. To address this, Fig. 5 illustrates the ratio of buildings converted from one specific function to another relative to the total number of buildings with a pre-conversion function in the dataset, including both converted and non-converted buildings. The matrix is read from left to right and from top to bottom, following the conversion direction. The colour coding highlights the conversion ratio, where lighter shades represent a lower conversion ratio and darker shades indicate a higher conversion ratio relative to all the buildings with this pre-conversion function in the dataset. A conversion ratio of “office–to–residential” functions is highlighted with a circle and is equal to 3.4 %. It can be observed from the figure that the conversion ratios are quite different compared to the absolute number of conversions, and the “shopping mall–to–shop” conversion pair has the highest conversion ratio.

3.3. Characteristics of converted buildings

The mean conditioned floor area of both converted and non-converted buildings is presented in Fig. 6. The vertical axis represents pre-conversion building functions, and the horizontal axis represents post-conversion building functions. Each cell displays the mean area of buildings involved in that specific conversion pair, with colour coding used to indicate variations in building size. Lighter shades represent smaller buildings, while darker shades represent larger buildings.

Additionally, the mean areas of non-converted buildings are displayed in their respective diagonal cells. They are distinguished with a line beneath the number. For instance, the mean area of non-converted office buildings is 4 441 m^2, while the mean area for the “office–to–residential” conversion pair, highlighted with a circle, is 2 144 m^2. The results indicate that the mean areas of both converted and non-converted buildings are comparable, being in the range of 1 000 m^2–5 000 m^2, suggesting no strong preference for specific building sizes in adaptive reuse projects.

The mean year of construction for both converted and non-converted buildings is shown in Fig. 7. The matrix format mirrors the structure of previous figures, with the vertical axis representing pre-conversion building functions and the horizontal axis representing post-conversion building functions. Each cell displays the mean construction year of buildings involved in that specific conversion pair. Colour

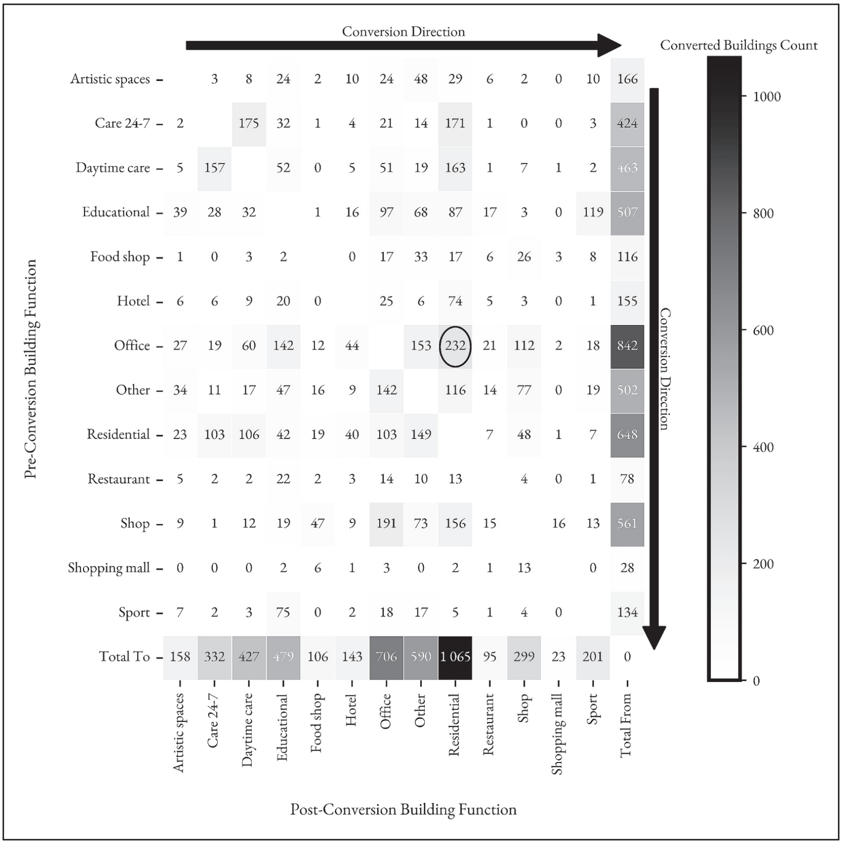

Fig. 4. Matrix of conversions from and to specific building functions.

coding highlights variations in building age, with lighter shades representing older buildings and darker shades indicating newer buildings. The mean construction years of non-converted buildings are displayed in their respective diagonal cells and are distinguished by a line beneath the number. For example, the mean year of construction for non-converted office buildings is 1948, while the mean year of construction for the "office–to–residential" conversion pair, highlighted with a circle, is 1946. The analysis reveals that most buildings selected for conversion were constructed between the 1930s and 1970s, a trend that aligns closely with the age distribution of non-converted buildings. This suggests that building age does not inherently present an obstacle to adaptive reuse. Alternatively, it may indicate that adaptive reuse tends to correlate with the end-of-life phase of buildings.

3.4. Ownership in adaptive reuse projects

The ownership distribution of buildings converted from educational, office, residential, and shop functions is presented in Fig. 8. These building functions were selected because they represent the most frequently converted categories in the dataset, making them the most relevant for understanding ownership patterns in adaptive reuse.

The results are normalised against the total number of conversions in each conversion pair to mitigate the dominance of building functions overrepresented in the dataset, such as residential buildings. This ensures that the analysis focuses on the distribution of ownership patterns within each conversion pair rather than being skewed by the absolute prevalence of certain building functions.

Corporate/Partnership/Limited Partnership ownership emerges as the dominant property owner in all shown conversion pairs, with Public ownership following as the second most prominent ownership category. This dominance might indicate that corporate ownership groups are more likely to initiate adaptive reuse projects, potentially due to greater resources or strategic flexibility in converting their properties.

For offices and shops, it is evident that conversions are almost exclusively driven by Corporate/Partnership/Limited Partnership ownership, such as corporations and limited partnerships. Other private actors, such as individual property owners or cooperatives, are scarcely represented.

In the case of residential buildings, there is an approximate distribution of 40 % public housing companies and 60 % corporations. This indicates that both ownership categories are active in repurposing multifamily housing, for instance into specialised housing or commercial facilities.

For schools, the ownership pattern is more mixed. Corporations account for a substantial share, but there is also a notable presence of other categories, including foundations and non-profit associations.

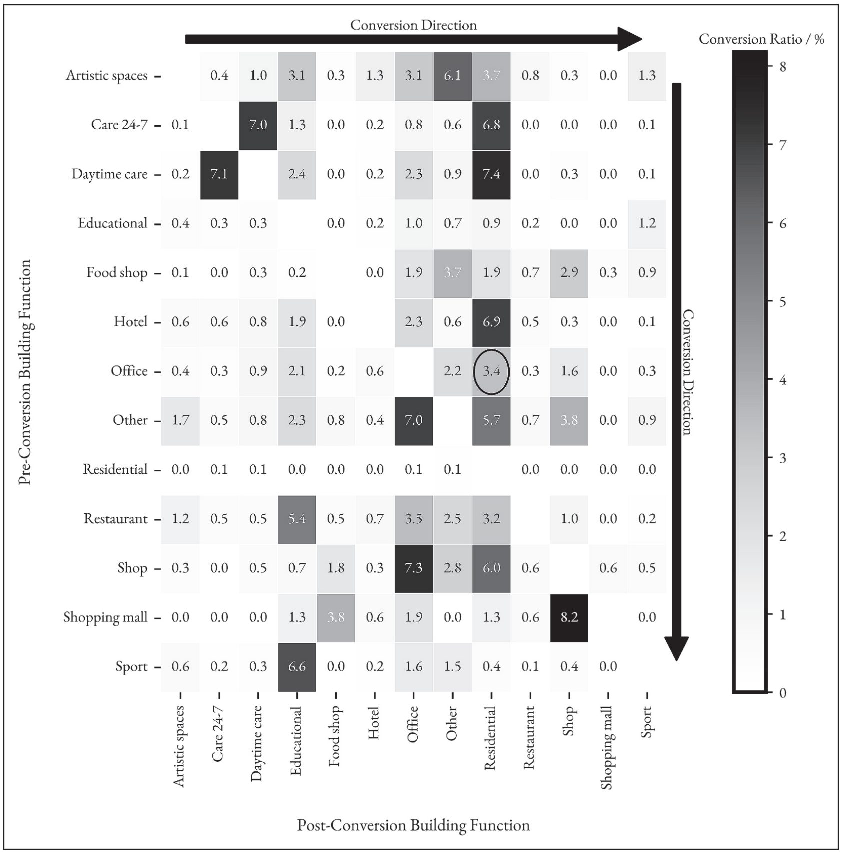

Fig. 5. Conversion ratio of the buildings. Every cell shows a number equal to the number of conversions in the specific conversion pair, divided by the total number of buildings (converted and non-converted) with a specific pre-conversion function.

3.5. Space heating energy use in adaptive reuse projects

The space heating energy use of the converted buildings, aggregated by their pre-conversion building function, is shown in Fig. 9. Each pre-conversion building function contains two boxplots: one in black, representing the space heating energy use before the conversion and one in grey, representing the space heating energy use after the conversion.

The results demonstrate a general decrease in space heating energy use after conversion across all building categories. This is particularly evident in “Restaurant”, “Daytime care”, “Food shop”, “Shop”, and “Office” building functions, where post-conversion heating energy use consistently decreases below the pre-conversion levels.

The mean difference in space heating energy use for both converted and non-converted buildings is shown in Fig. 10. The matrix is structured with the pre-conversion building function displayed on the vertical axis and the post-conversion building function on the horizontal axis. Each cell represents the mean difference in space heating energy use, calculated as “post-conversion space heating energy use – pre-conversion space heating energy use.” Darker shades signify an increase in heating energy use, while lighter shades indicate a decrease. The black numbers denote a decrease in energy use, while the white numbers highlight an increase.

The diagonal cells represent non-converted buildings, displaying the mean difference in energy use within the same building function. These cells are marked with a line under the value for distinction. For example, the “office–to–office” non-converted buildings show a mean reduction of 8 kWh/m^2y, providing a baseline for comparison with converted buildings of this function.

To support the interpretation of these trends, a one-sided binomial sign test was performed for each conversion pair. This test assessed whether the majority of buildings in each pair had a change in heating energy use consistent with the direction of the mean (either a reduction or an increase). Cells with statistically significant results ($p < 0.05$) are marked with an asterisk (*).

Only 31 conversion pairs achieved statistical significance based on the sign test, indicating that for many conversions the direction of energy use change is not robustly confirmed. Overall, 82 % of conversions were associated with a reduction in space heating energy use, and 54 % of conversion pairs exhibited greater average reductions than their non-converted counterparts. Non-converted buildings showed an average reduction of 9.3 kWh/m^2 per year, while converted buildings displayed a slightly larger average reduction of 9.6 kWh/m^2 per year. For instance, the “office–to–residential” conversion pair, highlighted with a circle, demonstrates a mean decrease of 19 kWh/m^2 per year, exceeding the reduction observed for non-converted office buildings. However, given the variability across conversion types and the limited number of

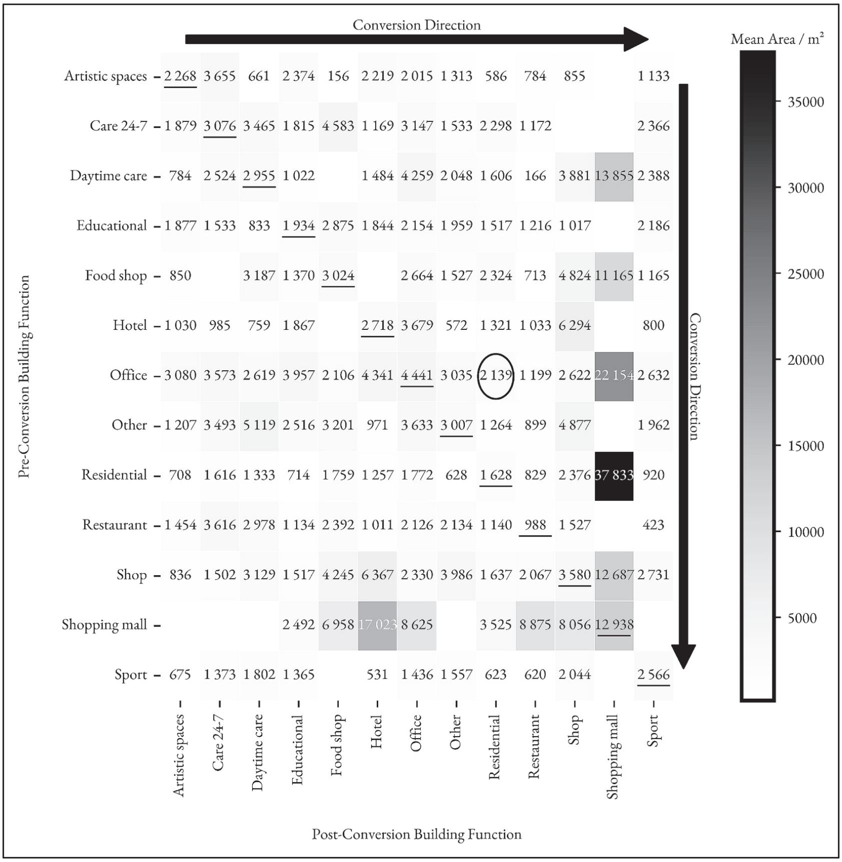

Fig. 6. Mean conditioned floor area of the non-converted and converted buildings in the dataset.

statistically confirmed results, these findings should be interpreted with caution and regarded as indicative trends rather than definitive outcomes.

4. Discussion

The results of this study provide insights into the adaptive reuse patterns in the Swedish building stock, revealing trends in building conversions, ownership, and changes in heating energy use. This section discusses these findings in the context of adaptive reuse practices, potential implications for energy efficiency, and how they contribute to a better understanding of the building sector's opportunities and challenges in sustainability.

4.1. Adaptive reuse patterns

The analysis revealed that only a small portion of buildings with two energy declarations (approximately 3 %, or 4 624 buildings) underwent adaptive reuse, highlighting that building conversions are relatively rare within the examined dataset. Among the 138 identified conversion pairs, "office–to–residential" conversions represented the largest single category in absolute terms, with 232 conversions accounting for 3.4 % of all conversions.

However, other conversion pathways became more prominent when normalised against the total number of buildings in the dataset. "Care 24/7–to–daytime care" (7.0 %), "daytime care–to–care 24/7″ (7.1 %), and "shopping mall–to–shop" (8.2 %) were among the most frequent conversions when normalised. Other notable pathways included "restaurant–to–educational" (5.4 %), "sport–to–educational" (6.6 %), and "shop–to–office" (7.3 %). These results suggest that "office–to–residential" conversions, though significant in absolute numbers, are reflective of the larger stock of office buildings rather than an inherent tendency toward this specific conversion.

The clustering of functionally similar conversion pairs (e.g., "care 24/7–to–daytime care" or "shopping mall–to–shop") suggests that functional proximity and compatibility play a key role in real-world feasibility. This pattern is highly relevant to decarbonisation efforts, as such conversions often minimise structural interventions, material demand, and carbon-intensive retrofits.

Conversions into residential functions stand out in absolute and relative terms. Residential buildings consistently emerge as a dominant target function, with conversions such as "care 24/7–to–residential" (6.8 %), "hotel–to–residential" (6.9 %), and "daytime care–to–residential" (7.4 %) illustrating their importance. This is particularly relevant in the Swedish context, where housing shortages persist. Converting existing buildings into residential use may reduce both embodied and operational emissions compared to new construction, supporting climate and housing policy alignment. Residential reuse may

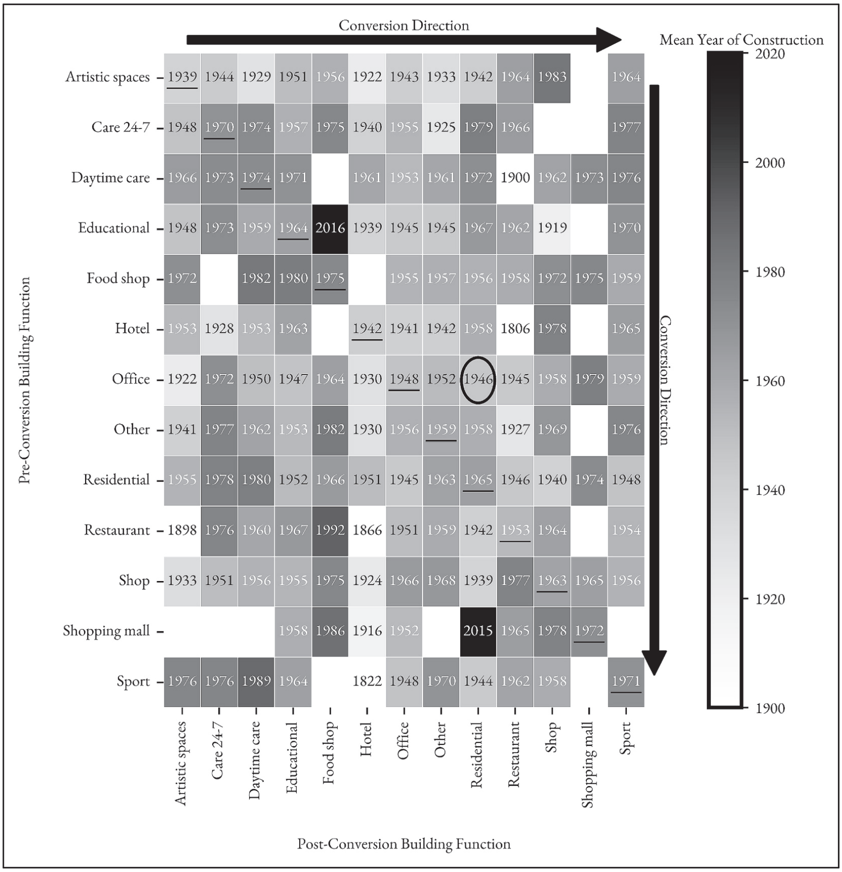

Fig. 7. Mean year of construction of the non-converted and converted buildings in the dataset.

also be technically favourable, as many source buildings (offices, care facilities, hotels) can be reconfigured with minimal intervention.

4.2. Characteristics of converted buildings

The analysis of building size and age further supports the idea that adaptive reuse is more common in buildings with a conditioned floor area between 1 000 m^2 and 5 000 m^2 for most buildings. This range aligns closely with the distribution of non-converted buildings in the dataset, suggesting that building size does not present a significant barrier to adaptive reuse.

The results also show that most buildings selected for conversion were constructed between the 1930s and 1970s, indicating that age is not a major barrier to adaptive reuse. This result is important for national retrofit strategies: it confirms that mid-century stock, while no longer optimal in original use, holds substantial reuse potential. This aligns with existing research that suggests buildings from these decades may have reached the end of their functional life in their original use but still possess structural integrity that makes them suitable for repurposing. The fact that older buildings are being reused highlights the potential for adaptive reuse to preserve historical and cultural value and contribute to sustainability by avoiding demolition and new construction.

4.3. Ownership

The analysis of ownership patterns in adaptive reuse projects reveals that Corporate/Partnership/Limited Partnership ownership and Public ownership dominate the converted building stock. These two categories collectively account for the majority of conversions, while Private ownership, Other ownership, and Cooperative housing associations play comparatively smaller roles.

The prevalence of corporate actors can be attributed to their greater access to financial resources, organisational capacity, and risk management strategies. Corporations are typically better equipped to absorb the high development and construction costs associated with reuse projects and to navigate the complex regulatory environments that such projects entail [29]. Public ownership, similarly, benefits from long-term management priorities and the ability to align adaptive reuse with broader societal goals, such as providing social services or preserving community infrastructure [30].

In contrast, the relatively low participation of private individuals and cooperative housing associations may be linked to structural and institutional barriers. Private owners often face challenges related to limited access to capital, heightened sensitivity to financial risk, and the complexities of regulatory compliance [29,31]. Cooperative ownership structures add another layer of difficulty due to collective decision-

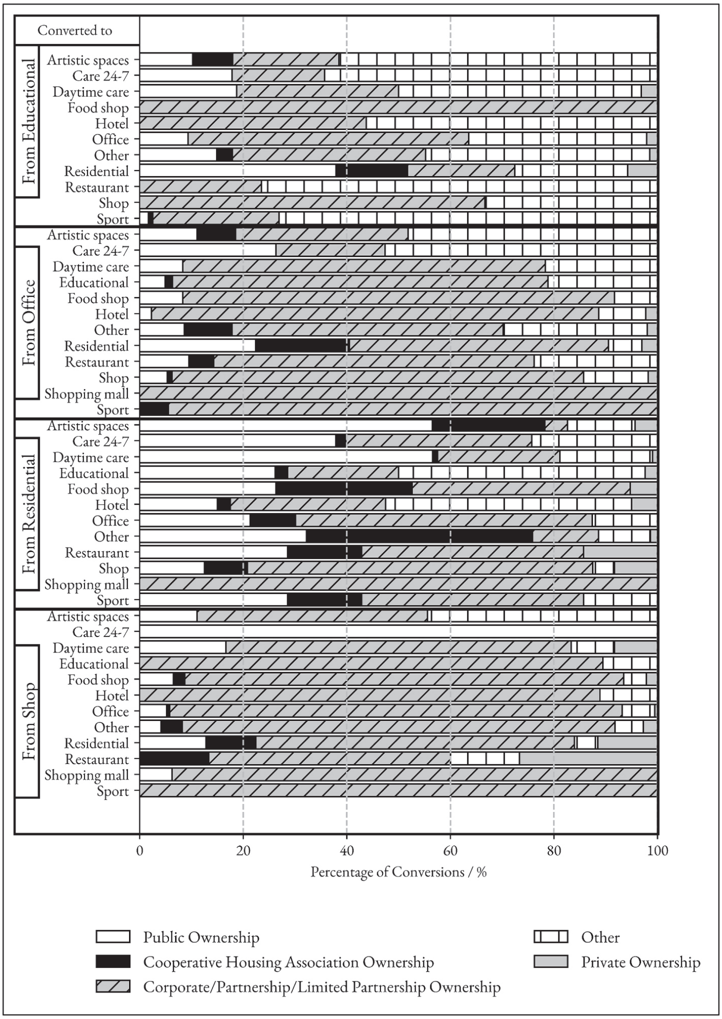

Fig. 8. Ownership distribution for converted and non-converted buildings, normalised against the total number of conversions within the conversion pair.

making processes, which can delay project approvals and exacerbate risk aversion [29]. These factors limit the flexibility and capacity of smaller ownership groups to undertake adaptive reuse projects.

Regulatory hurdles, particularly around building code compliance related to fire safety and accessibility, further complicate adaptive reuse and are more easily managed by large, well-resourced entities. Without targeted support, such as streamlined permitting processes, financial grants, or incentives like longer lease terms, the barriers facing smaller owners and cooperatives are likely to persist [30].

These findings suggest that expanding the scope of adaptive reuse will require policy interventions aimed specifically at lowering financial, technical, and procedural barriers for underrepresented ownership groups. Encouraging broader participation could unlock significant potential in the building stock that is currently overlooked due to institutional and financial constraints [32].

4.4. Space heating energy use in adaptive reuse projects

The analysis suggests that adaptive reuse is often associated with a reduction in space heating energy use, as indicated by the heatmap and boxplot analyses. On average, converted buildings exhibited a reduction of 9.6 kWh/m^2 per year, compared to 9.3 kWh/m^2 per year in non-converted buildings. This may indicate that adaptive reuse could align with broader energy efficiency improvements, although the observed differences are relatively modest.

Additionally, 82 % of conversion pairs showed a reduction in heating energy use, and 54 % achieved greater average reductions than their non-converted counterparts. For instance, the “office–to–residential” conversion pair demonstrated a mean reduction of 19 kWh/m^2 per year, exceeding the reduction observed in non-converted office buildings. This improvement could partly reflect lower airflow requirements and occupant densities in residential functions compared to offices, alongside regulatory requirements mandating energy upgrades in major

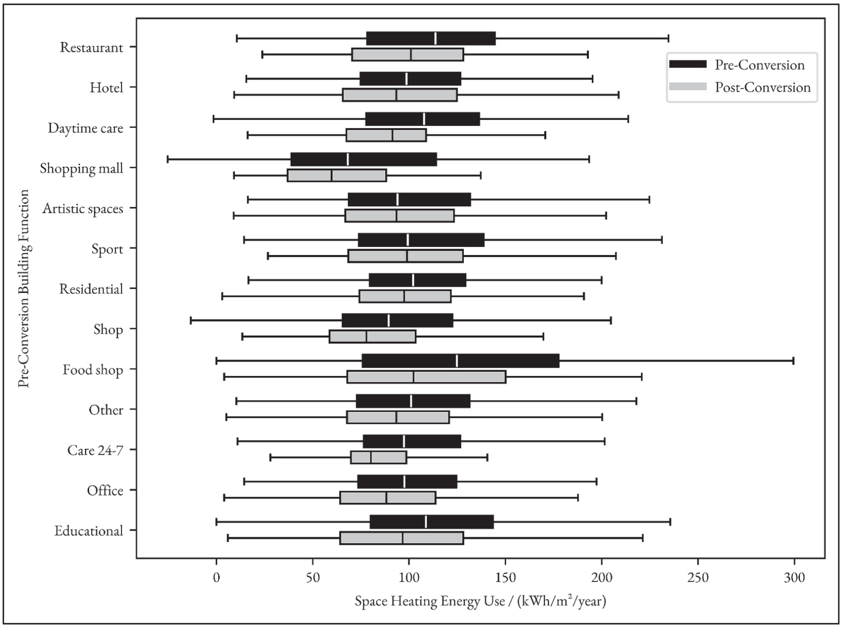

Fig. 9. Space heating energy use of the converted buildings, aggregated by the pre-conversion building function.

renovation projects.

However, a sign test conducted to assess the consistency of these trends showed that only 31 conversion pairs achieved statistical significance. This indicates that while reductions are common, the direction and magnitude of heating energy use changes are not uniformly robust across all conversion types. Consequently, the results should be interpreted as indicative rather than definitive, highlighting general patterns rather than conclusive causal relationships.

One consideration stemming from the reduction in space heating energy use in these conversions, where applicable, is the potential for reusing existing heating systems inside the buildings. Potentially, buildings undergoing adaptive reuse could retain parts of their original systems, such as radiators and piping, which were designed for higher pre-conversion heating loads. In the Swedish context, converted buildings are typically subject to regulatory requirements for renovation, including improved insulation, which reduces heat loss and peak heating demands. For example, in office–to–residential conversions, the lower energy demand of residential spaces may allow existing systems to continue operating, avoiding costly replacements and reducing the embodied carbon associated with new HVAC equipment.

At the same time, not all conversions resulted in reduced heating energy use. Increases were observed for certain conversions, such as from educational buildings to shops, and from shopping malls to hotels. These outcomes likely reflect different operational demands in the new functions, including variations in occupancy profiles, ventilation requirements, and internal heat gains. Hotels, for example, typically maintain stricter indoor climate control and higher ventilation rates compared to retail spaces, contributing to increased energy demand.

Overall, these findings demonstrate that adaptive reuse has the potential to contribute to energy and carbon reductions, but the outcomes vary considerably depending on building typology and the specifics of the conversion. Successful energy performance improvements are not automatic and require careful planning of building systems, envelope upgrades, and operational characteristics.

5. Conclusions

This study investigated adaptive reuse patterns in the Swedish building stock, focusing on building characteristics, ownership trends, and space heating energy performance. By systematically analysing over 141 000 buildings with paired EPC data, it provides the first national-scale, data-driven quantification of realised adaptive reuse projects in Sweden. The following key findings address the four primary research questions that guided this study:

- **Which building functions in Sweden are most frequently converted through adaptive reuse?** Adaptive reuse remains relatively rare, with only 3 % of buildings undergoing conversions. Office–to–residential conversions were the most common in absolute terms, but normalised rates revealed frequent conversions such as care 24/7–to–daytime care.
- **What are the typical conditioned floor areas and construction ages of buildings that undergo adaptive reuse?** Conversions are concentrated in buildings between 1,000 m^2 and 5,000 m^2, mostly constructed between the 1930s and 1970s, indicating that a broad segment of the national stock is physically suitable for reuse.
- **Which owners are most prone to initiate an adaptive reuse project?** Corporate and public entities dominate reuse activity, suggesting that financial capacity, institutional support, and risk tolerance are key enablers. Policies such as soft loans or simplified permitting could support greater participation by private individuals and cooperatives.
- **How does adaptive reuse affect space heating energy use across different conversions, and which conversions lead to the most substantial change**s? Converted buildings demonstrated an average reduction of 9.6 kWh/m^2 per year in space heating energy use, compared to 9.3 kWh/m^2 per year for non-converted buildings. Notably, office–to–residential conversions achieved a mean reduction of 19 kWh/m^2 per year.

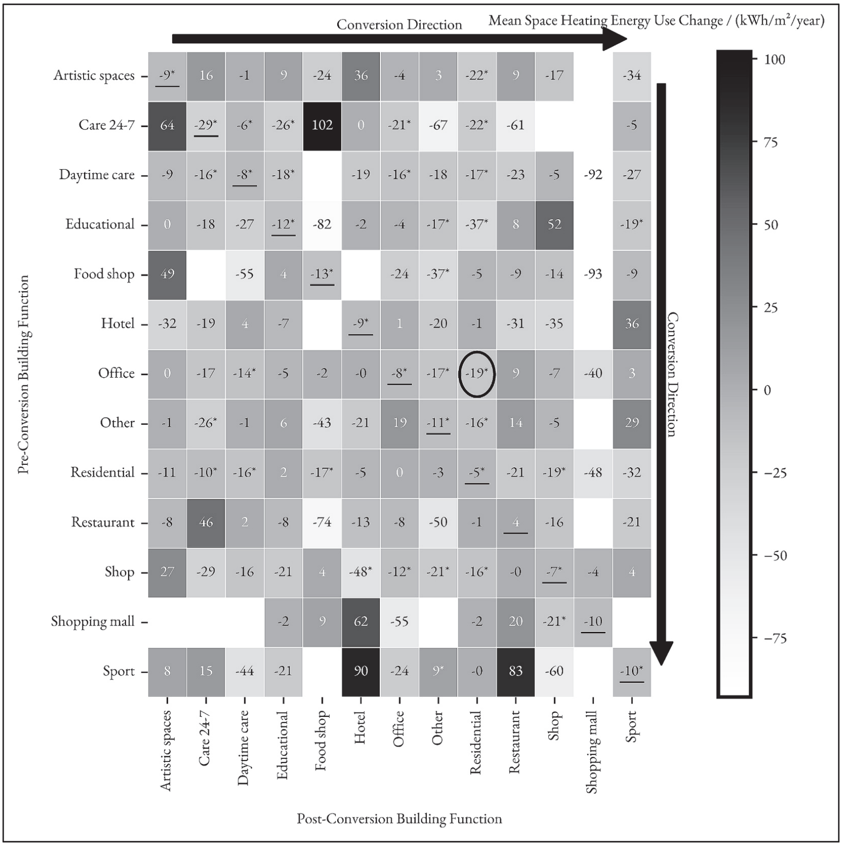

Fig. 10. Mean difference in space heating energy use for both converted and non-converted buildings.

Importantly, while the comparison between converted and non-converted buildings shows a general trend toward reduced energy use, the relative influence of functional change versus renovation measures cannot be fully isolated. Additionally, a sign test indicated that only 31 conversion pairs exhibited statistically significant trends, suggesting that the direction of change is not consistently robust across all conversion types. Therefore, the observed improvements should be interpreted as indicative of potential benefits rather than as guaranteed outcomes.

Although the study is national in scope, the methods are transferable to other regions with structured building energy databases or EPC frameworks. These insights are especially relevant to countries with heating-dominated climates and ageing building stocks.

Overall, this study provides robust evidence that adaptive reuse is not only technically feasible but can contribute meaningfully to operational energy savings and climate mitigation. The findings support integrating adaptive reuse into energy and housing policy, urban regeneration strategies, and national decarbonisation plans, particularly in contexts with underutilised mid-century buildings and district heating infrastructure.

6. Future work

This study highlights several important directions for future research. While it demonstrates that adaptive reuse can contribute to operational energy savings and more efficient use of the building stock, the findings also underline the complexity of reuse processes and the need for deeper analysis. Future work could address the following areas:

- Secondary use changes: Broaden the scope of analysis to capture cases where secondary uses are altered without a formal change in primary building function, which are not reflected in EPC data.
- Borderline cases: Investigate ambiguous conversions, such as internal reallocations versus full functional transformations, to refine definitions and improve the categorisation of adaptive reuse.
- Building services and system interventions: Conduct detailed studies on building systems, focusing on how the retention, adaptation, or replacement of heating, ventilation, and plumbing systems influence post-conversion energy performance.
- HVAC typologies: Analyse pre- and post-conversion HVAC systems to identify common intervention strategies and their impact on operational efficiency.
- Ownership structures and barriers: Explore how different ownership types, corporate, public, cooperative, and private, affect the likelihood and outcomes of reuse projects, and identify the financial, regulatory, or technical barriers that inhibit broader participation.

- International comparative studies: Apply the methodology to building stocks in different countries to generate comparative insights under diverse climatic conditions and policy environments.

Future studies that incorporate more granular building-level data, system-level interventions, and longitudinal performance tracking would provide deeper understanding of the dynamics of adaptive reuse. They could also employ detailed subgroup analysis to disentangle energy performance trends by specific conversion types. Expanding research beyond national contexts would also help establish whether the patterns observed in Sweden are consistent elsewhere, informing broader strategies for sustainable urban development.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used ChatGPT in order to improve readability. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

CRediT authorship contribution statement

Ilia Iarkov: Writing – original draft, Validation, Methodology, Formal analysis, Conceptualization, Writing – review & editing, Visualization, Software, Investigation, Data curation. **Victor Fransson:** Writing – review & editing, Validation, Resources, Methodology, Conceptualization, Visualization, Supervision, Project administration, Funding acquisition. **Dennis Johansson:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Validation, Resources, Methodology, Conceptualization. **Ulla Janson:** Validation, Resources, Funding acquisition, Writing – review & editing, Supervision, Project administration, Conceptualization. **Henrik Davidsson:** Writing – review & editing, Supervision, Project administration, Conceptualization, Validation, Resources, Methodology.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The data that has been used is confidential.

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Paper II

EPC-driven analysis of specific airflow and ventilation-type conversions in Swedish adaptive reuse

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Abstract

Adaptive reuse, the conversion of existing buildings to new functions, is increasingly promoted to reduce environmental impacts associated with demolition and new construction. Ventilation is a key parameter linking building function with energy use, indoor air quality, and regulatory compliance, yet its role in building conversions is often overlooked. This study examines how ventilation system types and reported airflow rates change during realised functional conversions of buildings in Sweden. Using over 4 600 matched entries from the national Energy Performance Certificate (EPC) database, the analysis identifies transitions in reported specific airflow and system configuration.

In 65% of conversions, statistically significant differences in reported airflow were observed. Within this group, 70% of buildings showed reductions in reported specific airflow. Among the remaining 35% of conversions, where changes were not statistically significant, 52% of the buildings still exhibited reduced airflow. These figures suggest a prevailing tendency for ventilation airflow to decrease after the functional conversion. At the same time, 73% of buildings retained their original ventilation system type, most frequently ventilation supply and exhaust systems with heat recovery.

Combined patterns indicate that many conversions involve reductions in reported specific airflow while the recorded ventilation system type remains unchanged. This could reflect adjustment of airflow within the same system type, e.g., through control settings, balancing, or revised targets, rather than a change of category.

The EPC records do not reveal whether equipment was retained or replaced like-for-like, nor do they specify component-level actions such as fan replacement or control retuning. Overall, the ability to satisfy new functional airflow demands within an unchanged system type could facilitate conversions with the ventilation equipment preserved; however, post-conversion performance lies outside the scope of what EPC data can verify.

Keywords: Adaptive reuse, Building services, Energy Performance Certificate, Airflow, Ventilation.

1. Introduction

The building sector accounts for approximately 30% of global final energy use and 26% of global environmental impacts across both construction and operational phases [1]. Concurrently, population growth and urbanisation continue to increase demand for built space [2]. At the same time, substantial portions of the existing building stock remain underutilised due to industrial restructuring, demographic shifts, and post-pandemic work patterns, resulting in widespread vacancy or partial occupancy across multiple sectors [3–6]. This divergence between spatial demand and underuse raises questions regarding the environmental viability of meeting needs through new construction, which entails increased energy use and resource depletion [7,8].

Adaptive reuse, the conversion of existing buildings to new functional uses, has been proposed as a strategy to mitigate environmental burdens associated with demolition and new construction. It may contribute to climate mitigation targets and circular construction objectives by conserving embodied energy and reducing demand for new materials [9–12]. Although structural, architectural, and economic aspects of adaptive reuse have received considerable attention [13–15], comparatively little is known about the fate of building services during such transitions. In particular, ventilation systems remain largely absent from prior assessments [9,13,16,17], and the potential for their preservation has not been systematically examined [18].

Ventilation systems affect occupant health, comfort, and productivity [19,20], while contributing between 10% and 53% of the environmental impacts and 15% to 40% of total construction costs in typical projects [21–

23]. Unlike the space-heating demand of a building, which could be reduced through fabric-level measures, e.g., insulation, airtightness, and glazing upgrades, ventilation provision is closely coupled to functional requirements [24,25]. Despite this, ventilation is often treated peripherally in adaptive reuse studies. Addressing this gap is of interest not only for energy and environmental optimisation but also for reducing material inputs and improving technical feasibility in reuse projects.

In Sweden, energy performance certificates (EPCs) are mandatory for most buildings and record building function, ventilation system type, and an assessor-reported specific airflow, i.e. specific airflow ($l/s/m^2$) for the declared current use [26]. These administrative records enable national-scale identification and analysis of realised conversions. Combined with Sweden's comparatively structured building stock and detailed energy and ventilation regulations [27], EPC data provide a practical basis for stock-level examination of ventilation adaptation. To the authors' knowledge, ventilation outcomes under adaptive reuse have not been examined at the stock level. The patterns derived here could support practice by: (i) prioritising building–function pairs where reported airflow tends to decrease or remain within the same system type, suggesting potential to retain the existing ventilation strategy; (ii) selecting building types for which system retention may be feasible; and (iii) flagging conversion pathways where higher ventilation demand would likely require augmentation or reconfiguration to meet Swedish regulatory requirements.

This study contributes to the emerging literature on adaptive reuse by investigating ventilation system changes in the Swedish converted building stock. The following research questions are addressed, focusing on reported airflow rates and ventilation system categories before and after functional conversion:

- What changes in specific airflow are observed following functional conversions in Swedish buildings?
- How do ventilation system types change during functional conversions, and to what extent are original ventilation system types retained or changed?

- How are joint changes in building function and ventilation system type associated with changes in reported specific airflow?

2. Methods

This section builds on the methodological foundation introduced in a previous investigation of Swedish building stock conversions [28], where the structure and data composition of EPCs were outlined. The present analysis retains the core EPC dataset and functional classification approach but introduces additional analytical procedures aimed at ventilation performance. It examines declared ventilation airflow rates and system types before and after functional conversion, therefore extending the scope of the previous study. The following sections describe the modifications to the prior approach, outline the statistical procedures employed to examine ventilation changes, and discuss assumptions and potential sources of uncertainty relevant to this analysis.

2.1 EPC Data Processing

This analysis employed an EPC dataset restructured to enable ventilation-specific examination at the building level. Filtration steps and building-function classification procedures were retained from the previous study to ensure methodological consistency, applied to paired EPCs with property-to-building disaggregation and twelve primary function categories. The three filters (removing properties lacking a pair, mismatched declared building counts, and entries with calculated rather than measured space-heating energy use) yielded 233 916 EPCs. Of these, the converted subset comprised 8 342 EPCs representing 4 624 buildings, which formed the ventilation-focused analysis sample. Within the converted subset, multiple building functions within the same EPC were present: 2 026 buildings in the earlier period and 2 020 in the later period carried more than one function classification. Readers are advised to refer to [28] for a detailed description of these procedures and their underlying rationale.

The present analysis further adapted the disaggregation and replication algorithm to enable ventilation-focused examination. Properties consisting of a single building were directly included without modification.

New entries were generated for properties containing multiple buildings to correspond to the total number of buildings reported per property. Each new entry was populated with property-level attributes following the disaggregation and replication procedure illustrated in Fig. 1. Only 273 of the 4 171 converted properties listed more than one building.

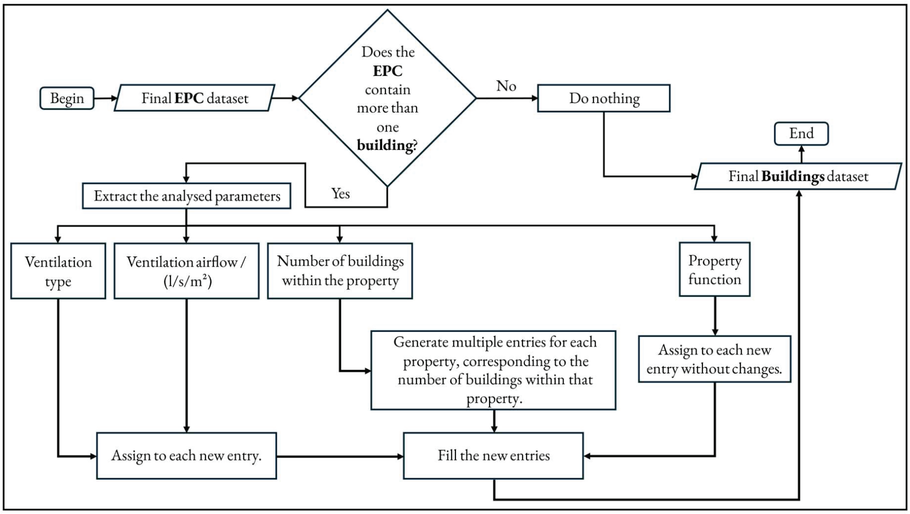

Fig. 1. Disaggregation and replication procedure used to construct the building-level dataset for ventilation-focused analysis.

Two ventilation-related parameters were extracted from the EPC records: the type of ventilation system and the reported airflow. The system type describes the technical configuration, including natural ventilation, mechanical exhaust, or supply and exhaust systems with or without heat recovery. Reported airflow values were used as an indicator of ventilation capacity at the building level.

Specific airflows within each conversion pair, defined by the transition between primary building functions, were examined. Airflow differences were calculated as the numerical change between post- and pre-conversion values for each building.

Ventilation system types were categorised into six groups: MV-HR (mechanical supply and exhaust ventilation with heat recovery), MV (mechanical supply and exhaust ventilation without heat recovery), MEV-HR (mechanical exhaust ventilation with heat recovery), MEV (mechanical exhaust ventilation), NV (natural ventilation), and None (no ventilation). Of the 4 624 buildings in the final dataset, 1 020 cases (22.1%) contained multiple reported ventilation system types before conversion, and 1 175 cases (25.4%) contained multiple system types after conversion. However, the EPC records do not specify how these systems are spatially distributed within the building, nor do they report floor area shares per configuration. Consequently, it is not feasible to assign ventilation types in proportion to building area. Each building was assigned a single dominant system type to address this. The dominant type was defined as the configuration providing the highest degree of mechanical airflow provision and control, prioritising systems with heat recovery when applicable. The selection followed a fixed hierarchy: MV-HR > MV > MEV-HR > MEV > NV > None. Conversion patterns were then analysed by comparing dominant configurations before and after functional change.

This dominant system approach was adopted to enable the identification of major changes in ventilation provisioning while avoiding the combinatorial fragmentation associated with unaggregated multi-system classifications. Without aggregation, six system types, including None, could theoretically produce 1 024 potential conversion pairs when comparing pre- and post-conversion states. Such fragmentation would severely constrain analytical tractability and limit the interpretability of system-level patterns. The dominant classification mitigates this issue while retaining the ability to track principal changes in ventilation provisioning. For transparency, the complete distribution of all reported multi-system configurations, prior to aggregation, is presented in the supplementary material.

2.2 Statistical Analysis

Statistical testing was used to assess whether observed changes in declared specific ventilation airflow and ventilation system type between pre- and post-conversion EPCs reflect systematic effects rather than random variation. The analysis evaluates whether:

1) Post-conversion changes in declared airflow differ from zero

2) Transitions in system type are associated with detectable differences in declared specific airflow.

The distributions of 4 624 before–and–after differences in declared specific airflow (overall; one per converted building), and the corresponding distributions within each conversion-pathway group, were treated as non-normal. This reflects the operational heterogeneity of conversions: target occupancies and regulatory airflow densities may differ by function; building size and system configuration vary across cases; EPC airflow entries may be calculation-based rather than measured; and partial-area modifications or commissioning changes could introduce skewness and outliers. The Shapiro–Wilk test was applied to verify this assumption, as it is suitable for small or moderate sample sizes and provides an opportunity to assess deviations from normality [29,30]. This verification step was used to confirm the suitability of non-parametric approaches and ensured that no unjustified distributional assumptions were applied to the data. The change in declared specific airflow was used as the primary outcome because it directly quantifies ventilation provision in a form comparable across buildings and is readily available in the EPCs. Alternatives such as air-change rate or per-person airflow could not be calculated due to missing building volume and occupancy data.

Based on the assumption of non-normality and its verification, changes in specific airflow before and after functional conversion were evaluated using the Wilcoxon signed-rank test [31]. This non-parametric test is used when data cannot be assumed to follow a normal distribution and is used to assess whether the median difference between paired observations deviates from zero. The null hypothesis stated that the median difference in airflow was zero, implying no systematic change. The alternative hypothesis suggested that the median difference was not zero, indicating a potential systematic shift associated with functional conversion. Statistical significance in this context was defined as a median airflow change differing from zero at the $p < 0.05$ threshold.

Conversion groups were categorised into two sets, based on the Wilcoxon test results: those with statistically significant airflow changes and those without. This categorisation was used to structure subsequent analyses of ventilation type conversions, allowing potential patterns in system reconfiguration to be examined in relation to the presence or absence of systematic airflow shifts. This separation also enabled the examination of whether changes in ventilation system type correspond to measurable changes in specific airflow.

Changes in ventilation system type were examined using the chi-square test of independence, which is a categorical test suitable for evaluating associations between nominal variables. This test was used to assess whether the distribution of post-conversion system types differs from what would be expected under the assumption of independence from pre-conversion configurations. The null hypothesis stated that post-conversion system types were independent of pre-conversion types, meaning the observed distribution would match the distribution expected by chance. The alternative hypothesis proposed that the two were not independent. Statistical significance was evaluated at a threshold of $p < 0.05$. Standardised Pearson residuals were further computed to indicate specific system type conversions that were over- or under-represented relative to expected frequencies. This approach was applied separately for groups with and without statistically significant airflow changes to examine possible interactions between airflow changes and system type reconfiguration.

Finally, groups with and without statistically significant airflow changes were included in a combined framework linking functional conversions and ventilation type conversions. Intersections were further classified according to the prevailing direction of airflow change, using categorical assignment to indicate whether the majority of buildings in each group exhibited an increase, reduction, or no dominant direction in airflow change. This final step was designed to structure the joint examination of functional and ventilation type conversions without pre-empting interpretation of patterns.

2.3 Limitations

Several limitations should be considered when interpreting the results of this study. As in earlier work relying on EPC data, this analysis depends on administrative records compiled at the property level. Although data processing was designed to approximate building-level resolution, EPC entries do not differentiate characteristics within multi-building properties. In such cases, the ventilation system type and airflow were distributed evenly across constituent buildings due to a lack of spatial allocation data, introducing a degree of approximation that may mask internal heterogeneity.

Ventilation systems in EPC records are listed as combinations of different types without spatial attribution. To facilitate categorical comparison, a single dominant system type was assigned to each building, defined as the most mechanically controlled system listed, regardless of its proportional floor area. However, this approach introduces a source of uncertainty. Mixed-use listings in EPCs mean that a building may carry several ventilation system types, e.g., a small MV-HR zone alongside MEV elsewhere. As data on spatial coverage are unavailable, a single dominant type was assigned per building; the rule selects the configuration with the highest degree of mechanical provision and control, prioritising heat recovery. This simplification avoids extreme fragmentation. With five ventilation types plus None (which cannot co-occur with any ventilation type), each period admits 32 distinct system-combination states. Across two periods, this yields 1 024 possible ventilation-combination transitions. When combined with 138 observed function-conversion pairs, the joint state space would expand to 141 312 strata, far beyond what the 4 624 converted buildings could support; most cells would be empty, precluding stable estimation. Reducing to a dominant type compresses ventilation transitions to $6 \times 6 = 36$ states, retaining the main distinctions relevant to regulation (supply vs exhaust, heat recovery, natural vs mechanical) and yielding tractable comparisons. This choice may obscure zonal strategies and mask internal variation; any resulting bias would tend to attenuate differences rather than create spurious directional effects.

Airflow values reported in EPCs were used to approximate ventilation capacity before and after conversion. The reliability of these values is uncertain, as EPCs do not specify whether airflow figures are measured, calculated, or estimated, and measurement standards may vary across assessors and over time. Incomplete or inconsistent reporting may introduce uncertainty in representing actual performance shifts.

Paired statistical tests were applied at the functional conversion group level to evaluate airflow changes. While this approach respects the paired structure of the data, small sample sizes in certain groups limit statistical power and may hinder the detection of systematic effects. The reported *p*-values and effect estimates pertain to the distributions of declared EPC entries rather than measured physical performance and may be affected by administrative artefacts or assessor uncertainty, such as calculation-based rather than measured flows, input errors, or rounding, as well as property-to-building disaggregation.

Functional classification follows the EPC scheme. Each EPC may list multiple functions with shares of heated floor area; the primary function is the one with the largest share. For each period, buildings were assigned to their primary function. A conversion is recorded only when the primary function changes between the paired EPCs; changes confined to secondary functions are not counted. For example, if a ground-floor retail unit is converted to a restaurant in an otherwise residential building whose largest heated area remains residential, the change is not captured. This definition focuses the analysis on full reclassifications at the building level and may underestimate partial or mixed-use conversions.

The EPC database excludes certain building types, particularly industrial and agricultural buildings not covered by mandatory reporting. Additionally, EPCs are only required at points of sale or new tenancies, which may introduce selection bias toward buildings with recent market activity. This constraint limits representativeness for the entire Swedish building stock.

Finally, the decadal cycle of EPC updates restricts temporal resolution and confines the analysis to a single transition event per building. Thus, longer-term trajectories, sequential adaptations, or repeated conversions cannot be captured.

3. Results

This section presents the results of the ventilation-focused analysis, extending the findings of the previous study [28] by incorporating airflow performance and system-type changes observed in functional conversions. The descriptive characteristics of the dataset are provided first, followed by statistical assessments of airflow changes and conversions of the ventilation system type. The final part of the section integrates functional and ventilation type conversions, allowing for a combined examination of conversion pathways within the context of ventilation systems.

The distribution of airflow changes between post- and pre-conversion states was first examined to inform the selection of appropriate statistical methods for evaluating paired airflow changes. This distribution is illustrated in Fig. 2, and utilises Freedman–Diaconis binning. This rule sets the bar width based on the data (the spread of the middle half of values and the number of buildings), so an arbitrary bin choice does not drive the plot. In this dataset, each bar spans approximately 0.054 $l/s/m^2$, and the bar height represents the number of buildings within that airflow change range. The black line is a kernel density estimate (KDE) fitted to the raw before–and–after values and rescaled to the same vertical units as the bars. With this binning, most cases lie close to zero change; there is greater weight on the reduction side, and long tails are present in both directions. The five most populated ranges are centred near −0.66 $l/s/m^2$, −0.44 $l/s/m^2$, −0.34 $l/s/m^2$, −0.28 $l/s/m^2$, and −0.01 $l/s/m^2$ (approximately 281, 555, 229, 422, and 735 buildings, respectively). The overall shape is an asymmetric non-Gaussian distribution, which motivates the non-parametric paired analysis.

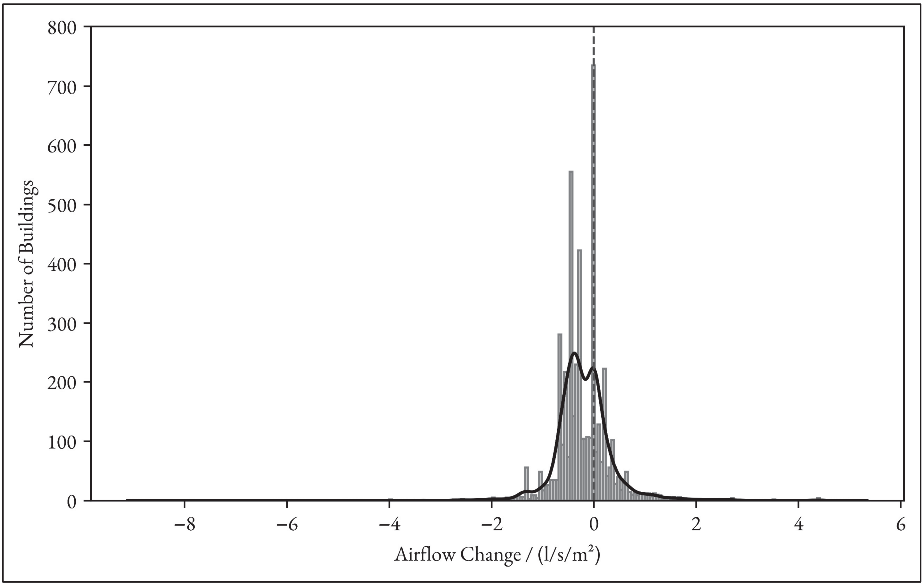

Fig. 2. Change in specific airflow ($l/s/m^2$) between pre- and post-conversion across 4 624 buildings. Bars show the number of buildings per range using Freedman–Diaconis binning (bar width ≈ 0.054 $l/s/m^2$; grey bin edges); the black curve is a KDE fitted to the raw differences and scaled to the count axis. The dashed vertical line marks zero change.

The Q–Q plot in Fig. 3 further demonstrates deviations from normality, particularly evident in the lower and upper quantiles. This plot clarified how the empirical distribution diverged from a theoretical normal distribution, which is not apparent in the histogram. The largest deviations occurred in the lower and upper tails, indicating a degree of asymmetry. This was formally verified by the Shapiro–Wilk test, which yielded a test statistic of 0.8008 and a *p*-value below 0.001. These results confirmed the assumption of non-normality and supported the use of non-parametric methods, specifically the Wilcoxon signed-rank test, for evaluating paired airflow changes.

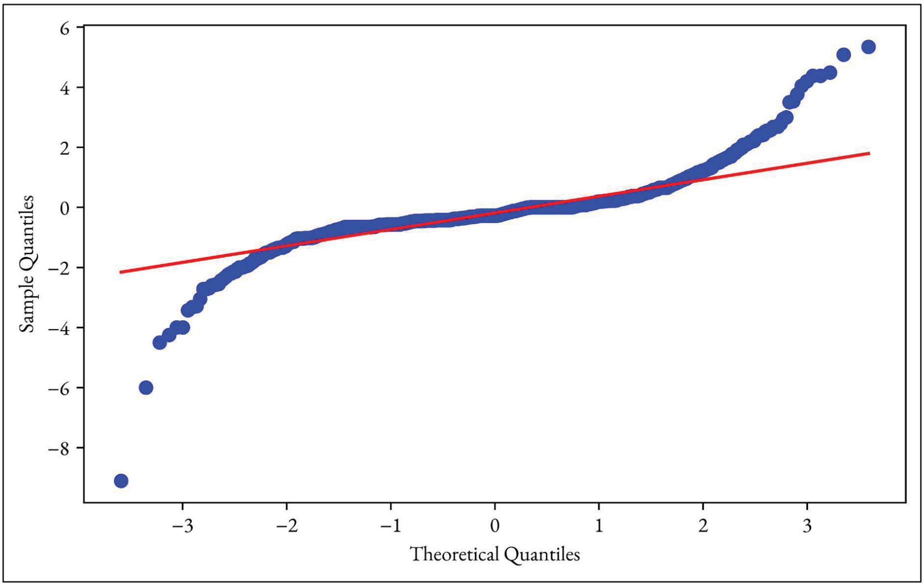

Fig. 3. Q–Q plot comparing observed airflow differences to a theoretical normal distribution. Deviations in the lower and upper quantiles indicate a non-normal pattern, supporting the use of non-parametric statistical methods.

3.1 Airflow performance shifts following functional conversion

This subsection examines airflow differences in relation to functional conversions, beginning with an overview of group-level specific airflow across individual building functions before and after conversion. This functional baseline is illustrated in Fig. 4, where mean airflow values are marked with dots, median positions are indicated with crosses, and approximate 95% ranges, defined by the 2.5th and 97.5th percentiles, are shown as vertical lines to highlight the central spread within each function. These ranges indicate both the central tendency and the extent of the tails within each group, based on observations at the building level. A box-and-whisker format was not adopted because it emphasises the central 50% (interquartile range) and defines whiskers by a rule (typically 1.5×IQR) that may down-weight tail behaviour in skewed, heavy-tailed groups and does not display the mean. The present summary displays the mean and median alongside an empirical 95% quantile interval, which could be more informative for interpreting pre- to post-conversion shifts in area-normalised airflow when distributions are asymmetric and group sizes differ.

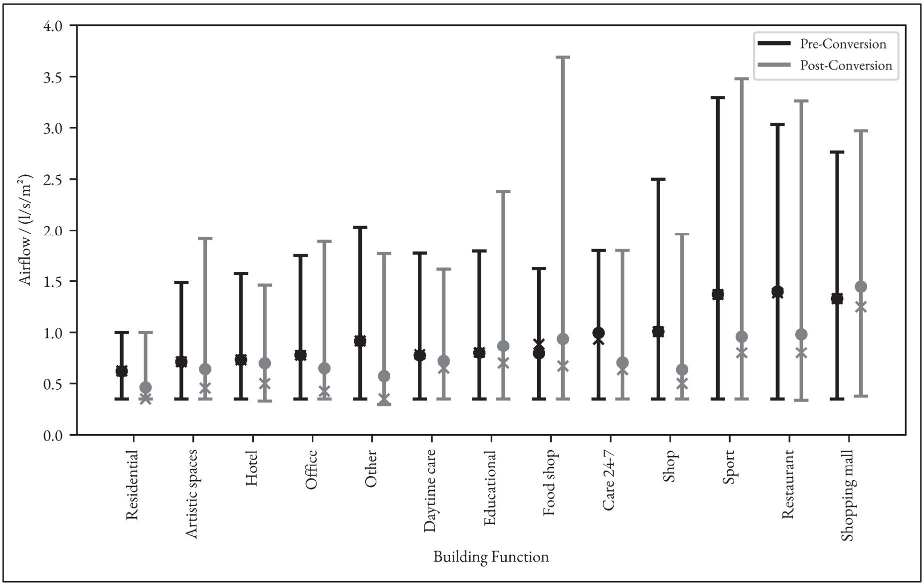

Fig. 4. Mean and median reported airflow capacities before and after conversion by building function. Dots represent mean values, crosses indicate medians, and vertical lines mark the approximate 95% range (2.5th to 97.5th percentiles).

Specific airflow exhibits substantial spread in most building functions, indicating high variability across individual buildings. Several building types show only minor shifts between pre- and post-conversion mean and median values, whereas others suggest increases or reductions that may reflect adjustments to function-specific ventilation demands. The lower range limit near 0.35 l/s/m^2 observed across multiple functions potentially signals a systematic reporting artefact in EPC data, as this is the baseline outdoor-air supply minimum for dwellings in the Swedish Building Code, and does not reflect activity- or occupancy-driven rates for non-residential uses. This observation reinforces the data quality concerns described in Section 2.3, suggesting that reported airflow figures may be subject to assessor approximation or default value entry rather than detailed measurements or actual design.

Following this functional overview, mean airflow changes were further aggregated and visualised in a matrix format to illustrate differences across all functional conversion pairs. The resulting distribution of mean airflow changes across functional conversion pairs is shown in Fig. 5.

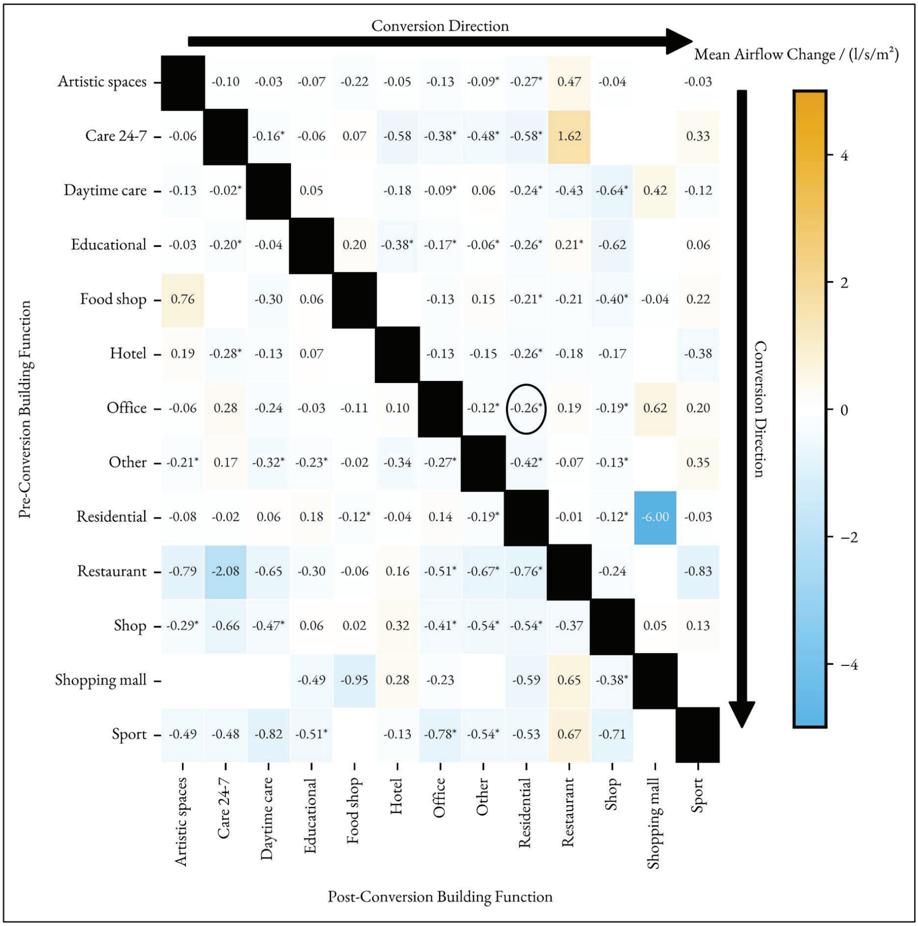

Fig. 5. Matrix of mean airflow changes by functional conversion pair. Blue shades indicate reductions and orange shades indicate increases in specific airflow after conversion, with lighter tones representing values closer to zero. Annotated values show mean differences in l/s/m², and asterisks (*) denote statistically significant changes based on the Wilcoxon signed-rank test at $p < 0.05$. The cell corresponding to conversions from office to residential function is highlighted with a circle.

The matrix visualises the direction and magnitude of airflow change, with the vertical axis representing the original (pre-conversion) building function and the horizontal axis indicating the new (post-conversion) building function. Each cell displays the mean difference in reported airflow, read from left to right and top to bottom, illustrating the direction of conversion. For example, the mean airflow change for buildings converted from office to residential function is highlighted with a circle and shows a change of −0.26 $l/s/m^2$.

The colour coding indicates the magnitude and sign of the airflow change, where blue shades represent reductions and orange shades represent increases in specific airflow after conversion. Diagonal cells, representing non-converted buildings (e.g., residential-to-residential), were excluded from this analysis and are shown in black. Lighter tones closer to white indicate values near zero. Annotated values within each cell include asterisks (*) to indicate statistically significant differences based on the Wilcoxon signed-rank test ($p < 0.05$). For example, the conversion from office to residential function is associated with a statistically significant reduction in airflow.

Among the 138 total conversion pairs examined, only 44 exhibited statistically significant changes in specific airflow, as determined by the Wilcoxon signed-rank test at a significance level of $p < 0.05$. These significant pairs account for 3 019 conversions (65% of all conversions), while the remaining 94 non-significant pairs represent 1 605 conversions (35% of all conversions). This suggests that functional conversion does not necessarily imply systematic changes in ventilation performance, or that group-level heterogeneity may obscure such effects. Given the potential for skewed and non-normal distributions, relying solely on mean values can be misleading, as extreme values may disproportionately influence the results. Separate boxplots were generated for conversions with and without statistically significant airflow changes to further examine the distributional properties of airflow changes within each conversion pathway. This approach allowed for the assessment of median shifts and internal variability, complementing the mean-based heatmap.

The boxplots for conversion pairs with statistically significant airflow changes ($p < 0.05$) are presented in Fig. 6. The horizontal axis shows the conversion pairs ordered by median airflow change, while the vertical axis indicates the change in specific airflow. Many of these conversion pathways show median reductions in airflow, with approximately 70% of individual building cases exhibiting negative differences. Although most medians lie below zero, indicating an overall tendency toward reduced airflow, several groups display wide whiskers extending across zero. This suggests internal variability within these conversions, indicating that not all buildings within each group experienced consistent directional changes. However, this result should be interpreted cautiously given uncertainty in EPC-derived specific airflow values and within-pathway heterogeneity.

Notably, conversions from educational to restaurant functions are the only case where the interquartile range lies entirely above zero. This indicates that the central 50% of buildings, situated between the first and third quartiles in this conversion pair, exhibit increased airflow. The upward trend continues beyond the third quartile, as the upper whisker includes additional buildings with larger increases. Although the lower whisker extends into negative values, these cases are fewer. The distribution is therefore positively skewed, with heterogeneous but predominantly upward outcomes.

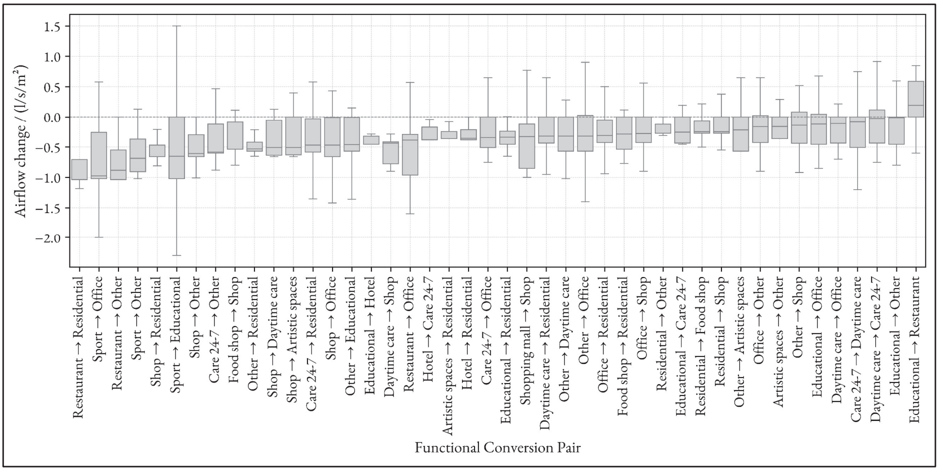

Fig. 6. Boxplots of airflow changes for conversion pairs with statistically significant changes ($p < 0.05$).

The boxplots for conversion pairs without statistically significant airflow changes ($p \geq 0.05$) are presented in Fig. 7. The vertical axis displays the conversion pairs, while the horizontal axis indicates the change in specific airflow. The axis arrangement was reversed in this figure to improve visual presentation and accommodate the larger number of groups.

Fig. 7. Boxplots of airflow changes for conversion pairs without statistically significant changes ($p \geq 0.05$).

The distributions within these non-significant pairs are notably wide, with many median values positioned close to zero. In a few cases, the boxes lie entirely on one side of zero, suggesting more uniform tendencies despite the absence of statistical significance. For example, conversions from restaurant to care 24/7 and from educational to shop show boxes fully below zero, while conversions from office to shopping mall lie entirely above zero. However, most groups contain boxes or whiskers that cross zero, indicating high internal variability and the absence of consistent directional shifts at the group level.

3.2 Ventilation type transitions following functional conversion

This subsection presents the distribution of ventilation type conversions observed in the analysed functional conversions. As the analysis in this section relies on the dominant system classification, only a single ventilation type is shown per building. For transparency, the full distribution of ventilation system transitions based on non-aggregated configurations, prior to the application of the dominant system classification, is provided in Figures S1 and S2 in the Supplementary Material. These supplementary figures present the distribution of composite ventilation setups before and after conversion, with transitions separated by cases with and without statistically significant changes in airflow ($P < 0.05$), respectively. Each composite label also includes, in parentheses, the corresponding dominant system type that was assigned during aggregation.

The transitions between pre-conversion and post-conversion ventilation system types for cases with statistically significant airflow changes ($p < 0.05$) are illustrated in Fig. 8. The vertical axis indicates the original (pre-conversion) ventilation type, while the horizontal axis shows the adopted (post-conversion) ventilation type. Each cell displays the number of conversions in the corresponding pathway, with darker shading reflecting higher counts.

The most frequent pathway involves buildings retaining MV-HR systems, accounting for 1 764 of 3 019 conversions. This is followed by cases where MEV systems are preserved (273 of 3 019), and conversions from MV to MV-HR systems (150 of 3 019). Additional prevalent conversions include MEV to MV-HR (140 of

3019) and NV to NV (131 of 3019). These dominant pathways suggest that, in many cases, buildings either retain their initial ventilation systems or shift towards MV-HR configurations.

To further support and contextualise these observations, a chi-square test of independence was performed to examine whether the distribution of ventilation type conversions could be explained by random assignment, independent of the original system type. In this context, independence would imply that the pre-conversion configuration does not influence the choice of the post-conversion system. The resulting standardised Pearson residuals are shown in Fig. 9. Positive residuals indicate conversions occurring more frequently than would be expected under independence, while negative residuals suggest underrepresentation. Statistically significant residuals ($p < 0.05$) are marked with asterisks

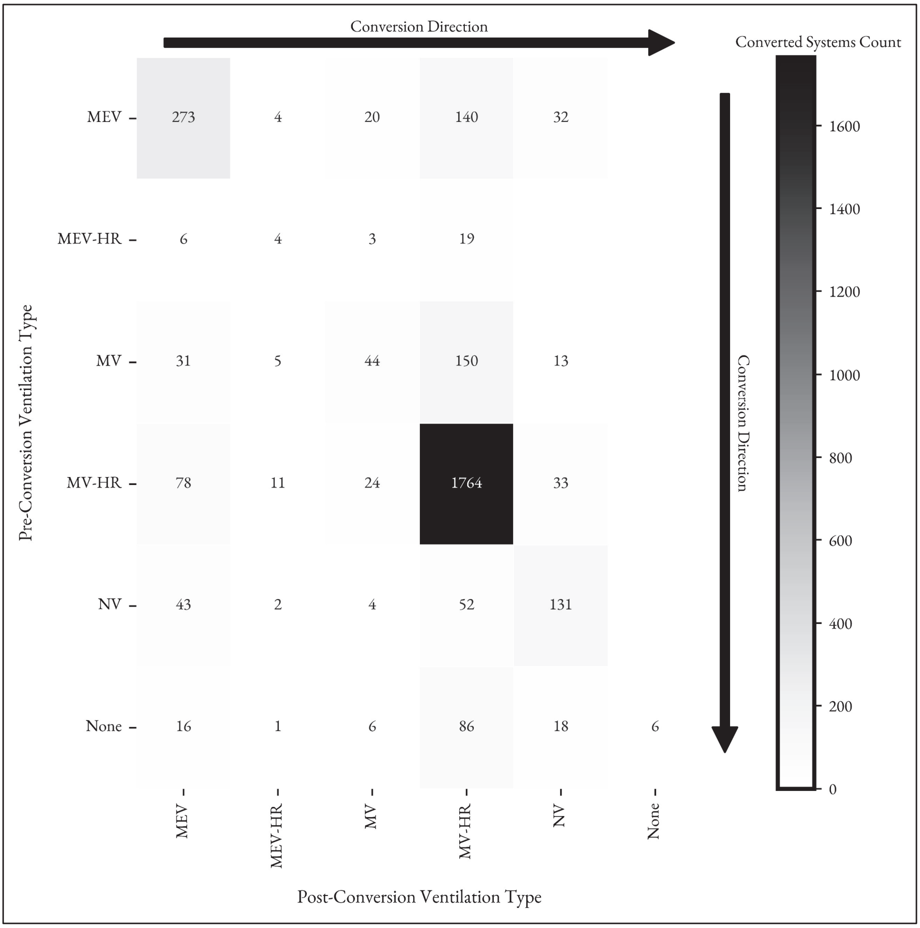

Fig. 8. Transitions between pre-conversion and post-conversion ventilation system types for cases with statistically significant airflow changes ($p < 0.05$).

Positive residuals are most pronounced for transitions where the same system type is retained (MEV to MEV, MEV-HR to MEV-HR, MV to MV, MV-HR to MV-HR, NV to NV, and None to None), suggesting a tendency to maintain original system types. Additional positive residuals for conversions such as MEV-HR to MV and None to NV may indicate a preference for upgrading system types. Negative residuals are observed in transitions such as MEV to MV-HR, MV-HR to MEV, MV-HR to MV, MV-HR to NV, and NV to MV-HR, implying these pathways occurred less frequently than expected under independence.

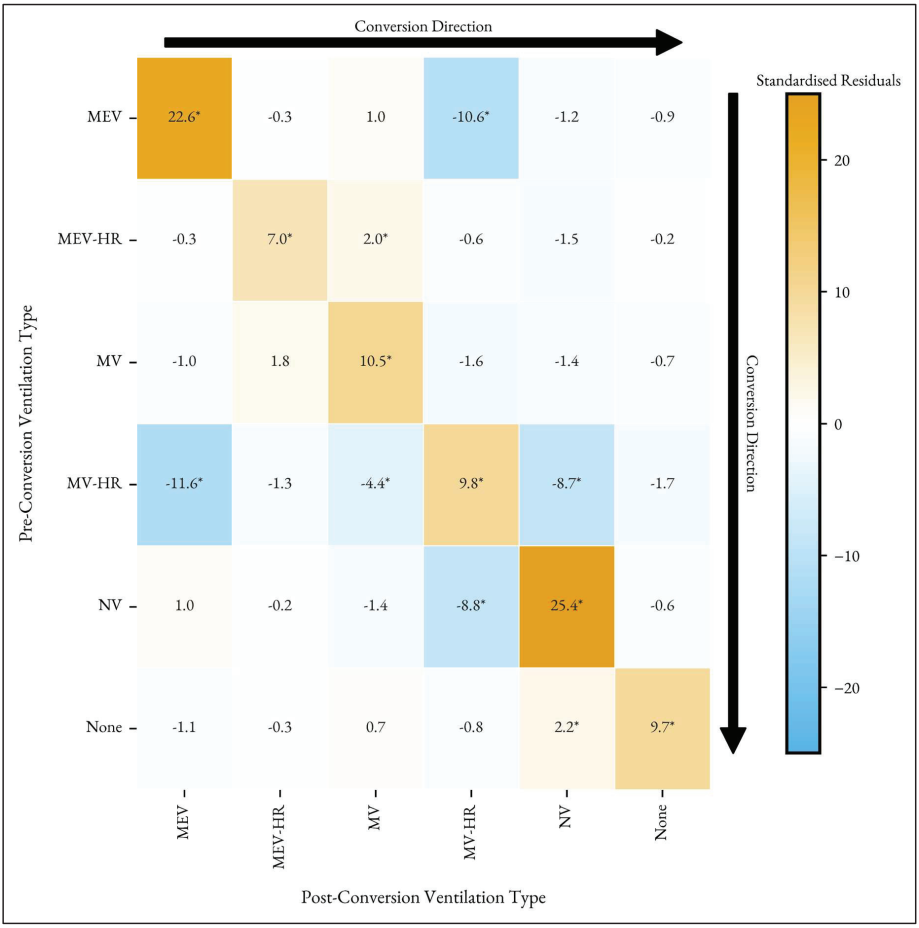

Fig. 9. Standardised Pearson residuals for ventilation type transitions in conversion pairs with statistically significant airflow changes ($p < 0.05$).

The transitions among ventilation system types for conversions without statistically significant airflow changes ($p \geq 0.05$) are shown in Fig. 10. The vertical axis represents the original system type, and the horizontal axis indicates the post-conversion type. Each cell displays the number of transitions in that pathway, with darker shading reflecting higher counts.

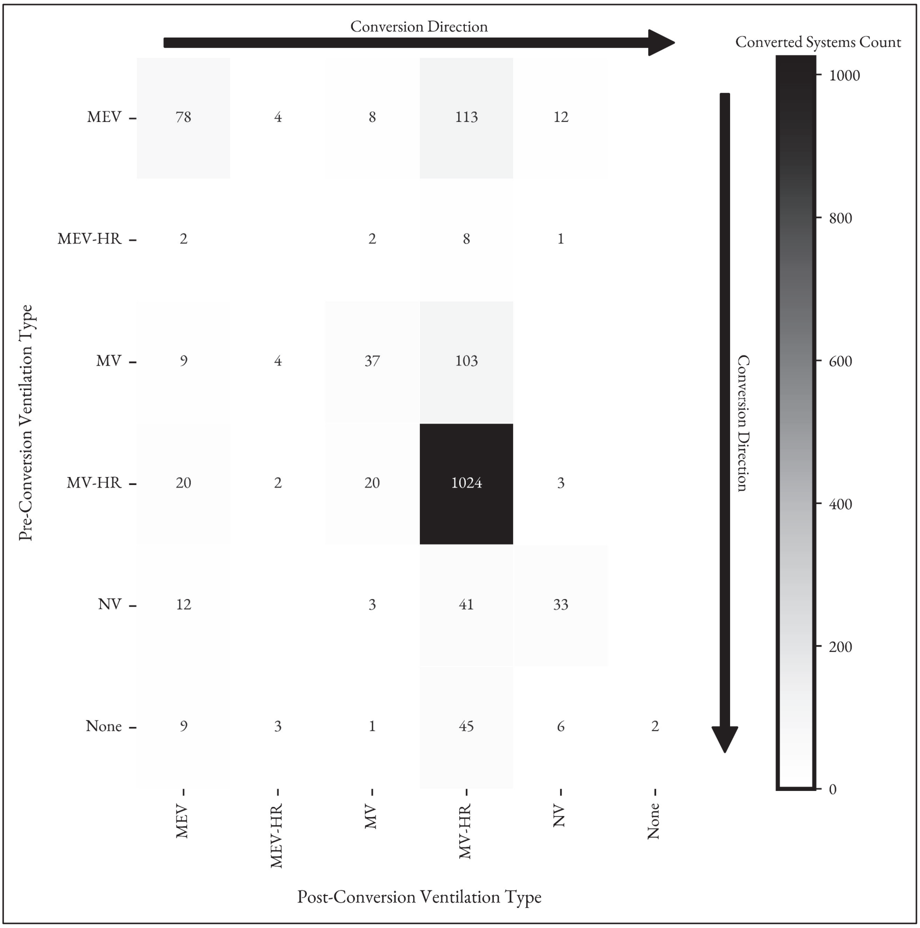

Fig. 10. Transitions between pre-conversion and post-conversion ventilation system types for cases without statistically significant airflow changes ($p \geq 0.05$).

Similar to the significant group, the most frequent pathway in these non-significant cases involves buildings retaining MV-HR systems, accounting for 1 024 of 1 605 conversions. This parallels the strong tendency for MV-HR continuity observed previously. Another shared feature is the retention of MEV systems, which remains a recurrent pathway (78 of 1 605).

However, in contrast to the significant group, the relative prominence of conversions from MEV to MV-HR (113 of 1 605) and from MV to MV-HR (103 of 1 605) is more apparent here. In the significant group, MEV to MEV and MV to MV appeared slightly more prominent relative to these cross-type shifts. Moreover, the overall distribution in the non-significant group appears more concentrated around MV-HR as a post-conversion system, suggesting a preference for either maintaining or adopting MV-HR, regardless of airflow performance shifts.

The standardised Pearson residuals for non-significant airflow conversion cases are shown in Fig. 11. The shading indicates deviations between observed and expected frequencies under the assumption of independence, with orange tones reflecting positive residuals (more frequent than expected) and blue tones indicating negative residuals (less frequent than expected). Asterisks mark cells where residuals have statistical significance at a threshold of $p < 0.05$.

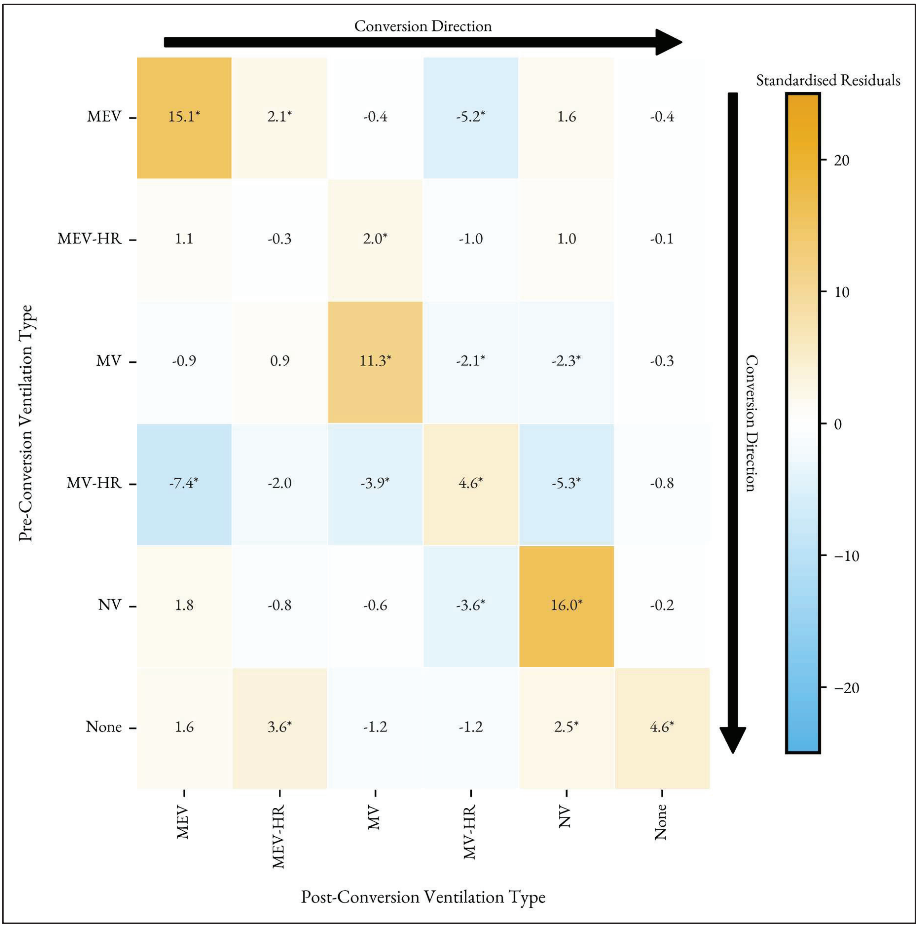

Fig. 11. Standardised Pearson residuals for ventilation type transitions in conversions without statistically significant airflow changes ($p \geq 0.05$).

Similar to the significant cases presented earlier, several conversions exhibit positive residuals, suggesting systematic tendencies even in the absence of overall significant airflow shifts. Transitions retaining the same system type (e.g., MEV to MEV, MV to MV, MV-HR to MV-HR, NV to NV, and None to None) show positive and statistically significant residuals, suggesting a strong tendency to preserve existing systems. Additional pathways with positive and statistically significant residuals include MEV to MEV-HR, None to MEV-HR, and None to NV, though at lower frequencies.

In contrast, blue-shaded cells such as MEV to MV-HR, MV to MV-HR, MV to NV, MV-HR to MEV, MV-HR to MV, MV-HR to NV, and NV to MV-HR exhibit statistically significant negative residuals, indicating that these conversions are less common than would be expected under independence. This suggests that certain ventilation type shifts, particularly towards or away from MV-HR, may be intentionally avoided when airflow performance remains unchanged.

3.3 Integrated analysis of functional and ventilation system conversions

This subsection examines the overlap between functional conversion pathways and ventilation type conversions, providing a combined perspective on how changes in use relate to modifications in technical systems.

The overlap between functional conversion pairs and ventilation type conversions for cases with statistically significant airflow changes ($p < 0.05$) is shown in Fig. 12. The vertical axis presents the functional conversion pairs arranged alphabetically, while the horizontal axis indicates the ventilation system conversion pairs. Bubble size corresponds to the number of buildings observed in each combined pathway, and bubble colour denotes whether more than 50% of buildings experienced an airflow increase (orange), reduction (blue), or if no clear majority direction could be identified (grey). The "no majority" category reflects situations where neither increase nor reduction dominates within a given group.

The largest bubbles are observed around conversions where MV-HR system types are retained (MV-HR to MV-HR), indicating that this system type is frequently preserved. A second prominent concentration is observed for MEV to MEV conversions, especially in functional conversions to residential functions. Additional clusters emerge for conversions from MEV to MV-HR among residential conversions, suggesting a tendency to adopt this configuration.

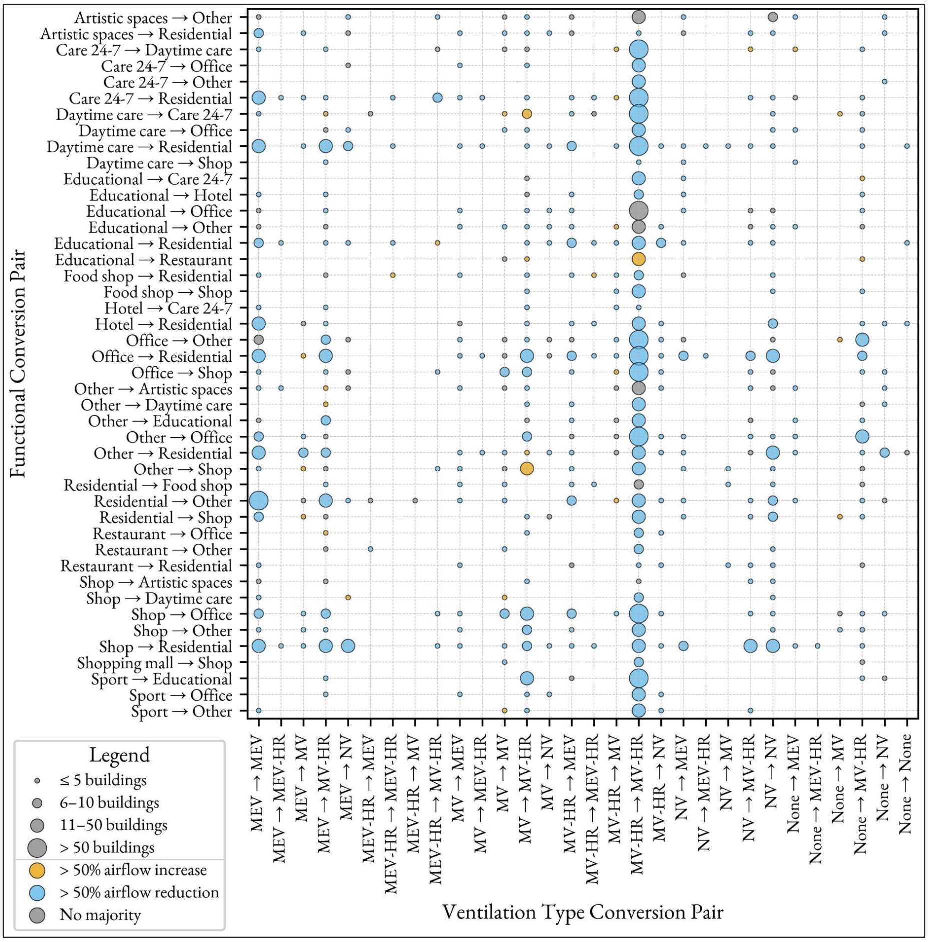

Fig. 12. Overlap between functional conversions and ventilation conversions for cases with statistically significant airflow changes ($p < 0.05$).

Across all categories, almost all bubbles are shown in blue, reflecting that the majority of buildings in these combined pathways experienced reductions in specific airflow. This dominant blue shading is consistent with previously noted group-level median reductions and may suggest that adaptive reuse involving significant functional changes often coincides with deliberate reductions in airflow. The small number of orange or grey bubbles indicates that the clear majority of increases or mixed airflow outcomes are relatively uncommon within this subgroup.

The integrated plot for cases without statistically significant airflow changes ($p \geq 0.05$) is shown in Fig. 13. In this plot, the vertical axis presents the functional conversion pairs, while the horizontal axis shows the ventilation type conversion pairs. Bubble size indicates the number of buildings within each combined pathway.

The colour coding of bubbles represents the prevailing direction of reported airflow change within each group: orange indicates cases where over 50% of buildings experienced an increase, blue indicates over 50% experienced a reduction, and grey signifies no clear majority direction.

As in the significant group, MV-HR to MV-HR transitions dominate, representing the largest share of cases among all combinations. This suggests a tendency to retain MV-HR systems even in the absence of systematic airflow shifts. MEV to MV-HR and MEV to MEV pathways are also visible, although they remain substantially smaller in absolute terms.

All three groups are mainly prominent in conversions from residential functions. This pattern indicates that when residential buildings are adapted, they are often either equipped with MV-HR systems or retain pre-existing MEV configurations.

While grey bubbles form the majority, reflecting the absence of a clear group-level directional tendency, orange and blue bubbles are also present across various combinations. This observation suggests that even where no systematic airflow changes are identified at the group level, individual buildings within each conversion pathway may still experience directional shifts in specific airflow.

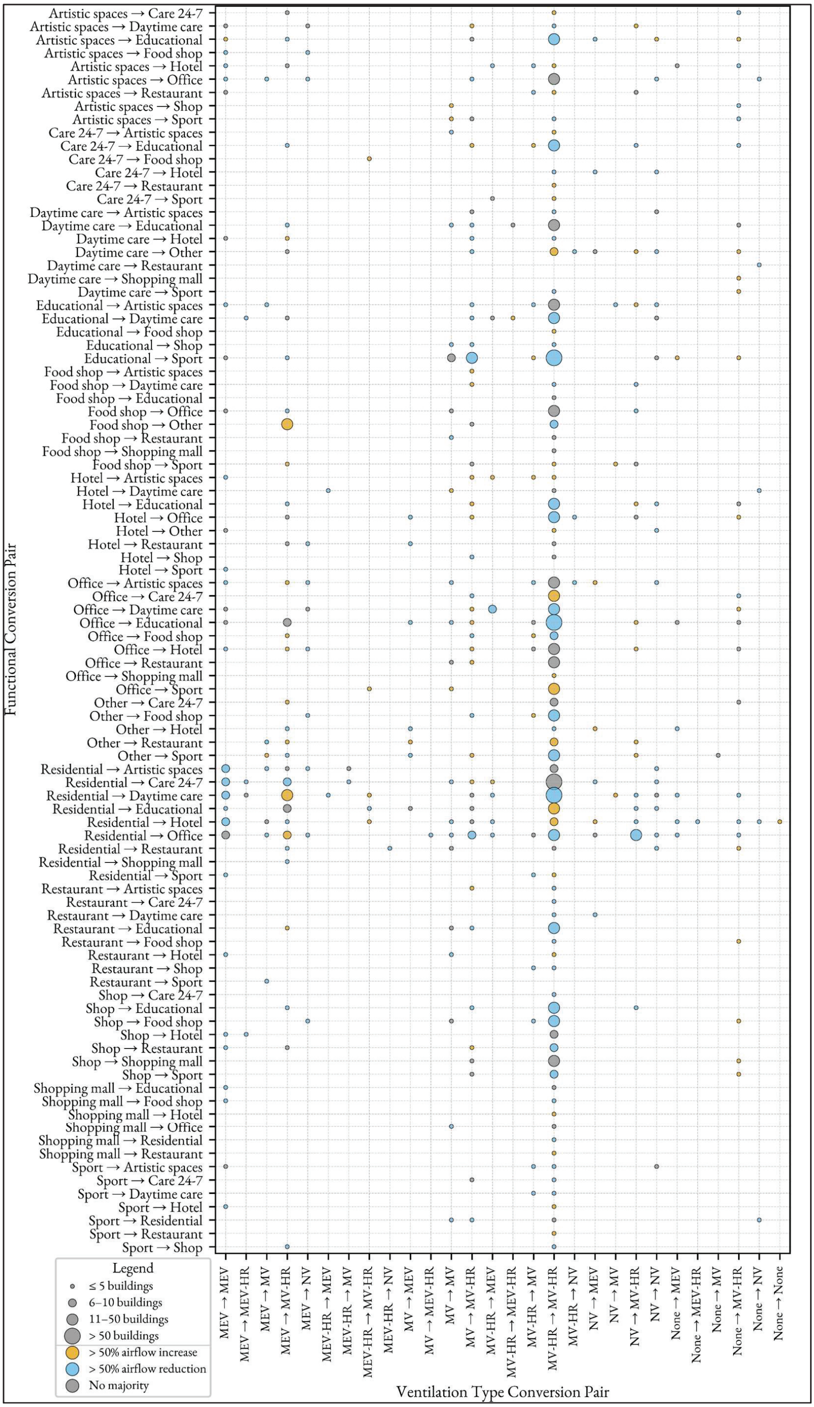

Fig. 13. Overlap between functional conversions and ventilation conversions for cases without statistically significant airflow changes ($p \geq 0.05$).

4. Discussion

The results presented in this study characterise ventilation system types and reported specific airflow before and after functional conversions in the Swedish building stock. This section presents the findings in relation to the three research questions posed at the outset, with each subsection addressing a separate question. The discussion focuses on how observed ventilation patterns may inform adaptive reuse practices, influence technical decision-making, and intersect with regulatory constraints related to airflow provision and system configuration.

4.1 Ventilation airflow changes following functional conversion

Reported specific airflow before and after conversion shows limited differentiation across most building functions; mean and median values are generally between 0.5 and 1.0 $l/s/m^2$. The interquartile range and the empirical 2.5th–97.5th percentile interval indicate substantial within-function variability. Several functions display medians or lower bounds near 0.35 $l/s/m^2$. This value corresponds to the minimum outdoor-air supply for dwellings in current Swedish regulation; repeated occurrence across non-residential groups may reflect default or rounded entries rather than measurement-based values. Specific airflow entries are assessor-reported and may be calculation-based; the basis for these calculations is not recorded. Records are compiled at the property level without spatial allocation of system types or airflow in multi-building properties. These features could compress distributions and concentrate values at discrete levels, introducing uncertainty when attributing observed shifts to physical change.

Across the 138 functional conversion pairs, 44 exhibited statistically significant differences in reported airflow, accounting for approximately 65% of the buildings in the dataset. Reductions were more common than increases, although magnitudes were generally modest. In these pairs, approximately 70% of building-level differences were negative, and most medians lay below zero. The only case with the interquartile box entirely above zero was “Educational to Restaurant”, indicating a more consistent upward shift. Most other pairs showed boxes mainly below zero, with whiskers extending across zero, indicating internal variation despite a prevailing downward tendency. Among the 94 non-significant pairs, the medians were typically near zero, although several exhibited boxes entirely above or below zero, suggesting directional changes within subsets of buildings, even where group-level tests did not reach significance.

The predominance of reductions among significant pairs may arise from several non-exclusive mechanisms. Functional transfers into categories with lower target-specific airflow could lower area-normalised provision without changing the system type. Recommissioning within an unchanged system type might reduce operational setpoints after conversion. Reporting practices in EPCs, including calculation-based entries and rounding toward category minima, could increase the frequency of small negative differences. Selection effects may also operate, insofar as conversions may proceed preferentially where required specific airflow can be met by downscaling existing provision, reducing the need for augmentation. These explanations cannot be distinguished with EPC records alone; results should therefore be interpreted as indicative rather than causal.

4.2 Ventilation system type shifts following functional conversion

Ventilation system types that undergo functional conversion exhibit a strong tendency to retain their original configuration. Among conversions associated with statistically significant airflow changes, 73% of buildings retained their pre-conversion system type, with 58% specifically maintaining ventilation supply and exhaust systems with heat recovery. A similar pattern is present in the non-significant group, where 73% also preserved their initial system type, and 63% remained within the MV-HR category. This consistency suggests that system type replacement is uncommon in both cases, regardless of whether changes in reported airflow occur. While this retention may indicate technical compatibility between functions, it could also reflect cost, space, or procedural constraints that limit opportunities for redesigning the ventilation system during adaptive reuse, necessitating further evaluation of the actual reason.

The associated Pearson residuals reinforce this interpretation. In both airflow-significant and non-significant subsets, the highest positive residuals are linked to cases where the same system type is preserved, such as MV-HR to MV-HR, MEV to MEV, and MV to MV. These transitions occurred more frequently than would be expected under the assumption of independence, indicating that post-conversion system selection is not random but systematically influenced by pre-conversion configuration. In contrast, several cross-type transitions involving MV-HR, including MV-HR to MV, MV-HR to MEV, and MV-HR to NV, show negative and statistically significant residuals. These outcomes suggest that movement away from MV-HR is less common than would occur under independence, even when airflow adjustments are present. The inverse holds for some upgrade pathways in the non-significant group, such as MEV to MV-HR and MV to MV-HR, where positive residuals are more prominent. This pattern may indicate the selective introduction of more energy-efficient or controllable ventilation systems, even where performance shifts are not reflected in the reported airflow.

While system type classifications suggest a high rate of continuity, this observation does not imply technical stasis at the component level. Within retained categories such as MV-HR or MEV, individual air handling units may be replaced, reconfigured, or upgraded without altering the categorical assignment recorded in EPC data. Consequently, categorical transitions underestimate the extent of intervention in ventilation equipment and may obscure internal shifts in system control, filtration, or heat recovery performance. The observed stability in system type, therefore, requires cautious interpretation. It may reflect real technical continuity, or it may instead signal the limitations of a classification framework that compresses heterogeneous configurations into a small number of nominal categories.

4.3 Integrated analysis of functional and ventilation system conversions

The results in this subsection are based on the aggregated dominant ventilation system classification. Comparison with the non-aggregated configuration matrices provided in the Supplementary Materials indicates that overall patterns of major system shifts are consistent between the two approaches, suggesting that the simplification does not materially affect the main interpretations.

In cases with statistically significant airflow changes, three distinct clusters dominate the combined distribution of functional and ventilation system conversions. The most prevalent is the retention of MV-HR system types across a wide range of functional pathways. These cases occur throughout the dataset and are consistently associated with a majority of buildings exhibiting reduced airflow, suggesting that even where functional demands shift, the ventilation strategy remains within the same formal category. A second cluster consists of MEV to MEV transitions, concentrated in conversions toward residential use, again coupled with prevailing airflow reductions. The third cluster includes MEV to MV-HR transitions, found in both directions, involving residential functions. Despite indicating a shift to more controlled ventilation systems, these cases are also characterised by a majority of airflow reductions. The consistency of this pattern across functionally diverse conversions suggests that adaptive reuse, when accompanied by measurable airflow changes, is often implemented through adjustments to ventilation provision within a constrained set of categorical system pathways. Whether these transitions involve physical intervention or reconfiguration within existing typologies remains unresolved in the data. Still, the observed outcomes suggest that downward airflow modulation is a common response to new functional conditions.

Among conversions without statistically significant changes in specific airflow, the distribution of combined functional and ventilation system transitions presents a more varied profile. The MV-HR to MV-HR pathway remains the most frequent, often accompanied by a majority of buildings showing airflow reductions, although several combinations display a larger share of increases. MEV to MEV transitions continue to appear predominantly in conversions from residential functions, again typically associated with reduced airflow. In contrast to the significant group, a higher number of MEV to MV-HR cases in this subset are marked by airflow increases, particularly in conversions originating from residential use. These instances suggest that, even in the absence of statistically detectable group-level changes, some transitions may involve ventilation enhancement at the building level. The broader distribution of bubble colours, including more grey and orange outcomes, indicates that performance shifts within this group are less uniform and more context-dependent. While categorical system types remain stable or follow familiar patterns, the variability in directionality suggests a wider range of technical responses, possibly shaped by localised conditions or project-specific constraints.

The combination of reduced airflow and retained system type observed across many conversions may suggest that, in some cases, the original ventilation systems could be preserved during adaptive reuse. If the new functional demands require lower specific airflow and remain within the limits of the existing configuration, it is plausible that the air handling unit and associated infrastructure might be reused rather than replaced. This possibility is relevant from a practice perspective, as the ability to retain equipment could reduce both costs and material use, therefore improving the technical and environmental efficiency of adaptive reuse. While this outcome cannot be confirmed solely from EPC data, the observed patterns suggest a scenario in which ventilation adaptation may be achieved through adjustment rather than substitution, provided that system conditions, control capacity, and regulatory thresholds are compatible with the new use.

5. Conclusions

This study examined how ventilation provision in Swedish buildings is affected by functional conversion, using over 4 600 realised adaptive reuse cases with paired EPC records. The analysis focused on three research questions concerning specific airflow, system type transitions, and the combined configuration of functional and technical change. The following key findings address the three primary research questions that guided this study:

- **What changes in specific airflow are observed following functional conversions in Swedish buildings?** Across all conversions, 44 functional pairs showed statistically significant changes in airflow, representing 65% of all analysed buildings. Within this group, 70% of cases displayed reductions in reported airflow. Among the remaining 35% of buildings, where no statistically significant change was observed, 52% still exhibited reduced airflow. Although magnitudes were generally modest, these figures indicate a prevailing tendency toward downward adjustment. However, the occurrence of the 0.35 l/s/m² threshold across multiple functions raises concerns regarding the use of default values in EPC reporting.

- **How do ventilation system types change during functional conversions, and to what extent are original ventilation system types retained or changed?** Ventilation system type was retained in 73% of cases, both among conversions with and without statistically significant airflow changes. Mechanical supply and exhaust systems with heat recovery were the most frequently preserved configuration, with MV-HR to MV-HR representing the most common pathway overall. This indicates a strong tendency to maintain this ventilation strategy even when functional demands changed. Pearson residuals further confirmed that same-type transitions, including MV-HR to MV-HR, occurred more frequently than expected under independence, suggesting that the pre-conversion system configuration systematically influences post-conversion choices.
- **How are joint changes in building function and ventilation system type associated with changes in reported specific airflow?** Three common combinations were observed among conversions with significant airflow changes: MV-HR to MV-HR transitions across functions, MEV to MEV in residential conversions, and MEV to MV-HR around residential conversions. In most of these combinations, the majority of buildings experienced reductions in airflow. Conversions without a significant change in airflow showed a more varied distribution, but often followed similar categorical pathways.

These patterns suggest that adaptive reuse may be facilitated when ventilation demand decreases or remains within the specific airflow of the existing system type. While replacement of physical equipment cannot be ruled out, the categorical stability of ventilation type observed in the data may indicate that such replacement is not always necessary. In cases where the existing system strategy remains technically compatible with the new function, conversion projects could proceed with limited intervention in ventilation type, potentially reducing both cost and implementation complexity.

The findings also suggest that ventilation adaptability is one potential condition that influences the feasibility of reuse. Buildings where ventilation systems can be recalibrated to suit the new function, rather than substituted entirely, might be more readily converted. This possibility requires further empirical examination, particularly regarding interventions at the component level and the regulatory adequacy of adapted systems.

6. Future work

Several areas warrant further investigation to extend the empirical and practical relevance of this study. The observed consistency in ventilation system types following functional conversion raises the question of whether existing equipment is technically capable of supporting new functional demands. Future research should include site-level documentation and technical inspections to determine whether air handling units and associated components are retained and, under what conditions, such preservation is feasible. Comparative case studies could support the identification of reuse strategies where ventilation systems are adjusted rather than replaced.

The use of EPC-reported airflow data introduces uncertainty regarding the extent and nature of physical adaptation. On-site measurements, conducted before and after conversion, could help establish whether recorded airflow changes correspond to actual ventilation adjustments. This would also allow for the validation of reporting practices and clarify whether common values, such as the recurring 0.35 $l/s/m^2$ threshold, reflect physical realities or administrative defaults.

Further analytical work is needed to examine how ventilation systems, particularly AHUs, perform under altered conditions following functional conversion. Simulation or empirical modelling could assess the effect of modified airflow demands on key performance parameters such as specific fan power, pressure conditions, and control performance. Such investigations would help determine whether retained systems continue to operate within acceptable efficiency and regulatory margins when the building is converted, and could inform future standards for evaluating the compatibility of reuse.

Finally, the accuracy and consistency of EPC records should be examined more systematically. Although the current dataset enables large-scale pattern identification, the underlying data sources remain partially opaque. Targeted audits and assessor-level verification could support improved understanding of EPC reliability and inform the use of administrative data for ventilation-related research.

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The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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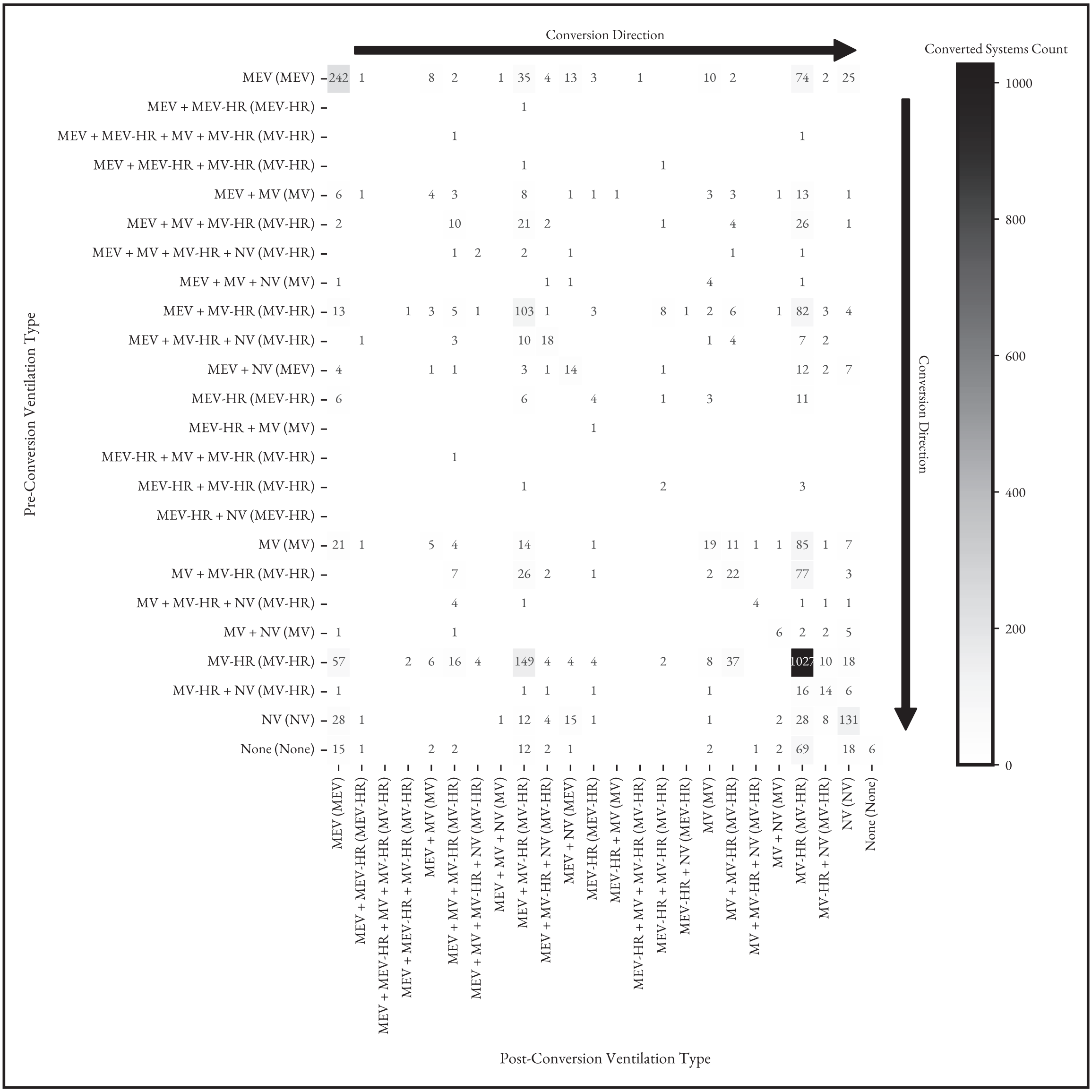

Fig. S1. Distribution of ventilation system transitions among statistically significant conversion cases, based on non-aggregated configurations. Each cell represents the number of buildings transitioning from a given pre-conversion ventilation setup (rows) to a post-conversion setup (columns), with shading indicating conversion frequency. Only cases with statistically significant changes in airflow (P < 0.05) are included. Composite types represent non-aggregated ventilation types prior to the dominant system application. Parentheses indicate the corresponding dominant system type after aggregation.

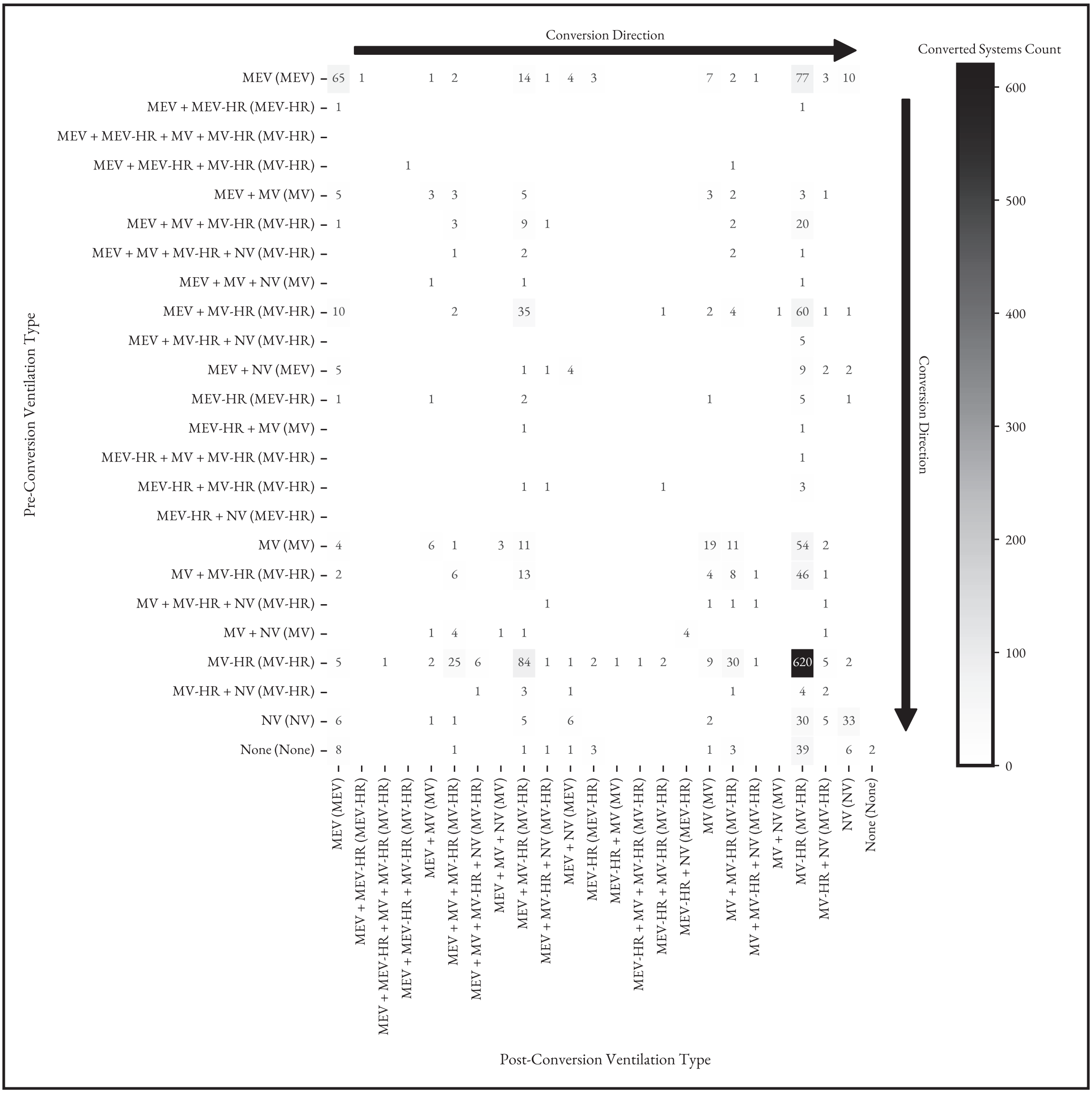

Fig. S2. Distribution of ventilation system transitions among non-significant conversion cases, based on non-aggregated configurations. Each cell represents the number of buildings transitioning from a given pre-conversion ventilation setup (rows) to a post-conversion setup (columns), with shading indicating conversion frequency. Only cases without statistically significant airflow changes ($P \geq 0.05$) are included. Composite types represent non-aggregated ventilation types prior to the dominant system application. Parentheses indicate the corresponding dominant system type after aggregation.

Paper III

Building services and adaptive reuse – an overview of the regulations and potential in Swedish context.

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Abstract. Adaptive reuse of buildings, repurposing existing structures for new functions, is gaining attention for its potential in sustainable development and optimisation of building materials usage. This practice is particularly relevant in the building sector, where space heating, ventilation, and air conditioning (HVAC) systems represent a significant portion of project costs, embodied energy, greenhouse gas emissions, and impact on indoor air quality and thermal comfort. Despite its importance, the scientific literature on converting HVAC systems within adaptive reuse projects remains limited, particularly in distinguishing between adaptive reuse and traditional renovation. To address this gap, this study analyses historical and contemporary Swedish building regulations, focusing on HVAC requirements across various building types and eras. This analysis assesses similarities and differences between building types in different periods. It uncovers that the absence of stringent contemporary regulations offers no formal barriers to converting HVAC systems across different building types. For example, office buildings emerge as strong candidates for conversion into residential apartments due to compatible HVAC requirements. However, buildings constructed before 1968 may necessitate extensive modifications to meet current standards. The findings suggest that post-1968 buildings, particularly apartments, align more closely with modern HVAC norms, facilitating easier renovation. This research contributes to the field by outlining practical boundaries for renovating and converting buildings based on their construction period. It provides insights into the feasibility of repurposing existing buildings in the absence of drawings and other technical details, which is instrumental for sustainable urban planning and efficient resource utilisation.

1 Introduction

Contemporary sources indicate that sustaining the current lifestyle of modern society would require the equivalent of three Earth-sized planets [1]. Climate change and energy poverty challenges represent formidable threats to human well-being [2]. Consequently, urgent and decisive action is imperative to maintain economic growth, ensure clean and affordable energy access, and narrow the inequality gap. Most (56 %) of the global population currently resides in urban areas [3]. Projections suggest that in 2050, urban inhabitants will constitute about 66% of the global populace [4]. This urban expansion directly impacts the building sector, accounting for an estimated 62 % of total energy usage [5] and 55 % of greenhouse gas emissions [6]. As cities expand, so do the construction and operation of buildings, intensifying their energy and carbon emissions footprint. In Sweden, buildings are responsible for approximately 34 % of energy use and 21 % of greenhouse gas emissions [7], [8]. Building services — such as heating, ventilation, and air conditioning systems (HVAC), electric lighting, and water supply and disposal systems — play a substantial role, accounting for 50 % and 48 % of these figures, respectively [9]. While sustainable renovation – enhancing the energy efficiency of buildings – has been a key strategy in reducing environmental impacts [10], the concept of adaptive reuse emerges as a possible yet underexplored approach. Adaptive reuse involves repurposing existing buildings for new functions, a method with the potential to reduce energy usage and environmental impacts in the building sector [11]. However, current regulations and scientific literature show a noticeable gap in addressing the reuse of building services. This gap limits a systematic approach to the implementation of adaptive reuse strategies [12–15]. An analysis of historical building regulations in Sweden emphasising HVAC systems is performed in this article to bridge this gap. The aim is to identify and compare the key requirements for HVAC systems across different building types and eras. For instance, an exploration of the regulatory similarities of building services between an office building constructed in the 1960s and a residential building constructed in the present day was conducted. This historical cross-comparison is necessary for understanding the potential and challenges in adapting buildings from different

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periods for new uses. The findings of this analysis are intended to serve as a preliminary guide for evaluating the feasibility of adaptive reuse, focusing specifically on building services.

2 Methodology

Historical and contemporary Swedish building regulations, spanning from BABS 46 (1946) to BFS 2011:6, including amendments up to BFS 2020:4, were analysed to identify key HVAC requirements across various building types [16–58]. The focus was to discern similarities and differences in these requirements, assessing the potential of transitioning between old and new buildings. The comparison benchmark was the current BBR 29 regulation. The regulations where HVAC requirements are the same were grouped together. The analysis primarily focused on four parameters:

- Air flows per premise (measured in l/s)
- System types (heating, cooling and ventilation)
- Operative temperature set points.
- Air distribution patterns

Technical aspects of air distribution patterns were examined. The 1968 to 1975 period was generalised in the analysis due to its more detailed nature compared to other periods.

Certain assumptions were made to ensure the analysis reflected realistic scenarios and facilitated comparative evaluations. When airflow was indicated in l/s/m², it was recalculated into l/s based on the following assumptions:

- Apartment Building: Assumed area of 75 m², housing four residents, reflecting the average area and occupancy rate.
- School: The classroom area is assumed to be 60 m², with an average of 20 students.
- Office: Cellular office assumed to be 60 m², with six workers.

The study excluded industrial and hospital buildings due to their unique layouts and requirements and the absence of specific HVAC regulations for these types. It was also assumed that the buildings perfectly complied with the regulations wherever applicable. The types of ventilation systems were identified based on building regulations and were defined as follows:

- S (självdragsventilation): Natural ventilation.
- F (fläktventilation där frånluftsflödena är fläktstyrda): Mechanical exhaust ventilation.
- FT (fläktventilation där både frånluft- och tilluftsflödena är fläktsyrda): Mechanical supply and exhaust ventilation.
- FX (fläktventilation där frånluftsflödena är fläktstyrda med värmeåtervinning): Mechanical exhaust ventilation with heat recovery.
- FTX (fläktventilation där både frånluft- och tilluftsflödena är fläktsyrda med värmeåtervinning): Mechanical supply and exhaust ventilation with heat recovery.

This study did not consider fire safety or any regulations besides BBR and its older counterparts.

3 Results and discussion

The findings of this research are described below. This section begins with a description of the general observations from the regulations and continues with an analysis of the specific requirements for space heating and ventilation. The final part of this section is the similarity matrix between different building types and periods.

The historical progression of building regulations in Sweden can be divided into three distinct phases, each defined by its unique approach to HVAC requirements for various building types.

Regulatory Wild West (1946 – 1960): Characterised by the introduction of BABS 46, BABS 50, and BABS 60, this era is noted for broad and general HVAC requirements, where distinctions between building types were minimal. The primary focus was on single- and multi-family houses, occasionally mentioning offices and classrooms. Natural ventilation was the prevalent system. This period is marked by the specification of duct cross-section areas rather than airflow rates for natural ventilation. Building commissions could also prescribe mechanical ventilation for specific circumstances like the removal of excess heat, vapours, or other hazardous substances or when natural air circulation was inadequate. Mechanical ventilation had requirements for airflow rates and air preheating for supply air during this period. Notably, there was no mention of thermal comfort or heating systems, posing challenges in assessing the reuse potential of buildings from this period and often necessitating the introduction of new mechanical systems.

Period of Regulatory Centralisation (1968 – 1975): Coinciding with the "Miljonprogrammet" era of rapid housing construction in Sweden, this phase features more detailed and descriptive regulations. It includes the most complex rules of all periods, specifying system types, duct sizes, air flows, and instructions for replacement air supply. The FT system type is officially introduced during this phase. A notable change is a decrease in the required clearance between ceiling and floor in offices from 2.9 m to 2.7 m, which is likely to accommodate mechanical ventilation installations. This period also introduces considerations for operative temperature, activity type, air temperature, relative humidity, temperature gradient, and floor temperature – parameters that have remained mainly unchanged to the present day. For schools and offices of this period, the regulations prescribed fully mechanical ventilation. Natural ventilation was used in single-family houses, limited to buildings not exceeding two floors in height. This phase also marks the first instance of regulations prescribing operative temperature and mandating central heating in all buildings.

Period of Regulatory Privatisation (1976 – Today): The current phase is characterised by a reduction in prescriptive requirements and a shift towards more outcome-based standards, leaving decision-making to individual engineers and consultants. System type requirements have been removed; any system fulfilling air flow requirements is now permissible. With BBR 12's introduction, the regulation pivoted to stipulating air flow requirements per floor area, omitting premise-specific requirements. Concurrently, energy usage regulations for buildings were introduced and progressively tightened, leading to a preference for the FTX ventilation type. When it comes to renovation and transformation, the current regulations suggest using existing performance indicators as guidelines, especially when meeting requirements is economically unfeasible.

The results of the ventilation systems analysis are visualised in Fig. 1 and Fig. 2. Fig. 1 illustrates the minimal permitted airflow for the mechanical supply ventilation. Fig. 2 shows the minimal permitted airflow for exhaust mechanical ventilation across different periods and building types. In both figures, the X-axis quantifies the required air flows in litres per second (l/s) for each building category. On the Y-axis, the building types are codified as 'A' for apartments, 'O' for offices, and 'S' for schools. The following colour coding is used to enhance the clarity and ease of interpretation: black represents the minimum airflow requirements for apartment buildings, light grey for offices, and yellow for schools. The colour-coded lines are connected to the values from the modern building code and provided to facilitate comparison between different building types and periods.

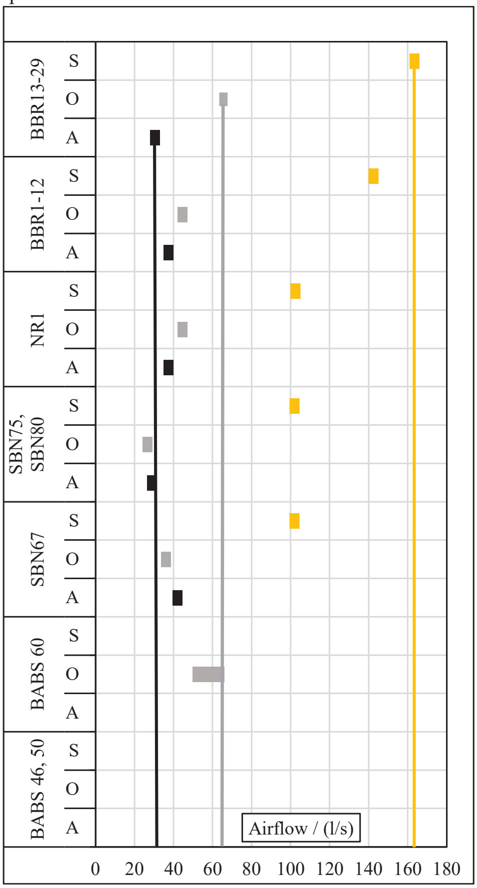

Fig. 1. Evolution of regulations for mechanical supply ventilation.

The results from the space heating system regulations analysis are provided in Table 1. For buildings constructed before 1968, there are no specified requirements for thermal comfort or heating systems. In contrast, buildings constructed after 1968 are more aligned with contemporary standards, as regulations from SBN 67 BABS 1967 through to BBR 29 recommend central heating systems with operative temperatures ranging from 18 °C to 20 °C.

Table 1. Heating system regulations over history

	Residential spaces	Offices	Schools
BABS 46, 50, 60 (1946-1968)	Not prescribed	Not prescribed	Not prescribed
SBN 67 BABS 1967 (1968-1975)	20 °C ; central heating	Central heating	20 °C ; central heating
SBN 75 – BBR 29 (1976-today)	18 °C – 20 °C* ; central heating	18 °C – 20 °C* ; central heating	18 °C – 20 °C* ; central heating

*: 5 °C operative temperature variation is permitted at different points of the premise.

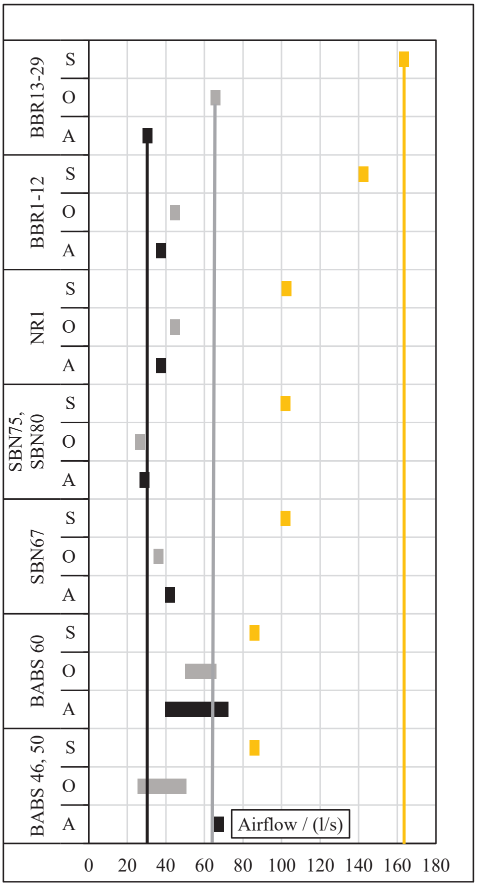

Fig. 2. Evolution of requirements for mechanical exhaust ventilation.

Regarding cooling systems, their regulatory evolution mirrors that of heating systems. The earlier standards, including BABS 46, 50, and 60 and SBN 67, did not stipulate any requirements for cooling systems. Starting with SBN 75 and persisting through to BBR 11, a limitation was placed on the maximum floor temperature, measured at 0.5 meters from the floor, at 27 °C. This limitation was reduced to 26 °C in BBR 12 and has remained unchanged through BBR 29. The regulations have consistently focused on outcomes rather than specifying cooling system designs.

The air distribution strategy described in building regulations ranging from BABS 46 to BBR 29 is uniform in its core principle: air is supplied to zones with the highest occupancy and air quality demands, typically bedrooms and living rooms, and removed from areas with lower air quality requirements, such as kitchens and toilets. Additionally, these regulations uniformly mandate the minimisation and prevention of odour and pollutant spread, with an exclusive emphasis on pollutant spread in SBN 75 and SBN 80.

However, there are differences in the air-mixing aspects of these regulations. SBN 67 allowed mixing exhaust air with the supply air, primarily for energy efficiency purposes, specifically in preheating supply air. This regulation stipulates that such mixing is permissible, provided there are effective measures to prevent the spread of odour and pollutants, such as dust and dangerous substances. Subsequently, SBN 75 and 80 expanded this allowance, even permitting the inclusion of air from toilets in the mix, on the condition that the ratio of low-quality air to total supply air remains below a threshold of 1:15. In contrast, from BFS 1988:18 NR1 through to BBR 12, the delivery of mixed air to high air quality zones was prohibited. This stance was revised in BBR 13, reinstating the permissibility of air mixing, stipulating that such air must be returned to the original premise from which it was extracted, ensuring the prevention of odour and pollutant spread.

Regarding duct layout, each set of standards prescribes different guidelines. BABS 46, 50, and 60 allow the use of shared ducts between apartments in mechanical ventilation systems while prohibiting this in natural ventilation systems. Within an individual apartment, the standards mandate separate ducts for kitchens and bathrooms, allowing a maximum of two living rooms to connect to kitchen and bathroom exhausts, provided the ductwork traverses only through corridors and not other premises. SBN 67 allows for a deviation of up to 10% in air flows and duct sizes, which should not be a systematic feature across the entire system but limited to specific cases. It also permits common ducts for different apartments, conditioned on effective fire and noise spread prevention measures. Additionally, separate exhaust ducts for bathrooms and kitchens were mandatory. SBN 80 sets forth stringent requirements for the removal of dangerous substances, necessitating the implementation of airtight and segregated ventilation systems in hospitals and industrial buildings. It also stipulated the use of specialised exhaust hoods in laboratories and kitchens designed to capture dangerous substances effectively. From BFS 1988:18 through to the current standards, the only overarching requirement stipulated for air distribution is that the entire occupancy zone in all buildings must receive ventilation conforming to the prescribed airflows.

Table 2 presents the regulatory similarity matrix, comparing air distribution, heating and cooling system types and setpoints (HC), and mechanical intake (I) and exhaust airflows (E) across various building types and periods. The following colour-coding system to indicate similarity levels was used:

- Light grey: Indicates high similarity or identical requirements, suggesting feasible adaptation or reuse of existing systems.
- Yellow: Represents requirements that exceed modern setpoints, potentially offering more than current standards.
- Brown: Denotes requirements slightly below modern setpoints, implying minor adjustments or updates may be needed.
- Dark grey: Indicates lack of information, making it challenging to determine compatibility or needed modifications.
- White: Signifies substantial differences from modern requirements, indicating that significant renovation or conversion efforts would be necessary.
- Black: Represents the comparison benchmark.

Table 2. The regulatory similarity matrix

		BBR 29								
		A			O			S		
		HC	I	E	HC	I	E	HC	I	E
BBR13-29	A	black	black	black	light grey	white	white	light grey	white	white
	O	light grey	yellow	yellow	black	black	black	light grey	white	white
	S	light grey	yellow	yellow	light grey	yellow	yellow	black	black	black
BBR1-12	A	light grey	light grey	light grey	light grey	white	white	light grey	white	white
	O	light grey	light grey	light grey	light grey	brown	brown	light grey	white	white
	S	light grey	yellow	yellow	light grey	yellow	yellow	light grey	brown	brown
NR1	A	light grey	yellow	yellow	light grey	white	white	light grey	white	white
	O	light grey	yellow	yellow	light grey	brown	brown	light grey	white	white
	S	light grey	yellow	yellow	light grey	yellow	yellow	light grey	brown	brown
SBN75, SBN80	A	light grey	light grey	light grey	light grey	white	white	light grey	white	white
	O	light grey	light grey	light grey	light grey	white	white	light grey	white	white
	S	light grey	yellow	yellow	light grey	yellow	yellow	light grey	brown	brown
SBN67	A	yellow	light grey	light grey	dark grey	white	white	yellow	white	white
	O	dark grey	light grey	light grey	dark grey	white	white	dark grey	white	white
	S	yellow	yellow	yellow	dark grey	yellow	yellow	yellow	white	white
BABS 60	A	dark grey	dark grey	light grey	dark grey	dark grey	light grey	dark grey	white	white
	O	dark grey	light grey	yellow	dark grey	light grey	light grey	dark grey	white	white
	S	dark grey	dark grey	yellow	dark grey	dark grey	light grey	dark grey	white	white
BABS 46,50	A	dark grey	dark grey	yellow	dark grey	dark grey	light grey	dark grey	dark grey	white
	O	dark grey	dark grey	light grey	dark grey	dark grey	white	dark grey	dark grey	white
	S	dark grey	dark grey	yellow	dark grey	dark grey	yellow	dark grey	dark grey	white

Regulatory similarities indicate a number of possibilities for the adaptive reuse and renovation of various building types within specific regulatory frameworks. Historical buildings from 1946 to 1968 offer limited potential for adaptive reuse due to the absence of precise HVAC requirements. This lack of detail makes aligning these buildings with contemporary standards for any new purpose challenging. Post-1968 apartment buildings, despite meeting or surpassing current airflow standards, do not present straightforward opportunities for conversion into other building functions, such as offices or schools, due to the typically lower airflow requirements of residential spaces. Office buildings constructed between 1968 and 2023 demonstrate potential for conversion, but only into apartments. This is attributed to the compatible airflows that can accommodate residential needs. With their airflow requirements, offices from periods before 1988 might not easily lend themselves to modern renovation due to significant differences in airflow demands. Schools, however, exhibit considerable flexibility for adaptive reuse, with the only constraint being their educational function. Their historically higher airflows provide a viable basis for transforming into apartments and offices, particularly for those built after 1968. These buildings can generally maintain their original function easily, with older schools requiring more attention to ensure alignment with the latest standards. Renovation prospects are consistently favourable for apartments across all periods, particularly after 1968, due to the often higher historical airflows that readily meet modern criteria. Conversely, the office renovation is more complex as the requirements for offices decreased between BABS 60 and SBN 80 and increased between BFS 1988:18 NR 1 and contemporary BBR 29. This escalation in airflow demands post-1988 complicates the renovation process, suggesting that certain modifications may be necessary to achieve compliance with current standards.

4 Conclusions and future work

The study's examination of Swedish HVAC regulations from the past to the present provides an overview of the adaptation possibilities of various building types. The analysis uncovers that the absence of stringent contemporary regulations presents no formal barriers to converting HVAC systems across different building types. Notably, office buildings emerge as the most viable candidates for conversion into residential apartments, given the compatibility of their HVAC requirements. The potential for schools to undergo similar transformations exists; however, their dedicated educational function diminishes the practical likelihood of such conversions. Regarding renovations, apartment buildings stood out for their straightforward compliance with modern standards after 1968. Pre-1968 constructions, by contrast, may necessitate a higher degree of intervention to meet current HVAC norms. The schools have a high disparity between contemporary and historical requirements, posing more significant challenges due to discrepancies in minimal airflow rates. Office buildings present a different scenario, where only those built between 1960 and 1968 align closely with contemporary standards, and both older and newer offices deviate markedly or lack clear regulations altogether. The article contributes to the field by bridging informational gaps in understanding of the building services within existing structures. Its primary value lies in providing a methodological approach to infer HVAC system specifications in buildings without detailed drawings or specific data. This approach allows for preliminary analysis, enabling stakeholders to make informed assumptions about the existing building services before conducting site visits.

The next research phase aims to delve into the specifics of HVAC systems inventory within each building category, assessing the type and conditions of existing equipment and the economic and environmental feasibility of their reuse to obtain a practical basis for adaptive reuse and renovation measures.

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Paper IV

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Adaptive reuse and building services: stakeholder perspectives on obstacles and pathways

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Abstract. The reuse of building services, particularly HVAC (Heating, Ventilation, and Air Conditioning) components, remains underexplored in adaptive reuse practices despite their substantial environmental impact and material intensity. This study investigates the feasibility of HVAC component reuse through a mixed-methods approach, combining a structured questionnaire with semi-structured interviews involving professionals from HVAC manufacturing, design, and regulatory sectors. Based on prior literature and stakeholder insights, the research identifies four main barriers: governance, environmental, technical, and economic. Due to their modularity and passive design, air ducts, diffusers and air handling units (AHUs) were most frequently considered suitable for reuse. However, concerns about corrosion, outdated standards, and lack of warranties limit the broader application of reuse. Stakeholders emphasised the need for regulatory support, standardised verification tools, and new business models to make reuse economically viable. The study concludes that HVAC reuse must be integrated into a broader adaptive reuse framework and highlights the need for further research on building typologies, performance, lifecycle protocols, and implementation strategies.

1. Introduction

The building sector accounts for 30% of global final energy use and 26% of global environmental impact during the construction and operational phases [1]. Increasing urbanisation and evolving work patterns, particularly in the post-COVID-19 era, have led to high vacancy rates in existing buildings [2,3]. Meanwhile, the demand for affordable housing continues to rise. It is estimated that by 2030, urban populations will reach three billion, requiring 96 000 new housing units to be built daily [4]. This discrepancy between the growing demand for new spaces and underutilised existing buildings calls for alternative solutions beyond new construction.

Adaptive reuse allows retaining embodied energy, reducing material demand, and extending building lifespans [5,6]. While extensively researched, adaptive reuse has predominantly focused on structural elements such as façades, load-bearing systems, and spatial configurations [7]. Building services, such as HVAC (Heating, Ventilation, and Air Conditioning) systems, are often excluded from reuse despite their significant contribution to a building's environmental footprint, accounting for up to 30% of total impact in some cases [8,9]. Studies suggest that HVAC reuse is technically feasible under specific conditions, though its success depends heavily on system layout, component accessibility, and reliable documentation [10]. Nonetheless, challenges such as non-standardised retrofit practices, potential energy penalties from pressure losses, and mismatched sizing complicate the reuse of ductwork and related components [11]. Ventilation systems, in particular, have been identified as poorly suited to spatially flexible or adaptable buildings due to their rigid, space-intensive configurations [12]. While circularity frameworks exist at broader scales, reuse at the service layer remains underexplored and poorly supported by empirical evidence [13,14].

This study addresses that gap by focusing on the reuse of HVAC components in adaptive reuse. Drawing on actor-network theory (ANT) [15], and recent literature on circularity and reuse in construction, the research investigates the feasibility, barriers, and stakeholder dynamics involved in HVAC reuse. Unlike broader studies on circular construction, this study examines the specific technical, economic, regulatory, and cultural factors that shape decisions related to building services. It does so through a combination of questionnaire data and semi-structured interviews with HVAC manufacturing, regulation, and design professionals. The following research questions are answered in this study:

1. Which HVAC components are more suitable for reuse, according to stakeholders?
2. What are the key barriers preventing the adaptive reuse of HVAC components in building conversions?
3. How do industry stakeholders perceive responsibility for enabling HVAC reuse, and whom do they rely on for support?
4. What strategies or measures do stakeholders believe would support the reuse of HVAC components?

2. Method

This study examines the feasibility of HVAC component reuse through questionnaires and semi-structured interviews structured around four key themes identified in existing literature: governance, environmental impact, technical constraints, and economic considerations. Governance barriers include the lack of collaboration between stakeholders and insufficient regulatory frameworks. Environmental concerns relate to the presence of hazardous substances and the broader potential for reducing embodied carbon emissions. Technical challenges include performance degradation, component accessibility, and limitations in integrating reused systems into new designs. Economic considerations involve cost-effectiveness, financial incentives, and market demand. These themes have been discussed in previous research on material reuse within construction contexts [16–19].

2.1. Questionnaire design

A structured questionnaire was developed to gather insights from building industry professionals, including architects, HVAC specialists, sustainability consultants, and developers. It aimed to identify barriers, opportunities, and enabling conditions for HVAC component reuse. The questionnaire was organised into three sections: background information, general questions applicable to all respondents, and profession-specific questions. Participants selected from predefined options related to barriers and infrastructure needs (e.g., regulations, material banks), with open-ended fields allowing elaboration on overlooked topics. The research design was informed by ANT, which considers both human, e.g., engineers, regulators, and non-human, e.g., HVAC components, standards, actors as shaping reuse outcomes. This approach highlights how HVAC reuse is influenced not only by technical performance but by socio-economic and regulatory networks.

2.2. Interview design

Semi-structured interviews were conducted with professionals from HVAC manufacturing, building regulatory authorities, and sustainability consulting to supplement the questionnaire. While the survey captured broad patterns, the interviews provided more insights into feasibility, logistics, and governance.

The open-ended format allowed respondents to expand on themes and introduce unanticipated issues relevant to reuse implementation.

2.3. Limitations

This study has several limitations. The number of interview participants was modest, limiting the breadth of perspectives and generalisability. Voluntary participation may have introduced self-selection bias, favouring respondents already engaged with sustainability or reuse. While diverse roles were targeted, some actors, such as maintenance professionals, demolition contractors, and financial stakeholders, were not represented, potentially omitting perspectives on operational, end-of-life, and investment challenges. Although anonymity was assured, social desirability bias may have influenced some responses. Additionally, findings reflect the Swedish regulatory and market context and may not directly translate to regions with differing frameworks, economic conditions, or cultural attitudes toward reuse.

3. Results and discussion

The questionnaire was completed by 32 participants, with 19 respondents based in Sweden. Among them were architects, professionals in HVAC-related fields, including HVAC manufacturing and mechanical engineering, building owners, sustainability consultants, and researchers. The remaining ten participants represented a diverse group, including project managers, structural engineers, and professionals involved in building regulations. The full panel of respondents to the questionnaire is shown in Figure 1.

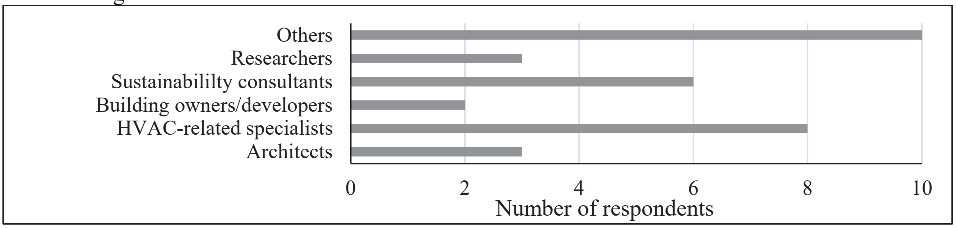

Figure 1. The professional background of questionnaire respondents.

In addition to the questionnaire, eight industry specialists participated in semi-structured interviews. These included an energy engineer from a building development company, an LCA specialist from an HVAC manufacturer, and a technical manager from an HVAC manufacturing firm. Two interviewees held the position of director of sustainability and external regulations at HVAC manufacturing companies. Other participants included a business development manager from a building installations and services company, a sustainability expert in building regulations and planning, and a head of market development from a sustainability services company.

3.1. Suitability of HVAC Components for Reuse

Figure 2 presents the answers to the question regarding which HVAC components are perceived to have the highest potential for reuse. This question targeted professionals in HVAC-related fields. Air ducts and air handling units (AHUs) were most frequently selected, followed by diffusers, hydronic pipes, and fans. Justifications emphasised component simplicity, durability, and ease of refurbishment. Respondents highlighted ducts as relatively low-risk components due to their passive nature. As one participant explained, "Air ducts could likely be reused given they are of acceptable size, have acceptable insulation, and have been tested for air leakage." AHUs were also seen as partially reusable: "AHUs are bigger and more expensive and can relatively easily be upgraded by switching out several components." By contrast, moving or water-connected parts were viewed as problematic: "All moving parts, motors, etc., will have a loss in effectiveness after a while; all water-connected products might have a corrosion problem." Age was another concern: "Most of the equipment is beyond its expected life expectancy and should be replaced to avoid operational failure or significant efficiency decline."

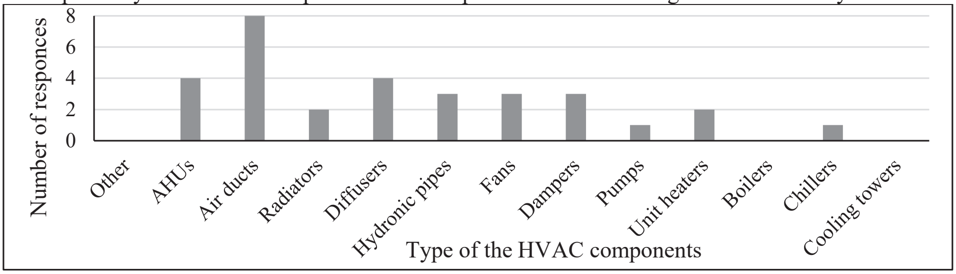

Figure 2. Responses to the questionnaire question: "Which HVAC components do you believe have the greatest potential for reuse? Multiple selections were allowed.

Interviewees largely reinforced these views. One developer noted that reuse already occurs "if they fit the conditions of the new building and the building function remains the same." A technical manager described "air ducts [as] the most ideal" component for reuse, while water-related systems "are tough to reuse because they are welded together." An LCA specialist added that "supply air ducts tend to be cleaner," but pointed out that "air ducts are the cheapest part," making reuse economically uncertain. Quality assurance was also emphasised: "The quality assurance would consist of cleaning and checking for leakage… a visual inspection." Logistical constraints were noted as well: "Ducts would require large amounts of space for storage, and transporting them could also pose challenges." One respondent concluded that "it is better to focus first on residential and office buildings," suggesting that reuse potential may depend on building typology.

3.2. Key Barriers to HVAC Component Reuse

Participants were asked to identify the main barriers to the reuse of HVAC components by responding to the question, "What barriers/challenges exist with the reuse of HVAC components?" They could select from four predefined categories or specify additional barriers under the "Other" option. Figure 3 shows that technical challenges were cited most frequently, particularly among HVAC engineers and sustainability consultants. One respondent summarised, "The main problem is the technical one: if there is no knowledge on how it can be done, then none of the other problems can be addressed." Governance-related obstacles included limited stakeholder coordination, weak regulatory frameworks, and a lack of enforcement. Environmental concerns focused on hazardous legacy materials, particularly chromium VI and asbestos: "Toxic materials in HVAC are a big no. If such are detected, it is automatically impossible."

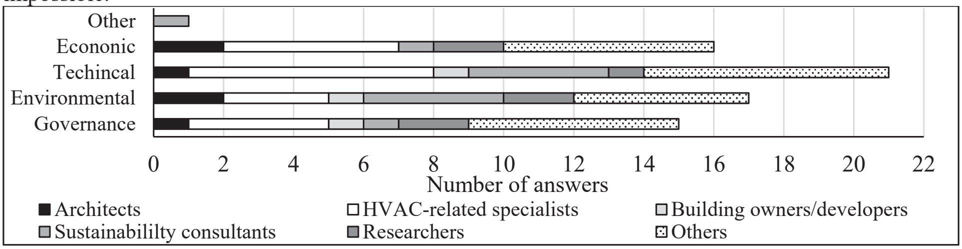

Figure 3. Distribution of perceived barriers to HVAC component reuse, as reported by questionnaire respondents. Multiple selections were allowed.

Economic constraints, including high labour costs, perceived inefficiency, and uncertainty around long-term performance, were also prominent. One respondent wrote, "The building industry is extremely price-driven. If a new build is cheaper than reusing, it will only be used if there are guidelines." Others reinforced that "money leads the way."

Interviewees echoed these concerns. Developers and manufacturers pointed to technical degradation, evolving standards, and warranty limitations. One HVAC manager explained, "Trying to meet certain energy efficiencies... may be difficult with reused components. Innovation could prevent reuse." Another observed, "The cost of reuse, including the cost of storage, transportation, disassembling, and cleaning, could be roughly twice the cost of buying new."

3.3. Stakeholder Responsibility and Support Networks

Participants were asked to identify which actors they would rely on to implement the reuse of HVAC components. Figure 4 shows that HVAC engineers and building owners were most frequently selected, followed closely by the sustainability consultants. Government regulations were also noted, though often seen as a prerequisite rather than a driver.

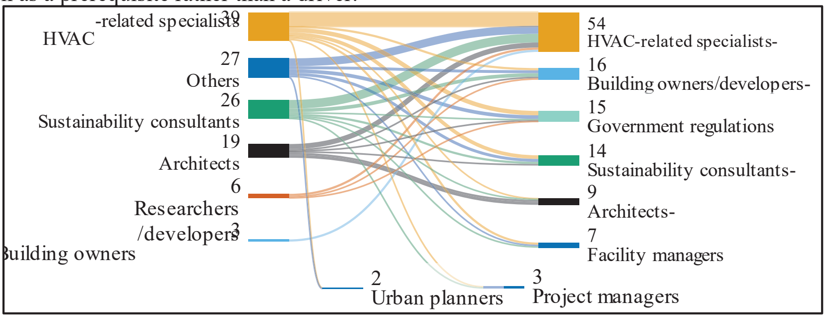

Figure 4. Perceived responsibility for HVAC reuse implementation. Multiple selections were allowed.

Interview responses reinforced the role of property developers. One manufacturer noted that "government regulations and demand from building owners would have to happen simultaneously." Another added, "contractors/designers don't have this mandate... reuse must be less costly than building with new components for any market demand to develop." Many participants described reuse as dependent on coordinated effort across the supply chain. As one interviewee explained, "Everyone would be leaning on each other for the process to work. However, everyone is concerned with their own financial gains."

3.4. Strategies to Facilitate HVAC Component Reuse

Participants were asked what framework or infrastructure would be needed to initiate the reuse of HVAC components. Open responses could also be provided. As shown in Figure 5, regulations and material banks received the highest number of selections, followed by market demand. Material passports and EPDs were selected less frequently but were still acknowledged by architects and HVAC engineers as important traceability tools. While grouped together in the questionnaire, these serve different functions: EPDs, based on EN 15804+A2 standard, quantify environmental impacts but do not assess reusability [20], whereas material passports aim to document component composition and condition to support reuse strategies [21].Open-ended responses called for "strict enforcement on recycled materials regulations" and "guidelines that make reuse the default, not the exception." Several participants emphasised standardisation and guarantees: "Owners are going to need a warranty on reused or refurbished components."

Interviewees elaborated on the infrastructure needed. Some proposed that manufacturers manage storage and refurbishment, noting their technical capacity and space. One manufacturer stated, "The manufacturers have the space and expertise to store the ducts and can provide quality reassurance for reuse." Others envisioned business models where manufacturers or contractors reclaim and refurbish components, potentially with policy support or financial incentives. Education and collaboration were also highlighted. As one sustainability consultant argued, "There should be better interaction between manufacturers, technical consultants, architects, and contractors to facilitate this."

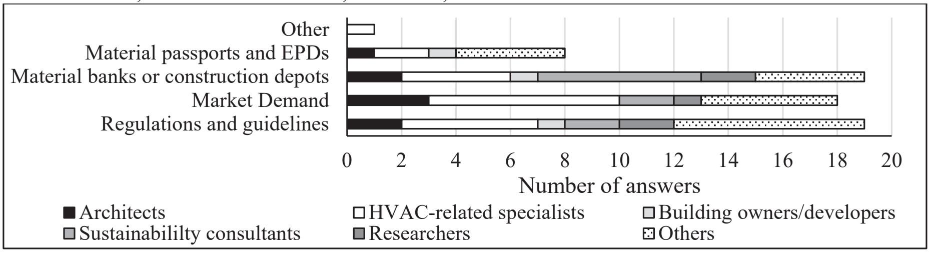

Figure 5. Responses to the questionnaire question: "What framework/infrastructure do you need to start this practice?" Multiple selections were allowed.

4. Conclusions and future work

The findings from this study demonstrate that while the reuse of HVAC components is technically feasible and generally supported by industry professionals, its practical implementation remains constrained by regulatory uncertainty, economic disincentives, and technical challenges. Passive elements, such as air ducts and modular systems like AHUs, were viewed as having the highest reuse potential. However, concerns about performance degradation, absence of warranties, and compliance with evolving energy efficiency standards continue to present substantial barriers. The role of governance was repeatedly emphasised, with stakeholders highlighting the need for clear regulations, standardised verification tools, and market-based incentives to support reuse. Notably, the results indicate that HVAC reuse cannot be treated as an isolated technical issue; it is embedded within broader decision-making networks involving manufacturers, developers, contractors, regulators, and increasingly, property managers and maintenance actors. Adaptive reuse of buildings has traditionally focused on the structural envelope; yet, this study shows the need to include building services, particularly ventilation systems, as a critical element of reuse strategies.

Future research should address identified gaps by including underrepresented actors such as maintenance professionals and property managers to capture insights into system reliability, warranties, and long-term operational risks. Comparative studies across building typologies, especially between residential and office settings, could help to account for variations in system complexity, renewal cycles, and retrofit potential. Further development of reuse-oriented performance assessment protocols, including in-use testing, simulation-based modelling, and refurbishment standards, could enhance the technical credibility of HVAC reuse. Case studies from countries with more advanced reuse policies could provide benchmarks and inform regulatory frameworks elsewhere. Additionally, integrated scenario modelling and traceability tools, including material passports, could help align reuse strategies with lifecycle-based sustainability goals and facilitate broader market adoption. Finally, future research should systematically investigate the economic and environmental impacts of HVAC reuse, providing data to policymakers and industry stakeholders to encourage informed and sustainable reuse strategies.

Conflict of Interest and Acknowledgements

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Paper V

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A novel method for early-stage evaluation of adaptive reuse potential through functional division matching

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Keywords: Adaptive reuse; Building conversion; Early-stage evaluation; Functional division matching; Programme structuring; Typological compatibility.

ABSTRACT

The building sector accounts for a significant portion of global final energy use and greenhouse gas emissions, demonstrating the need to find low-carbon alternatives to new construction. Adaptive reuse offers a sustainable alternative to new construction, yet early-stage assessments of reuse potential often rely on surface-level metrics, failing to consider a building's internal spatial logic. This paper presents a novel method for evaluating adaptive reuse potential by comparing functional divisions – operationally linked clusters of rooms – across existing and proposed building functions. The method was developed in close collaboration with industry stakeholders to ensure practical relevance and applicability in real project contexts. It proceeds through four steps: comparing spatial requirements, identifying adjacency relationships, grouping rooms into functional divisions, and comparing these across programmes. It enables structured, early-stage screening of spatial compatibility before design development. The method was tested through a workshop on the potential conversion of a pre-school to an elderly care facility. The case demonstrated how spatial mismatches and economic infeasibility, such as insufficient living units for operational viability, can be identified early, avoiding costly redesigns. The method also supports reversible planning by highlighting flexible spatial nodes and fostering long-term adaptability.

INTRODUCTION

The building industry accounts for approximately 30% of global final energy use and 26% of greenhouse gas emissions during both construction and operation phases [1]. Notably, the embodied energy from construction activities alone typically accounts for approximately 3% and 35% of lifecycle energy demand, depending on building type, lifespan, and geographical context. Similarly, embodied carbon generally represents between 37 % and 68% of total lifecycle carbon emissions over a 60-year building lifespan, further emphasising the substantial environmental benefits achievable through adaptive reuse [2].

In response to climate targets and resource constraints, adaptive reuse, the practice of converting old buildings to new functions, has emerged as a key strategy to reduce the environmental impact of buildings by extending their service lives and reducing the need for new construction [3,4]. At the same time, changing demographic needs, evolving welfare provision, and urban restructuring have created increased pressure to find new uses for underutilised buildings, particularly in Nordic countries, where ageing populations, migration patterns, and school closures intersect with growing demand for care facilities and housing [5].

While adaptive reuse is widely recognised as a sustainable practice, assessing the suitability of a specific building for conversion remains a challenge [6]. Early-phase decisions are often

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made without structured analysis, relying instead on surface-level indicators such as total floor area, building age, or location [7]. These indicators, while helpful, do not account for the internal functional organisation of the building or the spatial demands of the intended new use. Consequently, buildings that appear suitable on paper may prove unworkable in practice, leading to costly redesigns, inefficient layouts, or project abandonment [8].

This gap in early-phase evaluation highlights the need for methods focused on programme structure: how spaces are functionally organised, how rooms relate through adjacency, and how these groupings align between building typologies. Recent methodological advancements include multi-case spatial mapping, where adaptability was systematically assessed by matching apartment layouts with assisted-living requirements [9], and configurational methods such as SAGA, which quantify adaptability through spatial permeability and connectivity using weighted graph analysis [10]. However, these approaches primarily emphasise spatial and theoretical dimensions, without explicitly addressing practical considerations such as reversibility of interventions, technical constraints, or economic viability.

In contrast, this study proposes a method for evaluating the adaptive reuse potential at an early stage, based on an operational comparison of functional divisions between existing and intended uses. Rather than focusing on building form or physical condition, the method analyses spatial programmes through adjacency relationships and functional clustering, explicitly integrating technical feasibility, economic viability, and reversibility of spatial interventions. The method thus provides practitioners, planners, and researchers with a transparent and scalable framework to assess spatial compatibility across building typologies prior to detailed design or significant investment. The method was developed in collaboration with industry partners to ensure its practical applicability in real project contexts.

METHOD

The proposed method supports early-stage evaluation of adaptive reuse potential by comparing the internal spatial structures of existing and proposed building functions. It is intended for contexts where both functions, such as care, education, or office use, can be described through spatial programmes: structured lists of required spaces with associated area demands and adjacency relationships. The method focuses on functional organisation rather than form or condition, aiming to estimate spatial compatibility before design development.

The method proceeds through four sequential steps. These steps mirror established architectural design practice for new buildings, where spatial requirements, adjacency logic, and functional groupings are systematically examined step by step to ensure operational coherence.

- Comparing spatial requirements
- Identifying adjacency logic
- Grouping rooms into functional divisions
- Comparing these divisions across the existing and target programmes.

In the first step, the existing and intended operational specifications are described in terms of their required rooms or premises. A room in this study is defined as an enclosed space bounded by walls, regardless of whether these are structural or non-structural. Each room type is associated with a minimum floor area derived from design standards, operational benchmarks, or client requirements. This results in two structured programme lists, independent of any specific building geometry. These serve as abstract representations of functional demand and are treated as the conceptual basis for subsequent spatial reasoning.

The second step involves identifying the relationships between different functions within each programme. These adjacency logics describe which spaces should be co-located or spatially separated, depending on operational, accessibility, or privacy considerations. Professional practice, institutional guidelines, or user interviews typically inform these relationships. In cases where adjacency is critical, such as between staff areas and care rooms or between kitchens and dining rooms, these relationships guide the grouping logic used in the next stage.

In the third step, rooms are grouped into coherent higher-order units referred to here as functional divisions. Each division is composed of rooms that are operationally linked and should be located in close spatial proximity to one another. For example, in a care facility, a division might consist of private rooms, shared sanitary spaces, and a small staff area. In a school, it might include classrooms and adjacent group rooms. The total floor area of each division is calculated, and its internal structure, namely, the types of rooms and adjacency patterns, is recorded. These divisions form the core unit of analysis for the next step.

The fourth step is the comparative analysis of divisions across the two building uses. The aim is to identify whether any division in the existing building function corresponds, in both scale and structure, to a division in the proposed function. Compatibility is assessed on quantitative (total floor area) and qualitative (similarity in room types and spatial relationships) levels. The result is not a binary 'fit/no-fit' judgment, but a spectrum of alignment: some divisions may match fully, others only partially, and some not at all. These findings are typically recorded in a table or diagram showing potential mappings, overlaps, or gaps between functions.

This division-level approach helps identify buildings with adaptive reuse potential that are structurally embedded in space organisation, as opposed to those where conversion would require major reconfiguration.

The method does not account for technical systems, structural grids, or legal compliance. It is intended as a conceptual screening tool in the early stages of a project to support prioritisation and decision-making before architectural design or detailed feasibility studies are undertaken.

ANALYSIS

The proposed method was tested through a full-day workshop to assess its usability in a real-world setting. The case study focused on a building currently operating as a pre-school in an urban area where demographic changes have led to a decrease in the number of children requiring pre-school facilities, and an increase in the need for elderly care facilities. This shift in local needs provided a relevant scenario for applying the method. The architecture firm FOJAB, based in Malmö, initiated the workshop and brought together a multidisciplinary team consisting of representatives from a well-established Swedish property owner, architects with expertise in pre-school and elderly care design, and researchers specialising in adaptive reuse and circularity in technical systems. One architect led the workshop to ensure structured progression through the method's stages.

The first step involved specifying the spatial programmes for both uses. Architects with domain-specific expertise listed the required room types and associated minimum floor areas for pre-school and elderly care operations. These programme items may be derived from plan evaluations, room function plans, or, as in this case, from the experiential knowledge of specialists familiar with designing both building types. For reversible transformations, such specialists have full knowledge of the operational demands of the existing and the intended functions. The resulting programme table, alongside the floor plan of the current building, is shown in Figure 1.

In the second step, relationships between rooms were analysed. Using movable sticky notes representing each room and its area, participants clarified critical adjacencies, such as the proximity required between home rooms and common areas. Degrees of adjacency tolerance were discussed to distinguish between rooms that require strict co-location and those that can be separated within a shared zone. Grouping spaces in this way generated clusters that reflect the operational need for adjacency during use. Functions with minimal dependencies appeared as solitary or standalone elements, offering greater flexibility when fitting into a fixed spatial layout.

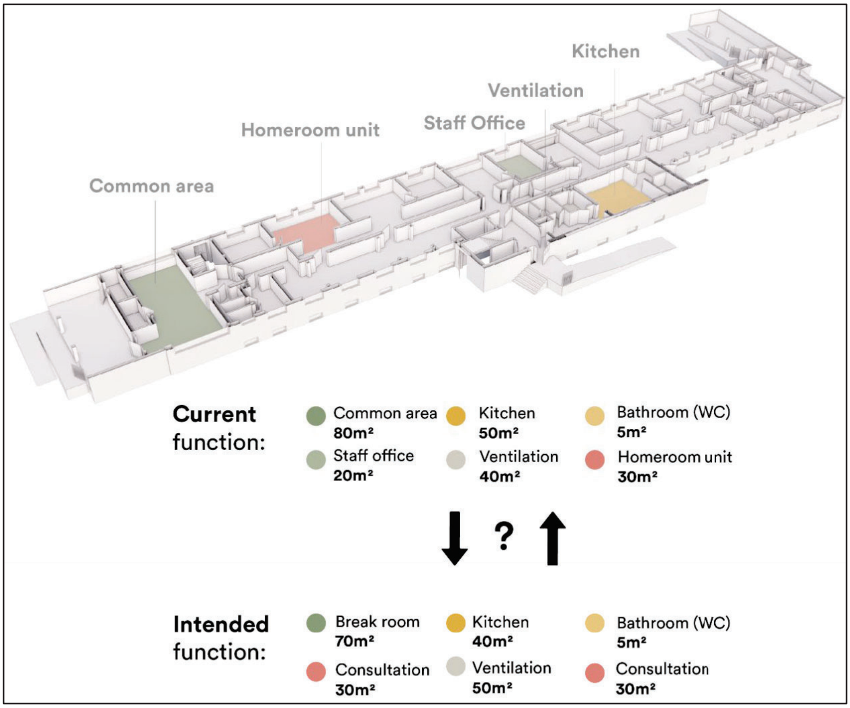

Figure 1. Programme requirements and floor plan of the existing pre-school building, illustrating spatial distribution and available area in relation to the proposed new use.

In the third step, rooms were grouped into functional divisions based on operational logic. Sticky notes were clustered into circles representing functional entities such as staff zones, service cores, or user-specific environments. The internal structure and total floor area of each division were noted, forming the basis for the comparative analysis in the next step. Clusters can also be organised into thematic categories to support legibility and analysis, e.g., support areas, user-oriented areas, or staff areas.

Finally, the functional divisions of the existing and proposed uses were compared to assess the feasibility of the building's adaptive reuse. The analysis considered both quantitative matches, primarily floor area alignment, and qualitative matches, including room types and adjacency relationships. While strict one-to-one correspondence was not always necessary, a reasonable deviation in area was acceptable provided that the regulatory and functional requirements of the intended use could still be met. In some cases, parts of a division from the proposed function were distributed across multiple clusters from the current function. This matching logic allowed the method to accommodate imperfect alignments without dismissing the reuse potential outright. The combined process of adjacency mapping, clustering, and division-level comparison is illustrated in Figure 2, which visually summarises all analytical stages and highlights the resulting spatial compatibility and transformation potential.

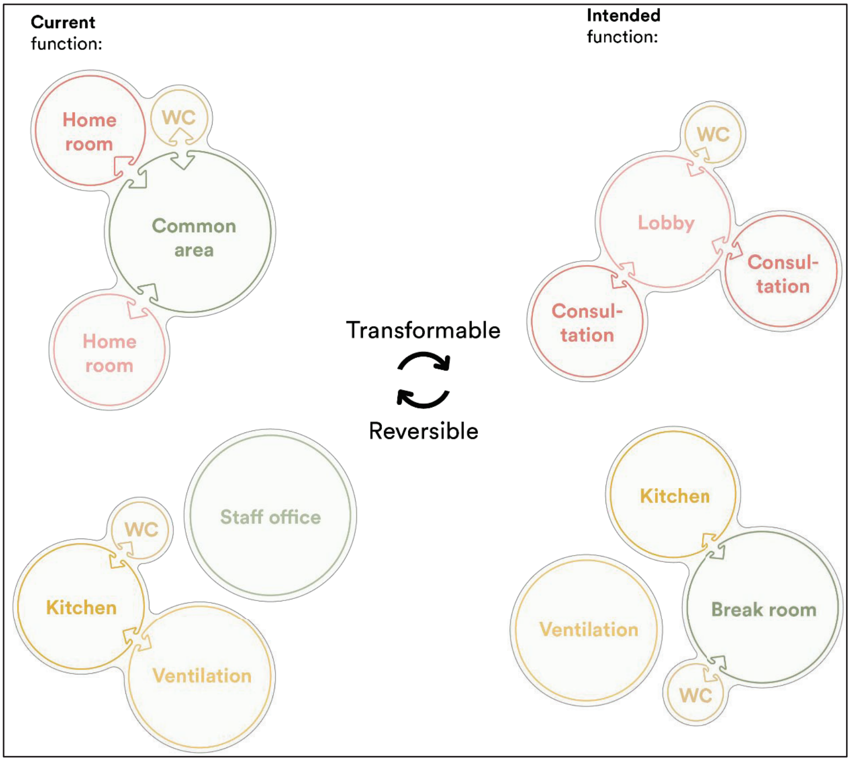

Figure 2. Combined analytical stages of the method: adjacency mapping, functional clustering into operational divisions, and comparative analysis showing spatial compatibility.

DISCUSSION AND CONCLUSIONS

This paper introduced a method for early-stage evaluation of adaptive reuse potential by comparing functional divisions between existing and proposed building uses. The approach provides a structured alternative to surface-level assessments, focusing on room types, area requirements, and adjacency relationships.

The method's key strength is its focus on internal spatial organisation, which enables comparison across building types with differing functions but similar structural logic. The use of functional divisions as the analysis unit supports precision and flexibility, making the method applicable to institutional and service-oriented settings. It also proved effective in participatory settings, helping stakeholders evaluate spatial compatibility through shared analysis. This is particularly useful in public-sector projects with diverse and shifting needs.

The case study demonstrated not only spatial limitations but also revealed a fundamental economic barrier: the proposed elderly care function would require around 50 living units to achieve economic viability, while the existing pre-school building could accommodate only about 10. Additionally, critical adjacencies could not be achieved without major reconfiguration of support systems, further reducing feasibility. These results highlight the importance of integrating economic and operational viability into early-stage assessments, thereby preventing costly investments in conversions that may be technically feasible but financially unsustainable.

While promising, the method remains conceptual, as it does not yet integrate technical systems or structural constraints, nor does it account for modifications to room boundaries, such as the addition or removal of non-load-bearing walls or doorways. The decision to exclude potential additions or removals of walls is deliberate; the method prioritises preserving existing spatial configurations to enable reversible conversions in the future. By maintaining the original room boundaries, technical systems such as ventilation and services, which are designed for specific occupancy patterns, can remain largely intact. While this conservative approach may underestimate the adaptability of certain buildings if modifications were allowed, it aligns with a long-term strategy of minimising intervention and maximising future flexibility. Considering selective modifications as an additional analysis layer represents an important direction for future methodological development.

The case study highlighted the importance of technical reversibility in adaptive reuse. Future development will address whether building services, such as ventilation, plumbing, can support reversible transformations with minimal intervention. Ongoing work will refine the matching logic, incorporate technical infrastructure, and test broader applicability across reuse scenarios. The method could also benefit from further formalisation to improve consistency and uptake, as it currently relies on professional judgement.

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Paper VI

Adaptive reuse and ventilation: a novel approach for reducing embodied environmental and economic impacts

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Abstract. Adaptive reuse, the conversion of buildings for new functions, is gaining prominence for its cost-saving and environmental benefits. However, prior research primarily focuses on preserving the building envelope, often overlooking building services such as ventilation, which affect occupant well-being, costs, and environmental performance. This study explores a novel adaptive reuse approach by reusing existing ventilation systems in a conceptual office-to-residential conversion in Malmö, Sweden. The architectural layout was designed around existing diffusers to minimise environmental impact and life cycle costs. Using Life Cycle Assessment (LCA) and Life Cycle Costing (LCC), two reuse scenarios were evaluated against a baseline with full duct replacement. The fixed-position reuse scenario, where ducts remained in place with minor changes, achieved a 99% reduction in costs and global warming potential (GWP). The full disassembly and reinstallation scenario, where ducts were removed, inspected, and reinstalled, resulted in 50% cost savings and a 98% GWP reduction. Cleaning, long-term maintenance, and reusability testing were excluded due to data limitations. Therefore, these percentage-based results reflect only partial lifecycle impacts and should be interpreted with caution. A reference LCA and LCC metrics per metre of reused duct were developed to support comparison across different projects.

1. Introduction

The building sector accounts for 30% of global final energy use and 26% of global environmental impact during the construction and operational phases [1]. Urbanisation and shifts in work habits, accelerated by the COVID-19 pandemic, have contributed to elevated vacancy levels in the existing building stock [2,3]. At the same time, the pressure to provide affordable housing is intensifying. Projections indicate that by 2030, urban areas will need to accommodate three billion people, necessitating the construction of approximately 96,000 housing units each day [4]This growing mismatch between surplus commercial space and escalating residential demand shows the need to reconsider reliance on new construction and explore alternatives.

Adaptive reuse has emerged as a viable strategy, offering a means to retain embodied energy, minimise material use, and extend building lifespans [5,6]. While adaptive reuse is a well-researched topic, most studies focus on preserving the building envelope, often overlooking building services [7]. Among these, ventilation systems play a critical role in occupant well-being, comfort, and productivity [8] while contributing to 10% – 53% of a construction project's total environmental impact [9–11]. This study addresses this gap by proposing a novel approach to adaptive reuse, focusing on preserving ventilation systems in the conceptual conversion of an office building into a residential building in Malmö, Sweden. Research has identified office-to-residential conversion as the most common reuse pathway for buildings repurposed for residential use [12]. The Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) methodologies were utilised to evaluate the cost savings and environmental impact reduction of the proposed approach. Specifically, the following research questions were addressed:

1. What are the quantified environmental and economic impacts of reusing ventilation components in building conversions?
2. How do different reuse strategies compare in terms of embodied cost and emissions reduction to the complete replacement of the ventilation system?

2. Method

2.1. Description of the building and the reuse scenarios

The case study building, located in Malmö, Southern Sweden, was constructed as a factory in the early 1900s and has since been converted for various uses. It now functions as a mixed-use building with five sections (A, B, C, D, and E), serviced by five air handling units (AHUs). The existing HVAC system, installed in 2021, includes a ventilation-based cooling system, with heating provided by radiators. The building layout is shown in Figure 1. This study focuses on Sections A, B, and C, currently leased by an architecture firm. This part of the building comprises five storeys with a heated floor area of 4 825 m².

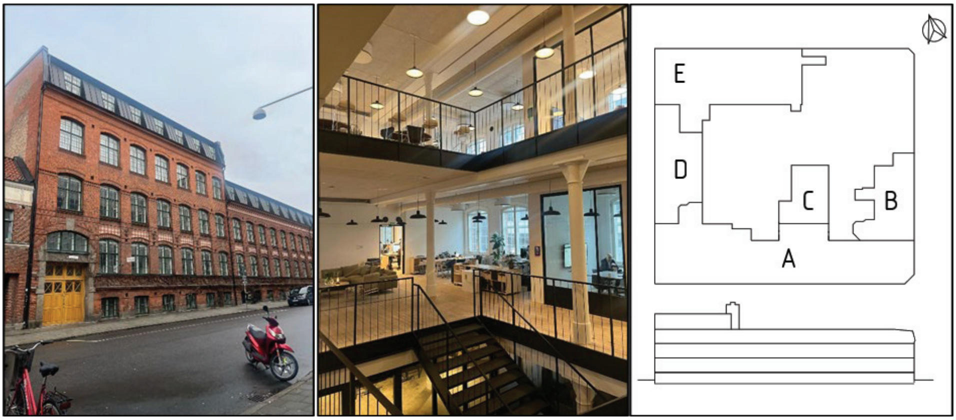

Figure 1. The exterior of the project site (left), the current office space (middle), and the layout of the property (right).

The building was redesigned for residential use, centring the new layout around existing diffusers and preserving the supply-side ventilation system. The exhaust system was excluded due to potential contamination [13]. Two scenarios were evaluated for the reuse of the ventilation system:

- Fixed-position adaptive reuse: The supply ventilation remained mostly intact, with only minor layout adjustments to accommodate the residential architectural design.
- Full disassembly and reinstallation adaptive reuse: The supply ventilation layout was unchanged, but the system was disassembled, cleaned, inspected, stored, and reinstalled

Both scenarios were compared to each other and to a baseline scenario in which the existing office ventilation system was fully decommissioned and replaced with a new one.

2.2. Life Cycle Assessment

The LCA was performed following the SS-EN 15804+A2 standard [14] using generic and product-specific data. Autodesk Revit was used to extract ventilation duct diameters and lengths from a 3D model provided by the building owner, enabling the assignment of Environmental Product Declarations (EPDs) to the corresponding duct dimensions. Generic EPD data for Sweden were prioritised to ensure comparability with similar projects. However, due to the unavailability of generic EPDs for all the components, missing information was substituted with the manufacturer-specific EPDs where necessary. The study focused on the Global Warming Potential (GWP) category as a metric for evaluating the environmental impact of the proposed approach. This metric was chosen for its quantifiability and relevance in sustainable decision-making, as emphasised by carbon initiatives and international regulations [15]. Previous research also highlights GWP as a major driver for shaping environmental strategies, particularly in construction and building materials manufacturing [16]. The functional unit of the analysis is the entire ventilation system for the designated building.

The LCA scope included stages A1–A5, B2, C2, and C3, excluding energy use-related stages. For A4 (transportation), a 110 km transport distance was assumed. Stage B2 included the environmental impacts associated with the disassembly and reinstallation of the ducts, either limited to minor layout adjustments in the fixed-position adaptive reuse scenario or applied to the entire system in the full disassembly scenario. However, the impact of cleaning and any further maintenance was excluded due to methodological uncertainties and the lack of reliable data on the condition and cleaning requirements of the reused components.

2.3. Life Cycle Costing Analysis

The life cycle cost analysis accounted for material and labour costs for installation and disassembly, both dependent on duct length. As with the LCA, the cleaning, reusability testing, and long-term maintenance were excluded due to methodological uncertainties and a lack of reliable data. Cost data for different diameters and lengths were sourced from Wiksell Sektionsfakta, excluding value-added tax (VAT) [17].

A facility quote was obtained to estimate storage costs, yielding a rate of 12 SEK/m²/month. With a total duct area of 210 m², storage was assumed for up to two years. The nature of the considered storage is short- to medium-term, indoor, dry storage for cleaned ducts between disassembly and reinstallation. Inflation adjustments were included, considering the project is set for 2030. While Sweden's target inflation rate is 2% [18], past inflation trends have been volatile [19]. Storage costs were analysed at 2%, 3%, 5%, and 7% inflation rates to reflect economic fluctuations.

The inclusion of a separate storage analysis was motivated by observed practices in heritage-driven adaptive reuse, where material preservation often entails substantial storage and handling costs. One example involved a redevelopment project in Munich where historically protected components were dismantled, stored, and reused, resulting in increased labour demands, storage costs, and schedule impacts [20].

2.4. Reference points

Two reference metrics were developed to enhance comparability across reuse scenarios and support broader applicability to other building projects. For the LCC, costs were expressed in SEK per reused metre of duct; for the LCA, GWP savings were calculated per reused metre of duct. This dual-metric approach benchmarks both economic and environmental performance, especially across duct sizes and system layouts. While normalisation per square metre is standard in whole-building studies, it is less suitable for isolating component-level interventions such as duct reuse, which impacts scale with the geometry of the distribution system rather than the floor area. Recent guidance on embodied carbon accounting in mechanical systems supports the use of declared units based on physical attributes, such as length for ducts and pipes, since both material quantities and labour requirements are driven by installed length and diameter [21].

2.5. Limitations and assumptions

Several assumptions were necessary due to data limitations. It was assumed that commercial storage would not be required, as sufficient on-site capacity was available during the renovation process. Accordingly, storage and transportation costs were excluded from the main LCC and LCA calculations. However, potential commercial storage costs were analysed separately to provide comparability with real-world conditions where on-site storage may not be feasible.

Both the LCA and LCC analyses included the direct activities related to disassembly and reinstallation of the ductwork, either partially, in the fixed-position scenario, or fully, in the disassembly scenario. These interventions were treated as one-time events and classified under stage B2 in the LCA framework. However, subsequent lifecycle processes, such as cleaning, reusability testing, and long-term maintenance, were excluded from both assessments. This decision was based on the absence of standardised data and procedures for evaluating reused ventilation components. The omission introduces a degree of uncertainty into the results, particularly regarding long-term cost-effectiveness and environmental performance. It also limits comparability with full-scope lifecycle analyses, where these elements may significantly influence outcomes. In practical terms, the feasibility and benefit of reuse may be affected by future maintenance burdens or the need for more intensive pre-installation testing, neither of which was captured in this study.

In this study, "duct" includes fittings such as tees and elbows. Duct reuse was assumed feasible if an existing duct matched the required diameter and length. It was also assumed that the ducts were in an acceptable condition to reuse. The existing ventilation system was deemed oversized for the apartment layout since office airflow demands exceed those for residential applications, as per Swedish building regulations [22]. Thus, no efficiency loss or need for a new AHU was anticipated.

3. Results

For both analysed scenarios of ventilation system reuse, 92.25% of the existing office ductwork was retained, while 7.75% was removed and discarded, resulting in a fully reused ventilation system.

3.1. Life Cycle Assessment

The LCA impact across the baseline scenario and both ventilation system reuse scenarios is shown in Figure 2.

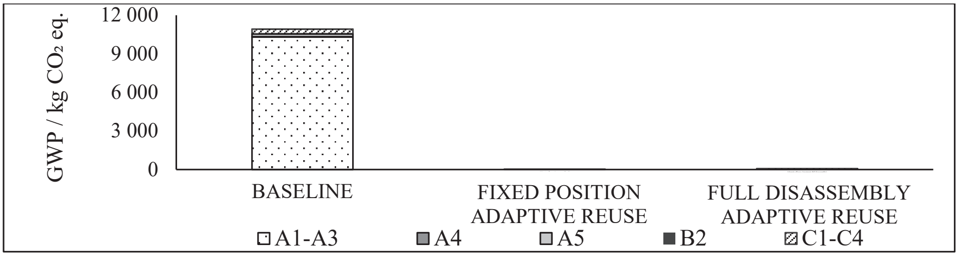

Figure 2. LCA impact comparison between the ventilation system reuse scenarios and the baseline scenario.

The baseline scenario has the highest environmental impact as it requires new duct production, generating emissions from LCA stages A1–A5, accounting for 10 887 kg CO_2 eq. In contrast, the fixed-position adaptive reuse scenario eliminates these emissions, with its impact occurring mainly in stages C1–C4 due to the discarded ducts, accounting for 21 kg CO_2 eq. Compared to the baseline, this scenario achieves a 99.8% reduction in emissions. The full disassembly and reinstallation scenario also reduces emissions by 98%, accounting for 59 kg CO_2 eq. These values represent only the embodied carbon impacts and do not account for full lifecycle impacts.

3.2. *Life Cycle Costing Analysis*

The LCC comparison across the baseline scenario and both ventilation system reuse scenarios is shown in Figure 3. Since both adaptive reuse scenarios utilise only the existing air ducts, there are no costs for purchasing new material.

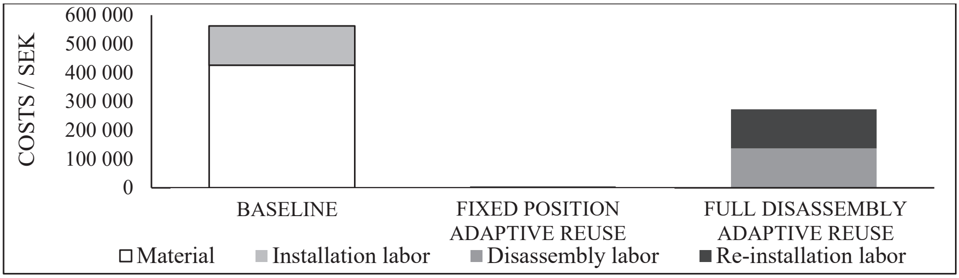

Figure 3. LCC comparison between ventilation system reuse scenarios and the baseline scenario.

The disassembly and reinstallation costs were minimal in the fixed-position reuse scenario, as most of the ductwork remained in place, with only a few sections requiring removal and repositioning in areas lacking air supply. The estimated cost for the baseline scenario was 562 500 SEK. In comparison, the fixed-position adaptive reuse scenario incurred only 5 100 SEK, resulting in a 99% reduction in costs compared to the baseline. A cost estimate was also conducted for the full disassembly and cleaning scenario, assuming all ducts would need to be dismantled, cleaned, and reinstalled. In this case, the total cost was estimated at 273 000 SEK, approximately half the cost of the baseline scenario. These values represent only the capital costs and do not account for full lifecycle expenditures.

3.3. *Potential Cost of Storage*

Figure 4 illustrates the projected storage cost over two years, assuming commercial storage is required. The current estimated rate is 12 SEK per m² per month, resulting in a total cost of approximately 61 400 SEK at today's prices. With a 7% inflation rate, the total cost would increase to 112 500 SEK. Although storage costs were not included in the main LCC analysis, this separate evaluation demonstrates that even when factoring in storage expenses, both ventilation adaptive reuse scenarios are more economically viable compared to the baseline scenario.

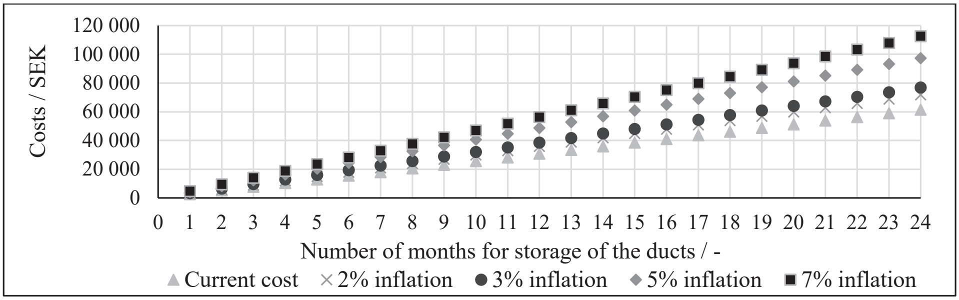

Figure 4. Projected storage costs over two years under different inflation scenarios.

3.4. *Reference points*

Figure 5 presents the GWP per reused metre of duct for different diameters in the full disassembly scenario. The results show that most emissions originate from end-of-life processing and disassembly/reinstallation activities, as stage A emissions are avoided. This demonstrates the substantial potential for carbon savings that could be achieved through reuse. As expected, larger diameters are associated with higher emissions per metre due to increased material volume.

The cost analysis in Figure 5 illustrates that storage requirements increase with duct size, leading to higher reuse costs. The graph accounts for storage, transportation and dismantling costs, showing that the cost of reusing 1 m of duct varies from 1 SEK (for one month of storage) to 90 SEK (for 12 months of storage). The cost of reuse scales almost linearly with the duct size, similarly to the GWP trend, highlighting the economic implications of larger duct diameters in adaptive reuse projects.

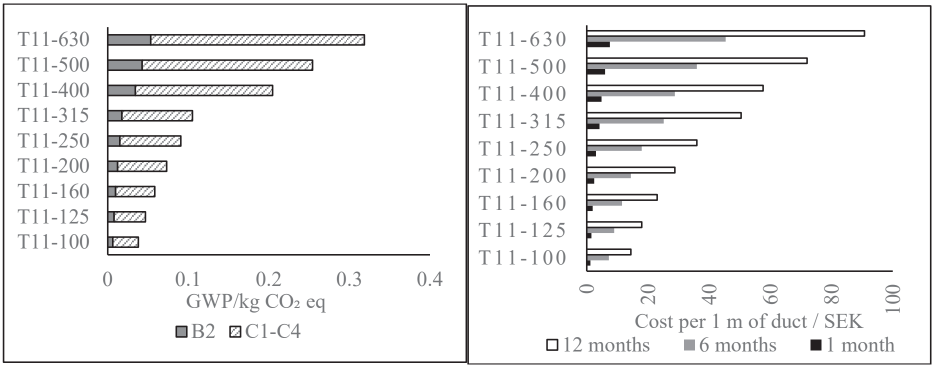

Figure 5. LCA reference point (left) and LCC reference point (right).

4. Discussion and conclusions

The proposed strategy of reusing ventilation components demonstrates clear potential to reduce both environmental impacts and capital costs, provided that system compatibility, spatial planning, and project logistics enable high reuse rates. However, the scope of the life cycle analysis must be clearly understood in order to interpret these results accurately.

Both the LCA and LCC included disassembly and re-installation activities, corresponding to a partial representation of stage B2. These activities were limited to minor layout modifications in the fixed-position scenario and applied to the entire system in the full disassembly scenario. However, critical lifecycle elements, such as component cleaning, reusability testing, and long-term maintenance, were excluded from both assessments due to the absence of standardised methods and reliable data. As a result, the reported reductions of 98-99% in GWP and up to 99% in costs reflect only the embodied impacts and immediate capital expenses associated with reuse logistics, not the system's full operational or lifecycle performance.

Storage was analysed separately to reflect potential constraints in other projects with limited on-site capacity. These storage costs were not incorporated into the percentage-based comparisons and should therefore be regarded as indicative rather than definitive. While their inclusion would not alter the overall trend in favour of reuse, it could reduce the magnitude of potential cost savings.

Despite these limitations, the reuse of ventilation systems in adaptive reuse contexts appears to offer considerable short-term environmental and financial benefits. Nevertheless, further research is needed to evaluate the effects of component ageing, maintenance regimes, and cleaning requirements to support the broader implementation of reuse strategies in HVAC system design.

Conflict of Interest and Acknowledgements

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