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Minh-Tien TRAN

Construction d'un indicateur agrégé de la qualité de l'environnement intérieur dans les écoles

Construction of an Aggregate Indicator of Indoor Environmental Quality in Schools

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Composition du Jury :

Président :	Chantal GUILLARD	Directrice de recherches, CNRS, Université Claude Bernard Lyon 1, Villeurbanne, France
Rapporteurs :		
Ulla HAVERINEN-SHAUGHNESSY		Professeure, Faculty of Technology, University of Oulu, Oulu, Finlande
Monika WOLOSZYN		Professeure, Université Savoie Mont-Blanc, Le Bourget du Lac, France
Dir. de thèse :	Valérie HEQUET	Professeure, IMT Atlantique, Nantes, France
Co-dir. de thèse :	Pawel WARGOCKI	Professeur, Denmark Technical University, Lyngby, Danemark
Encadrante :	Wenjuan WEI	Dr., Ingénieure de Recherche et d'Expertise, CSTB, Champs-sur-Marne, France
Invitées		
Co-encadrante	Claire DASSONVILLE	Dr., Ingénieure de Recherche et d'Expertise, CSTB
Co-encadrante	Corinne MANDIN	Dr., Directrice de Laboratoire, IRSN

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Nomenclature

IEQ	Indoor environmental quality
IAQ	Indoor air quality
CO_2	Carbon dioxide
TAIL	Thermal, Acoustic, IAQ, Lighting
GBC	Green building certification
SM	Supplementary material
HVAC	Heating, ventilation, and air conditioning
PMV	Perceived mean vote
PPD	Percentage person dissatisfied
VOCs	Volatile organic compounds
BTEX	Benzene, toluene, ethyl-benzene, xylene
SVOCs	Semi-volatile organic compounds
PM	Particulate matter
ACR	Air change rate
VR	Ventilation rate
NO_2	Nitrogen dioxide
CFU	Colony forming unit
RH	Relative humidity
LAeq	Background noise equivalent level
RT	Reverberation time
SNR	Speech to noise ratio
STI	Speech transmission index
HPLC	High-performance liquid chromatography
UV	Ultra violet

TVOC Total volatile organic compounds

DNPH 2,4-dinitrophenylhydrazine

PAH Polycyclic aromatic hydrocarbons

BBP, DBP, DEHP, DEP, DiBP Phthalates

PUF Polyurethane foam

I. Résumé de la thèse

I.1. Contexte des travaux

La qualité des environnements intérieurs (QEI) est devenue depuis ces vingt dernières années une préoccupation de santé publique en France en raison du temps que les individus passent dans les espaces clos et les problématiques de confort et de pollution de ces espaces. La QEI est définie par l'Organisation mondiale de la santé (OMS) comme la combinaison de quatre éléments : l'environnement thermique, défini par des paramètres physiques tels que la température de l'air, l'humidité relative et la vitesse de l'air ; l'environnement acoustique, défini par les propriétés acoustiques des bâtiments et les sources de bruit environnantes ; la qualité de l'air intérieur (QAI), définie par les pollutions présentes dans l'air intérieur des bâtiments ; et l'environnement lumineux, résultant à la fois de la lumière naturelle et artificielle provenant de l'éclairage.

I.1.1. Spécificités des environnements intérieurs scolaires

Les écoles constituent des environnements intérieurs spécifiques au regard de la qualité de l'air intérieur : une densité de mobilier importante, une utilisation fréquente de produits pour les activités (colles, peintures, feutres, etc.) et le nettoyage. L'utilisation de craie, la proximité d'axes de circulation et la forte activité des enfants, induisant la remise en suspension des poussières déposées, sont des facteurs qui contribuent aussi à la pollution particulaire dans les salles de classe. Les travaux réalisés par l'Observatoire de la Qualité de l'Air Intérieur (OQAI) dans les écoles maternelles et élémentaires en France au cours de ces vingt dernières années ont permis de dresser un état des lieux de la qualité de l'air dans les établissements scolaires. Ils ont montré qu'une majorité des salles de classe en France étaient multi-polluées avec seulement moins de 1/5 des écoles ayant de faibles concentrations de polluants dans l'air et en poussières déposées [1]. Par ailleurs, il a aussi été constaté dans ces écoles un renouvellement d'air insuffisant, lié à un défaut de ventilation et d'aération des salles de classe [2], pouvant impliquer une qualité de l'air dégradée.

La qualité des environnements intérieurs scolaires représente un enjeu sanitaire essentiel puisque l'école est l'espace clos le plus fréquenté par les enfants après leur logement. En France, à la rentrée 2021, environ 6 500 000 élèves du premier degré étaient scolarisés dans 49 000 écoles maternelles et élémentaires (Direction de l'évaluation de la prospective et de la performance (DEPP), Repères et références statistiques 2022). Il est estimé que le temps d'occupation des enfants dans les écoles varie de 4 à 24,5 heures au cours de la semaine, avec une valeur moyenne de 14,6 ± 5,3 heures [3]. Les enfants, en pleine croissance, sont vulnérables aux pollutions environnementales notamment celles retrouvées dans les environnements intérieurs : ils respirent un plus grand volume d'air par rapport à leur poids en comparaison des adultes et leur organisme et leur système immunitaire sont en cours de développement. Ils passent aussi du temps sur le sol et mettent fréquemment leurs mains à la bouche et ainsi peuvent ingérer de la poussière contaminée par les pollutions.

La vocation des bâtiments scolaires est d'offrir aux enfants des lieux sains et confortables pour leur apprentissage et leur développement. L'acquisition des savoirs et des compétences s'appuie à la fois sur la communication orale entre les adultes et les enfants, une bonne vision permettant les différentes activités et doit respecter les exigences des rythmes biologiques des enfants ainsi qu'une ambiance intérieure favorable au bien-être et à la santé. Cependant, depuis ces dernières années, des travaux de recherche rapportent que les pollutions des environnements intérieurs scolaires peuvent contribuer à des effets aigus ou chroniques sur la santé des enfants [4–6]. Des effets sur l'apprentissage et la réussite scolaire des enfants ont aussi été rapportés incriminant le confinement de l'air et la teneur en dioxyde de carbone [6,7], le confort thermique [4,6,8], le bruit dans les salles de classe [9] et la qualité et la quantité de lumière [10].

I.1.2. Outils permettant de caractériser la qualité des environnements intérieurs scolaires

I.1.2.1. Les mesures

Il y a plusieurs paramètres mesurables dans chaque composante de la QEI, avec leurs propres impacts sur la santé, le bien-être et la performance cognitive des enfants. Ces mesures couvrent un large spectre, incluant la qualité de l'air intérieur, la température, l'humidité, le bruit et la lumière. De plus, les protocoles de mesure des paramètres sont variés et complexes, parfois même pour un même paramètre. Des facteurs tels que l'aspect économique et logistique restent

des enjeux supplémentaires à la surveillance de la QEI dans les écoles. Cette multiplicité et cette complexité représentent un défi crucial pour les responsables de la santé et de l'éducation. La prise en compte de ces diverses variables est essentielle pour assurer un environnement sain et propice à l'apprentissage, mais leur gestion efficiente requiert une approche holistique et intégrée pour garantir la sécurité et le bien-être des élèves et du personnel enseignant. Une liste des paramètres pertinents à mesurer dans les écoles doit être concrétisée.

I.1.2.2. Les normes et certifications

L'évaluation de la QEI à travers la mesure de paramètres nécessite ensuite une évaluation de leur conformité. Plusieurs paramètres de la QEI possèdent des valeurs seuils et des valeurs indicatives établies dans des normes internationales, certains étant réglementés dans les codes de construction de plusieurs pays. L'utilisation de ces valeurs seuils permet de déterminer l'état de la QEI et leur conformité aux normes et réglementations. Cependant, l'évaluation de multiples paramètres de la QEI peut être définie comme une combinaison de quatre éléments :

- l’environnement thermique : paramètres physiques tels que la température de l'air, l'humidité relative et la vitesse de l'air qui affectent la perception du confort thermique par les occupants.

- l’environnement acoustique : les propriétés acoustiques environnantes et leur interaction avec l'enveloppe du bâtiment.

- la qualité de l'air intérieur : la qualité globale de l'air résultant de tous les polluants présents dans le mélange d'air.

- l’environnement lumineux : la qualité de l'environnement ambiant résulte à la fois de la lumière du jour et de l'éclairage artificiel.

À partir de ses quatre composantes, il est également nécessaire de mettre en place un moyen simple et direct de communication des résultats aux parties concernées. Les valeurs de référence, dérivées d'études approfondies et de connaissances sur les risques liés à différents polluants, sont cruciales pour communiquer efficacement le niveau de conformité aux parties prenantes et pour les aider à prendre les mesures appropriées. Simplifier la communication des résultats des divers paramètres de la QEI sans jargon technique est essentiel pour une meilleure compréhension et une action rapide.

I.1.2.3. Les indices de QEI

L'enjeu majeur dans la caractérisation de la qualité des environnements intérieurs est d'évaluer et de combiner plusieurs paramètres provenant de diverses composantes. L'utilisation d'un indice est un moyen opérationnel pour pouvoir satisfaire cet enjeu. Il consiste à classer des paramètres de la QEI par rapport à des seuils et à proposer un niveau de catégorie de qualité. Par la suite, sur la base de ces catégories, un algorithme définira le résultat global de la QEI. L'obtention d'une note globale simplifie le processus de communication entre les parties concernées. Les notes obtenues pour chaque paramètre au sein de chaque composante permettent de mettre en évidence les points critiques sur lesquels devraient porter en priorité les actions d'amélioration.

Depuis ces dernières années, de nombreux indices ont été proposés dans la littérature internationale pour différents lieux de vie. Cependant leur intérêt et pertinence n'ont pas tous été évalués. C'est dans ce contexte et notamment dans le cadre du projet ALDREN (2017-2020), Alliance for Deep Renovation in Buildings (https://aldren.eu/), qu'un indicateur global de qualité de l'environnement intérieur, l'indice TAIL (Thermique, Acoustique, qualité de l'air Intérieur, Lumière) a été développé conjointement entre le Centre Scientifique et Technique du Bâtiment (CSTB) et l'université DTU du Danemark. Le projet ALDREN avait pour objectifs de proposer des méthodes et outils incitant les gestionnaires de bâtiments existants à s'engager dans une rénovation énergétique. La qualité des environnements intérieurs fait partie des leviers pris en compte pour motiver les propriétaires à mettre en œuvre une rénovation énergétique qui bénéficiera en outre à la santé et au bien-être des occupants. Ainsi, une revue exhaustive de la littérature scientifique, des certifications environnementales et des normes a permis d'identifier 90 paramètres différents relatifs à la qualité de l'environnement intérieur dans chacune des quatre composantes, thermique, acoustique, QAI et visuelle. Parmi ces paramètres, douze ont été retenus pour construire un indice global de la QEI dans les bureaux et hôtels. Appliqué à ces bâtiments, l'indicateur TAIL a montré sa pertinence pour exprimer de façon synthétique la qualité globale de l'environnement intérieur du bâtiment, tout en permettant d'identifier parmi les quatre composantes de l'environnement intérieur prises en compte, les points faibles et les leviers d'amélioration [11].

I.2. Objectifs des travaux de thèse

Dans ce contexte, sur la base de l'indice TAIL développé pour les bureaux et les hôtels, l'objectif de ce travail a été de construire et d'étudier la pertinence d'un indicateur global de qualité de l'environnement intérieur dans les écoles. Cet indicateur a ensuite été déployé sur les données issues des mesures réalisées dans les écoles françaises lors de la Campagne Nationale dans les Ecoles (CNE) de l'OQAI menées entre 2013 et 2017. Le cas échéant, il a été proposé de faire évoluer l'indice TAIL pour tenir compte de la spécificité de ces lieux. Pour répondre à cet objectif, les travaux se sont déroulés en trois étapes correspondant aux trois années de thèse :

- La première partie a consisté en la construction de l'indicateur TAIL pour les écoles sur la base d'une synthèse de la littérature pour retenir les paramètres pertinents à intégrer dans l'indice ;
- La deuxième étape a consisté à tester l'applicabilité et la pertinence de l'indice TAIL, construit à l'issue de la première partie, sur le jeu de données provenant de la campagne nationale dans les écoles (CNE) de l'OQAI [1];
- Enfin, dans la troisième partie de ce travail, l'indice TAIL a été croisé avec les données de perception des enseignants relatives au confort thermique, acoustique, visuel et à la QAI, collectées lors de la CNE.

I.3. Première partie - Construction de l'indice TAIL

La construction de l'indicateur TAIL pour les écoles a été réalisée en deux étapes. La première étape a consisté en une recherche des paramètres de QEI pertinents à mesurer dans les écoles sur la base d'une synthèse bibliographique. Dans la seconde étape, un processus de sélection a été mis en place afin de sélectionner une liste de paramètres de QEI pertinents dans les environnements intérieurs scolaires.

I.3.1. Synthèse bibliographique

Afin d'obtenir des études pertinentes et des protocoles de mesure récents, la synthèse bibliographique a porté sur les articles publiés à partir de 2010 sur les thèmes suivants : " sciences de l'environnement ", " ingénierie ", " sciences sociales ", " énergie " et

“ multidisciplinaire ”. La combinaison des mots-clés suivants a été utilisée : ("indoor environmental quality" OR "QEI" OR "thermal" OR "acoustic" OR "indoor air quality" OR "IAQ" OR "luminous" OR "visual" OR "lighting") AND ("school" OR "daycare center" OR "nursery" OR "university") AND ("measurement"). Enfin, la recherche a été limitée à l’Europe et à l’Amérique du Nord, pour avoir des études portant sur des bâtiments scolaires de caractéristiques similaires à ceux rencontrés en la France et pour un climat similaire. Cette recherche a abouti à la sélection de 88 articles scientifiques (Table 1). L’analyse de ces papiers a permis d’identifier 32 paramètres mesurés dans les environnements intérieurs scolaires : six paramètres sont relatifs à l’environnement thermique, quatre à l’environnement acoustique, dix-huit à la qualité de l’air intérieur et quatre à l’environnement visuel (Table 2, Table 3, Table 4, Table 5).

I.3.2. Sélection des paramètres et construction de TAIL

Cette étape a permis de construire l’indice TAIL spécifique aux écoles sur la base de l’indice TAIL construit dans les hôtels et les bureaux. Dans un premier temps, les paramètres ont été sélectionnés puis affectés d’une catégorie de qualité au regard d’une valeur de référence et enfin une note de qualité globale est calculée.

I.3.2.1. Sélection des paramètres

Sur la base de la synthèse bibliographique, un processus de sélection des paramètres pertinents à mesurer pour les écoles a été appliqué à l’aide des trois critères suivants :

- Existence de preuves scientifiques montrant des liens avec la santé et le bien-être des enfants ;
- Praticabilité du protocole de mesure pour une utilisation à large échelle ;
- Existence de valeurs de référence réglementaires, normatives ou indicatives pertinentes pour les environnements scolaires.

Les paramètres de QEI devaient satisfaire les exigences des trois critères pour être inclus dans l’indice TAIL. Ainsi, 14 paramètres ont été sélectionnés pour construire l’indice TAIL pour les écoles à savoir, la température de l'air pour la composante thermique, le niveau de bruit de fond,

le temps de réverbération pour la composante acoustique, les teneurs en benzène, formaldéhyde, l'humidité relative, la teneur en CO_2, le radon, les $PM_{2,5}$, le taux de ventilation, le dioxyde d'azote (NO_2), les moisissures visibles pour la composante QAI et le facteur de lumière du jour et l'éclairage artificiel pour la composante visuelle. Il a été jugé pertinent d'ajouter deux paramètres à l'indice TAIL par rapport aux hôtels et aux bureaux : le temps de réverbération et la teneur en NO_2.

En complément, un protocole de mesure détaillé pour chaque paramètre a été établi afin de proposer un indice prêt à l'emploi par les exploitants et gestionnaires des bâtiments scolaires.

I.3.2.2. Construction de l'indice TAIL pour les écoles

Le principe de notation qui a été défini pour l'indice TAIL dans les hôtels et les bureaux a été conservé pour l'indice TAIL dans les écoles. L'objectif est d'éviter les compromis par composante et d'inciter à l'amélioration de la QEI de manière globale. Pour chaque établissement scolaire, la note de chaque paramètre est calculée en faisant la moyenne des notes obtenues à chaque point de mesure en arrondissant à l'entier supérieur. Ensuite, la note d'une composante est imposée par la note la plus défavorable des paramètres inclus. Enfin, la note finale de l'indice TAIL de l'école est imposée par la note la plus défavorable des quatre composantes.

I.4. Deuxième partie - Application de l'indice TAIL aux données de la CNE

Dans cette deuxième partie, afin de tester les performances et les limites de l'indice TAIL construit dans la première partie, un test de sensibilité a été réalisé en utilisant les données issues de la Campagne Nationale dans les Ecoles (CNE) de l'Observatoire de la Qualité de l'Air Intérieur (OQAI).

I.4.1. Présentation du jeu de données

La campagne nationale dans les écoles a été réalisée dans 602 salles de classe de 308 écoles maternelles et élémentaires de France métropolitaine entre 2013 et 2017. Dans chaque école, les mesures des paramètres ont été effectuées dans deux salles de classe, à une seule reprise, pendant une semaine scolaire sur une année scolaire, soit pendant la période de chauffage, soit

pendant la période hors chauffage. Les composés organiques volatils (COV), les aldéhydes, le dioxyde d'azote (NO_2) et les particules $PM_{2,5}$ ont été mesurés à l'aide de prélèvements d'air passifs et actifs réalisés du lundi au vendredi. Parallèlement, la température de l'air, l'humidité relative et le dioxyde de carbone ont été mesurés à l'aide d'enregistrements sur un pas de temps de 10 minutes sur la même période. Le niveau de bruit a aussi été mesuré dans chaque salle de classe avec un sonomètre, l'enregistrement commençant le vendredi précédant la semaine d'enquête. Des mesures ponctuelles de l'éclairement artificiel ont été réalisées sur les tables et les tableaux des salles de classe. Il est à noter que le radon n'a pas été mesuré dans cette campagne et que le temps de réverbération, le facteur de lumière du jour et le taux de ventilation n'ont pas pu être calculés. Ainsi, le test d'applicabilité a été effectué sur 10 paramètres sur les 14 proposés par l'indice TAIL.

I.4.2. Traitement des données

Étant donné que les mesures effectuées durant la campagne ont été réalisées en amont des suggestions de l'indice TAIL, les données de mesure de certains paramètres ont nécessité des traitements pour appliquer le principe d'évaluation de l'indice. Pour plus de détails, les informations concernant les moyens de mesure des paramètres de QEI durant la campagne se trouvent dans la Table A.1. Pour l'environnement thermique, il est nécessaire de connaitre la température extérieure pour pouvoir calculer la moyenne glissante à utiliser pour définir les valeurs seuils des catégories de qualité TAIL de l'environnement thermique. Cependant, la température extérieure n'a pas été mesurée pendant la campagne. Une solution a été trouvée pour collecter et calculer cette moyenne mobile de la température extérieure. Un outil en ligne, MEREEN (https://mereen.dimn-cstb.fr/home/en), permet d'accéder à un ensemble de données météorologiques historiques en Europe et aux États-Unis de 2005 à aujourd'hui. La température extérieure de chaque école a ainsi été collectée à l'aide de MEREEN en sélectionnant les données de la station météorologique la plus proche des écoles. Pour l'environnement acoustique, l'évaluation du niveau de bruit enregistré a été réalisée pendant le week-end précédant la semaine de mesure de la campagne, pendant les heures de cours habituelles. Ensuite, la moyenne logarithmique de la série de niveaux sonores enregistrés (intervalle d'une minute) a été calculée pour être évaluée à l'aide des valeurs seuils en prenant en compte tous les pics de bruit enregistrés. Pour l'environnement visuel, la différence entre les mesures avec et sans lumière artificielle a été calculée afin de caractériser l'indice.

I.4.3. Applicabilité de l'indice TAIL

Les résultats montrent que trois paramètres de la composante QAI (benzène, formaldéhyde, moisissures visuelles) affichent des niveaux de qualité de catégorie I ou II dans plus de 90 % des écoles. En revanche, quatre paramètres des composantes thermiques, QAI et visuelle (température de l'air, CO_2, $PM_{2.5}$, éclairement artificiel) présentent des niveaux de qualité faible (catégories III et IV) dans plus de 75 % des écoles. En raison de la méthode de classement de l'indice TAIL, 305 écoles ont été classées dans la catégorie IV du système de notation de l'indice. Il y a toujours un paramètre d'au moins une des quatre composantes qui obtient une note de catégorie IV. En effet, la concentration en $PM_{2,5}$ dépasse la valeur guide de l'OMS de 15 µg/m^3 dans plus de 75 % des salles de classe. Par ailleurs, il a aussi été observé en faisant ce travail que la température de l'air dans certaines salles de classe pouvait atteindre des niveaux élevés (supérieurs à 33°C) en période de chauffage et hors chauffage par rapport aux températures préconisées dans la norme 16798-1 d'où proviennent les valeurs qui ont été utilisées comme seuils. Cette norme est relative aux données d'entrées d'ambiance intérieure pour la conception et l'évaluation de la performance énergétique des bâtiments couvrant la qualité de l'air intérieur, l'ambiance thermique, l'éclairage et l'acoustique (2019). Au final, ce travail a permis de démontrer la capacité de l'indice à catégoriser la QEI dans des établissements scolaires ayant des caractéristiques distinctes. Ces résultats soulignent l'utilité de l'indice en tant qu'outil fournissant des informations pour orienter des interventions ciblées et pour élaborer un plan d'action visant à résoudre les problèmes spécifiques de QEI identifiés par l'indice.

I.5. Troisième partie - Croisement de l'indice TAIL et des données de perception du confort

La troisième partie de ce travail de thèse a porté sur l'étude de potentielles relations entre la perception des occupants des salles de classe et les catégories de qualité de QEI établies par l'indice TAIL telles que définies dans la deuxième partie. L'objectif était d'évaluer si les sensations à un stimulus et la perception globale à une composante QEI des occupants étaient liées aux catégories de l'indice TAIL.

I.5.1. Description du jeu de données et du traitement statistique

Dans le cadre de la Campagne Nationale dans les Ecoles (CNE), les enseignants ont renseigné un questionnaire auto-administré relatif à leur perception du confort thermique, visuel, acoustique, olfactif et par rapport à la QAI. Ce questionnaire intégrait à la fois des échelles de fréquence (5 points) et de gêne (7 points) qui permettaient aux occupants de spécifier et de quantifier leurs sensations de gênes vis à vis des paramètres de confort étudiés. Les réponses de 711 enseignants ont été récupérées et confrontées au classement de l'indice TAIL pour chaque composante. Des tests du Chi-2 ont été réalisés au risque d'erreur de 5%. Le test du V de Cramer a aussi été appliqué pour tester la force de la relation au risque d'erreur de 5% (logiciel R version 4.1.2).

I.5.2. Résultats

Les résultats montrent que les relations significatives observées concernent principalement les questions relatives aux sensations et les catégories de l'indice TAIL. Les résultats notables sont les suivants : davantage d'enseignants ont répondu avoir "chaud" aux questions relatives à la sensation de température de l'air dans les salles de classe correspondant à un niveau TAIL-thermique défavorable. Aussi, davantage d'enseignants ont été gênés par le bruit des meubles dans les salles de classe correspondant à un niveau TAIL-acoustique défavorable. Concernant la perception de la qualité de l'air et l'olfaction : plus d'enseignants ont répondu avoir une perception de confinement de l'air dans les salles de classe ayant un niveau TAIL-CO_2 défavorable et plus d'enseignants ont été dérangés par les odeurs dans les salles de classe correspondant à un niveau TAIL-$PM_{2.5}$ défavorable. En ce qui concerne l'environnement visuel, plus d'enseignants ont apprécié la qualité de la lumière d'ambiance dans les classes correspondant à un niveau TAIL-visuelle favorable.

Quelques relations significatives ont été observées entre les réponses des occupants portant sur la perception globale d'une composante QEI et les catégories de l'indice TAIL. Par exemple, le pourcentage d'enseignants appréciant la qualité globale de l'air est en effet plus faible dans les classes à TAIL-IAQ défavorable. Cependant, de façon contradictoire, dans plus d'un cas, des

enseignants dans les classes de catégorie IV de TAIL-IAQ ont répondu qu'ils "appréciaient" la qualité globale de l'air.

Le test statistique a mis en évidence des liens entre les réponses données par les enseignants à la perception de la QEI et les différentes catégories de QEI de TAIL. Cependant, il est à noter que ce lien est plus net entre la sensation à l'égard d'un stimulus spécifique de QEI et une composante QEI de TAIL que la perception globale à l'égard d'une composante de QEI. En outre, les réponses données par les enseignants sur leur perception d'un élément spécifique de QEI sont parfois en contradiction avec l'évaluation TAIL correspondante : les enseignants ont plutôt répondu que la température ambiante dans la salle de classe ou que la qualité de l'air était « satisfaisante », alors que les résultats de la classification TAIL indiquaient le contraire. Finalement, l'exercice montre que les questions de perception peuvent être utilisées parallèlement à une évaluation de la QEI mais elles ne peuvent pas remplacer la surveillance de la QEI par des mesures. Elles apportent une information additionnelle complémentaire.

I.6. Conclusion et perspectives

Avec pour perspective de caractériser la QEI dans les écoles d'une manière référencée et de fournir une aide à toute action future visant à améliorer la QEI, l'objectif de la thèse est de développer un indice spécifique de la QEI, destiné à être déployé dans les écoles, aussi appelé l'indice TAIL pour les écoles.

La première étape de ce travail a consisté à sélectionner les paramètres de l'indice. Une revue de la littérature a été réalisée, examinant 88 études sur la QEI dans les écoles, dans les pays d'Amérique du Nord et d'Europe entre 2010 et 2021. Les résultats de la revue ont permis de constituer une liste de paramètres les plus pertinents ainsi que leurs protocoles de mesure permettant de qualifier la QEI. Après un processus de sélection, 14 paramètres sur 32 initialement identifiés ont été inclus dans l'indice TAIL pour les écoles : la température de l'air, le niveau de bruit de fond, le temps de réverbération, la teneur en benzène, la teneur en formaldéhyde, l'humidité relative, la teneur en CO_2, le radon, les $PM_{2.5}$, le taux de ventilation, la teneur en NO_2, les moisissures visuelles, le facteur de lumière du jour et l'éclairage artificiel. Certains paramètres ont été écartés car ils ne répondaient pas à l'un des trois critères de sélection. Il s'agit de la température de fonctionnement, de l'intelligibilité de la parole, des PM_{10}, des COVS et de l'évaluation de l'éblouissement. En effet, ces paramètres ont un impact significatif sur la santé, le bien-être et les performances cognitives des enfants mais leurs

mesures à grande échelle ne sont pas à ce jour économiquement viables. Par conséquent, les inclure dans l'indice pourrait décourager les gestionnaires et exploitants des écoles à mesurer et contrôler la QEI. Les 14 paramètres de QEI inclus dans l'indice TAIL pour les écoles représentent une combinaison adéquate entre la caractérisation de la QEI dans les écoles et d'autres facteurs économiques ou logistiques. Lors de tout développement important, scientifique ou technique, de nouveaux paramètres QEI pourront être inclus afin de maintenir la pertinence de l'indice.

La deuxième étape de ce travail a consisté à mener un test de faisabilité de l'indice TAIL dans les écoles à l'aide des données issues de l'enquête nationale française sur la QEI, entre 2013 et 2017, portant sur 602 salles de classe dans 308 écoles. Le test de faisabilité n'a porté que sur 10 des 14 paramètres, car aucune mesure ou simulation du temps de réverbération, du radon, du taux de ventilation ou du facteur de lumière du jour n'était disponible. En outre, l'enquête sur la QEI dans les écoles nationales françaises a été réalisée avant l'élaboration de l'indice d'évaluation TAIL aussi un certain compromis a été fait pour combler les différences entre les protocoles de mesure utilisés lors de la campagne et ceux préconisés par TAIL. Néanmoins, la faisabilité étant démontrée dans ce travail, de futures études pourront réaliser des tests complets, les étendre à d'autres bases de données issues de différents secteurs géographiques et bénéficieront de cette expérience.

Dans une troisième étape, nous avons exploré la relation entre la perception des occupants, obtenue dans l'enquête nationale française sur la QEI, et les résultats de l'évaluation TAIL calculés à partir des données mesurées dans le cadre de la même enquête. Chaque combinaison de questions sur la perception et la note TAIL correspondante ont été examinés pour l'environnement thermique, l'environnement acoustique, la qualité de l'air et l'environnement visuel. En perspective de cette partie, en ce qui concerne le test explicatif entre la classification de la note TAIL et la perception des occupants, plusieurs améliorations peuvent être apportées dans les études futures. Le test statistique a été réalisé uniquement entre les réponses à une question de perception et la classification TAIL associée, chaque enseignant étant considéré indépendamment. Or, la perception des occupants peut être influencée par de multiples facteurs, tels que l'âge, le sexe, les antécédents et l'expérience. Un modèle statistique plus complexe, telle qu'une régression multivariée, est nécessaire pour explorer pleinement les relations sous-jacentes. En outre, l'étude actuelle s'est concentrée uniquement sur les perceptions des enseignants et non sur celles des enfants. Dans la littérature actuelle, la perception de la QEI

par les enfants est moins bien connue que celle des adultes. Les réponses des enfants peuvent dépendre de leur différence de préférences en matière de QEI, de leur métabolisme et de leur compréhension du concept de "confort". En perspective, de futures études axées sur les perceptions des enfants permettront d'étoffer les relations entre perceptions et classifications de la QEI de l'indice TAIL.

En conclusion, ce travail de thèse a abouti au développement de l'indice TAIL, visant à simplifier l'évaluation de la Qualité Environnementale Intérieure (QEI) dans les écoles. En attribuant une note globale, cet indice permet de contourner la complexité liée à l'évaluation et à l'interprétation des multiples paramètres de la QEI, offrant ainsi à toutes les parties prenantes la possibilité d'agir en vue d'améliorer la QEI dans les écoles. L'indice TAIL développé fera probablement l'objet de modifications dans l'avenir. Celles-ci pourraient inclure l'ajout de nouveaux paramètres, profitant des développements des techniques de mesure permettant une évaluation fiable et économique des paramètres pertinents. De même, des ajustements des valeurs seuils pourraient être nécessaires en cas de modifications des normes de référence. Ces évolutions visent à maintenir la pertinence de l'indice et à assurer une évaluation correcte et performante de la QEI dans les écoles, favorisant ainsi la caractérisation de la QEI.

En d'autres termes, l'indice TAIL contribue à mettre en lumière l'invisible, à savoir la Qualité Environnementale Intérieure (QEI) dans les écoles, fournissant ainsi un soutien précieux à toutes les parties concernées. Les enfants méritent les meilleures conditions scolaires, et nous devrions déployer tous les efforts nécessaires pour les atteindre.

II. Introduction

Nowadays, humans are transitioning to being an indoor species. It is estimated that in cities, people spend an average of 90% of their time indoors in Europe and America [12]. There are different types of buildings, all of which have different uses and are destined for different populations, such as dwellings, offices, hospitals, and schools. Today, 55% of the global population lives in urban areas, and this number is constantly rising. The United Nations (UN) predicts that 68% of the world's population will live in urban areas by 2050 [13]. With advances in science, architecture, and design, more and more buildings are being constructed. Buildings offer shelter against the ever-changing outdoor environment conditions by creating their environment with their influence, and it can be altered by human activities (e.g., pollutants from anthropogenic sources and usage of indoor electronic devices). Following the EN 16798-1: 2019 standard on the "Energy performance of buildings" [14], the indoor environmental quality (IEQ) can be defined as a combination of four components:

- Thermal environment: Physical parameters such as air temperature, relative humidity, and air velocity affect thermal responses, including thermal comfort.
- Acoustic environment: Physical parameters, including the surrounding acoustic properties and their interaction with the buildings' envelope, can affect acoustic responses and comfort.
- Indoor air quality: The overall air quality results from all the pollutants present in the air mixture, which can affect occupants' health and perception.
- Lighting environment: The visual environment is affected by artificial light and daylight and can impact occupants' senses and comfort.

With a growing proportion of the population spending more and more time indoors, it is essential for all occupants to benefit from good IEQ. All four components of IEQ must be respected, as there are documented impacts of numerous pollutants on humans’ health, well-being, and cognitive performance. Existing studies have demonstrated that indoor environments have a significant influence on occupants’ physical and mental health [15,16]. Factors such as indoor air quality, lighting, thermal comfort and acoustics can have a direct impact on respiratory health, allergen sensitivity and general well-being [17–19]. Regarding the indoor air, high-risk pollutants such as benzene, formaldehyde and radon have been classified as Class I carcinogenic substances by the International Agency for Research on Cancer (IARC) [20],

while they are commonly detected in indoor environments. Improved ventilation and air quality in indoor spaces significantly reduced sick building syndrome symptoms and improved cognitive performance among occupants [21]. Regarding the thermal environment studies on its impact on occupants, including one by Fisk et al., have shown that thermal discomfort can lead to reduced cognitive function, and in contrast, a well-regulated thermal environment can enhance productivity and decision-making [22]. Regarding the lighting environment, insufficient light can damage eyesight and increase the risk for short-sight [23]. Regarding the acoustic environment, research by Shield and Dockrell [24] highlighted the detrimental effects of noise on concentration, learning, and memory. In brief, when optimized, the indoor environment's various components can profoundly influence human health, well-being, and cognitive performance, ultimately underscoring the importance of maintaining high IEQ standards in indoor spaces.

When it comes to measuring and evaluating multiple IEQ parameters from the four IEQ components, there must be a simple and direct way of communicating the measured results to the parties concerned. Communicating the results of various IEQ parameters to people without technical knowledge complicates understanding. Especially when these are the stakeholders with the power to make mitigation and IEQ improvement decisions. The creation and use of a rating scheme is a rational way of measuring and evaluating several parameters from various components. It consists of classifying all IEQ parameters, using threshold levels for each parameter and providing a quality category level. In the end, an algorithm will define the overall result of the IEQ in schools, using classified results of the IEQ of each assessed parameter. Obtaining one overall rating will simplify the communication process with different stakeholders. The rating of each parameter and component remains available for consultation before taking action to improve the IEQ in the building.

IEQ rating schemes already exist, in the form of green building certification (GBC). Multiple GBCs exist worldwide, with notable examples such as the Leadership in Energy and Environmental Design (LEED) in the United States [25] and the Building Research Establishment Environmental Assessment Method (BREEAM) in the United Kingdom [26]. GBCs have different visions and objectives, but they all aim to promote sustainability and energy-efficient buildings. Some GBCs stated that their IEQ assessment method could be suitable for schools. However, GBC schemes have broader scopes than IEQ assessment, e.g. energy consumption, waste management, and potable water management. IEQ can be

compromised to achieve a high overall score, and vice versa, as it represents 47% of the scores in LEED, 28% of the scores in BREEAM, or 25% of the scores in DGNB [27]. Furthermore, there is no consensus on the weighted scoring for IEQ parameters between different GBCs [27]. Each GBC has its scoring method, which hindered the opportunity to compare between them. The association between GBC rating and IEQ has also been questioned, as Tham et al. 2015 pointed out [28], that in certified Green-mark buildings, there were no significant differences in the amount of sick leave days people took, compared to uncertified buildings. Given these observations, there is a need for a dedicated IEQ assessment based on measured pertinent IEQ parameters.

A rating scheme was developed under the name of TAIL, an abbreviation for Thermal, Acoustic, Indoor air quality, and Lighting, as a work package inside the European project ALDREN (Alliance of Deep Renovation in Buildings) [29]. It was aimed at hotels and offices to promote deep energy renovation without compromising and with the hope to improve the IEQ in buildings. Twelve IEQ parameters have been proposed in the TAIL rating scheme, along with a detailed measurement protocol in the rating scheme. A feasibility test was conducted in 11 buildings, and the results showed that the rating scheme could help classify and compare IEQ and its components before and after an energy renovation, underlining the gain in energy performance and improving IEQ in parallel [11]. From this experience and the context mentioned above, there is a growing interest in developing a similar rating scheme destined to be used in other types of buildings, such as schools.

The IEQ in schools, which primarily cater to a specific demographic – children, is equally essential to be well managed, if not more. Firstly, the number of children attending schools is non-negligible. The French Ministry of Education and Youth estimates that at the start of the 2022 school year, there are an estimated 6.48 million pupils in daycare centers, kindergartens, and elementary schools [30]. Children also spend a considerable portion of their time at schools, on average 180 days in the US, 190 days in the UK, and 208 days in East Asian countries [31]. In France, estimated children occupancy in schools ranged from 4 to 24.5 hours during the week, with a mean value of 14.6 ± 5.3 h [3]. Children are considered more vulnerable than adults to inadequate IEQ [6]. Their bodies are still developing, making them more vulnerable and sensitive to unfavorable physical conditions [32,33]. For example, their breathing rate is higher than adults, making them more vulnerable to air pollutants [34]. There are also documented impacts on children's cognitive performance in classrooms with inadequate IEQ

conditions. The acquisition of knowledge and skills relies on oral communication between adults and children, good vision to enable different activities and meet the requirements of children's biological rhythms, and an indoor environment conducive to well-being and health. In recent years, however, research has shown that pollution in indoor school environments can contribute to acute or chronic effects on children's health [4–6]. In addition, effects on children's learning and academic achievement have also been reported with air confinement based on carbon dioxide measurement [6,7], thermal comfort [4,6,8], noise in classrooms [9], and light quality and quantity [10].Compared to adults in homes, hotels or offices, children in schools also have little control over the state of the IEQ in their classrooms, eliminating some of the mitigation actions (e.g. open windows, change the heating setting, etc.) they might have taken. Given the above, careful monitoring of IEQ in schools will considerably improve the condition experienced by children, empowering them to thrive in a safe and rewarding indoor environment. As a result, it is legitimate to ask how it is possible to determine whether the quality of the indoor environment in schools is adequate or not. Since several IEQ parameters have threshold and guideline values established in international standards or are even regulated in building codes of several countries, measuring, and monitoring these parameters using threshold values can help indicate the state of IEQ and their conformity.

Another point of discussion is about the relationship between the IEQ's quality and the occupants' sensation and perception in the buildings. Physical measurement devices offer quantitative data, providing objective and precise assessments of the conformity of the indoor environment. Meanwhile, occupants' perception-based evaluations involve subjective experiences reflecting their feelings, comfort, and satisfaction within the indoor space, which may vary among individuals [35–37]. It considers factors beyond measurable metrics, encompassing personal preferences, psychological comfort, and individual sensitivities towards various environmental aspects [28,38]. Occupants' perception-driven evaluations offer insights into overall satisfaction and well-being, offering more insights than reflected solely through objective measurements. Integrating physical measurements and occupants' perceptions can lead to a more comprehensive approach to evaluating indoor environmental quality, enabling targeted improvements that cater to objective standards and occupants' comfort needs. An example is the BSI standard [39], where both assessments using physical measurement and perception questionnaires addressed to a panel of experts were used. A rating scheme of IEQ in schools would greatly benefit from including the occupants' perception assessment.

Nevertheless, a relationship between the characterized factors of the objective measurement and the occupants' subjective assessment should be established.

To propose a potential solution within this context, this thesis aimed to create a rating scheme for IEQ in schools using the TAIL rating scheme as a prototype for evaluating the thermal, acoustic and luminous environment, and the indoor air quality. To achieve these objectives, the thesis was structured in three main parts (chapters), which correspond to the three main steps: the development of the IEQ rating scheme for schools, the feasibility test of the scheme, and a validation of the scheme using teachers' responses to question on their sensation and perception of the IEQ. The subsequent flow chart (Figure 1) delineates the arrangement of ideas in this thesis, as well as describes the structure of the remainder of the document. There will be three main steps in the adaptation of the TAIL rating scheme to the schools' environment, numbered Chapter III, IV, and V.

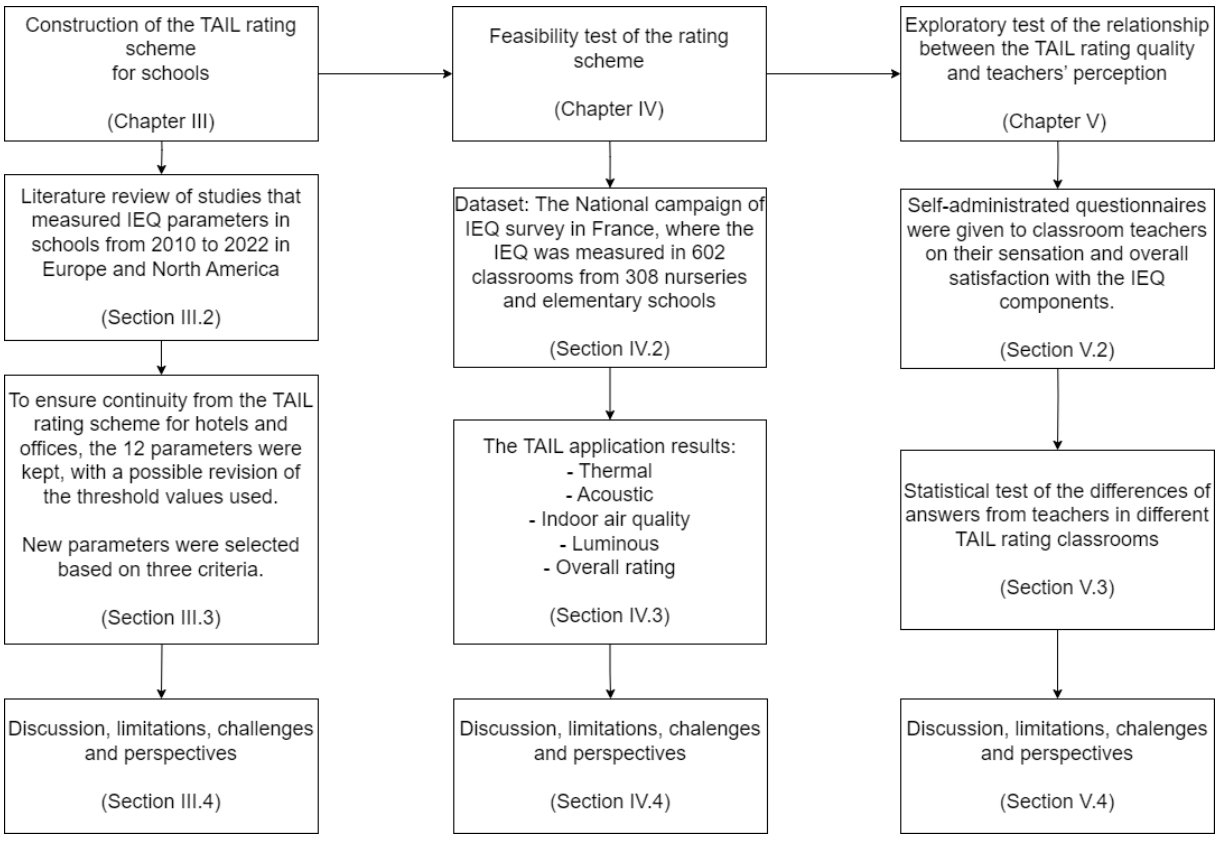


Figure 1: Flow chart describing the arrangement of the ideas in this thesis

The first chapter (III) describes the development of the rating scheme for schools, also called TAIL but for schools (TAIL for schools, TAILs). To ensure continuity from the original TAIL rating scheme for hotels and offices, all twelve parameters in the original TAIL were kept. Nevertheless, revision of the threshold values was still performed. Then, additional IEQ parameters were assessed to select relevant IEQ parameters for the school environment and develop an objective evaluation protocol based on measurements. A literature review of all IEQ parameters measured in schools was performed to identify relevant parameters. A selection process was performed to identify additional parameters representing the IEQ in schools while aiming for simplicity to ensure that schools find it manageable when implementing it. As a result, two new parameters were added to TAILs: the reverberation time and the concentration of nitrogen dioxide, making a total of 14 parameters. An assessment protocol was also drafted, ready to be used directly by schools that want to measure the IEQ in their buildings.

The second chapter (IV) describes the application of the TAILs rating scheme for schools. The test used measurement data from the French IEQ surveillance campaign conducted by the Observatory for Indoor Air Quality (OQAI). Between 2013 and 2017, the Scientific and Technical Centre for Building (CSTB) coordinated the measurement campaign to evaluate children's exposure to pollutants in maternity and elementary schools. 602 classrooms in 308 randomly chosen schools from the French stock of daycare and elementary schools participated in the survey. Sixteen parameters were measured during the survey (i.e., air temperature, relative humidity, carbon dioxide, background noise level, formaldehyde, benzene, volatile organic compound, semi-volatile organic compound, aldehyde, nitrogen dioxide, particulate matter up to 2.5 µm, total particle count, lead in paint, heavy metal, dust mites, artificial lighting). By applying the TAILs rating scheme to measurement data obtained during the campaign, the rating principle of the rating scheme and its practicality when used in different schools can be tested. Results from the test show that the TAILs have helped underline the problems encountered with the IEQ in schools and discriminate the state of IEQ between schools in different surrounding environments.

The third chapter (0) discusses the exploratory study examining the relationship between the TAIL ratings in school buildings and the teachers' sensations and perceptions. Alongside the measurements of IEQ, five sets of questionnaires on the perception of the thermal environment, the acoustic environment, the olfactive environment, the quality of air, and the visual environment were used to collect responses from teachers. Two types of questions were asked:

firstly, on the teachers' sensation of a specific stimulus, and secondly, on their overall satisfaction with the state of the IEQ. Statistical tests were used to examine whether a difference in the quality category given by the TAIL rating scheme resulted in a difference in teachers' responses to questions. Results show that the TAILs rating correlated more with the teachers' answers to the sensation questions than with the teachers' answers to the overall satisfaction questions.

Chapter VI offered a discussion of the results and contribution to the literature stemming from the thesis, limits encountered during the construction, the validation of the TAIL rating scheme for schools, and perspectives for future studies and development. Finally, chapter VII concludes.

III. Construction of the IEQ rating scheme for schools: TAIL for schools or $TAIL_S$

III.1. Context and objectives

At its essence, a rating scheme embodies a structured methodology designed to assess, quantify, and categorize various aspects or qualities of a given environment. An IEQ rating scheme empowers stakeholders, enabling them to take appropriate mitigation measures in response to inadequate IEQ within classrooms. Within educational spaces, establishing a robust IEQ-rating scheme holds substantial promise in delineating and enhancing the occupants' experiences in the classrooms.

A meticulously designed rating scheme serves as a comprehensive evaluative tool and operates as a catalyst for fostering conducive learning environments. However, the effectiveness and credibility of such an index rely upon the judicious selection and accurate assessment of pertinent IEQ parameters, ensuring the scheme's reliability and applicability within educational frameworks.

Central to this chapter's exploration is the chosen methodology employed in selecting and including essential IEQ parameters within the TAIL rating scheme tailored explicitly for the educational environment. The intricate process of parameter selection and assessment forms the cornerstone of an effective rating scheme, bolstering its capability to holistically evaluate indoor environmental conditions while aligning with the unique requisites of educational spaces. Through a systematic exposition, this chapter unveils the intricacies of designing a comprehensive and pragmatic IEQ rating scheme tailored to school environments.

This work aimed to develop the TAIL rating scheme for schools. The chapter is organized as follows: Subsection III.2 presents the method by which the TAIL rating scheme for schools was constructed, starting with the difference of objectives between the precursor, TAIL rating scheme for hotels and offices (subsection III.2.1) and the adaptation, TAIL rating scheme for schools (subsection III.2.2), and the methodology behind the adaptation process (subsection III.2.3). Subsection III.2.4 presents the literature review of all scientific studies that measured IEQ in schools starting from 2010 in Europe and North America. The review identified all measured IEQ parameters in schools, their measurement frequency, and measurement protocol.

This review has been published and can be found in the appendix [40]. The integral TAIL rating scheme for schools, including selected parameters, their threshold levels, measurement protocols, and rating principles, can be found in subsection III.3. Section III.4 discusses the adaptation methods and provides further perspectives. Section III.5 concludes the chapter.

III.2. Research setting

III.2.1. The objective of the TAIL rating scheme for hotels and offices

Under the European ALDREN project, which promoted deep renovation in buildings for better energy efficiency, the TAIL rating scheme for IEQ in hotels and offices was developed, as there is a lack of a widely endorsed approach for assessing the overall IEQ in buildings. TAIL measured 12 IEQ parameters before and after renovations, ensuring that any energy renovation action also improved IEQ performance. 12 parameters were selected based on four criteria:

- The parameters are likely to change in the process of deep energy renovation even when it has included no deliberate action concerning IEQ.
- The parameters are widely recommended in existing building certification schemes and standards and endorsed by guidelines addressing the health and comfort of occupants.
- The parameters' influence on the health, well-being, comfort, work performance, or sleep quality of building occupants has been documented in scientific literature.
- The parameters can be assessed using validated and widely assessable measurement protocols.

Figure 2, cited from the original TAIL article [11], presents all IEQ parameters included in the TAIL rating scheme for hotels and the recommended targeted renovation actions that can be made.

TAIL indicators.

TAIL component	Indicator	The possible influence of renovation operations
Thermal environment (T)	Air temperature	(1) Thermal rehabilitation (insulation) of an envelope, roof, ground floor, etc. (2) New low-energy windows (3) Installation of low-temperature heating and high-temperature cooling hydronic systems (4) Air-based cooling and heating systems (5) Improved control of heating/cooling systems (6) Installation of sunscreens
Acoustic environment (A)	Sound pressure level	(1) New windows (2) Tightening of the envelope and thermal rehabilitation of envelope
Indoor air quality (I)	Ventilation rate	(1) New ventilation system
	Carbon dioxide concentration	(1) New ventilation system (2) Tightening of the envelope
	Formaldehyde concentration	(1) New ventilation system (2) Tightening of the envelope (3) New materials
	Benzene concentration	(1) Tightening of envelope (2) Thermal rehabilitation of envelope and new windows (3) New ventilation system
	Particle ($PM_{2.5}$) concentration	(1) Tightening of envelope (2) Thermal rehabilitation of envelope and new windows (3) New ventilation system
	Radon concentration	(1) Tightening of envelope (2) Thermal rehabilitation (3) New ventilation system
	Air relative humidity	(1) New ventilation system
	Visible mould area	(1) Thermal rehabilitation (reduced cold bridges) (2) New ventilation system
Visual (luminous) environment (L)	Illuminance	(1) Renovation of a low-energy artificial lighting system
	Daylight factor	(1) Skylights (2) New windows

Figure 2: IEQ parameters in the TAIL rating scheme for hotels and offices, and possible recommended renovation operations

The feasibility test has been performed in 11 hotels and offices, in which the TAIL rating scheme could discriminate the different IEQ conditions from different buildings. Conveniently, this opens the opportunity to adapt this vision of characterization of the IEQ to other types of buildings and even create an overall marker of the IEQ performance in said other types of buildings.

III.2.2. The objectives of the TAIL rating scheme for schools

The adaptation of the TAIL rating scheme to schools' environment revolved around the objective of characterizing the overall IEQ in schools. This indicates that selected parameters must represent the overall IEQ and what children are exposed to, emphasizing health, well-being, and cognitive performance. Parameters are, therefore, not selected based on their reparability and renovation capacities. Therefore, in the TAIL rating scheme for schools, parameters were only selected based on three out of four earlier criteria:

- The parameters are widely recommended in existing building certification schemes and standards and endorsed by guidelines addressing the health and comfort of occupants.
- The parameters' influence on the health, well-being, comfort, work performance, or sleep quality of building occupants has been documented in scientific literature.
- The parameters can be assessed using validated and widely assessable measurement protocols.

III.2.3. The adaptation process

To keep the continuity from the TAIL rating scheme for hotels and offices, all 12 parameters in the TAIL rating scheme for hotels and offices were kept in the TAIL rating scheme for schools, as they all satisfied the three selection criteria. Then, new IEQ parameters were evaluated to be included using the three selection criteria. However, to figure out what IEQ parameters to consider to be included, a literature review of what was measured in IEQ studies in schools was performed. Figure 3 details this adaptation process.

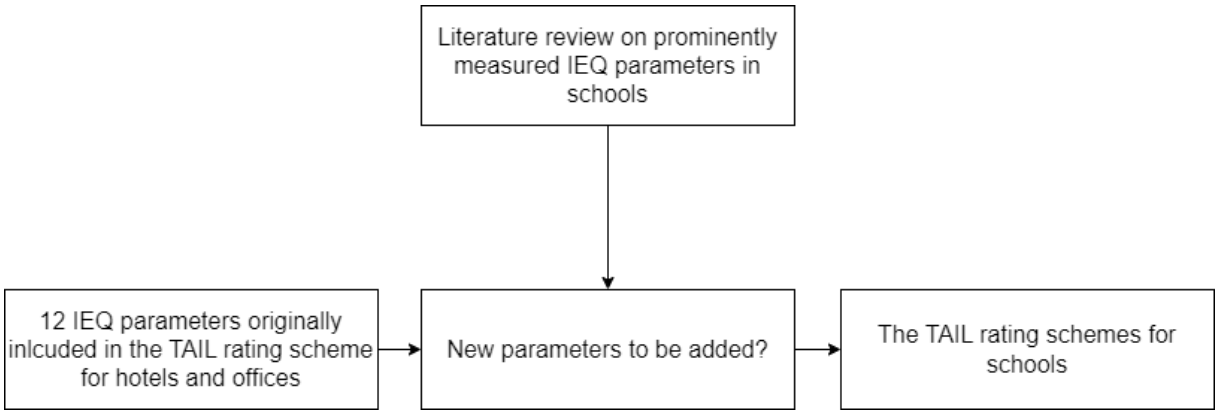


Figure 3: Flow chart describing the adaptation process from the TAIL rating schemes for hotels and offices to the TAIL rating schemes for schools

III.2.4. State of the art of IEQ measurements in schools

The literature review was performed using the Scopus database. To ensure a collection of relevant studies with the latest and up-to-date measurement protocols, the decision was made only to include papers published from 2010 with the following topics: environmental sciences, engineering, social sciences, energy, and multidisciplinary. The following combination of keywords was used: (“indoor environmental quality” OR “IEQ” OR “thermal” OR “acoustic” OR “indoor air quality” OR “IAQ” OR “luminous” OR “visual” OR “lighting”) AND (“measurement”) AND (“school” OR “daycare center” OR “nursery” OR “university”). The last combination of keywords indicates that studies in all types of educational buildings were analyzed, regardless of the age of students or pupils in occupancy. By doing this, the intricacies of all IEQ parameters measured in studies across all types of educational buildings can be studied, as well as providing ranges of results that can be compared across different types of schools. Furthermore, there was a limit to only studies from Europe and North America, so studies carried out on schools with similar building characteristics and related environmental properties were included. Figure 4 presents the PRISMA flow diagram of the literature review, with a corresponding number of articles in each step, leading to the final number of 88 selected for final review.

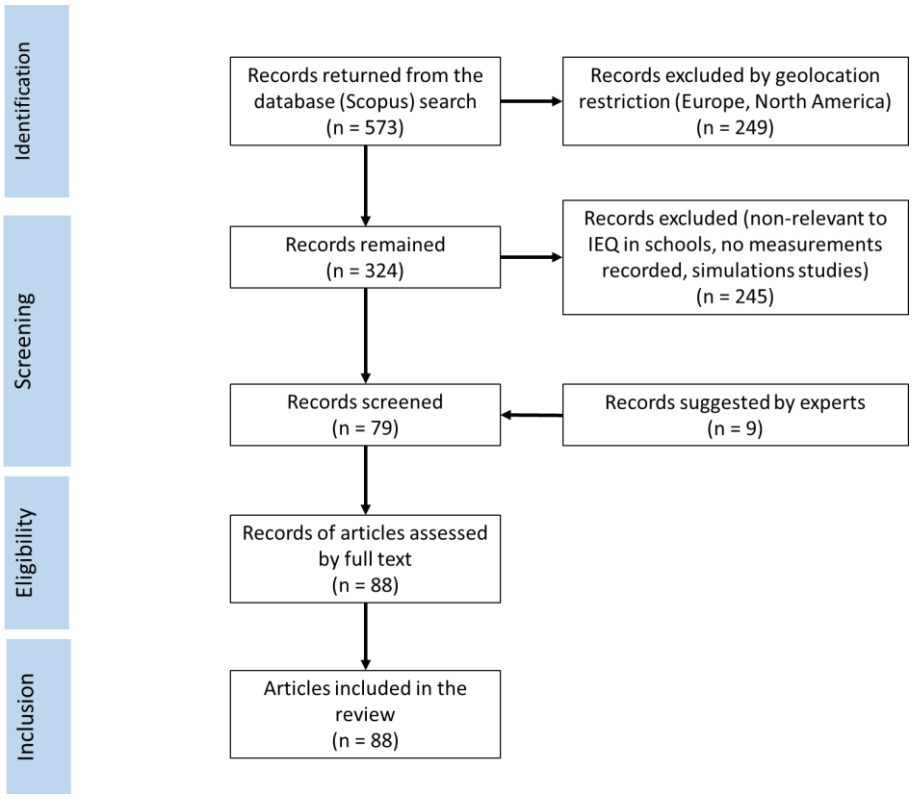


Figure 4: PRISMA flow diagram of the literature review

Details on these 88 articles, i.e., the season when measurements were done and countries, the type of schools, and the measured IEQ components, can be found in Table 1. In total, studies were measured in 28 countries from Europe and North America. Nine studies were conducted in day-care centers, nine in nursery schools, 40 in elementary schools, 24 in secondary schools, 12 in high schools, and 11 in universities. In these 88 articles, two sets of two reported results from the same study: a measuring campaign in four nurseries in Porto, Portugal [41,42], and the SINPHONIE pan-European study [10,43].

Table 1: IEQ studies analyzed in the literature review (n = 88 studies)

Study [reference]	Location	Season	Type of school	IEQ component
Aguilar et al. 2022 [44]	Spain	Winter	University	Thermal, IAQ
Ahmed et al. 2019 [45]	Finland, Estonia	Winter	Daycare, elementary	Thermal, IAQ
Alves et al. 2013 [46]	Portugal	Winter	Kindergarten, elementary	Thermal, IAQ
Annesi-Maesano et al. 2012 [47]	France	N/A	Elementary	IAQ

Azara et al. 2018 [48]	Italy	Spring Summer	Elementary, secondary, high school	IAQ
Baloch et al. 2021 [10]	Europe	Spring Summer	Kindergarten, elementary	Visual
Barmparesos et al. 2018 [49]	Greece	Summer	Elementary	Thermal, IAQ
Becerra et al. 2020 [50]	Spain	Spring	Kindergarten, elementary, secondary, high school	IAQ
Branco et al. 2015 [41]	Portugal	Spring Autumn	Daycare	Thermal, IAQ
Branco et al. 2015 [42]	Portugal	Spring Autumn	Daycare	IAQ
Branco et al. 2016 [51]	Portugal	Year long	Daycare, elementary	IAQ
Brdaric et al. 2019 [52]	Croatia	Spring	Elementary	Thermal, IAQ
Buratti et al. 2018 [53]	Italy	Spring Autumn	University	Thermal, Acoustic, Visual
Canha et al. 2016 [3]	France	Winter	Daycare, elementary	Thermal, IAQ
Cequier et al. 2014 [54]	Norway	Winter Spring	Elementary	IAQ
Chetoni et al. 2016 [55]	Italy	N/A	Secondary, high school	Acoustic
Csobod et al. 2014 [43]	Europe	Spring Summer	Kindergarten, elementary	Thermal, IAQ, Visual
de Gennaro et al. 2013 [56]	Italy	N/A	Elementary	IAQ
De Giuli et al. 2012 [57]	Italy	Spring	Elementary	Thermal, IAQ, Visual
De Giuli et al. 2014 [58]	Italy	Spring	Elementary	Thermal, IAQ, Visual
De Giuli et al. 2015 [59]	Italy	Spring	Elementary	Thermal, IAQ, Visual
de la Hoz –Torres et al. 2022 [60]	Portugal, Spain	Fall	University	Thermal, Acoustic, IAQ, Visual
Dhoqina et al. 2019 [61]	Albania	Spring	Elementary, secondary, high school	IAQ
Erlandson et al. 2019 [62]	United States	N/A	University	Thermal, IAQ
Fabbri 2013 [63]	Italy	Fall	Kindergarten	Thermal
Franci et al. 2014 [64]	Italy	Winter	Elementary, secondary, high school	IAQ
Gaffin et al. 2018 [65]	United States	Fall Spring	Elementary, secondary	IAQ
Harcarova et al. 2020 [66]	Slovakia	N/A	Elementary	Thermal, Acoustic, IAQ, Visual
Heracleous et al. 2019 [67]	Cyprus	Winter	Secondary	Thermal, IAQ
Irulegi et al. 2017 [68]	Spain	Spring	University	Thermal

Istrate et al. 2016 [69]	Romania	Summer	High school	Thermal, IAQ
Ivanova et al. 2014 [70]	Bulgaria	Spring	Kindergarten	IAQ
Ivanova et al. 2021 [71]	Bulgaria	Fall Winter	Elementary	IAQ
Jovanovic et al. 2014 [72]	Serbia	Spring	Elementary	Thermal, IAQ
Klatte et al. 2010 [73]	Germany	N/A	Elementary	Acoustic
Kojo et al. 2020 [74]	Finland	Winter Spring	Daycare, Elementary	IAQ
Korsavi et al. 2019 [75]	England	Summer Fall Winter Spring	Elementary	Thermal, IAQ, Visual
Kristiansen et al. 2011 [76]	Denmark	Fall Winter Spring	Secondary	Acoustic
Krugly et al. 2014 [77]	Lithuania	Winter	Elementary	IAQ
Laborda et al. 2020 [78]	Spain	Winter	Secondary	Thermal, IAQ, Visual
Larsson et al. 2017 [79]	Sweden	Spring Fall	Kindergarten	IAQ
Leccese et al. 2020 [80]	Italy	Spring Fall	University	Visual
Liaud et al. 2021 [81]	France	Spring	High school	IAQ
Loreti et al. 2016 [82]	Italy	N/A	Secondary	Thermal, Acoustic, IAQ, Visual
Madudeira et al. 2015 [83]	Portugal	Fall Winter	Elementary	Thermal, IAQ
Mainka et al. 2015 [84]	Poland	Winter	Daycare	IAQ
Mikulski et al. 2011 [85]	Poland	N/A	Elementary	Acoustic
Müllerova et al. 2017 [86]	Hungary, Poland, Slovakia	Fall Winter	Kindergarten	IAQ
Nunes et al. 2016 [87]	Portugal	Spring	Nursery	IAQ
Oldham et al. 2020 [88]	United States	Fall Spring	Elementary	Thermal, IAQ, Visual
Oliveira et al. 2016 [89]	Portugal	Spring	Kindergarten	Thermal, IAQ
Oliveira et al. 2017 [90]	Portugal	Winter Spring	Kindergarten	IAQ
Oliveira et al. 2017 [91]	Portugal	Spring	Kindergarten	Thermal, IAQ
Onishchenko et al. 2017 [92]	Russia	N/A	Kindergarten	IAQ
Papadopoulos et al. 2020 [93]	Greece	Winter	University	Thermal, IAQ
Papazoglou et al. 2019 [94]	Greece	Summer	University	Thermal
Pereira et al. 2014 [95]	Portugal	Spring	Secondary	Thermal, IAQ
Pereira et al. 2015 [96]	Portugal	Spring	Secondary	Thermal, IAQ
Persson et al. 2018 [97]	Sweden	Year long	Kindergarten	IAQ
Poulin et al. 2012 [98]	Canada	Winter	Elementary, secondary, high school	IAQ

Raffy et al. 2017 [99]	France	N/A	Nursery, elementary	IAQ
Ramalho et al. 2015 [100]	France	N/A	Nursery, elementary	IAQ
Rivas et al. 2014 [101]	Spain	Winter Spring Summer	Elementary, secondary	IAQ
Romagnoli et al. 2014 [102]	Italy	Winter Spring Summer	Elementary, secondary, high school	IAQ
Rovelli et al. 2014 [103]	Italy	Winter	Elementary, secondary	IAQ
Rucinska et al. 2020 [104]	Poland	Winter	University	Visual
Russo et al. 2019 [105]	Italy	N/A	Elementary	Acoustic
Sarantopoulos et al. 2014 [106]	Greece	Spring	Elementary	Acoustic
Sarka Langer et al. 2020 [107]	Sweden	Fall Winter Spring	Elementary	Thermal, IAQ
Senitkova et al. 2017 [108]	Czech Republic	N/A	Daycare	Thermal, IAQ
Shield et al. 2015 [109]	England	N/A	Secondary	Acoustic
Simanic et al. 2019 [110]	Sweden	Fall Winter Spring	Elementary	Thermal, IAQ
Sivanantham et al. 2021 [1]	France	Fall Winter Spring	Daycare, Elementary	Thermal, IAQ
Slezakova et al. 2019 [111]	Portugal	Winter Spring	Elementary	IAQ
Smith et al. 2019 [112]	United States	N/A	Elementary, secondary	Acoustic
Stamp et al. 2020 [113]	United Kingdom	N/A	Secondary	Thermal, IAQ
Toftum et al. 2015 [114]	Denmark	N/A	Elementary	Thermal, IAQ
Trevisi et al. 2012 [115]	Italy	Year long	Daycare, elementary, secondary	IAQ
Ulla Haverinen-Shaughnessy et al. 2015 [116]	United States	Fall Winter Spring	Elementary	IAQ
Verriele et al. 2016 [117]	France	N/A	Elementary, secondary	Thermal, IAQ
Vilcekova et al. 2017 [118]	Slovakia	Fall	Elementary	Thermal, Acoustic, IAQ, Visual
Villanueva et al 2018 [119]	Spain	Spring	Elementary	IAQ
Vornanen Winqvist et al. 2018 [120]	Finland	Spring	Secondary	Thermal, IAQ
Vornanen Winqvist et al. 2020 [121]	Finland	Winter	Secondary	Thermal, IAQ
Z.Curguz et al. 2020 [122]	Bosnia and Herzegovina	N/A	Elementary, secondary, high school	IAQ
Zecevic et al. 2018 [123]	Bosnia and Herzegovina	Winter Summer	University	Thermal, IAQ

Zhong et al. 2017 [124]	United States	Winter Spring	Elementary	Thermal, IAQ
Živković et al. 2015 [125]	Serbia	Winter Spring	Elementary, secondary, high school	IAQ

Among the 88 articles, IAQ parameters were the most frequently measured (in 73 studies). The thermal parameters were measured in 43 studies, visual parameters in 15, and acoustic parameters in 13. Several studies measured parameters from multiple components. In Figure 5, each number represents the frequency of studies that measured the corresponding IEQ component. At each intersection of ellipses, the number represents studies that measured parameters from at least two IEQ components. In 40 articles, at least two IEQ components were measured: 28 studies measured thermal and IAQ parameters, seven studies measured thermal, IAQ, and visual parameters, and only one study measured thermal, acoustic, and visual parameters. Finally, four studies measured parameters from all four IEQ components.

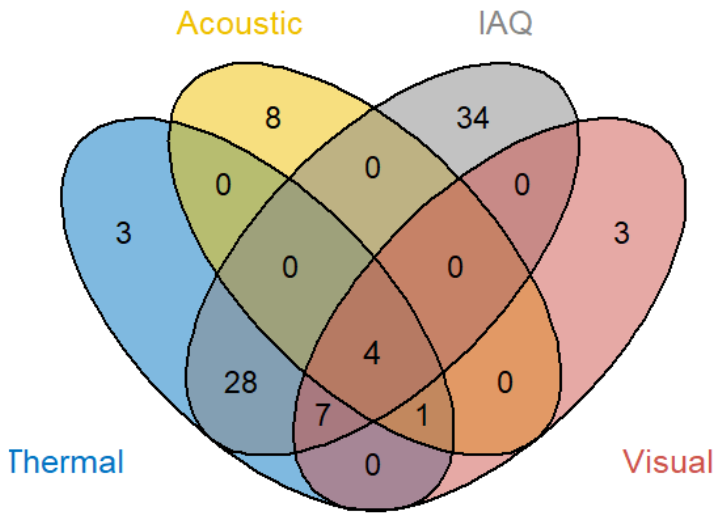


Figure 5: Number of studies according to the measured IEQ components (n = 88 articles)

In these 88 articles, the median number of schools where the measurements were made was six, and the median number of classrooms where the measurements were made was 17. In 26

articles, IEQ measurements were made in only one school, including three of the four studies that measured all parameters from all four IEQ components [66,82,118]. The most extensive study contains measurements from 1000 classrooms in 438 schools, but it only measured radon concentration with passive dosimeters [48]. Overall, it is rare that multiple parameters in all four IEQ components were measured when the study included many schools. Table 2, Table 3, Table 4, and Table 5 describe all parameters measured in the reviewed studies and provide details on their measurement protocol and the ranges of the results. Each subsection centers around a summary table where details of every parameter can be found, i.e., frequency of measurement, measurement protocols, and ranges of results. For each parameter, multiple lines of results will be arranged in decreasing frequency order. Each line represents studies that used an identical measurement protocol, from the sensors used, the number of sensors, their placement, measured duration, and their ranges of results. In case there are multiple lines of results with the same number of frequencies, they will be arranged by decreasing the order of the measurement duration.

In the 43 articles that studied the thermal environment in schools, five parameters were measured: air temperature (°C), relative humidity (%), mean radiant temperature (°C), operative temperature (°C), and airspeed (m/s), additionally, thermal comfort was characterized using the model. Table 2 summarizes all details regarding the measurement frequency, sensor placement throughout the classrooms, measured duration, and the results ranges.

In the 13 articles that studied the acoustical environment in schools, four parameters were used to characterize the acoustic environment. These were background noise level, reverberation time, speech intelligibility, and sound insulation between the exterior façade and the interior volume. Table 3 summarizes all details regarding the measurement frequency, sensor placement throughout the classrooms, measured duration, and the results ranges.

In the 73 articles that studied the IAQ, 18 parameters were measured: the concentration of carbon dioxide (CO_2), nitrogen dioxide (NO_2), radon, formaldehyde, and other substances from the aldehydes family, BTEX (Benzene, Toluene, Ethylbenzene, Xylene) and other volatile organic compounds, Total VOCs, semi-volatile organic compounds, particulate matter, from 0.1 µg, 1 µg, 2.5 µg, 5 µg, to 10 µg, ventilation rate, air change rate, mold inspection by culture, and visual mold inspection. Table 4 presents all details regarding the measurement frequency, sensor placement throughout the classrooms, measured duration, and the results ranges.

In the 15 articles that studied the luminous environment, two parameters were measured: natural daylight and artificial lighting. In some studies, the total illumination, meaning an assessment of the luminance coming from both these sources of light in the classroom, was measured. Table 5 presents all details regarding the measurement frequency, sensor placement throughout the classrooms, measured duration, and the results ranges.

Table 2: Measured or modelled parameters to characterize the thermal environment, with details on the measurement protocol and obtained results (n = 43 studies)

Measurement protocol					
Frequency	**Number of measured sensors**	**Measurement device**	**Location in the classroom**	**Measured duration**	**Ranges of results**
Air temperature (43 studies)					
34	1	Thermo-hygrometer sensor	Placed at the center of the classroom, at a height varied from 0.5 to 2.5 meters	Ranged from 8 hours to 7 weeks	Ranged from 12 to 38 °C
3	3	Thermo-hygrometer sensor	Placed at a height of 0.6 meter	1 hour	Ranged from 15 to 28 °C
2	1	Thermo-hygrometer	Location not reported	Spot measurement	Ranged from 14 to 30 °C
1	1	Thermometer	Location not reported	Spot measurement	Ranged from 14 to 30 °C
1	2	Thermo-hygrometer sensor	Sensor fixed on a wall, at a height of 0.6 meter	4 spot measurements and continuous measurements for 3 months	Ranged from 21 to 28 °C
1	12	Thermo-hygrometer sensor	6 sensors at 0.6 meter and 6 sensors at 1.7 meters	30 minutes	21 ± 1.4 °C during winter 22

Measurement protocol					
Frequency	**Number of measured sensors**	**Measurement device**	**Location in the classroom**	**Measured duration**	**Ranges of results**
					± 2.1 °C during midseason
1	11	Thermo-hygrometer sensor	Placed around the classroom, at height varied from 0.5 to 2.5 meters	30 minutes	21 ± 3.9 °C
Humidity (43 studies)					
34	1	Thermo-hygrometer sensor	Placed at the center of the classroom, at a height varied from 0.5 to 2.5 meters	Ranged from 8 hours to 7 weeks	Ranged from 22 to 78 %
3	1	Thermo-hygrometer sensor	Location not reported	Spot measurement	Ranged from 32 to 54 %
3	3	Thermo-hygrometer sensor	At 0.6-meter height	1 hour	Ranged from 19 to 58 %
1	2	Thermo-hygrometer sensor	Sensor fixed on a wall, at 0.6-meter height	4 spot measurements and continuous measurement for 3 months	Ranged from 32 to 54 %

Measurement protocol					
Frequency	**Number of measured sensors**	**Measurement device**	**Location in the classroom**	**Measured duration**	**Ranges of results**
1	12	Thermo-hygrometer sensor	6 sensors at 0.6 meter and 6 sensors at 1.7 meters	30 minutes	51 ± 6 %
Air speed (12 studies)					
12	1	Hot-wire anemometer	Location not reported	Spot measurement	Ranged from 0.1 to 5.0 m/s
Mean radiant temperature (11 studies)					
8	1	Globe thermometer	Location not reported	Spot measurement	Ranged from 13 to 24 °C
2	1	Radiant plane temperature	Placed at a height of 0.6 meter	Spot measurement	
1	1	Thermal imaging camera	Location not reported	Spot measurement	
Assessment of the comfort by model (9 studies)					
8	N/A	Fanger heat balance model	N/A	N/A	N/A

Measurement protocol					
Frequency	**Number of measured sensors**	**Measurement device**	**Location in the classroom**	**Measured duration**	**Ranges of results**
1	N/A	Adaptive thermal comfort model	N/A	N/A	N/A
Operative temperature (6 studies)					
5	1	Derived from the measurement of dry bulb, air temperature, MRT, and the air speed	Location not reported	Spot measurement	Ranged from 19 to 22 °C
1	1		Location not reported	Spot measurement	

Table 3: Measured or modelled parameters to characterize the acoustical environment, with details on the measurement protocol and obtained results (n = 13 studies)

Measurement protocol					
Frequency	**Number of measured sensors**	**Measurement device**	**Location in the classroom**	**Measured duration**	**Ranges of results**
Noise level (dB(A)) (9 studies)					

Measurement protocol					
Frequency	**Number of measured sensors**	**Measurement device**	**Location in the classroom**	**Measured duration**	**Ranges of results**
3	1	Sound meter	Placed at the center of the room	Ranged from 30 minutes to 2 days continuously	Ranged from 22 to 85 dB(A)
4	1	Sound meter	Location not reported	Ranged from 1 minute to 2 days continuously	
2	2	Sound meter	One placed at the center of the room, one placed one meter away from the windows	Continuous measurement for 30 minutes	Ranged from 23 to 63 dB(A)
Reverberation time (s) (8 studies)					
3	12	Microphones	Placed around the classroom	Spot measurement, all follow the impulsive noise method	Ranged from 0.9 to 1.1 s
1	18	Microphones	Place around the classroom, at 1.1 meters		
1	9	Microphones	Place around the classroom, at 1.2 meters, and 1 meter from the wall		
1	4 to 6	Microphones	Place around the classroom, at 1.1 meters		

Measurement protocol					
Frequency	**Number of measured sensors**	**Measurement device**	**Location in the classroom**	**Measured duration**	**Ranges of results**
1	2	Microphones	One placed at the center of the room, one placed one meter away from the windows		
1	1	Sound analyzer	Location not reported		
Speech transmission index (STI) (6 studies)					
6	1	Sound analyzer	Location not reported	Calculated from impulsive noise	Ranged from 53 to 74 %
Clarity index (C_{50}) (4 studies)					
2	12	Microphones	Placed around the classroom	Spot measurement, all follow the impulsive noise method	Ranged from -6.3 to 5.6 dB
1	18	Microphones	Placed around the classroom		
1	1	Sound analyzer	Location not reported		
1	1	Microphones	Placed 2 meters away from the teachers	Spot measurement of 1 minute	Ranged from 0.6 to 21.3 dB(A)

Measurement protocol					
Frequency	**Number of measured sensors**	**Measurement device**	**Location in the classroom**	**Measured duration**	**Ranges of results**
1	1	Sound meter	One placed one meter away from the windows to measure the noise in the classroom.	Continuous measurement for 30 minutes	Ranged from 15 to 33 dB

Table 4: Measured or derived parameters to characterize the indoor air quality, with details on the measurement protocol and obtained results (n = 73 studies)

Measurement protocol					
Frequency	**Number of measured sensors**	**Measurement device**	**Measured duration**	**Location in the classroom**	**Ranges of results**
CO_2 (ppm) (42 studies)					
11	1	NDIR sensor	5 days	Location not reported	Ranged from 394 to 3530 ppm
5	1	NDIR sensor	1 day or 24 hours	Placed at the center of the room, from 0.75 to 1.1 m	Ranged from 374 to 1927 ppm

3	1	NDIR sensor	1 week	Location not reported	Ranged from 500 to 5383 ppm
2	1	NDIR sensor	2 days	Placed at an occupants' desk, from 0.6 to 1 m	Ranged from 1434 to 1611 ppm
2	1	NDIR sensor	Several spot measurements	Placed at the teachers' desk, from 0.6 to 0.75 m	Ranged from 1149 to 1494 ppm
1	1	NDIR sensor	3 months	Placed at the back of the room, at 0.6 m	Ranged from 400 to 3000 ppm
1	1	NDIR sensor	2 months (10 weeks)	Placed at the center of the room, at 0.4 to 1 m	Ranged from 381 to 2003 ppm
1	1	NDIR sensor	1 months	Location not reported	More than 90% of classrooms under 950 ppm
1	1	NDIR sensor	2 weeks	Location not reported	N/A
1	1	NDIR sensor	8 days	Location not reported	Ranged from 562 to 592 ppm
1	1	NDIR sensor	1 week	Placed at the center of the room	Ranged from 399 to 829 ppm
1	1	NDIR sensor	1 week	Mounted on the wall, at 1.1 m	Max of 2310

1	1	NDIR sensor	1 week	Placed at the center of the room, at students' breathing zone	Range from 577 to 1787 ppm
1	1	NDIR sensor	1 week	Location not reported	Ranged from 296 to 1953 ppm
1	1	NDIR sensor	5 days	Placed at the back of the room, at 0.6 m	Ranged from 567 to 1370 ppm
1	1	NDIR sensor	5 days	Placed at the back of the room, at 1.2 m	Ranged from 1766 to 3494 ppm
1	1	NDIR sensor	5 days	Placed at an occupants' desk, at 0.6 m	N/A
1	1	NDIR sensor	5 days	Placed at the center of the room, at 2 m	Max: 2726 ppm
1	1	NDIR sensor	3 days	Location not reported	N/A
1	1	Hygrometer sensor	8 hours	Placed at 1.5 m	AM: 493 ± 1.3 ppm
1	1	NDIR sensor	1 hour	Placed at the back of the room, at 1.1 m	Ranged from 1238 to 1415 ppm
1	1	NDIR sensor	30 minutes	Placed around the classroom, at height varied from 0.5 to 2.5 m	Ranged from 1316 top 1920 ppm

1	1	NDIR sensor	One spot measurement, and one on continuous measurement	Location not reported	Median of maximum 20 min running average: Windows opening: 2875 Mechanical exhaust: 2372 Mechanical balanced: 1344
1	12	NDIR sensors	30 minutes	6 sensors at 0.6 m and 6 sensors at 1.7 m	Ranged from 1267 to 1951 ppm
$PM_{2.5}$ (µg/m^3) (19 studies)					
3	1	Gravimetric counter	5 days on continuous	Location not reported	AM: 22 ± 8 Ranged from 47 to 106
1	1	Optical counter	6 to 8 months	Location not reported	N/A
1	1	Gravimetric counter	24 hours on continuous for a total of 192 hours	Location not reported	AM: 44 ± 13
1	1	Optical counter	1 week on continuous	Placed at the center of the room, at students' breathing zone	AM: 10 ± 1.2 and 25 ± 4.6
1	1	PM-meter: MiePDR1500	1 week on continuous	Placed at the center of the room	AM: 1.3 µG/m3
1	1	Optical counter	5 days on continuous	Placed at the back of the room, at 1.2 m	Ranged from 47 to 117

2	1	Gravimetric counter	8 hours on continuous for 4.5 days	Location not reported	AM: 56 ± 34 and 44 ± 37 AM: 37 ± 13 µg/m3
1	1	Optical counter	7 hours on continuous	Placed at the back of the room, at 0.6 m	AM: 33 ± 10 µg/m3
1	1	Optical counter	2 days on continuous	Placed at an occupants' desk, from 0.6 to 1 m	AM: 9.2 ± 7.4 µg/m3
1	1	Gravimetric counter	3 days on continuous	Placed at the center of the room, at 0.4 to 1 m	Ranged from 4.5 to 85
1	1	Gravimetric counter	3 days on continuous	Placed at the back of the room	N/A
1	1	Gravimetric counter	48 hours on continuous	Placed at 1.5 m	AM: 1.9 ± 2.2
1	1	Portable dust Trak	1 day on continuous	Location not reported	Ranged from 39 to 244
1	1	Gravimetric counter	24 hours on continuous	Placed at the center of the room, at 0.4 to 1 m	Ranged from 5.8 to 34.8
1	1	Gravimetric counter	8 hours on continuous	Placed 1 m from the wall, and at 2 m of height	N/A
1	1	Optical counter	50 minutes on continuous	Placed at the back of the room, at 1.1 m of height	AM: 14 ± 1.7

Radon (Bq/m^3) (15 studies)					
1	1	Passive dosimeter	1 year on continuous	Measured in both ground and top-floor classrooms	Ranged from 89 to 4244
1	1	Passive dosimeter	6 months on continuous, 2 times per year	Location not reported	AM: 209 ± 9
1	1	Passive dosimeter	3 months on continuous	Ground floor classroom, at 1 to 2 m	Ranged from 31 to 633
1	1	Passive dosimeter	3 months on continuous	In cabinet, at 1 m of height and 10 cm from the wall	Ranged from 24 to 995
1	1	Passive dosimeter	3 months on continuous	Location not reported	Ranged from 15 to 663
1	1	Passive dosimeter	2 - 3 months on continuous	Location not reported	AM: 120
1	1	Passive dosimeter	2 months on continuous	Ground floor classroom	Ranged from 63 to 1157
1	1	Passive dosimeter	2 months on continuous	Location not reported	Max: 4205
1	1	Radon scout device	595 hours on continuous	Top floor classroom	Ranged from 40 to 320
1	1	Passive dosimeter	2 weeks on continuous	Location not reported	AM: 154

1	1	Radon detector monitors	2 - 9 days on continuous	Location not reported	AM: 62
1	1	Passive dosimeter	5 days on continuous	Location not reported	AM: 205 and 579
1	1	Passive dosimeter	48 hours on continuous	At 1.5 - 2 m of height, 1 m from the wall	AM: 154
1	1	Radon detector monitors	60 minutes on continuous, for 2 weeks	Location not reported	AM: 390
1	1	Radon detector monitors	60 minutes on continuous, 1 day in total	Ground floor classroom	Max: 1147
Formaldehyde (µg/m^3) (15 studies)					
6	1	Diffusive sampler	5 days on continuous	Location not reported	N/A
1	1	Diffusive sampler	595 hours on continuous	Location not reported	AM: 87
1	1	Diffusive sampler	2 weeks on continuous	Placed from 1.5 to 2 m, at 0.5 m from the wall	Ranged from 11 to 66
1	1	Diffusive sampler	8 days on continuous	Location not reported	Ranged from 43 to 88
1	1	Diffusive sampler	5 days on continuous	Placed at an occupants' desk, at 0.6 m	Ranged from 0.6 to 13

1	1	Diffusive sampler	5 days on continuous	Placed at an occupants' desk, from 0.6 to 1 m	Ranged from 5.6 to 21
1	1	Diffusive sampler	48 hours on continuous	Placed at 1.5 m	AM: 7.0 ± 2.3
1	1	Electrochemical detection	1 day on continuous	Placed at the center of the room, from 0.75 to 1.1 m	AM: 2 ± 12
1	1	Active sampling, at 100 L/min	2.5 hours on continuous	Location not reported	Ranged from 8.2 to 126
1	1	Electrochemical detection	30 minutes	Placed at an occupants' desk, from 0.6 to 1 m	AM: 86
BTEX (14 studies)					
Benzene (µg/m^3) (11 studies)					
7	1	Diffusive sampler	5 days on continuous	N/A	Ranged from 0.7 to 3.8
1	1	Diffusive sampler	2 weeks on continuous	N/A	Ranged from 0.4 to 0.9
1	1	Diffusive sampler	2 days on continuous	N/A	AM: 0.5
1	1	Active air sampling, 80 mL/min	30 minutes on continuous	Place at the back of the room	AM: 17

1	1	UV detector	30 minutes on continuous	N/A	AM: 2.7 ± 0.7
Toluene (µg/m^3) (9 studies)					
5	1	Diffusive sampler	5 days on continuous	N/A	Ranged from 1.6 to 9.2
1	1	Diffusive sampler	2 weeks on continuous	N/A	Ranged from 1.4 to 31
1	1	Diffusive sampler	2 days on continuous	N/A	AM: 0.2
1	1	Active air sampling, 80 mL/min	30 minutes on continuous	Place at the back of the room	AM: 17
1	1	UV detector	30 minutes on continuous	N/A	AM: 2.8 ± 1.3
Ethylbenzene (µg/m^3) (9 studies)					
5	1	Diffusive sampler	5 days on continuous	N/A	Ranged from 0.1 to 2.3
1	1	Diffusive sampler	2 weeks on continuous	N/A	Ranged from 0.3 to 2.2
1	1	Diffusive sampler	2 days on continuous	N/A	AM: 0.2
1	1	Active air sampling, 80 mL/min	30 minutes on continuous	Place at the back of the room	AM: 6

1	1	UV detector	30 minutes on continuous	N/A	AM: 5.0 ± 3.3
m,p-xylene (µg/m^3) (9 studies)					
5	1	Diffusive sampler	5 days on continuous	N/A	Ranged from 0.6 to 4.1
1	1	Diffusive sampler	2 weeks on continuous	N/A	Ranged from 0.6 to 0.9
1	1	Diffusive sampler	2 days on continuous	N/A	AM: 0.9
1	1	Active air sampling, 80 mL/min	30 minutes on continuous	Place at the back of the room	AM: 6
1	1	UV detector	30 minutes on continuous	N/A	AM: 1.6 ± 0.7
o-xylene (µg/m^3) (8 studies)					
5	1	Diffusive sampler	5 days on continuous	N/A	Ranged from 0.6 to 52.4
1	1	Diffusive sampler	2 days on continuous	N/A	AM: 0.3
1	1	Active air sampling, 80 mL/min	30 minutes on continuous	Place at the back of the room	AM: 2
1	1	UV detector	30 minutes on continuous	N/A	AM: 7.1 ± 4.7

SVOCs (11 studies)					
Tributyl phosphate (ng/m^3) (3 studies)					
1	1	PUF Filter 12 L/min flow rate	24 hours on continuous	N/A	AM: 3.1
1	1	XAD-2 absorbent 0.2 L/min flow rate	24 hours on continuous	N/A	AM: 36
1	1	Φ 76 mm PUF at 2.1 L/min flow rate	4.5 days on continuous	N/A	N/A
Acenaphthene (ng/m^3) (2 studies)					
1	1	75 mm pre-cleaned PUF plugs 38.3 L/min flow rate	24 hours on continuous	N/A	Ranged from 0.03 to 8.19
1	1	PUF Quartz filter (TSP) 38 L/min flow rate	1 week on continuous	N/A	Range from 7.15 to 72.02
Anthracene (ng/m^3) (2 studies)					

1	1	75 mm pre-cleaned PUF plugs 38.3 L/min flow rate	24 hours on continuous	N/A	Ranged from 0.3 to 0.6
1	1	PUF Quartz filter (TSP) 38 L/min flow rate	1 week on continuous	N/A	N/A
Benzo(a)pyrene (ng/m^3) (2 studies)					
1	1	75 mm pre-cleaned PUF plugs 38.3 L/min flow rate	24 hours on continuous	N/A	Ranged from 0.06 to 4.2
1	1	PUF Quartz filter (TSP) 38 L/min flow rate	1 week on continuous	N/A	N/A
Fluoranthene (ng/m^3) (2 studies)					
1	1	75 mm pre-cleaned PUF plugs 38.3 L/min flow rate	24 hours on continuous	N/A	Ranged from 0.04 to 3.3
1	1	PUF Quartz filter (TSP) 38 L/min flow rate	1 week on continuous	N/A	N/A
NO_2 (µg/m^3) (11 studies)					

2	1	Passive sampler	5 days on continuous	Location not reported	N/A
1	1	Passive sampler	8 weeks on continuous	Location not reported	Ranged from 7.5 to 22.5
1	1	Passive sampler	14 days on continuous	Location not reported	Ranged from 11.3 to 42.9
1	1	Passive sampler	1 week on continuous	Placed from 1.5 to 2 m of height, at 0.5 m from the wall	Ranged from 5.4 to 25.2
1	1	Passive sampler	1 week on continuous	Location not reported	Ranged from 4.3 to 29.7 ppb
1	1	Passive sampler	4.5 days on continuous	At the center of the room	AM: 8.4
1	1	Passive sampler	4.5 days on continuous	Placed at the center of the room, at 2 m	AM: 15.3
1	1	Passive sampler	4 days on continuous	Location not reported	Ranged from 5.1 to 69
1	1	Electrochemical analyzer	24 hours on continuous	Location not reported	N/A
1	1	Portable IAQ monitor	30 minutes	Placed at the back of the room, at height varied from 0.5 to 2.5 m	AM: 80
PM_{10} (µg/m^3) (8 studies)					

1	1	Optical counter	6 to 8 months	Location not reported	N/A
1	1	Optical counter	1 week on continuous	Placed at the center of the room, at students' breathing zone	AM: 96 ± 49 and 406 ± 292
1	1	Optical counter	5 days on continuous	Placed at the back of the room, at 1.2 m	AM: 362 ± 84
1	1	Optical counter	7 hours on continuous	Placed at the back of the room, at 0.6 m	AM: 134 ± 68 µg/m3
1	1	Optical counter	2 days on continuous	Placed at an occupants' desk, from 0.6 to 1 m	AM: 4.4 ± 2.9 µg/m^3
1	1	Gravimetric counter	48 hours on continuous	Placed at 1.5 m	AM: 7.5 ± 2.4
1	1	Portable dust Trak	1 day on continuous	Location not reported	Ranged from 39 to 244
1	1	Optical counter	50 minutes on continuous	Placed at the back of the room, at 1.1 m of height	AM: 122 ± 33
Air change rate (h^{-1}) (6 studies)					
6	1	Calculate using measured CO_2 concentration and the decay method	N/A	N/A	Ranged from 0.08 to 3.1 h-1

TVOC (µg/m^3) (3 studies)					
1	1	Photoionization UV detector	1 hour on continuous	N/A	Ranged from 1416 to 3367
1	1	Portable sensor	24 hours on continuous	N/A	Max: 30 ppm
1	1	Photoionization UV detector	2 - 3 days on continuous	N/A	Ranged from 79.23 to 488.33
Ventilation rate (l/s/p) (3 studies)					
3	1	Derived from the calculated air change rate	N/A	N/A	Ranged from 0.6 to 13.3
PM_1 (µg/m^3) (2 studies)					
1	1	Optical counter	7 hours on continuous	Placed at the back of the room, at 0.6 m	AM: 19 ± 7.2 µg/m^3
1	1	Gravimetric counter	24 hours on continuous	Placed at the center of the room, at 0.4 to 1 m	Ranged from 1.5 to 26.1
Visual mold inspection (cm^2) (2 studies)					

1	1	N/A	N/A	N/A	7 % of measured classrooms had visible mold
1	1	N/A	N/A	N/A	2 out of 17 schools had visible mold
Mold inspection by culture (CFU) (2 studies)					
1	N/A	N/A	N/A	N/A	AM: 22 CFU/m^3
1	N/A	N/A	N/A	N/A	AM: 260 CFU/m^3
$PM_{0.1}$ (µg/m^3) (1 studies)					
1	1	Portable condensation particle counter	8 hours per day, 5 days in total	Placed at 1.2 to 1.4 meters of height, and 1.5 meters from the wall	AM: Count of 7798 ± 2981
PM_5 (µg/m^3) (1 studies)					
1	1	Optical counter	7 hours on continuous	Placed at the back of the room, at 0.6 m	AM: 104 ± 50 µg/m^3

Table 5: Measured or modelled parameters to characterize the luminous environment, with details on the measurement protocol and obtained results (n = 13 results)

Measurement protocol					Ranges of results
Frequency	**Number of measured sensors**	**Measurement device**	**Measured duration**	**Location in the classroom**	
Assessment of the artificial lighting (3 studies) (lux)					
1	From 4 to 9 per classroom	Mavolux 5032 lux meter	Spot measurement	On students' tables	AM: 251 ± 115
1	1	Thermal microclimate HD32.1 sensor	Spot measurement	On students' tables	AM: 435 ± 166
1	1	Testo 545 illuminance meter	Spot measurement	At 1.1 meters of height	Ranged from 364 to 1122
Assessment of the total illuminance (7 studies) (lux)					
3	1	Minolta CL200 Lux meter	Measured in different condition, with both window blinds opened and closed	On students' tables	Ranged from 47 - 2600
1	6	PCE-134 lux-meter	Spot measurement	On students' tables	Ranged from 461 to 560

Measurement protocol					
Frequency	**Number of measured sensors**	**Measurement device**	**Measured duration**	**Location in the classroom**	**Ranges of results**
1	1	Testo 435-4 multifunctional measuring device	Spot measurement	On students' tables	Ranged from 53 to 413
1	1	Testo 545 illuminance meter	Spot measurement	On students' tables	AM: 8206 ± 9114
1	1	Illuminance meter	Spot measurement	On students' tables	AM: 847
Daylight illuminance assessment (1 study)					
1	N/A	Daylight factor simulation	N/A	N/A	N/A

III.3. The TAIL rating scheme for schools, selected parameters, its threshold values, and assessment protocols

The TAIL rating scheme for schools consists of 14 parameters, with two newly added parameters compared to the TAIL rating scheme for hotels and offices. The following subsections present parameters in each IEQ component, the threshold values used to determine the TAIL rating quality, and a suggested measurement protocol.

III.3.1. Thermal environment

For the thermal environment, the air temperature was selected as the assessment parameter, as was the case from the TAIL rating scheme for hotels and offices. A growing body of studies has shown the relationship between the thermal environment and children's health and well-being. Decreasing the air temperature from 30°C to 20°C is associated with a 20% increase in children's school performance on standardized tests [8]. This result shows that the assessment of the thermal environment using the air temperature can be applied in schools.

The second key discourse element is the possible inclusion of new parameters, adapting to the school's environment.

In various studies, mean radiant temperature, operative temperature, air speed, and other thermal assessment models have been used to characterize the thermal environment, as these parameters better represent the occupants' thermal comfort. However, measuring these parameters in schools, especially in a large sample, poses a considerable challenge. A study that measured mean radiant temperature using globe thermometers has raised concern economically when deploying the equipment in 145 classrooms [110]. Furthermore, in the same study, measured in low-energy buildings, the observed difference between the air and operative temperatures is relatively small. Thus, no new parameter will be added to the thermal component of the TAIL rating scheme for schools.

Table 6 presents the different threshold values for different quality categories of the TAIL-rating of the air temperature. The threshold values of the air temperature have been defined using the EN 16798-1 standard [126].

Table 6: Ranges of the thermal environment parameter in the TAIL rating scheme for schools

Category I	Category II	Category III	Category IV
Building with mechanical cooling			
Heating season: 22 ± 1 °C Non- heating season: 24.5 ± 1 °C	Heating season: 22 ± 2 °C Non- heating season: 24.5 ± 1.5 °C	Heating season: 22 ± 3 °C Non- heating season: 24.5 ± 2.5 °C	If other quality levels cannot be achieved
Building without mechanical cooling			
Heating season: 22 ± 1 °C Non-heating season: Upper limit: 0.33 θ_{rm} + 18.8 + 2°C Lower limit: 0.33 θ_{rm} + 18.8 - 3°C	Heating season: 22 ± 2 °C Non-heating season: Upper limit: 0.33 θ_{rm} + 18.8 + 3°C Lower limit: 0.33 θ_{rm} + 18.8 - 4°C	Heating season: 22 ± 3 °C Non-heating season: Upper limit: 0.33 θ_{rm} + 18.8 + 4°C Lower limit: 0.33 θ_{rm} + 18.8 - 5°C	If other quality levels cannot be achieved

There are two different sets of values to be used in heating season and non-heating season. For measurement made during the non-heating season in building without a mechanical cooling system, the upper limit and lower limit of different threshold are defined based on the calculation of the outdoor running mean temperature (θ_{rm}), calculate by:

$$\theta_{rm} = (1 - \alpha)(\theta_{d-1} + \alpha.\theta_{d-2} + \alpha^2.\theta_{d-3})$$

Or the following approximate formula can be used alternatively:

$$\theta_{rm} = \frac{(\theta_{d-1} + 0.8.\theta_{d-2} + 0.6.\theta_{d-3} + 0.5.\theta_{d-4} + 0.4.\theta_{d-5} + 0.3.\theta_{d-6} + 0.2.\theta_{d-7})}{3.8}$$

Where:

θ_{rm} = outdoor running mean temperature for measured day (°C)

θ_{d-i} = daily mean outdoor air temperature for the i^{th} previous day (°C)

α = constant between 0 and 1 (recommended value is 0.8)

To evaluate the air temperature, the rating scheme recommended using a thermo-hygrometer with an accuracy of 0.5 °C for continuous measurement for one month or at least one school week from Monday to Friday. The interval between measurements' instances should be 1 to 10 minutes. To avoid seasonality bias, measurements in both winter and summer are recommended, but they are not mandatory. For the assessment of air temperature, only the portion of school hours should be looked at (from 08:00 to 17:00). To be classified in one category, at least 94% of measured instances must stay inside threshold values of that category, or the thermal rating will be demoted to the next category quality. A flow chart detailing this rating principle can be found in Figure 6.

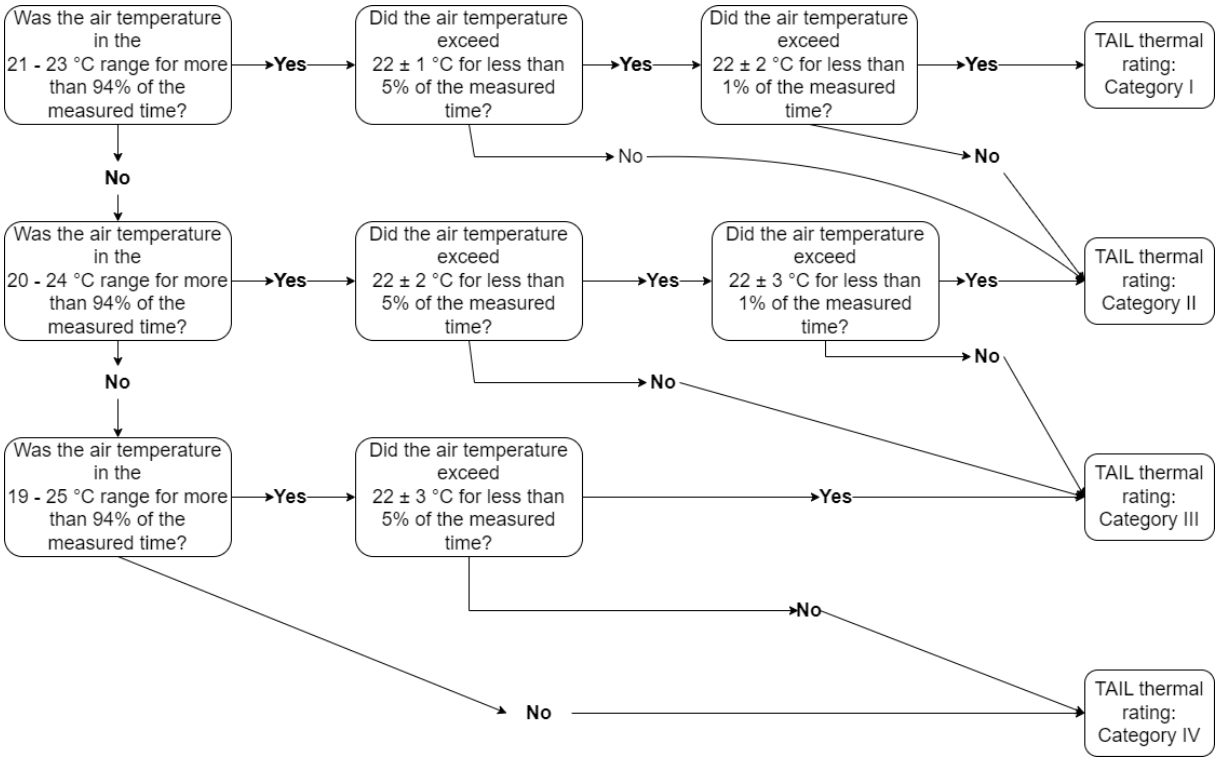


Figure 6: Flow chart describing the rating principle used to determine the TAIL thermal quality category

III.3.2. Acoustic environment

For assessing the acoustic environment in the school TAIL rating scheme, the background noise level (LA_{eq}) was retained from the original TAIL rating scheme for hotels and offices. LA_{eq} can be defined as the background sound pressure level at a given location [127]. The current literature has shown that they influence children's health, cognitive performance, and well-

being. Shield et al., in their study, have shown that children can read faster in a quiet classroom [128]. Other studies have also shown that anthropogenic noise from outside sources can hinder other aspects of children's classroom performance, and the younger the children, the more vulnerable they are [73,129,130]. For these reasons, the evaluation of the acoustic environment in schools needs to have an assessment of the background noise level.

Proceeding to the possible inclusion of other acoustical parameters, the reverberation time was added, making the total of two parameters used to characterize the acoustical environment. Reverberation time (RT) is required for the sound to decay to a certain level after the sound source has stopped. This test is critical as it is a parameter to define how sound can be a nuisance in a closed room. Children performed better on phonological processing in classes where RT was short, but RT had no significant impact on children's spelling ability [73]. Speech intelligibility is also essential for students, especially in younger children when their vocabulary and grammatical capability are still developing; they must fully hear the sentence to understand the meaning [131].

One key difference between the hotel and office environment and the classroom environment is that good vocal communication between teachers and children is essential in a classroom environment. In contrast, rooms in hotels and offices do not prioritize this aspect.

It depends on the familiarity with the spoken language, which may be limited for children due to the lack of vocabulary and grammar skills [132]. To assess speech intelligibility directly would be ideal. However, based on the literature review, speech intelligibility measurements are complex and require specialized technicians. Furthermore, guideline values for speech intelligibility have yet to be available in international standards or building regulations in several countries. Favorably, a recent simulation study on acoustic in a school setting has shown that both LA_{eq} and RT influence speech intelligibility [131,133]. Consequently, classrooms with high-quality LA_{eq} and RT will possess high-quality speech intelligibility.

Based on these justifications, the TAIL-rating scheme for schools included the LA_{eq} and the RT. Table 7 presents the threshold values for different quality categories of the TAIL rating of the acoustic environment. The threshold values of the LA_{eq} have been defined using the EN 16798-1 standard [14]. The threshold values of the RT come from Article 5 of the order of April 25, 2003, relating to the limitation of noise in healthcare establishments from France [134], and from the Danish buildings regulation code (BR10) [135].

Table 7: Ranges of the acoustic environment parameters in the TAIL rating scheme for schools

	Category I	Category II	Category III	Category IV
Background noise level (LA_{eq})	≤ 30 dB(A)	≤ 34 dB(A)	≤ 38 dB(A)	If other quality levels cannot be achieved
Reverberation time.	Classroom with volume < 250 m^3: 0.4 - 0.6 s Classroom with volume ≥ 250 m^3: 0.6 – 0.8 s	Classroom with volume < 250 m^3: 0.6 - 0.8 s Classroom with volume ≥ 250 m^3: 0.8 – 1.2 s	No criteria	If other quality levels cannot be achieved

The assessment of the LA_{eq} used a noise meter with an accuracy of 1 dB(A), a continuous measurement of one school week (Monday to Friday), and a time interval of 1 minute. For the assessment of the LA_{eq}, only the portion of school hours should be looked at (from 08:00 to 17:00). Preferably, LA_{eq} should be measured and assessed in non-occupied classrooms in case conditions do not align; measurement in occupied classrooms can be assessed by analyzing the 5th percentile of the recorded LA_{eq}.

The assessment of the RT used 12 microphones placed at various points in the classroom; measurement can either use the impulsive sound sequence or follow the ISO 3382-2: 2008[136]. Alternatively, RT can be calculated using the standard EN 12354-6: 2004: "Estimation of acoustic performance of buildings from the performance of elements – Part 6: sound absorption in enclosed spaced" [137].

III.3.3. Indoor air quality (IAQ)

For indoor air quality, eight parameters were retained from the TAIL rating scheme for hotels and offices. They were benzene, CO_2, formaldehyde, $PM_{2.5}$, radon, relative humidity, ventilation rate, and visible mold inspection. As for the most measured IEQ components, the literature on indoor air pollutants has shown that many indoor air pollutants significantly impact children's health, well-being, and cognitive performance. Benzene, formaldehyde, and radon are classified as class I carcinogens by the International Agency for Research on Cancer (IARC)

[20]. A study on children's performance on psychological tests and academic tasks shows that they can be improved by 12% in speed and 2% in accuracy when CO_2 concentration is reduced from 2100 ppm to 900 ppm [7]. $PM_{2.5}$ can penetrate deep into the respiratory system, causing inflammation and irritation of the airways, leading to respiratory issues such as asthma, bronchitis, and other respiratory infections in children [138]. Maintaining an optimal relative humidity level is generally recommended for comfort and well-being [139]. Furthermore, low RH can lead to dry air, potentially causing discomfort in the respiratory tract, throat, and eyes, and high RH can create a favorable environment for mold growth. Regarding these reasons, there were no arguments against retaining these eight parameters.

A new parameter has been included in the TAIL rating scheme for schools to better adapt to the schools' environment: NO_2. NO_2 is an asthma exacerbation factor, especially in children. NO_2 levels were associated highly with airflow obstruction, such that each 10-ppb increase in NO_2 level was associated with a 5% decrease in FEV1/forced vital capacity ratio (b520.05; 95% CI, 20.08 to 20.02; P 5.01) [65]. With children as the primary occupants in schools, the TAIL rating scheme for schools should measure NO_2 to represent the IEQ of schools better and consequently better assess its occupants' exposure.

As a result, the IAQ component of the TAIL rating scheme consists of nine parameters. Table 8 presents the different threshold values for different quality categories of the TAIL rating of the IAQ. The lower limit of the benzene concentration comes from the French regulation decree n° 2011-1727 [14], and its upper limit comes from the EU Directive 2008/50/EC, 2008. Threshold values for the CO_2 concentration, formaldehyde concentration, relative humidity, and ventilation rate come from the EN 16798-1: 2019 standard [126]. Threshold values for the radon concentration come from the WHO Housing and Health Guidelines, 2018 [18]. Threshold values for the $PM_{2.5}$ concentration come from the WHO Air Quality Guidelines 2021 [140]. The lower limit for the NO_2 concentration also comes from the same document, with its upper limit coming from the indoor air guideline values (VGAI) [141] from the French Agency for Food, Environmental, and Occupational Health & Safety, 2008. Finally, the visual mold inspection comes with threshold values from the Nordic classification system of mold assessment [142].

Table 8: Ranges of the indoor air quality parameters in the TAIL rating scheme for schools

	Category I	**Category II**	**Category III**	**Category IV**

Benzene concentration	< 2 µg/m^3	≥ 2 µg/m^3	No criteria	≥ 5 µg/m^3
CO_2 concentration	550 ppm above outdoor concentration	800 ppm above outdoor concentration	1350 ppm above outdoor concentration	If other quality levels cannot be achieved
Formaldehyde concentration	< 30 µg/m^3	≥ 30 µg/m^3	No criteria	≥ 100 µg/m^3
NO_2 concentration	< 10 µg/m^3	< 20 µg/m^3	No criteria	≥ 20 µg/m^3
$PM_{2.5}$ concentration	< 5 µg/m^3	≥ 5 µg/m^3	No criteria	≥ 15 µg/m^3
Radon	< 100 Bq/m^3	≥ 100 Bq/m^3	No criteria	≥ 300 Bq/m^3
Relative humidity	30 – 50%	25 – 60%	20 – 70%	If other quality levels cannot be achieved
Ventilation rate	≥ (10 L/s/p + 2.0 L/s/m^2 floor)	≥ 7 L/s/p + 1.4 L/s/m^2 floor and < 10 L/s/p+ 2.0 L/s/m^2 floor	≥ 4 L/s/p + 0.8 L/s/m^2 floor and < 7 L/s/p + 1.4 L/s/m^2 floor	If other quality levels cannot be achieved
Visible mold inspection	No visible sign	< 400 cm^2	< 2500 cm^2	≥ 2500 cm^2

Relative humidity measurements are made together with air temperature; thus both share the same protocol. The sensor's required precision is 5 % for the measurement of relative humidity. For the assessment, only the portion of school hours should be looked at (from 08:00 to 17:00). To be classified in one category, at least 94% of measured instances must stay inside threshold values of that category, or the relative humidity rating will be demoted to the next category quality. A flow chart detailing this rating principle can be found in Figure 7.

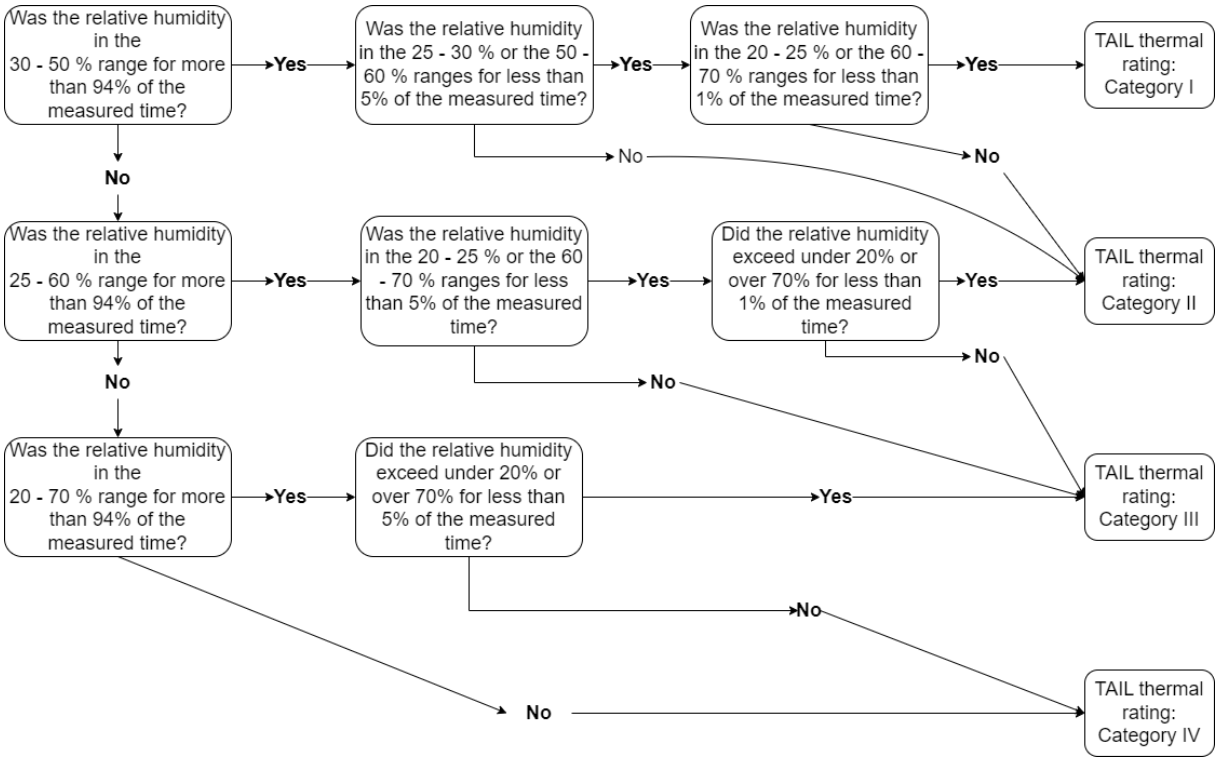


Figure 7: Flow chart describing the rating principle used to determine the TAIL relative humidity quality category

The measurement of CO_2 should be made using a non-dispersive infrared (NDIR) sensor with ±50 ppm accuracy, continuously for one school week (Monday to Friday), with a time interval of 10 minutes. For the assessment of the CO_2 concentration, only the portion of school hours should be looked at (from 08:00 to 17:00). To be classified in one category, at least 94% of measured instances have to be under that category, or the score will be one category higher. A flow chart detailing this rating principle can be found in Figure 8.

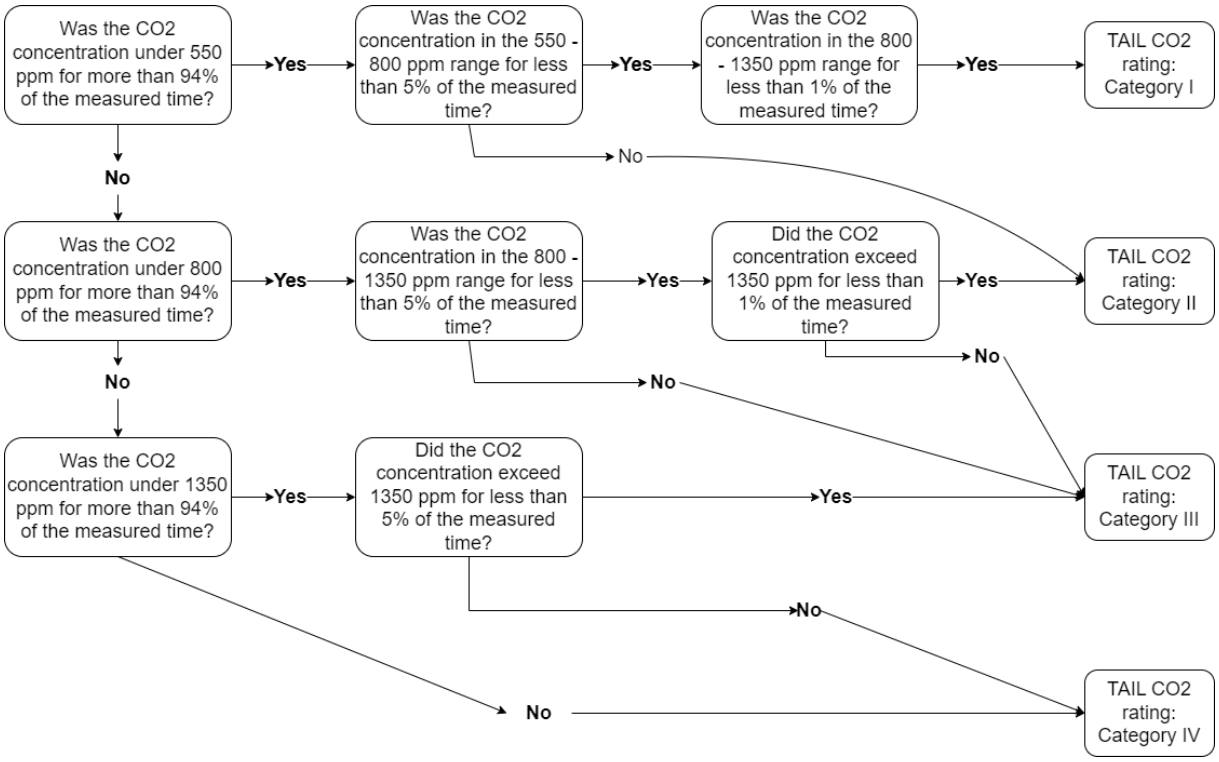


Figure 8: Flow chart describing the rating principle used to determine the TAIL CO_2 quality category

The measurement of NO_2 should be made using a passive sampler, continuously for one school week (Monday to Friday). The measurement should be in compliance with the ISO 16000-15:2008 standard [143]. Concentration analyzed using gas chromatography and mass spectrometry (GC-MS).

The measurement of benzene should be made using a passive sampler, continuous measurement of one school week (Monday to Friday), measurement in compliance with ISO 16017-2:2003. Concentration analyzed using gas chromatography and mass spectrometry (GC-MS).

The measurement of formaldehyde should be made using a passive sampler, continuous measurement of one school week (Monday to Friday), measurement in compliance with ISO 16000-3:2011. Concentration analyzed using high performance liquid chromatography-ultraviolet (HPLC-UV).

The measurement of radon should only be made in high-risk zones following the cartography from the European Environment agency (EEA). Measured using passive sampling with 2

dosimeters in ground floor, 2 months duration in winter only. Measurement to comply with ISO 11665-8:2013.

The measurement of $PM_{2.5}$ should be made using the gravimetric method, continuous measurement in one schools' week (Monday to Friday), suggestion of measure in 2 critical outdoor period, in this case, the average concentration is used for the ranking. Measurement to be comply with CEN – EN 12341:2014. In case the gravimetric method cannot be used, a substitution using an optical counter can be used.

The measurement of the ventilation rate must be conducted twice, one at the start and another at the conclusion of continuous monitoring for various building parameters, especially in spaces with mechanical supply and/or exhaust systems. For these measurements, a calibrated flow hood (commonly referred to as a capture hood) should be employed to gauge airflow at all the inlet and exhaust points within the chosen classrooms.

The inspection of visible mold should be made by observation in measured room, and in directly adjacent location based on relative humidity. Observation should be made by a trained technician.

III.3.4. Luminous environment

For assessing the luminous environment in the school TAIL rating scheme, the daylight factor and the total illuminance were retained from the TAIL rating scheme for hotels and offices. The benefit of daylight illuminance, and therefore daylight factor, has been proven, as daylight, besides bringing illuminance, has spectral properties that can regulate the circadian rhythm in children [23]. Artificial illuminance in schools should also be well maintained, as its role is to maintain enough light in case daylight illuminance cannot be used. Knoop et al., in their review, while underlining the essential benefits of daylight illuminance, also highlight the importance of artificial lighting, whose role is to maintain sufficient lighting indoors when daylight cannot be used appropriately [23]. Based on these results, there were no arguments against retaining these two parameters in the TAIL rating scheme for schools. Furthermore, in the literature review, there were no other parameters, thus no parameters will be added in the TAIL rating scheme for schools.

Table 9 presents the different threshold values for different quality categories of the TAIL-rating of the visual environment. The threshold values for the different quality categories of the daylight factor come from the EN 17037 -1 [144], with the values of Brussels. As stated above, schools in the different geographic zone are suggested to consult the standard and change the reference value to a corresponding city of their choice. The threshold values for the different quality categories of the artificial light come from the EN 12646-1 [145].

Table 9: TAIL visual environment quality categories

	Category I	**Category II**	**Category III**	**Category IV**
Daylight factor	≥ 5.0 %	≥ 3.3 %	≥ 2.0 %	If other quality levels cannot be achieved
Total illuminance (horizontal on students' tables and vertical on writing boards)	≥ 500 lux	≥ 300 lux	≥ 200 lux	If other quality levels cannot be achieved

Conduct dynamic daylight simulations for a one-year duration, following the guidelines outlined in EN 17037-1. In the absence of standardized simulation tools, it is advisable to use a simulation tool based on radiance. The threshold values applied should align with those specified in the EN 17037-1 standard for Brussels [146]. Schools in other countries are welcome to consult the standard for reference values in another countries that is more aligned with their location.

Spot measurement following the protocol in the EN 12464-1:2021 [145]. In case this protocol cannot be replicate, the following substitution is suggested: Spot measurements in at least six points, one directly under an artificial light, one directly situated between two overhead light, and one point situated between these two points. Another set of these 3 points should be measured in the same classroom. Calibrated sensors with an accuracy of at least 3 lx (or 3% of the measured value with the resolution of 1 lx) shall be used.

III.3.5. The rating principle

The principle of the TAIL rating scheme is to provide an overall IEQ rating for each school, based on the results of measurement in multiple classrooms in schools. The number of chosen

classrooms to be measured needs to be a balance between the need to ensure that the assessment represents the whole building and its technical and economic feasibility, as measurement cannot be made in every classroom, in consideration of the cost of measurements and the time required for the measurements.

Measurements were made at the classroom level (room in the TAIL hotels and offices), and at the end, an overall TAIL result can be attributed to the whole building. Thus, a calculation process must be determined to translate the measurement results into the overall TAIL rating result. However, compared to the TAIL rating for hotels and offices, a different approach has been used in calculating the score in the TAIL rating scheme for schools. Figure 9 outlines the calculation used in the TAIL rating scheme for hotels and offices.

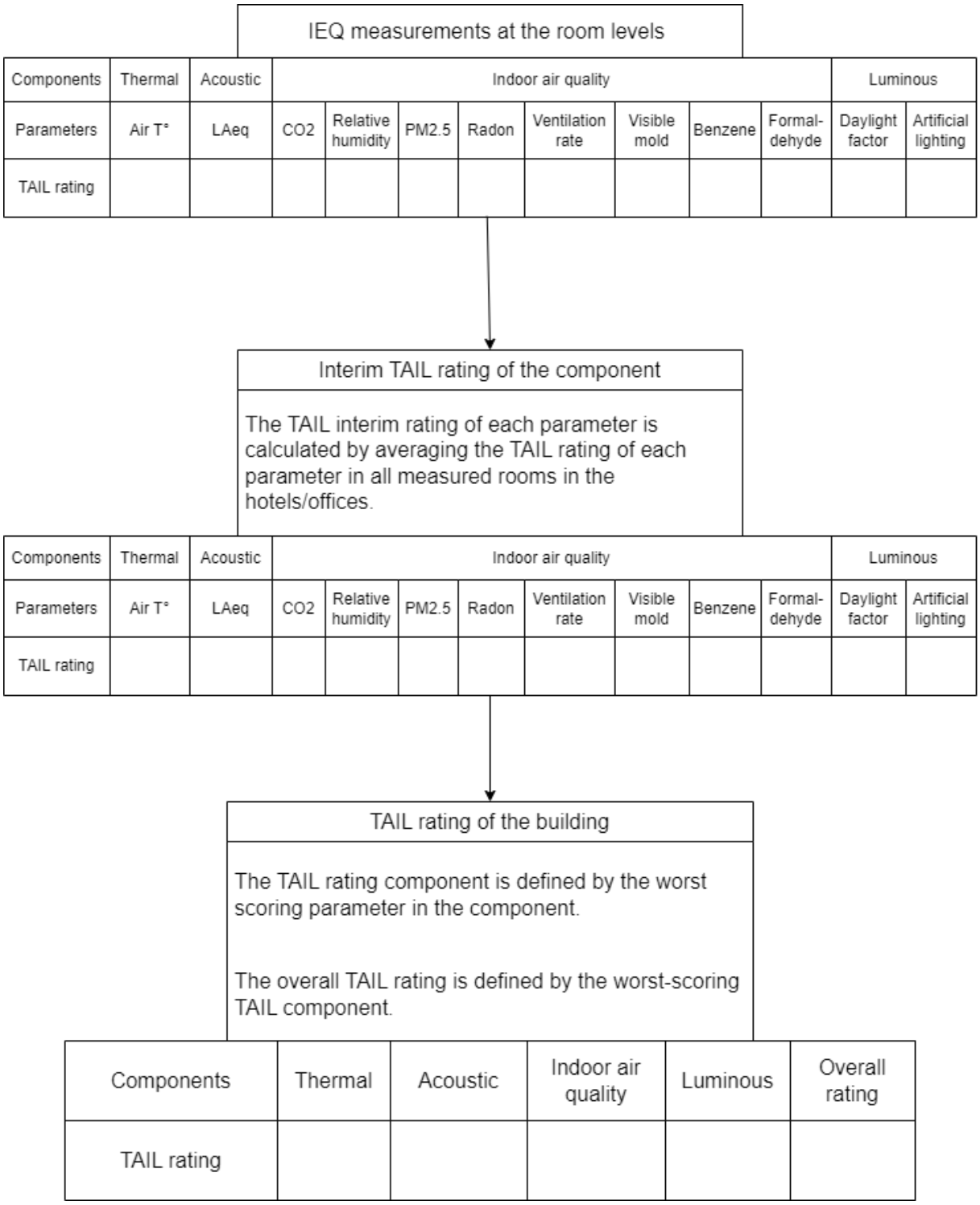


Figure 9: Flow chart describing the process of the rating calculation in the TAIL rating scheme for hotels and offices

The rating calculation process in the TAIL rating scheme for hotels and offices started with the measurements of each parameter at the room level. Based on the levels of the measurements, a

TAIL rating of each parameter can be assessed using the corresponding threshold level. Afterward, an interim TAIL rating of each parameter is calculated to be representative of the scale of the hotels/offices based on the number of measured rooms.

The following formula is used to calculate this interim rating:

$$Interim\ rating = \frac{\sum_1^k R_k * O_k}{n}$$

Where:

- K is the number of quality levels for each parameter in the components.
- R is the rank for the specific quality level (R = 1 for the category I level, R = 2 for the category II level, R = 3 for the category III level, and R = 4 for the category IV level)
- O is the number of measurements made for each quality level k
- n is the total number of measurements made.

The quality levels are categorized based on the interim rating. A rating between 1 and 1.4 is considered green, while a rating between 1.5 and 2.4 is categorized as yellow. An interim rating between 2.5 and 3.4 is labeled as orange, and a rating between 3.5 and 4 falls under the red category. These ranges of interim ratings were selected in order to ensure that the actual quality level of a building is consistent with the majority of quality levels observed. This interim rating thus represents the TAIL score on the building level of the IEQ parameters.

Secondly, the rating of each TAIL IEQ component will be determined. This score is determined by the worst interim score of all the components' parameters. An exception will be the score of the thermal environment, as there is only one IEQ parameter (the air temperature) in it.

Thirdly, the final TAIL score of the school is determined by the worst score of the four TAIL components. Selecting the lowest quality components encourages the holistic improvement of IEQ; this topic is discussed below.

Figure 10 outlines the calculation process in the TAIL rating scheme for schools.

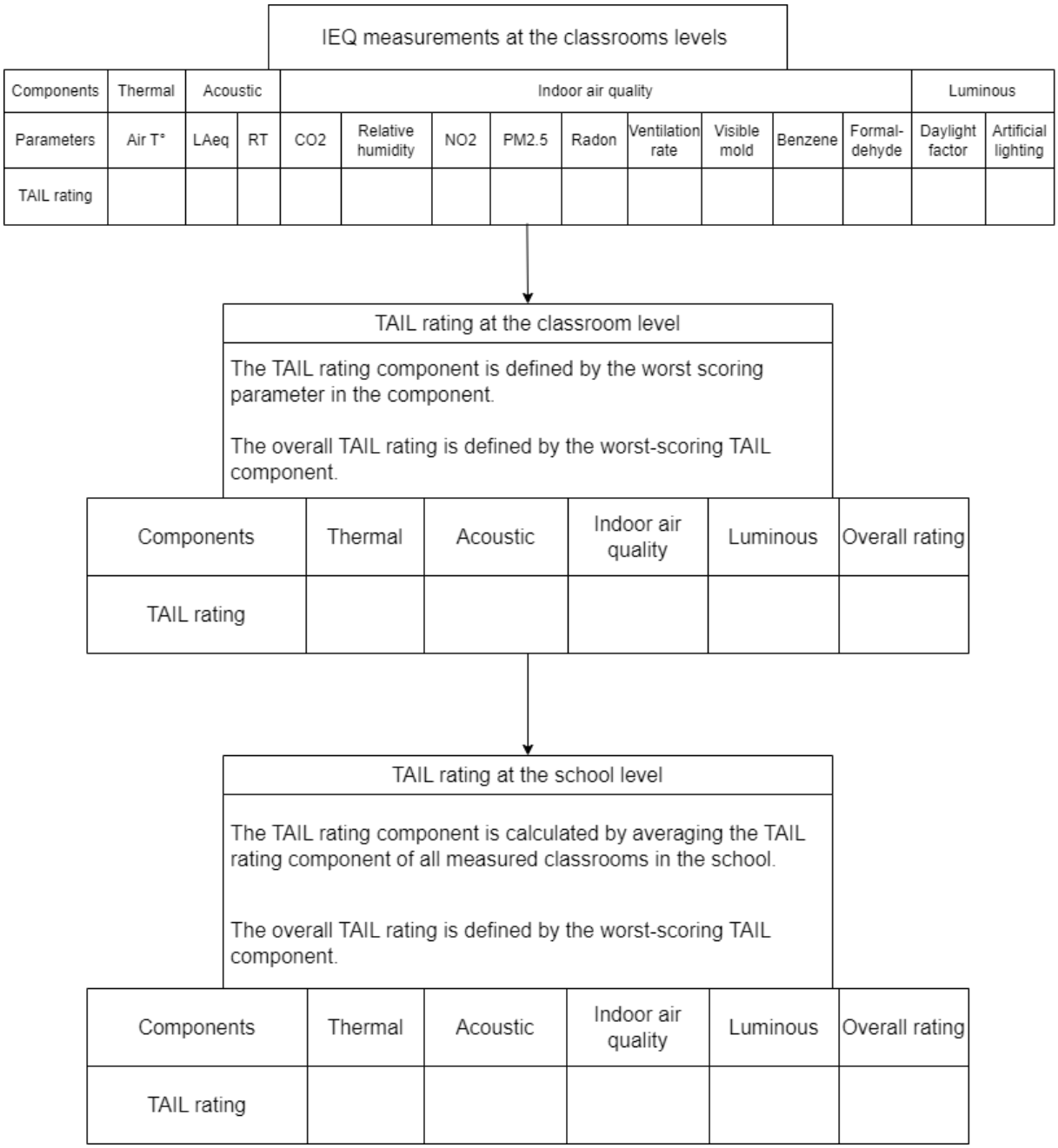


Figure 10: Flow chart describing the process of the rating calculation in the TAIL rating scheme for schools

The calculation process differs from the TAIL rating scheme for hotels and offices in the calculation between the rooms and the scale of the building. In the TAIL rating scheme for schools, a TAIL rating of each component was attributed at the classroom level. As a result, each classroom, therefore, had an overall TAIL classification. Afterward, to be representative in the school's scale, the TAIL rating of each component was then averaged from all the

measured classrooms. By changing the order of the calculation process, each classroom will now have its own TAIL classification for every IEQ component. Consequently, the measured IEQ parameters can be interpreted using the TAIL classification at a smaller scale. The IEQ condition of each classroom can thus be assessed individually. Therefore, IEQ improvement can be made on a smaller scale.

III.4. Discussion and perspective

The TAIL rating scheme was developed to bridge a gap and provide a measurement-based approach to assess the overall IEQ in schools. Along with the construction of the TAIL-rating scheme for schools, many observations and talking points were raised, as well as some perspectives for future development.

Following on the positive feedback of the TAIL rating scheme for hotels and offices, which aimed at evaluating the IEQ before renovations and suggesting renovations to improve the IEQ while gaining energy performance, this work presents an adaptation of the TAIL method to the school environment, called the TAIL rating scheme for schools.

However, evolution and adaptation are needed to apply the TAIL method to other building types. Intending to develop an overall rating scheme that makes comparisons of the IEQ in different schools possible, included IEQ parameters must be pertinent to be measured in schools. A literature review of 88 studies that measured IEQ parameters in schools was prepared. A list of 32 parameters that characterized the IEQ in schools has been collected, focusing on their measurement method and range of results. Derived from the literature review, this database will serve as the starting point for the rating scheme's future development steps and future studies. In a post-analysis context, the literature review process could be done more comprehensively, compared to only selecting studies from Europe and North America, as in the current state, there is a gap in IEQ studies in schools coming from other parts of the world.

Keeping the continuity from the original TAIL for hotels and offices, the original 12 IEQ parameters were kept in the school's TAIL rating scheme. The next step consists of selecting new parameters for schools to include in the TAIL rating scheme. New parameters were selected based on three criteria from the earlier list of pertinent parameters.

The first criterion focused on the requirement that the parameters have documented effects on the health and well-being of children. By choosing parameters that impact the health and well-being of children, the TAIL rating scheme aims to comprehensively evaluate the overall condition and exposure of children in classrooms, considering all relevant harmful parameters. The second criterion considered the practicality of the measurement protocol, particularly in the context of a large-scale study. This criterion ensures that no selected parameters in the rating scheme will discourage schools from participating due to economic or technical concerns. The rating scheme should instead encourage schools to adopt it willingly. The third criterion focused on the availability of guidelines and values in international standards or regulations. To establish multiple quality levels in the TAIL rating scheme, all included parameters should have guidelines specified in documents referenced from reputable institutions or regulatory bodies.

After screening new parameters, two parameters were added: reverberation time and nitrogen dioxide.

Effective verbal communication between teachers and students is essential in schools, particularly for younger students whose vocabulary and expressive abilities are still in the developmental stage. Therefore, the evaluation of speech intelligibility was deemed essential. However, as demonstrated in the literature review, the measurement protocol for this parameter is intricate and resource intensive. Additionally, there is a lack of guideline values of speech intelligibility in standards and regulations. Fortunately, since speech intelligibility depends on the RT, and this parameter satisfied all three selection criteria, it was considered a suitable inclusion in the TAIL rating scheme.

Considering the school environment primarily comprises children, whose daily activities and physiological characteristics differ from those of adults, the inclusion of nitrogen dioxide (NO_2) in the TAIL rating scheme was justified. NO_2 poses a heightened risk to children due to their higher respiratory rates compared to adults, exposing them more significantly to this asthma exacerbation factor.

Including these two new parameters acknowledges the flexibility to introduce new parameters, provided they meet all three selection criteria for future scheme iterations. As scientific knowledge regarding the impact of IEQ parameters on children's health continues to expand, along with advancements in the technical capacity to measure these parameters, the success of future TAIL iterations hinges on the integration of parameters previously deemed lacking in

scientific proof, challenging to measure, or lacking guideline values. Such parameters include operative temperature, speech intelligibility, PM_{10}, and SVOCs, significantly influencing children's health, well-being, and cognitive performance.

Acknowledging the economic impracticality of specific measurement protocols, especially in large-scale studies, efforts to include such parameters in the TAIL rating scheme will be pivotal in avoiding potential discouragement for schools to engage in IEQ measurement and monitoring. The 14 IEQ parameters incorporated in the TAIL rating scheme for schools strike a balance between characterizing the IEQ in schools and considering economic and logistical factors. The ongoing inclusion of new IEQ parameters in significant scientific or technical developments ensures the TAIL rating remains relevant and accurately represents the environmental conditions children are exposed to, marking a significant step towards comprehensively capturing the complexity of their surroundings.

Besides the inclusion of two new parameters, another fundamental change was made. It was the calculation process of the overall rating of the IEQ of the schools from the measurement of multiple parameters in each IEQ component and multiple measured classrooms in each school. Unlike the TAIL rating scheme for hotels and offices, which initiates measurement in various rooms across the buildings, averaging the ratings for each parameter to determine a building-level TAIL rating, the school rating scheme follows a different sequence. Here, the process begins by measuring IEQ parameters in individual classrooms, establishing the TAIL rating for each component and the overall TAIL rating at the classroom level. Subsequently, the TAIL rating for each component and the overall TAIL across all classrooms is obtained by averaging the TAIL rating for each component and overall rating at the school level. By reversing the calculation order, every classroom now possesses its TAIL rating based on individual measurement data. This minor adjustment empowers schools to implement IEQ-related mitigation or renovations at the classroom level, thereby enhancing IEQ within each classroom and consequently elevating the overall IEQ at the school level.

Table 10 details the changes made during the adaptation from the TAIL rating scheme for hotels and offices to the TAIL rating scheme for schools. Table 11 compares threshold values used in TAIL for hotels and offices and TAIL for schools. The threshold values used to assess the IAQ pollutants met the WHO air quality guidelines.

Table 10: Changes made in the adaptation of the TAIL rating scheme for schools

Adaptations made	TAIL for schools
IEQ parameters added	RT and NO_2
Calculation process	Modification of the calculation process so that TAIL rating is carried out at classroom scale rather than only at buildings' scale

Table 11: Comparison of threshold values used in TAIL for hotels and offices, and TAIL for schools

	Threshold used in TAIL for hotels and offices				**Threshold used in TAIL for schools**			
	Category I	**Category II**	**Category III**	**Category IV**	**Category I**	**Category II**	**Category III**	**Category IV**
Air temperature	Building with mechanical cooling, measured in heating season				No changes made			
	22 ± 1 °C	22 ± 2 °C	22 ± 3 °C	If other quality levels cannot be achieved				
	Building with mechanical cooling, measured in non-heating season							
	24.5 ± 1 °C	24.5 ± 1.5 °C	24.5 ± 2.5 °C	If other quality levels cannot be achieved				
	Building without mechanical cooling, measured in heating season							
	22 ± 1 °C	22 ± 2 °C	22 ± 3 °C	If other quality levels				

	Threshold used in TAIL for hotels and offices				Threshold used in TAIL for schools			
	Category I	**Category II**	**Category III**	**Category IV**	**Category I**	**Category II**	**Category III**	**Category IV**
				cannot be achieved				
	Building without mechanical cooling, measured in non-heating season							
	Upper limit: 0.33 θrm + 18.8 + 2°C	Upper limit: 0.33 θrm + 18.8 + 3°C	Upper limit: 0.33 θrm + 18.8 + 4°C	If other quality levels cannot be achieved				
	Lower limit: 0.33 θrm + 18.8 - 3°C	Lower limit: 0.33 θrm + 18.8 - 4°C	Lower limit: 0.33 θrm + 18.8 - 5°C					
	Small office				Classrooms			
Background noise level	≤ 30 dB(A)	≤ 35 dB(A)	≤ 40 dB(A)	If other quality levels cannot be achieved	≤ 30 dB(A)	≤ 34 dB(A)	≤ 38 dB(A)	If other quality levels cannot be achieved

	Threshold used in TAIL for hotels and offices				Threshold used in TAIL for schools			
	Category I	**Category II**	**Category III**	**Category IV**	**Category I**	**Category II**	**Category III**	**Category IV**
	Landscape office							
	≤ 35 dB(A)	≤ 40 dB(A)	≤ 45 dB(A)	If other quality levels cannot be achieved				
	Hotel rooms							
	≤ 25 dB(A)	≤ 30 dB(A)	≤ 35 dB(A)	If other quality levels cannot be achieved				
Reverberation time	Not measured				Classroom with volume < 250 m^3			
					0.4 - 0.6 s	0.6 - 0.8 s	No criteria	If other quality levels cannot be achieved

	Threshold used in TAIL for hotels and offices				Threshold used in TAIL for schools			
	Category I	**Category II**	**Category III**	**Category IV**	**Category I**	**Category II**	**Category III**	**Category IV**
					Classroom with volume ≥ 250 m^3			
					0.6 – 0.8 s	0.8 – 1.2 s	No criteria	If other quality levels cannot be achieved
Benzene concentration	< 2 µg/m^3	≥ 2 µg/m^3	No criteria	≥ 5 µg/m^3	No changes made			
CO_2 concentration	550 ppm above outdoor concentration	800 ppm above outdoor concentration	1350 ppm above outdoor concentration	If other quality levels cannot be achieved	No changes made			
Formaldehyde concentration	< 30 µg/m^3	≥ 30 µg/m^3	No criteria	≥ 100 µg/m^3	No changes made			
NO_2 concentration	Not measured				< 10 µg/m^3	< 20 µg/m^3	No criteria	≥ 20 µg/m^3

	Threshold used in TAIL for hotels and offices				Threshold used in TAIL for schools			
	Category I	**Category II**	**Category III**	**Category IV**	**Category I**	**Category II**	**Category III**	**Category IV**
$PM_{2.5}$ concentration	< 10 $\mu g/m^3$	≥ 10 $\mu g/m^3$	No criteria	≥ 25 $\mu g/m^3$	< 5 $\mu g/m^3$	≥ 5 $\mu g/m^3$	No criteria	≥ 15 $\mu g/m^3$
Radon	< 100 Bq/m^3	≥ 100 Bq/m^3	No criteria	≥ 300 Bq/m^3	No changes made			
Relative humidity	30 – 50%	25 – 60%	20 – 70%	If other quality levels cannot be achieved	No changes made			
Ventilation rate	≥ (10 L/s/p + 2.0 $L/s/m^2$ floor)	≥ 7 L/s/p + 1.4 $L/s/m^2$ floor and < 10 L/s/p+ 2.0 $L/s/m^2$ floor	≥ 4 L/s/p + 0.8 $L/s/m^2$ floor and < 7 L/s/p + 1.4 $L/s/m^2$ floor	If other quality levels cannot be achieved	No changes made			
Visible mold inspection	No visible sign	< 400 cm^2	< 2500 cm^2	≥ 2500 cm^2	No changes made			

	Threshold used in TAIL for hotels and offices				Threshold used in TAIL for schools			
	Category I	**Category II**	**Category III**	**Category IV**	**Category I**	**Category II**	**Category III**	**Category IV**
Daylight factor	≥ 5.0%	≥ 3.3%	≥ 2.0%	If other quality levels cannot be achieved	No changes made			
Total illuminance	% of the time with measured illuminance between 300 and 500 Lux, in offices				Measured in multiple spots in the classrooms			
	≥ 60% and ≤ 100%	≥ 40% and < 60%	≥ 10% and < 40%	If other quality levels cannot be achieved	≥ 500 lux	≥ 300 lux	≥ 200 lux	If other quality levels cannot be achieved
	% of the time with measured illuminance between 300 and 500 Lux, in hotel rooms							
	0%	> 0% and ≤ 50%	> 50% and ≤ 90%	If other quality levels cannot be achieved				

III.5. Conclusion

This concludes the development of the TAIL-rating scheme in schools. With the vision of providing an overall rating of the IEQ in schools, the rating scheme provides a set of IEQ parameters to be measured in schools. The measurement protocols were also presented to provide the school with a ready-to-use IEQ assessment method.

The construction of the TAIL rating schemes for schools started as an adaptation from the initially developed TAIL for hotels and offices. During the construction of the rating scheme, a review of the measurement of IEQ parameters in the school has been done. Results show that while some pertinent IEQ parameters are to be measured in school, some parameters pose a challenge in schools, as their protocol remains complex. Compared to the TAIL rating scheme for hotels and offices, two new parameters, RT and NO_2, have been added, raising the total number of parameters to 14.

These evolutions were done to represent the IEQ in schools better and allow an assessment of the IEQ regarding all impacts. With this rating scheme, the next step is a feasibility test, which underlines its performance when applied to actual cases.

IV. Application of TAIL to the French national school IEQ survey

IV.1. Context and objectives

In the last chapter, we have presented the construction of a rating scheme for educational buildings: TAIL for schools. The next step is to check the relevance and feasibility of the rating scheme when it comes to characterizing the IEQ state in a large number of schools. This, however, requires a sufficient amount of data, such as the measurement of several IEQ parameters from all four components in schools with different characteristics, to underline the strengths and weaknesses of the rating scheme. An example is the pan-European study, SINPHONIE, which measured parameters in the thermal and visual environment and the quality of air in 114 schools in 23 countries [10,43]. With the absence of accessibility to SINPHONIE data, we chose to perform the feasibility test for the TAIL rating scheme using measurement data from the French National IEQ survey in schools.

From 2013 to 2017, the “Observatoire de la qualité de l'air intérieur” (OQAI) conducted a national campaign, called the National Schools’ Survey, to describe the IEQ in classrooms in mainland France. With the aim of gaining a better understanding of children's exposure to a large number of pollutants never or rarely measured before in classrooms, as well as the ambient conditions to which they are exposed, the main objectives of the measurements campaign were as follows:

- Describe the school characteristics (building typology, systems, and equipment) and its uses.
- Carry out a survey on air pollution and dust in classrooms.
- Describe actual comfort conditions and the perceptions of teachers and children.

This chapter focuses on the application of the TAIL-rating schemes to the IEQ measurements results obtained during the measurement campaign, with the aim to demonstrate the robustness of the rating scheme by applying it to large-scale data to verify its relevance.

The chapter is organized into five sections. First, the National school survey in France is described along with the measured parameters, and its measurement protocol (Subsections IV.2.1.1 and IV.2.1.2). The parameters of the feasibility test, in particular the compromise made

to compensate for the difference between the TAIL measurement protocol and measurements made in the survey is described in subsection IV.2.2. The test results are presented in section IV.3, starting with the results of each TAIL component and concluding with the overall TAIL score. For each component, results are presented first at the classroom level and then followed at the school level. In some components, there will be specific case studies that illustrate the rating principle of the TAIL rating scheme. This is followed by an interpretation, discussion (subsection IV.4) and conclusions (subsection IV.5).

IV.2. Research setting

IV.2.1. The national school survey in France (2013-2017)

IV.2.1.1. Selected schools' sample

As stated before, the national schools survey contained measurements data from 602 classrooms in 308 nurseries and elementary schools in mainland France. To keep the cost of measurement economically viable, a random selection of schools was performed, and the data observed was extrapolated to all French schools. The sample selection was designed according to a stratified strategy. Three variables likely to have an impact on school indoor environmental quality were available in the sampling frame: geographical area, type of school (nursery or elementary), and environment (urban, suburban, or rural). A two-stage sampling was then carried out.

The first stage was to draw up geographical zones, based on the eight climatic zones defined in the French thermal regulations (RT 2005). These eight zones are characterized by their temperatures in the winter (H1, H2, and H3):

- Zone H1, where winter temperatures are coldest. This zone corresponds to the departments of eastern and northern France, which are under the influence of a semi-continental climate.
- Zone H2, where winters are more temperate. This zone also includes the departments of western France, which are under the influence of an oceanic climate.
- Zone H3, which corresponds to the territories around the Mediterranean, under the influence of a Mediterranean climate.

Zones H1 and H2 were further divided into three and four zones, respectively, based on the temperatures in summer. A letter from “a” to “d” was added, in which “a” represented the coldest region, and “d” represented the hottest region during summer. In total, the eight climatic zones are as follows: H1a, H1b, H1c, H2a, H2b, H2c, H2d, and H3.

In a second stage, schools were selected in each geographical area according to the type of school (nursery or elementary and the type of environment (urban, suburban, and rural). The typology defined by the “French National Institute for Industrial Environment and Risks” (INERIS) was applied to refine the description of schools' outdoor environment. This typology distinguished three types of school environment: rural, suburban, and urban according the following four criteria:

- Land-use class by geocoding identification. In the database, level 1 of school land-use classes is specified as follows:
    - Artificialized areas.
    - Agricultural areas.
    - Forests and semi-natural environments.
    - Wetlands.
    - Water surfaces.
- Majority land-use class within a 500 m radius of the school by geocoding identification.
- The proportion of artificial land within a 2 km radius of the school.
- Population density of the school's municipality.

Finally, 301 schools were randomly selected to represent the French school population, and a further seven schools voluntarily asked to be included in the campaign. For each school, two or three classrooms were selected for in-situ measurement. Additionally, measurements were performed for each classroom during only one school week. As a result, measurements at each school took place only during one season rather than both. Table 12 shows an overview of the measured schools based on the stratified characteristics and the season in which the measurement occurred.

Table 12: General characteristics of schools evaluated and the corresponding seasons (n = 308)

Variables	Measured season	
	Heating	**Non-heating**
Type of school		
Nursery	123 (40%)	35 (11%)
Elementary school	115 (37%)	35 (11%)
Surrounding environment		
Rural	103 (33%)	31 (10%)
Suburban	93 (30%)	18 (6%)
Urban	42 (14%)	21 (7%)
Climatic zone		
H1a	62 (20%)	15 (5%)
H1b	31 (10%)	8 (3%)
H1c	37 (11%)	19 (6%)
H2a	18 (6%)	4 (1%)
H2b	29 (9%)	8 (3%)
H2c	29 (9%)	2 (1%)
H2d	11 (4%)	2 (1%)
H3	21 (7%)	12 (4%)

IV.2.1.2. Measurement of the IEQ parameters

The main objective of the campaign was to provide a description of the school's condition (buildings' characteristics, systems and equipment, usage and alike) and to carry out a field survey of the state of air pollution and dust levels in classrooms. 16 parameters were measured during the campaign, and Table A.1 gives details of all IEQ parameters measured as part of the National schools' survey.

Air temperature, relative humidity, and indoor air pollutants were measured continuously over 4 and 1/2 days, from Monday morning to Friday afternoon, during a typical school week. The noise level recording began two days earlier in order to record the noise inside the classroom without contamination from other equipment measuring continuously IAQ. Finally, the measurement of artificial illumination in the classrooms was performed as spot measurements during the school week. Table 13 presents the measurements' timeline taking place in all 308 schools.

Table 13: Composition of a week of measurements as part of the National schools' survey. Green represents the measurement period; Red represents no measurement

	Saturday	Sunday	Monday	Tuesday	Wednesday	Thursday	Friday
Thermal environment							
Acoustic environment							
Indoor air quality							
Visual environment			Punctual measurement according to the technical team				

IV.2.2. Feasibility test setting

As presented in the first chapter, the TAIL rating scheme for schools consists of 14 IEQ parameters: one for the thermal environment, two for the acoustic environment, nine for the

IAQ, and two for the visual environment. Out of these 14 parameters in TAIL, there were only ten parameters measured in the survey. No measurements were made for reverberation time, radon, ventilation rate, and the daylight factor. The measurement protocols for these parameters during the survey were not identical to the measurement protocols suggested in the TAIL-rating scheme (Section III.3). The differences were as follows (A complete comparison of the measurement protocols deployed can be found in Table 14).

- Air temperature measurements were only performed continuously for one week, in only one season, while the protocol in TAIL for schools suggests continuous measurement for one month, in both heating and non-heating seasons.
- Noise levels were measured continuously over a one-week period, from the Friday afternoon preceding the primary campaign until the following Friday afternoon. However, during the primary campaign week, the recorded noise levels were contaminated with noise coming from other measurement equipment's, in particular, the air pump used to measure particular matter. Consequently, only the noise level recorded over the previous weekend was used when measurements of IAQ parameters had not yet begun.
- Inspection of mold was performed visually in one classroom by the field technician. However, the size of the visible mold was not measured.

Despite these differences in measured IEQ parameters, it was impossible to deploy a new measurement campaign or make additional measurements in the afore-measured school in the campaign. Additionally, no other significant dataset, which consisted of measurements from multiple IEQ parameters, was available to examine the TAIL rating scheme. As a result, it was decided to use data from the French National School campaign as best to illustrate TAIL for the school and examine its performance. As a reminder, the premise of the feasibility test is to demonstrate the capability of the TAIL rating scheme in characterizing the difference of IEQ in different schools, and not the state of IEQ and its conformity to guidelines values at the moment measurement took place.

Table 14: IEQ parameters measurement protocols in the TAIL-rating scheme and in the National schools' survey

IEQ parameters	Suggested measurement protocol in the TAIL-rating scheme	Measurement protocol during the National schools' survey
Air temperature	Thermo-hygrometer ± 0.5 °C accuracy for temperature ± 5% accuracy for relative humidity Continuous measurement of 4 weeks, during occupancy period Measured in both heating and non-heating season. Time interval from 1 to 10 minutes Assessment during normal class hour (08h00 – 17h00)	Thermo-hygrometer ± 0.2 °C accuracy for temperature ± 0.8 % accuracy for relative humidity Continuous measurement of 4.5 days, during occupancy period Measured in only one season. Time interval of 10 minutes Assessment during normal class hour (08h00 – 17h00)
Relative humidity		
Noise level	Sound meter 1 dB(A) accuracy Continuous measurement of one school week, in non-occupied room. Time interval of 1 to 10 minutes Assessment of the average recorded noise during normal class hour (08h00 – 17h00). If measurement was made during occupied period, the P5 of the recorded noise level will be used for assessment	Sound meter Class 2 accuracy Continuous measurement of one full week, in occupied room during the week, and non-occupied during the weekend Time interval of 2 seconds Assessment of the average recorded noise during normal class hour in the two precedent weekend days

IEQ parameters	Suggested measurement protocol in the TAIL-rating scheme	Measurement protocol during the National schools' survey
Reverberation time	12 microphones placed at various points in the classroom Used of the impulsive sound sequence or follow the ISO 3382-2: 2008	Not measured
Benzene	Passive measurement Continuous measurement of one school week Preferably (not mandatory) to be measured during both heating and non-heating season	Passive measurement Continuous measurement of 4.5 days Measured during only one season
Formaldehyde	Passive measurement Continuous measurement of one school week Preferably (not mandatory) to be measured during both heating and non-heating season	Passive measurement Continuous measurement of 4.5 days Measured during only one season
CO_2	Nondispersive infrared sensor (NDIR) sensors ± 50 ppm accuracy Continuous measurement of one school week Outdoor measurement of the CO_2 measurement should be made, if not, a concentration of 400 ppm can be assumed	Nondispersive infrared sensor (NDIR) sensors ± 50 ppm and 3 % reading accuracy Continuous measurement of one school week Outdoor measurement of the CO_2 measurement was not made; thus a concentration of 400 ppm has been assumed

IEQ parameters	Suggested measurement protocol in the TAIL-rating scheme	Measurement protocol during the National schools' survey
NO_2	Passive measurement Continuous measurement of one school week Preferably (not mandatory) to be measured during both heating and non-heating season.	Passive measurement Continuous measurement of 4.5 days Measured during only one season.
$PM_{2.5}$	Gravimetric (preferably), or optical counter Continuous measurement of one school week Preferably (not mandatory) to be measured during both heating and non-heating season	Gravimetric measurement, with a flow rate of 1.8 L/min (± 5%) Continuous measurement of 4.5 days Measured during only one season
Radon	Measured using passive sampling with 2 dosimeters in ground floor, 2 months duration in winter only	Not measured
Mold inspection	Observations in the classroom In case of mold, the total surface of any visible patch of mold is to be estimated	Observations in the classroom In case of mold, the total surface of the visible patch of mold was not estimated
Ventilation rate	Measured using calibrated flow hood (capture hood) at all the inlet and exhaust points within the chosen classrooms.	Not measured

IEQ parameters	Suggested measurement protocol in the TAIL-rating scheme	Measurement protocol during the National schools' survey
Daylight factor	Simulation of one-year duration, following the guidelines outlined in EN 17037-1.	Not simulated
Artificial illuminance (Horizontal on tables and vertical on writing board)	Lux meter ± 3 lx accuracy Spot measurements during the day, with solar protection closed, or during periods without natural daylight. At each location, there are two measurements, one with artificial light turn off, and one with artificial light turn on. Assessment should be made of the difference between the two values. Horizontal illuminance: measurements at 5 locations in the room (one at the middle of the room and at the four corners of the room) Vertical illuminance: measurements at 3 locations on the writing board (one at the bottom, one at the middle, and one at the top of the board)	Lux meter ± 3 lx accuracy Spot measurements were performed in the early morning, with solar protection closed, or during periods without natural daylight to ensure only an assessment of the artificial lighting. At each location, there are two measurements, one with artificial light turn off, and one with artificial light turn on. Assessment should be made on the difference between the two values. Horizontal illuminance: measurements at 5 locations in the room (one at the middle of the room and at the four corners of the room). 3 measurements at each point. The assessment is based on the average of three measurements. Vertical illuminance: measurements at 3 locations on the writing board (one at the bottom, one at the middle, and one at the top of the board). 3 measurements at each point.

To apply the TAIL-rating scheme to the IEQ measurements of the National schools' survey, some additional information had to be collected besides the measurement data.

To define the threshold values for the indoor air temperature for the TAIL quality categories in classrooms during the non-heating season following adaptive thermal model principle, the moving average of the measured outdoor temperature of seven previous days is needed. However, the outdoor temperature was not measured during the campaign. A solution was found by applying an online tool, MEREEN [147]. Developed by CSTB, the tool gives access to historical dataset of weather data in Europe and the USA from 2005. The outdoor temperature for each school was obtained using MEREEN by selecting data from the nearest weather station to the schools. Afterward, the moving average outdoor temperature was calculated and used to define the threshold values of the TAIL quality categories of the thermal environment.

As stated before, the assessment of the recorded noise level was done during the previous weekend to the primary campaign week, during the usual class hours, from 09h00 to 17h00, Monday to Friday. Based on the suggestion from the acoustical specialist, the log-average of the series of recorded noise levels (time interval of one minute) was calculated so it could be compared against the defined TAIL acoustic rating threshold values; in this way, all recorded noise peaks were considered.

The mold inspection was performed visually by the field technician, who did all the IEQ measurements. While the size of the visible mold was not measured, all field technicians reported that the mold patch was never as big as the size of a hand. Consequently, all classrooms without mold were classified as Category I of the TAIL mold rating, and classrooms with visible mold were classified as Category II regardless of their actual surface.

For all other IEQ parameters, their assessment followed the protocol described in Table 14. A TAIL classification was given directly using the defined quality category threshold for the background noise level, benzene, formaldehyde, $PM_{2.5}$, NO_2, mold, and artificial lighting. For IEQ parameters with time series results, i.e., the air temperature, relative humidity, and the CO_2 concentration, each measured instance during the school hours of the week was classified. A measured instance represents a measurement point. In TAIL, the proposed measurement period was one school week during the operative hours, which translates to 09h00 to 17h00, Monday to Friday. A time interval of 10 minutes between each measurement instance would result in 6 instances per hour, 48 per day, in total a 240 measurement instances in the assessment week.

The calculation process to obtain the TAIL rating on the school scale from the TAIL rating on the classroom scale follows the process described in subsection III.3.5. However, it would be intriguing to test another approach, where instead of averaging the TAIL rating of classrooms, the TAIL rating on the school scale would be defined by the worst TAIL rating obtained in classrooms. Thus, results obtained by using both approaches will be present in each correspondent TAIL component on the school scale.

IV.3. TAIL classification results

IV.3.1. Thermal environment

IV.3.1.1. TAIL thermal rating on the classroom scale

Table 15 presents the classification of the TAIL raring of the thermal environment on the classroom scale. In each cell, the number represents the percentage of classrooms, and the number in parentheses represents the actual number of classrooms. While only 6 % of the measured classrooms achieved a TAIL thermal environment rating of Category I, 44% only rated Category IV. Measurement data were not recovered in 10 classrooms; thus, no TAIL thermal rating can be classified.

Table 15: TAIL-rating of the thermal environment on the classroom scale (n = 602)

Quality category	Category I	Category II	Category III	Category IV	Missing data
Number of classrooms	6.1 % (37)	16 % (96)	32.1 % (193)	44.2 % (266)	1.6 % (10)

Regarding the rating process, the air temperature is one of the three continuously measured parameters, where the rating principle relies on the assessment of the total time spent in a zone of air temperature. In this feasibility test, an assessed school week from Monday to Friday will result in 48 hours. With a time interval of 10 minutes between each measurement instance, this translates into a total of 240 measurement instances. In order to be classified as category I of the TAIL thermal rating, at least 94% of the total measured duration had to stay at 22 ± 1 °C, less than 5% can exceed 22 ± 1°C, and less than 1 % can exceed 22 ± 2 ° C. Respectively, this corresponds to 45.1 hours, 2.4 hours, and 20 minutes. As a consequence, even if the air temperature in the classroom stayed in the 21 to 23 °C for at least 45 hours over 48 hours in a

school week, it could still get demoted to category II if the temperature stayed in the 20 to 21 °C or 23 to 24 °C for 2.4 hours, or in the 19 to 21 °C or 24 to 25 °C for 20 minutes.

Figure 11 mirrors the Figure 6, which illustrates the rating principle used to determine the quality of the TAIL thermal rating; however, it includes the corresponding number of classrooms for each step, in a total of 592 classrooms.

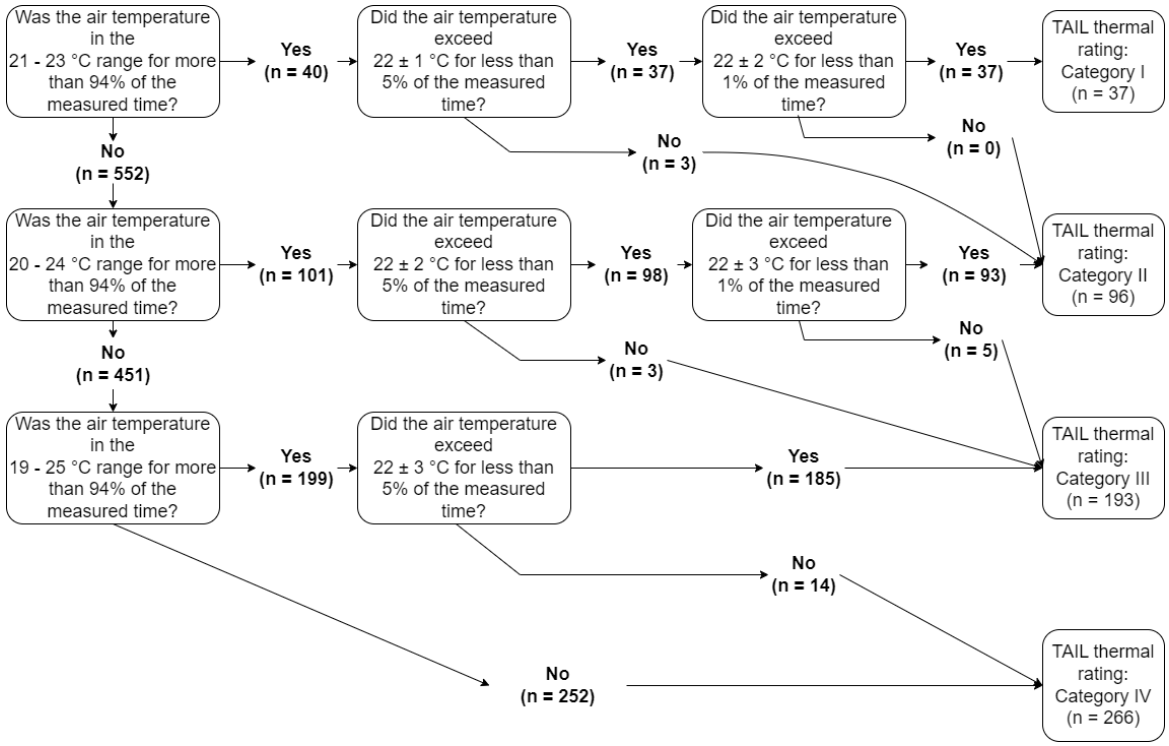


Figure 11: Flow chart describing the rating principle used to determine the TAIL thermal quality category, and the corresponded number of classrooms in each step (n = 592 classrooms)

A total of 25 classrooms (4.2 % of the total measured classrooms) got their TAIL thermal rating demoted. Three classrooms were demoted from Category I to Category II, eight were demoted from Category II to Category III, and fourteen were demoted from Category III to Category IV. Interestingly, no classrooms were demoted from Category I to Category II for exceeding the 22 ± 2 °C range for less than 1% of the measured time, or 20 minutes in assessment time.

IV.3.1.2. TAIL thermal rating on the school scale

Table 16 describes the overall classification of the TAIL thermal environment in the 308 measured schools, obtained by averaging the thermal rating of classrooms in each school. More

than half of the schools measured in the sample had a TAIL-rating category IV for the thermal environment, with three schools or 1.0 % of the sample associated with missing data.

Table 16: TAIL-rating of the thermal environment on the school scale, calculated by averaging the TAIL thermal classrooms' ratings (n = 308)

Quality category	Category I	Category II	Category III	Category IV	Missing data
Number of schools	4.2 % (13)	10 % (32)	33 % (102)	51 % (158)	1.0 % (3)

Table 17 describes the overall classification of the TAIL thermal environment in the 308 measured schools, defined by the worst individual TAIL classrooms' thermal rating of the school. One school got demoted from the Category I rating, and 25 schools got demoted to the Category IV rating, representing 8 % of measured schools.

Table 17: TAIL-rating of the thermal environment on the school scale, defined by the worst TAIL thermal classroom of the school (n = 308)

Quality category	Category I	Category II	Category III	Category IV	Missing data
Number of schools	3.9 % (12)	8.4 % (26)	27 % (84)	59 % (183)	1.0 % (3)

Table 18 presents the TAIL classification in various specific groups of schools with similar characteristics, which was used during the school drafting phases to constitute the sample. In every cell, the percentage represents the number of schools that achieved the corresponding TAIL quality category calculated per the group of variables and not the total number of schools.

Table 18: TAIL-rating of the thermal environment in different groups of schools (n = 308)

Variables	TAIL–thermal environment quality				
	Category I	**Category II**	**Category III**	**Category IV**	**Missing data**
Type of school					

Nursery	7 % (11)	13 % (20)	36 % (57)	44 % (69)	1 % (1)
Elementary school	1 % (2)	8 % (12)	30 % (45)	59 % (89)	1 % (2)
Surrounding environment					
Rural	4 % (5)	10 % (14)	37 % (50)	49 % (65)	0 % (0)
Suburban	3 % (3)	14 % (16)	27 % (30)	55 % (61)	1% (1%)
Urban	8 % (5)	3 % (2)	35 % (25)	51 % (32)	3 % (2)
Climatic zone					
H1a	4 % (3)	4 % (3)	39 % (30)	51 % (39)	3 % (2)
H1b	3 % (1)	8 % (3)	36 % (14)	54 % (21)	0% (0)
H1c	2 % (1)	4 % (2)	25% (14)	70 % (39)	0% (0)
H2a	9 % (2)	23 % (5)	41 % (9)	27 % (6)	0% (0)
H2b	8 % (3)	24 % (9)	30 % (11)	38 % (14)	0% (0)
H2c	0% (0)	13 % (4)	29 % (9)	58 % (18)	0% (0)
H2d	8 % (1)	23 % (3)	23 % (3)	46 % (6)	0% (0)
H3	6 % (2)	9 % (3)	36 % (12)	45 % (15)	3 % (1)
Measured season					
Heating	0.5 % (1)	8 % (20)	37 % (89)	53 % (127)	0.5 % (1)
Non – heating	17 % (12)	17 % (12)	19 % (13)	44 % (31)	3 % (2)

Regarding the type of schools measured, their surrounding environment, and the climatic zone, the difference in the distribution of schools' TAIL thermal quality categories is not significant.

Additionally, regardless of the measured season, around 50% of the schools only achieved a category IV in terms of TAIL thermal rating.

IV.3.1.3. Data interpretation

As the air temperature assessment protocol in the TAIL rating scheme for schools required the air temperature to stay within a certain range in order to be classified in the corresponded quality category. However, a question was raised on whether the air temperature crossed the upper limit (overheated classrooms), or the lower limit (overcooled classrooms). To help answer this question, the measured air temperature in classrooms with different classifications of TAIL thermal was analyzed.

Figure 12 presents the distribution of every air temperature measurement instance in every classroom, separated by their corresponding TAIL thermal quality category. Quick observations show that the interquartile of the boxplot of classrooms with a TAIL thermal Category I and II stayed relatively constant. However, it was the total time exceeding principal (illustrated in Figure 11) that separated these classrooms into different TAIL rating categories. Furthermore, in classrooms with poorer TAIL thermal quality, there was a larger dispersion of measured air temperature. This means that the air temperature varied more during the measured week in classrooms with an unfavorable TAIL-thermal quality. This trend persisted regardless of the measured season, as pointed out by Figure 13.

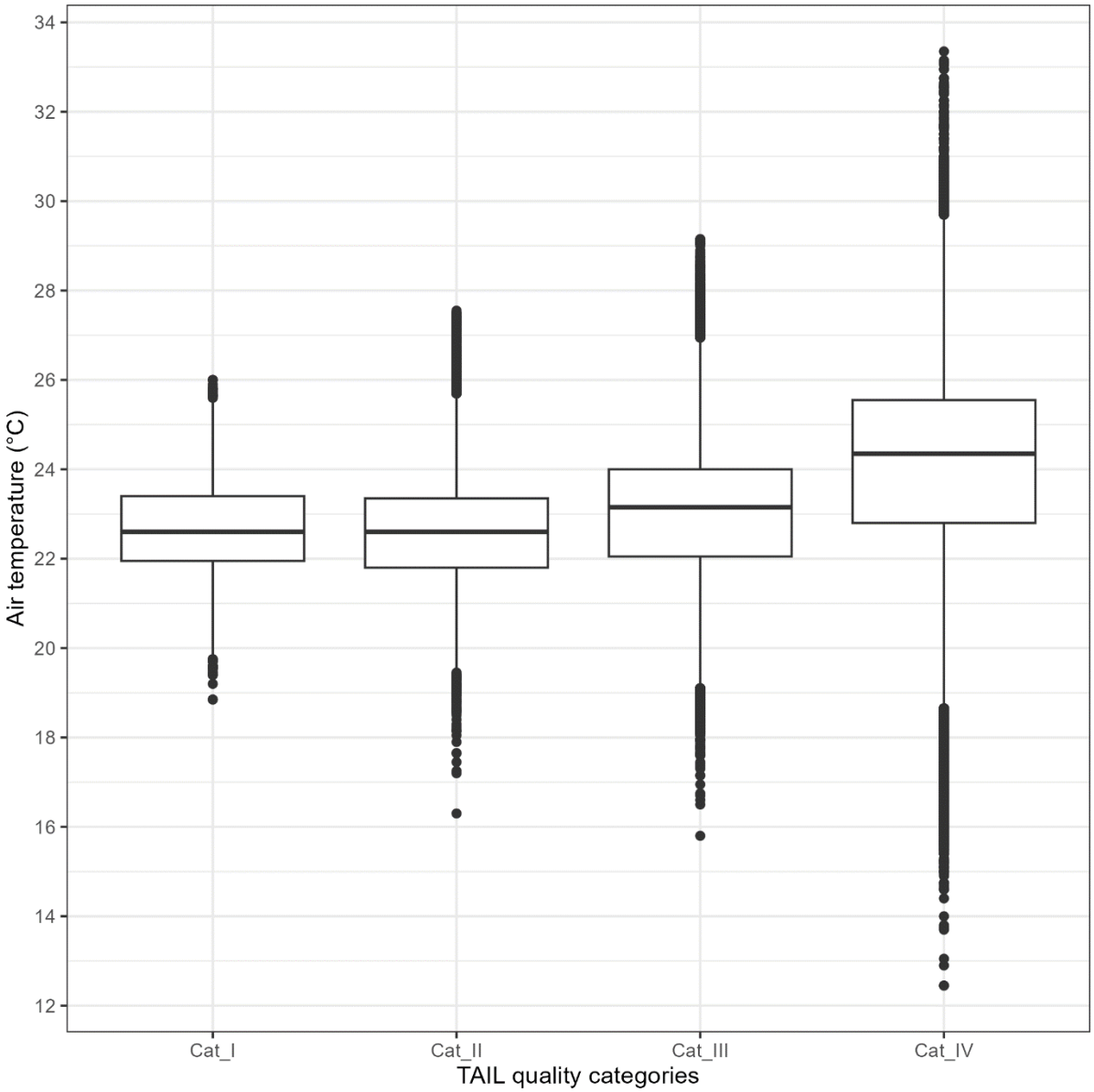


Figure 12: Distribution of air temperature measured in classrooms, separated by the classrooms TAIL thermal quality category

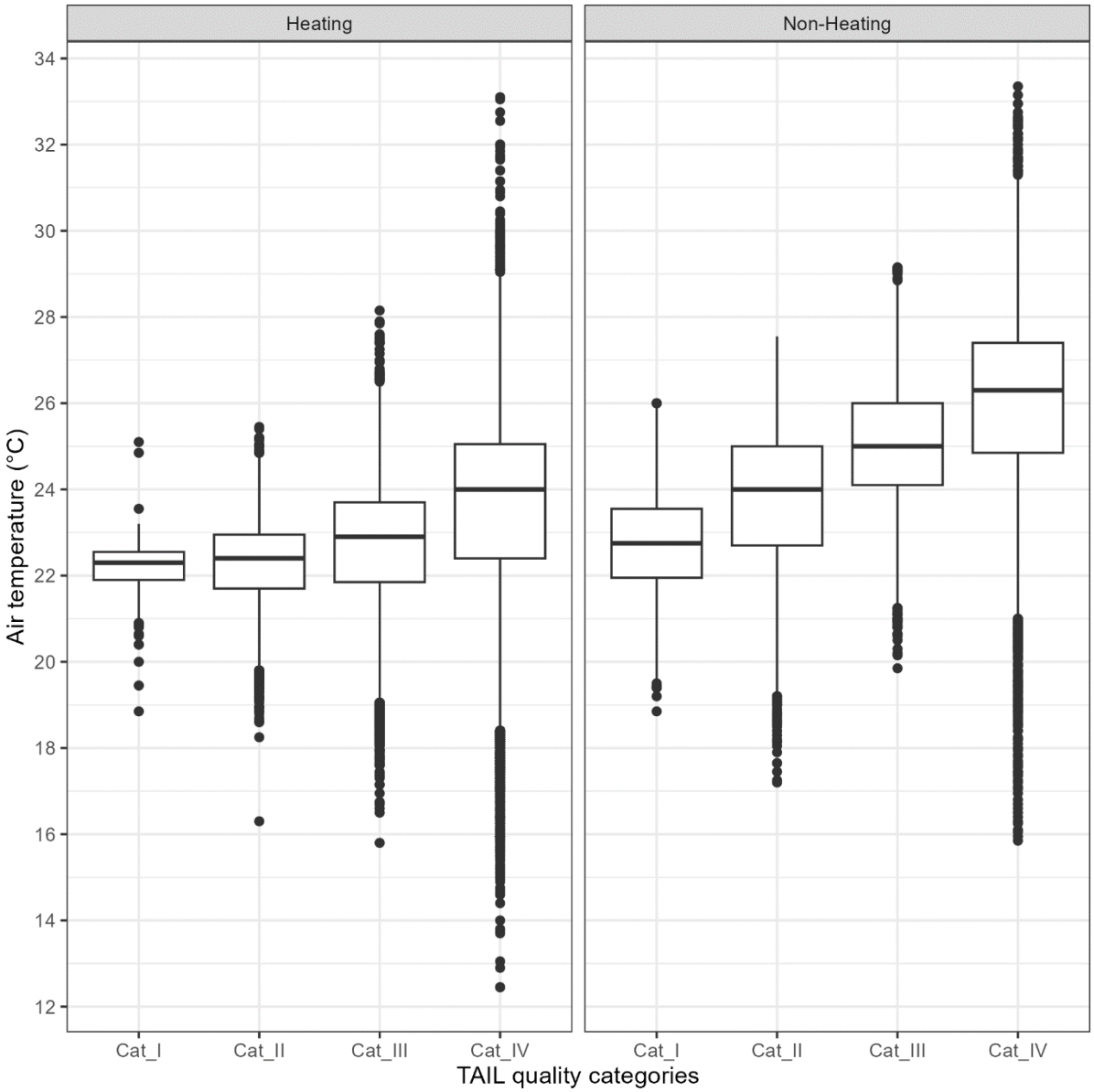


Figure 13: Distribution of air temperature measured in classrooms in different TAIL thermal environment, for both seasons

For both measured seasons, the highest air temperature recorded in classrooms was higher than 33°C. The lowest air temperature recorded in classrooms during the heating season is lower (13 °C) than during the non-heating season (16 °C). As explained earlier, the TAIL thermal rating assessment is based on exceedance, wherein each category, temperatures can only surpass the specified range by up to 1 °C for a maximum of 5% of the time and by up to 2 °C for a maximum of 1% of the time during which the measurements were conducted. This means that classrooms with favorable thermal quality should be equipped to keep the air temperature at the desired

level and maintain it during the school week, as both low and high temperatures can lead to a poor TAIL thermal quality (category III or category IV). However, a question can be raised on whether schools had an overheating or an overcooling problem.

A closer look at the evolution of the air temperature measured in a classroom will provide additional information. Starting with the heating season, Figure 14, Figure 15, Figure 16, and Figure 17 present the evolution of the measured air temperature during a day in the classroom with categories I, II, III, and IV TAIL thermal ratings, respectively. From every classroom that achieved the corresponding TAIL thermal rating, the minimal, median, and maximal air temperature from each measured day were plotted to represent a random school day. The dotted gray line represents the minimal and maximal air temperature, while the continuous black line represents the median air temperature. The colored area represents the corresponding portion of the threshold values used to determine the TAIL thermal category.

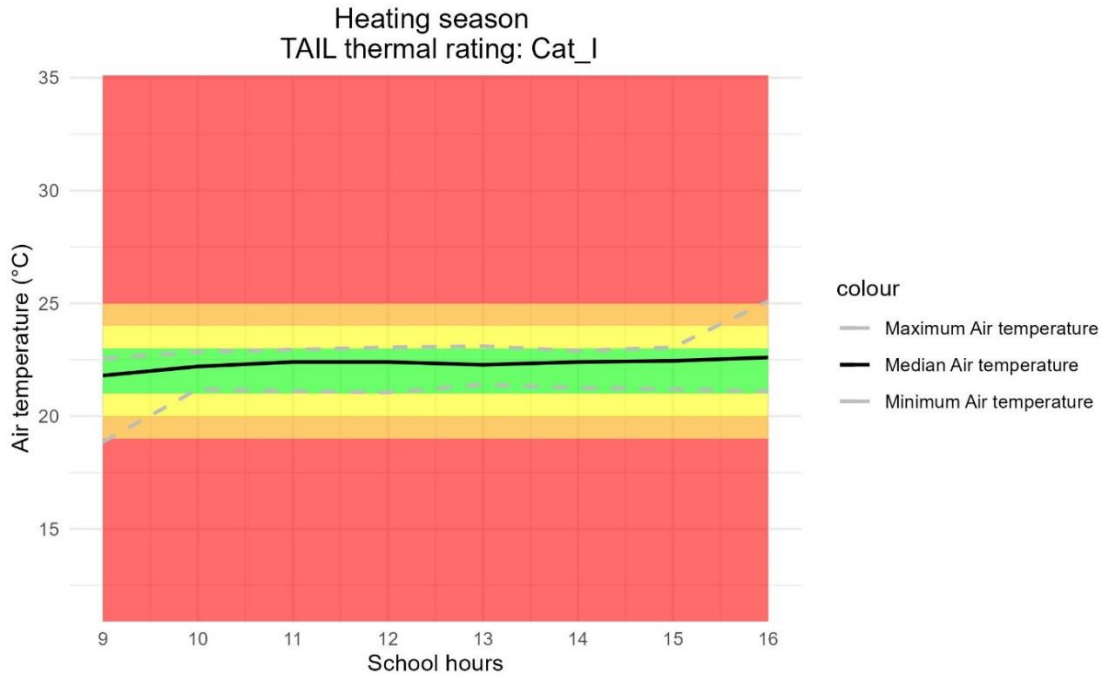


Figure 14: Evolution of the air temperature measured during a school day, in a category I TAIL thermal classroom during the heating season

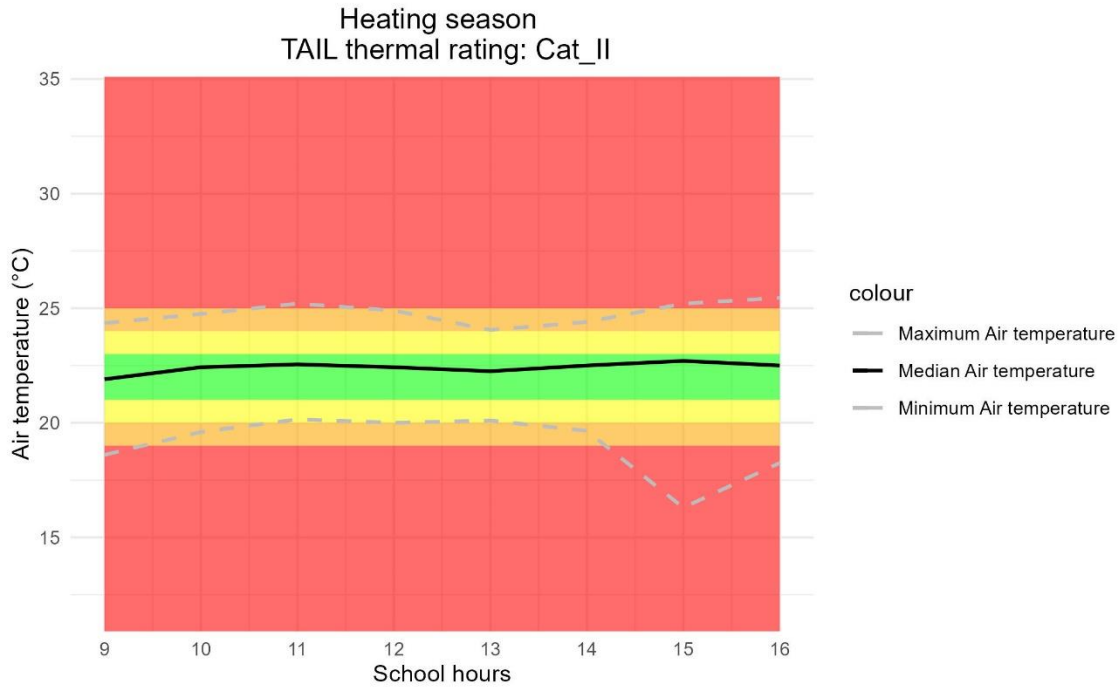


Figure 15: Evolution of the air temperature measured during a school day, in a category II TAIL thermal classroom during the heating season

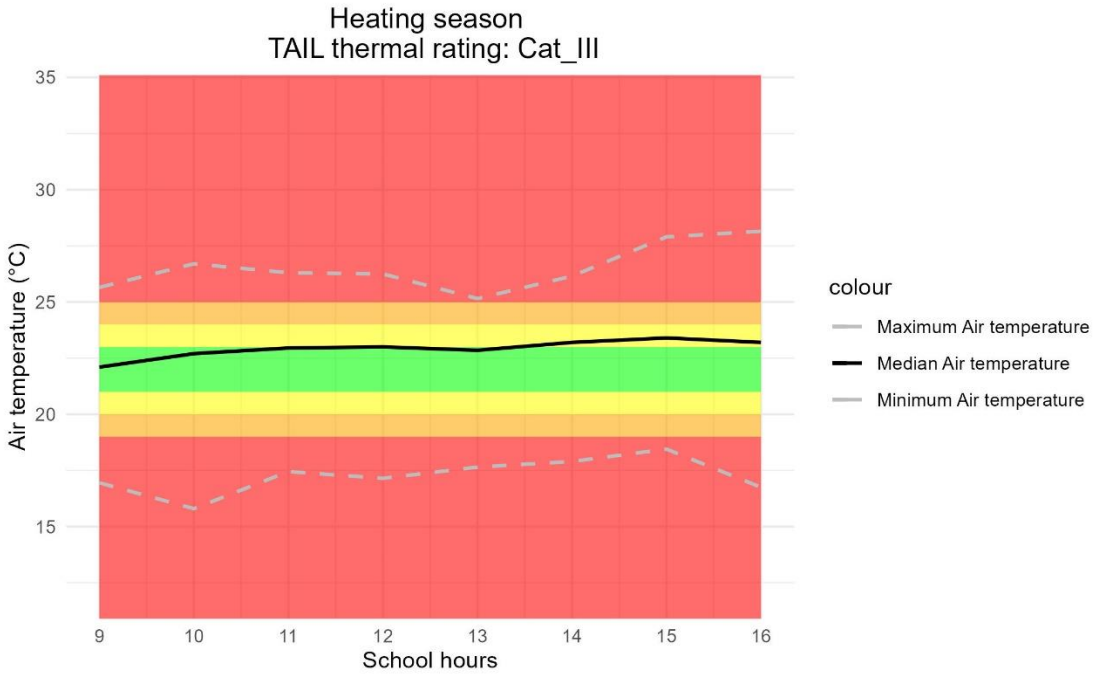


Figure 16: Evolution of the air temperature measured during a school day, in a category III TAIL thermal classroom during the heating season

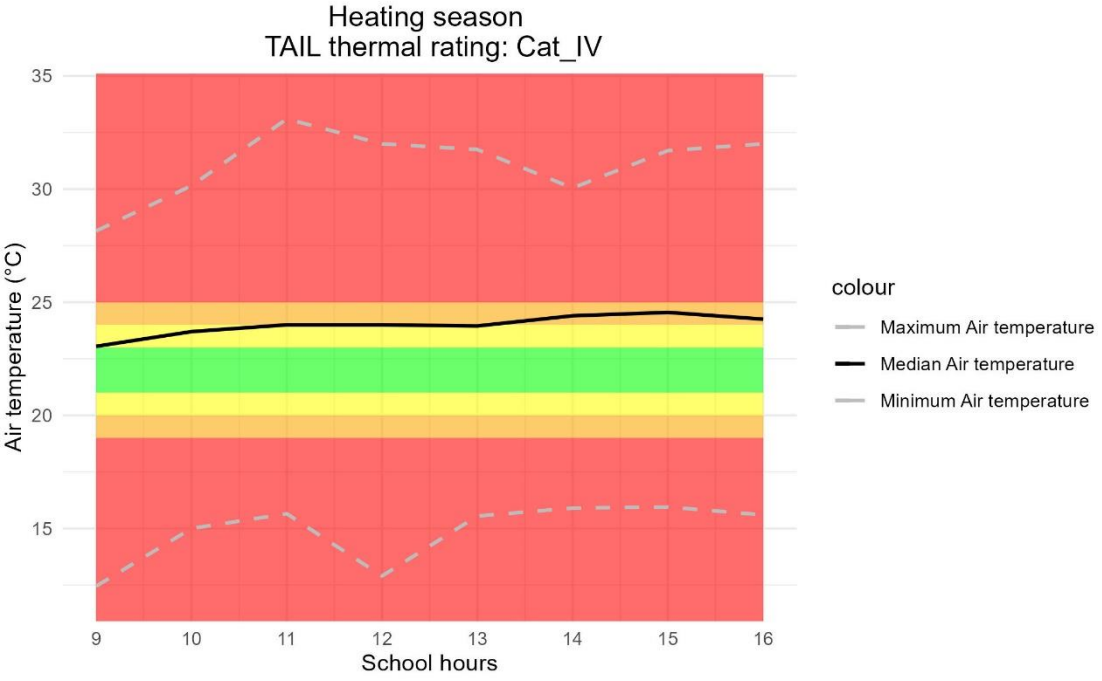


Figure 17: Evolution of the air temperature measured during a school day, in a category IV TAIL thermal classroom during the heating season

In the four figures, as the TAIL thermal quality deteriorated, a larger dispersion of the measured air temperature in classrooms was observed. Nevertheless, a trend in the evolution of the measured air temperature in a typical school day can be observed. The black median air temperature line shows a slight increase toward the end of the day as heat slowly builds up during the day in the classroom, regardless of the TAIL thermal rating of the classroom. Once again, the impact of the total time exceeding rating principle has been illustrated, as both the black line of the median measured air temperature in classrooms with a category I and category II TAIL thermal rating stay entirely in the green portion. Which means in category II classrooms, the air temperature exceeded 22 ± 2 °C for more than 5% of the measured time, or 2.5 hours.

Figure 18, Figure 19, Figure 20, and Figure 21 represent the air temperature measured during a typical school day during the non-heating season for classrooms with a TAIL thermal rating of category I, II, III, and IV, respectively. These four plots were constructed using the method mentioned earlier. However, there are no colored portions that represent the threshold values used to determine the TAIL quality, as during the non-heating season, the threshold used to determine the TAIL thermal rating changed each day and is different for each classroom.

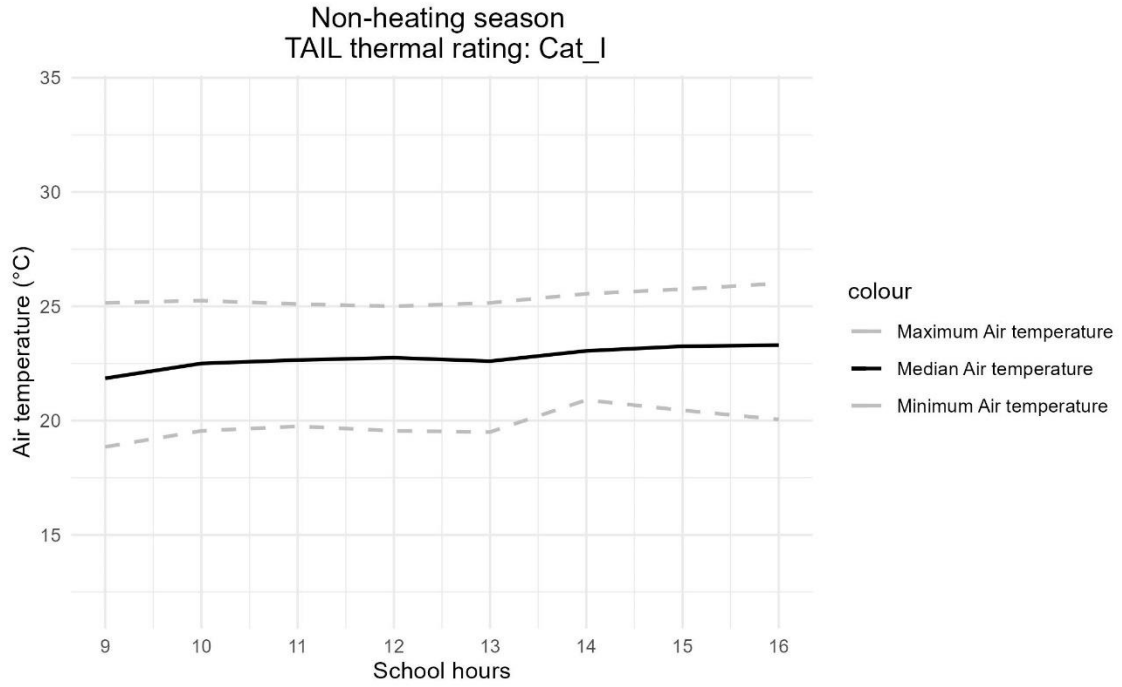


Figure 18: Evolution of the air temperature measured during a school day, in a category I TAIL thermal classroom during the non-heating season

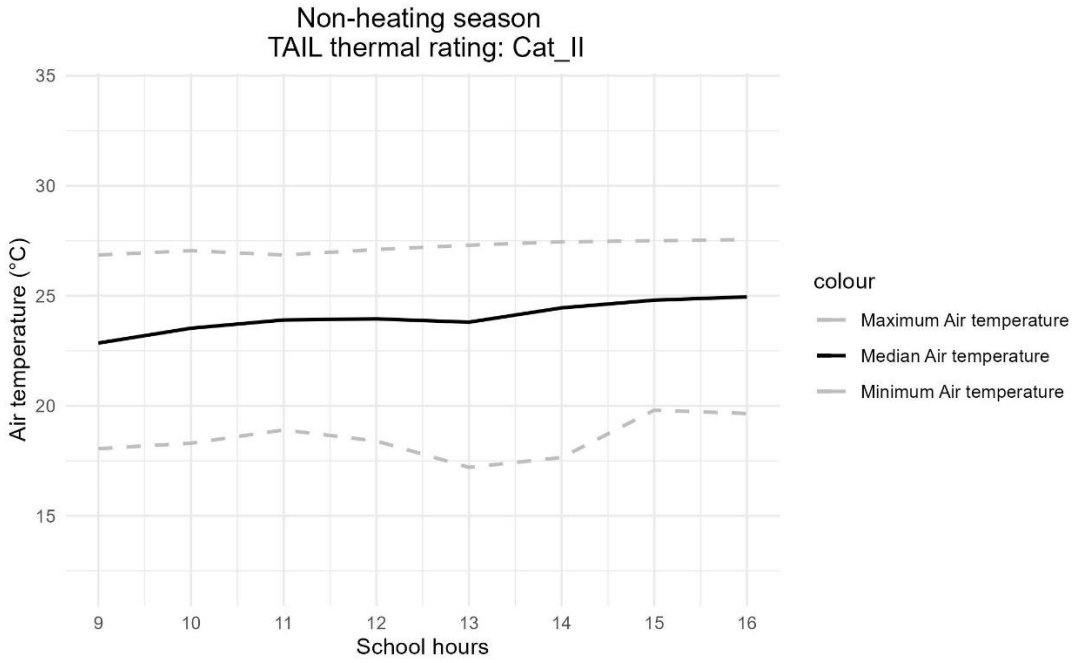


Figure 19: Evolution of the air temperature measured during a school day, in a category II TAIL thermal classroom during the non-heating season

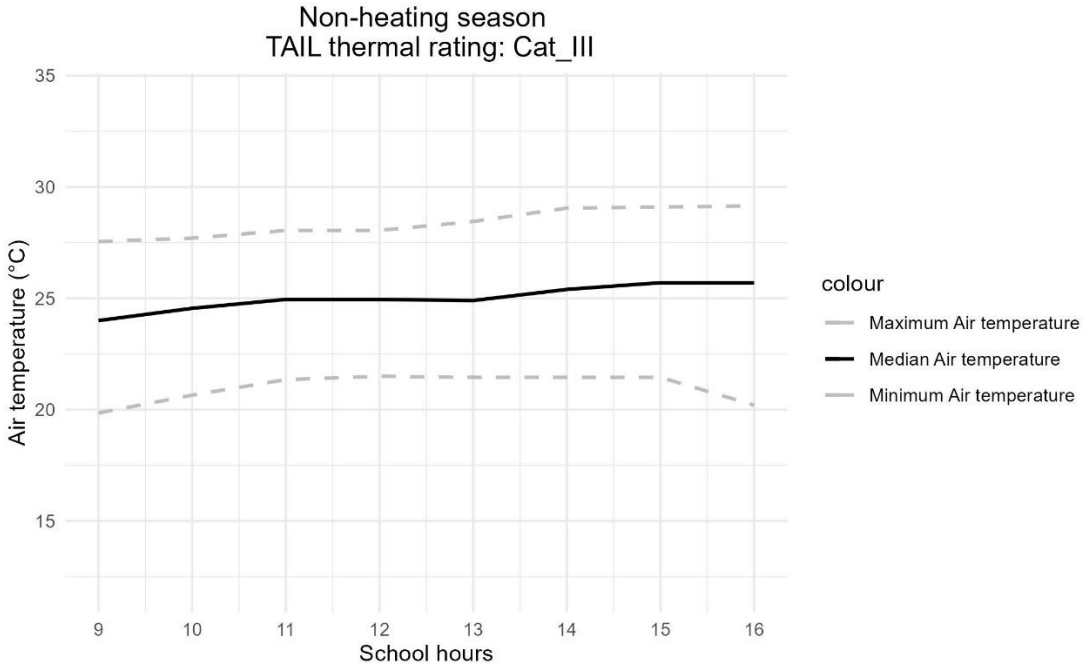


Figure 20: Evolution of the air temperature measured during a school day, in a category III TAIL thermal classroom during the non-heating season

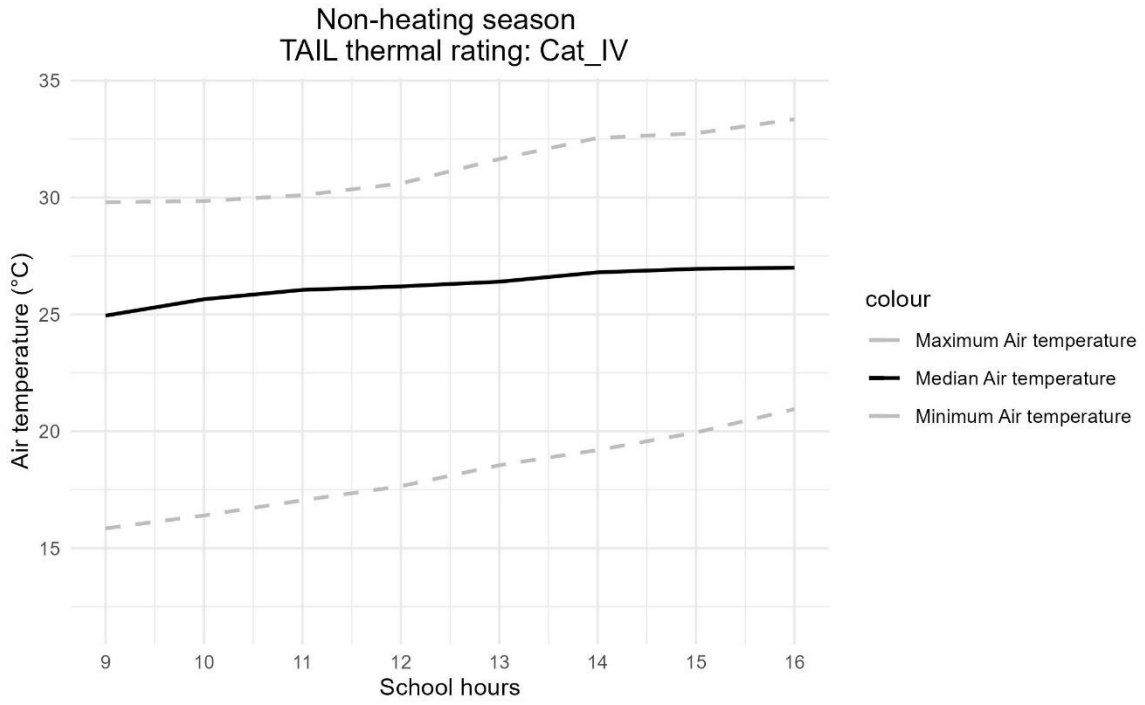


Figure 21: Evolution of the air temperature measured during a school day, in a category IV TAIL thermal classroom during the non-heating season

A slight increase in the measured air temperature can be observed toward the end of the school day. Consistently with classrooms measured during the heating season, a larger dispersion of the measured air temperature can still be observed in classrooms with the TAIL thermal quality going from category I to IV.

In conclusion, regardless of the measured season, the air temperature in poorer TAIL thermal rating classrooms exceeded the upper threshold values, especially toward the end of the school day, which translated to schools having an overheating problem in both heating and non-heating seasons.

IV.3.2. Acoustic environment

IV.3.2.1. TAIL acoustic rating on the classroom scale

Table 19 presents the distribution of the TAIL acoustic rating on the classroom scale. More than half of the measured classrooms achieved a TAIL acoustic rating of Category I, while less than 5 % of classrooms achieved a TAIL acoustic rating of Category III and IV. However, the

recording of the background noise level cannot be assessed in 61 classrooms, or 10 % of the total measured classrooms.

Table 19: TAIL-rating of the acoustic environment on the classroom scale (n = 602)

Quality category	Category I	Category II	Category III	Category IV	Missing data
Number of classrooms	59 % (355)	23.4 % (141)	4.8 % (29)	2.7 % (16)	10.1 % (61)

IV.3.2.2. TAIL acoustic rating on the school scale

Table 20 presents the distribution of the TAIL acoustic rating on the school scale. Compared to the percentage of Category I TAIL acoustic in classrooms, the percentage of Category I TAIL acoustic in schools has reduced, 29 % compared to 59%. On the contrary, the percentage of Category IV schools has increased, compared to that of Category IV classrooms, 16 % compared to 2.7%. Finally, there were only 13 schools where no recorded background noise levels in any of their measured classrooms could be assessed, thus classifying them as missing data.

Table 20: TAIL-rating of the acoustic environment on the school scale, calculated by averaging the TAIL acoustic classrooms' ratings (n = 308)

Quality category	Category I	Category II	Category III	Category IV	Missing data
Number of schools	29 % (90)	32 % (99)	18 % (57)	16 % (49)	5 % (13)

Table 21 describes the overall classification of the TAIL acoustical environment in the 308 measured schools, defined by the worst individual TAIL classrooms' acoustical rating of the school. Two schools got demoted from the Category I rating, and 21 schools got demoted to the Category IV rating, representing 7 % of measured schools.

Table 21: TAIL-rating of the acoustic environment on the school scale, defined by the worst TAIL classrooms' rating of the school (n = 308)

Quality category	Category I	Category II	Category III	Category IV	Missing data
Number of schools	29 % (88)	29 % (88)	16 % (49)	23 % (70)	5 % (13)

Table 22 presents the TAIL-rating results in schools according to the type of school, surrounding environment, climate zone and season.

Table 22: TAIL-rating of the acoustic environment in different groups of schools (n = 308)

Variables	TAIL –acoustic environment quality				
	Category I	**Category II**	**Category III**	**Category IV**	**Not available**
Type of school					
Nursery	32 % (50)	29 % (46)	16 % (25)	19 % (30)	4 % (7)
Elementary school	27 % (40)	35 % (53)	21 % (32)	13 % (19)	4 % (6)
Surrounding environment					
Rural	31 % (42)	28 % (38)	15 % (20)	20 % (27)	5 % (7)
Suburban	25 % (28)	36 % (40)	23 % (25)	14 % (16)	2% (2)
Urban	32 % (20)	33 % (21)	19 % (12)	10 % (6)	6 % (4)
Climatic zone					
H1a	27 % (21)	34 % (26)	10 % (8)	22 % (17)	6 % (5))
H1b	21 % (8)	31 % (12)	36 % (14)	13 % (5)	0 % (0)
H1c	34 % (19)	32 % (18)	18 % (10)	11 % (6)	5 % (3)

H2a	32 % (7)	36 % (8)	18 % (4)	14 % (3)	0% (0)
H2b	38 % (14)	27 % (10)	16 % (6)	16 % (6)	3 % (1)
H2c	29 % (9)	39 % (12)	13 % (4)	19 % (6)	0% (0)
H2d	15 % (2)	38 % (5)	15 % (2)	8 % (1)	23 % (3)
H3	30 % (10)	24 % (8)	27 % (9)	15 % (5)	3 % (1)
Measured season					
Heating	29 % (69)	32 % (75)	18 % (43)	18 % (42)	4 % (9)
Non – heating	31 % (21)	34 % (24)	20 % (14)	10 % (7)	6 % (4)

Among the four variables presented here, only the surrounding environment, and the type of school could have had an impact on the level of noise recorded in the school, as the source of noise in the classrooms should remain independent from the climatic zone and the measured season. However, no significant differences were observed in the TAIL-acoustic rating of schools located in different environments. Regardless of the surrounding environments: rural, suburban, or urban, more than half of the schools achieved at least a TAIL-acoustic rating of category II.

IV.3.2.3. Data interpretation

Figure 22 represents the measured background noise level in the classroom, with the colored portion corresponding to the threshold levels used to assess the acoustic environment. Some outliers were observed, e.g., two classrooms with a recorded background noise level of more than 95 dB(A).

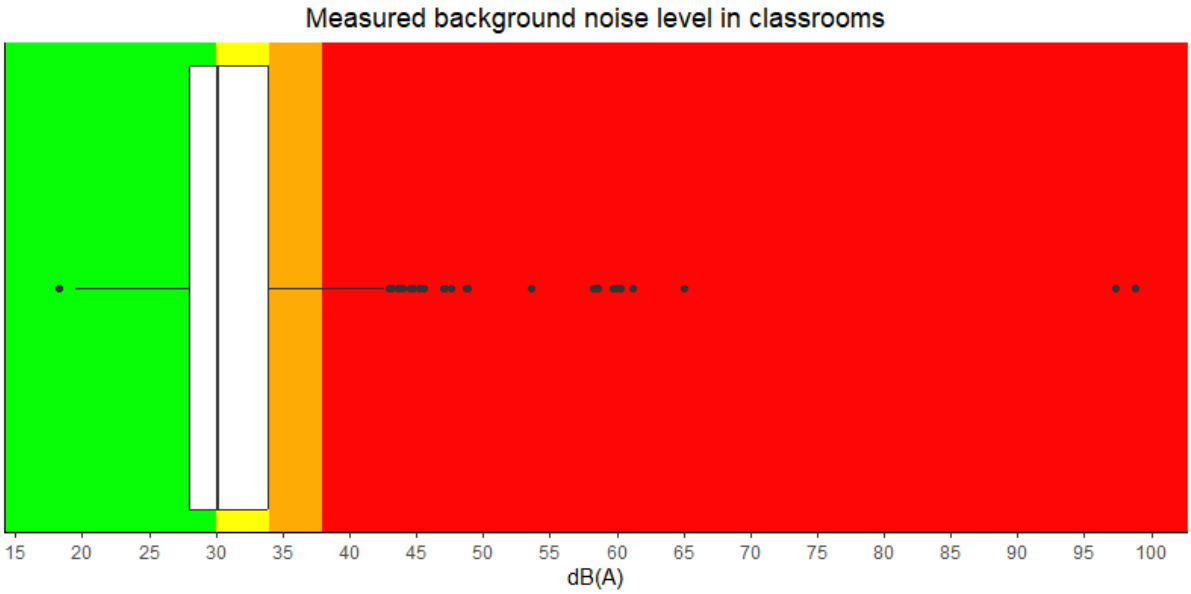


Figure 22: Measured background noise level (dB(A)) in classrooms and the respective threshold level used in the assessment of the acoustic environment

As the obtained TAIL acoustic rating distribution stayed relatively constant regardless of the schools' characteristics, an interpretation can be made, which resulted from the compromise made in this feasibility study.

One key difference between schools in the more populated areas and schools in the less populated areas is the amount of road traffic, which will lead to higher noise to schools in close vicinity to high traffic zones. However, as a compromise to the contaminated background noise level during the school week, only background noise levels during the weekend were assessed. Consequently, lower traffic during the weekend, regardless of the surrounding area, will lessen the difference in traffic-induced noise between schools in urban, suburban, and rural areas. Nevertheless, the fundamental idea behind assessing the TAIL acoustic was demonstrated. In future studies, it is best to assess the background noise level during the school week to fully capture all noise sources, thus fully representing children's noise exposure.

IV.3.3. Indoor air quality (IAQ)

IV.3.3.1. TAIL IAQ rating on the classroom scale

Table 23 presents the distribution of the TAIL IAQ rating in the classroom scale. In this table, the TAIL rating of each IAQ parameter classified at the classroom scale were presented, and to conclude, the overall IAQ TAIL rating was presented.

At first glance, the TAIL rating at the classroom scale of benzene, formaldehyde, and visible mold looks very promising. In all three parameters, less than 2 % of measured classrooms achieved Category IV quality. On the contrary, the TAIL rating of the other four parameters were more diverse.

Table 23: TAIL-rating of the indoor air quality on the classroom scale (n = 602)

TAIL IAQ rating	Category I	Category II	Category III	Category IV	Missing data
Benzene	82.9 % (499)	12.8 % (77)	0.0 % (0)	1.1 % (7)	3.2 % (19)
CO_2	2.3 % (14)	5.8 % (35)	25.9 % (156)	64.0 % (385)	2.0 % (12)
Formaldehyde	82.7 % (498)	17.3 % (104)	0.0 % (0)	0.0 % (0)	0.0 % (0)
NO_2	67.0 % (403)	20.0 % (120)	0.0 % (0)	12.4 % (75)	0.6 % (4)
$PM_{2.5}$	0.3 % (2)	30.4 % (183)	0.0 % (0)	64.5 % (388)	4.8 % (29)
Relative humidity	22.8 % (137)	47.0 % (283)	24.0 % (145)	4.5 % (27)	1.7 % (10)
Visible mold	96.3 % (580)	3.2 % (19)	0.0 % (0)	0.0 % (0)	0.5 % (3)
Overall IAQ	0.0 % (0)	3.2 % (19)	9.5 % (57)	87.3 % (526)	0.0 % (0)

At the classroom level, 67 % of the measured classrooms achieved Category I of NO_2. However, only 22 %, 2.3 %, and 0.3 % classrooms achieved a Category I of RH, CO_2, and $PM_{2.5}$ respectively.

In terms of rating principle, CO_2 and RH are the other two parameters where the principal of total time exceeding into the next category was applied. To illustrate the impact of this rating principle, Figure 23 mirrors Figure 7, which represents the flow chart of the rating principle of the RH but with the corresponding number of classrooms in each step, from the total of 592 classrooms with a TAIL RH attributed.

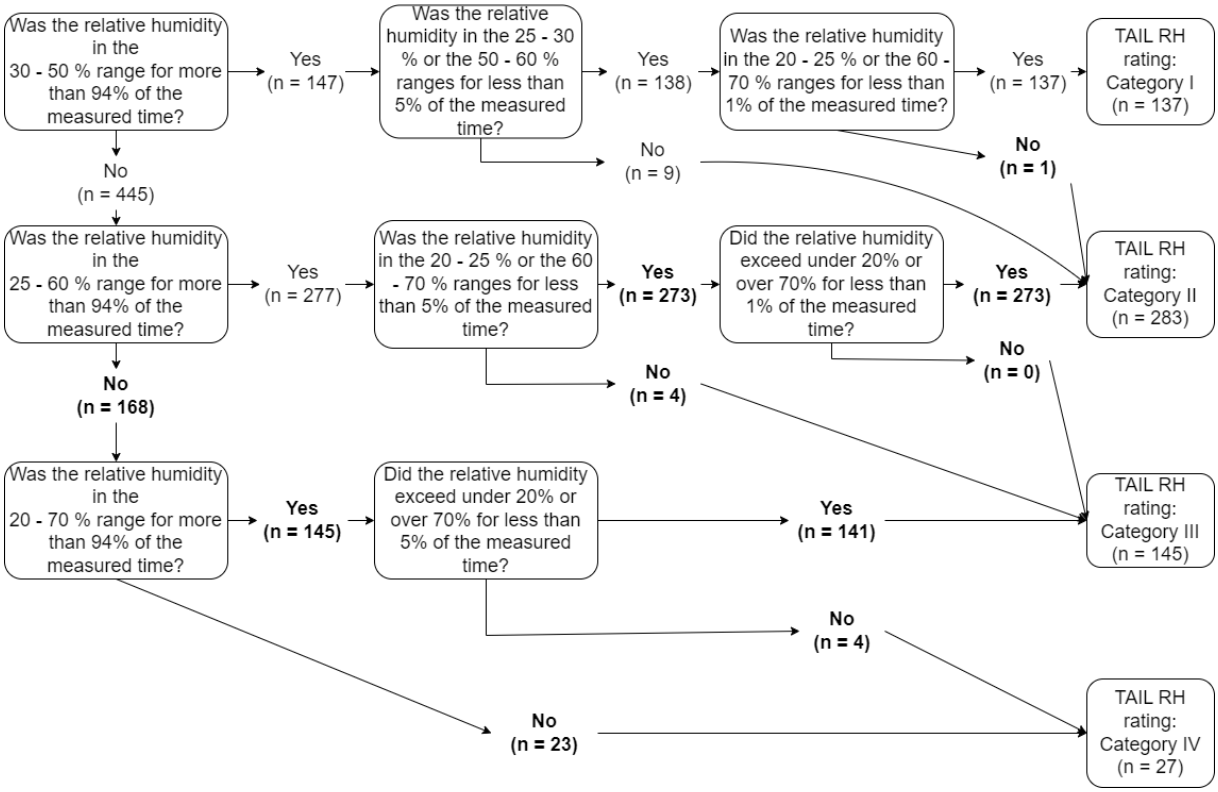


Figure 23: Flow chart describing the rating principle used to determine the TAIL RH quality category, and the corresponded number of classrooms in each step (n = 592 classrooms)

A total of 18 (3.0 %) of classrooms had their rating demoted from exceeding the allowance time in the next threshold. In more detail, from a total of 147 classrooms that had the RH in the 30 to 50 % range (Category I) for at least 94 % of the time, 9 classrooms (6.1 %) had more than 5 % of the time (2.4 hours) where the RH was in the 25 to 30 % or 50 to 60 % ranges; and 1 classroom (0.6 %) had more than 1 % of the time (20 minutes) where the RH was in the 20 to 25 % or 60 to 70 % ranges. Of a total of 277 classrooms that had the RH in the 25 to 60 % range (category II) for at least 94 % of the time, 4 classrooms (1.4 %) had more than 5 % of the time (2.4 hours) where the RH was in the 20 to 25 % or 60 to 70 % ranges. Finally, from a total of 145 classrooms that had the RH in the 20 to 70 % range (category III) for at least 94 % of the

time, 4 classrooms (2.7 %) had more than 5 % of the time (2.4 hours) where the RH was in the outside of the 20 to 70 % range.

As for the rating principle of the measured CO_2, Figure 24 mirrors Figure 8, illustrating the flow chart of the rating principle, but with the corresponding number of measured classrooms was added to each step from 590 classrooms where a CO_2 measurement occurred.

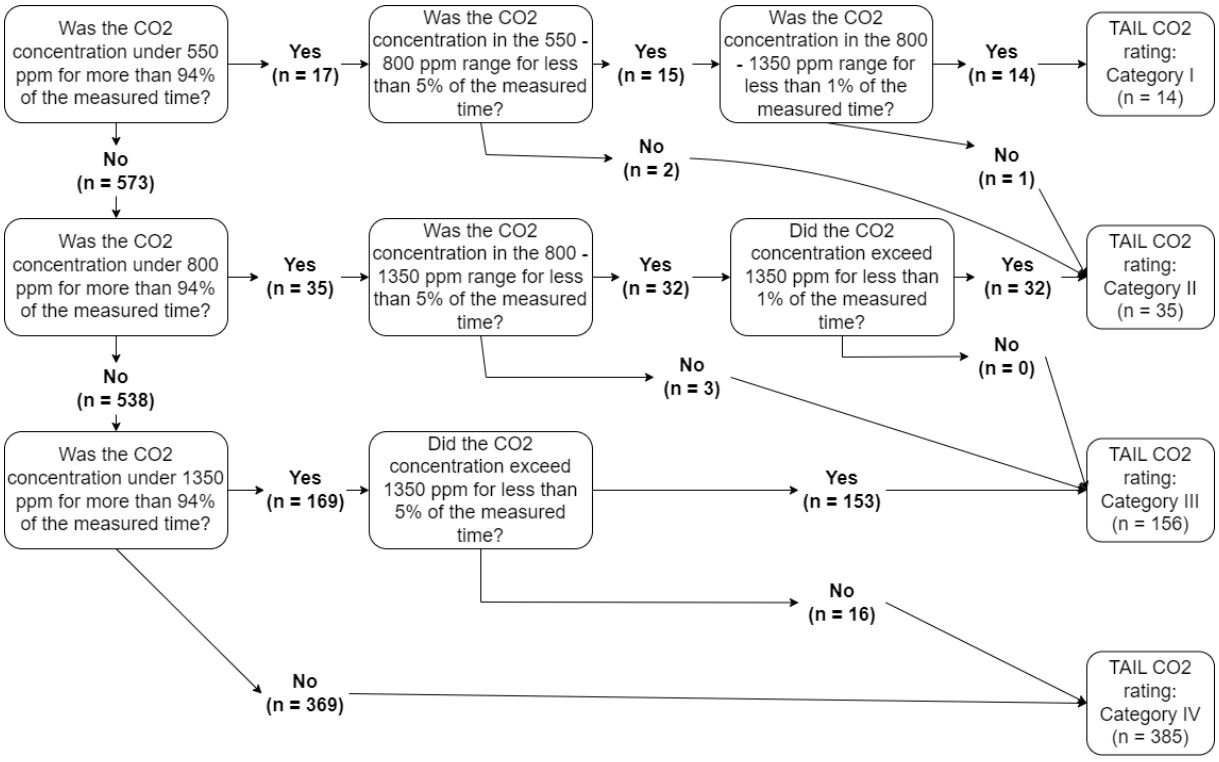


Figure 24: Flow chart describing the rating principle used to determine the TAIL CO_2 quality category, and the corresponded number of classrooms in each step (n = 590 classrooms)

A total of 22 (3.7 %) of classrooms had their rating demoted from exceeding the allowance time in the next threshold. In more detail, from a total of 17 classrooms that had the CO_2 concentration under 950 ppm (Category I) for at least 94 % of the time, 2 classrooms (12 %) had more than 5 % of the time (2.4 hours) where the CO_2 concentration was in the 950 to 1200 ppm range, and 1 classroom (5.8 %) had more than 1 % of the time (20 minutes) where the CO_2 rating was in the 1200 to 1750 ppm range. From a total of 35 classrooms that had the CO_2 rating in the 950 to 1200 ppm (category II) for at least 94 % of the time, 3 classrooms (8.5 %) had more than 5 % of the time (2.4 hours) where the CO_2 rating was in the 1200 to 1750 ppm range. Finally, from a total of 169 classrooms that had the CO_2 rating in the 1200 to 1750 ppm range

(category III) for at least 94 % of the time, 16 classrooms (9.4 %) had more than 5 % of the time (2.4 hours) where the CO_2 rating was higher than 1750 ppm range. For comparison, 3.7 % of classrooms impacted by the rating principle of the CO_2 rating was relatively unchanged for the rating principle of the air temperature (4.2 % of classrooms), and RH (3.0 % of classrooms).

Finally, an investigation will be made into which parameters most impact the TAIL IAQ rating at the classroom level. The rating principle of the TAIL rating scheme indicates that in a measured classroom, the worst scoring parameter will impose the overall rating of the IAQ components. Consequently, there would be classrooms with no Category I parameter, with 1 Category I parameter, with 2 Category I parameters, but classified as Category IV TAIL IAQ. Table 24 presents the distribution of these different Category IV classrooms, emphasizing only the TAIL rating of the four critical parameters (CO_2, NO_2, $PM_{2.5}$, RH).

Table 24: Distribution of the different types of Category IV TAIL-IAQ classrooms (n = 526)

Classrooms that had Category IV in all 4 parameters	2
Classrooms that had 0 category I parameter	132
Classrooms that had 1 category I parameter	291
Classrooms that had 2 category I parameters	101

Only two classrooms scored a Category IV TAIL IAQ in the 526 classrooms that achieved a Category IV in all four parameters. 55 % of the classrooms scored Category I in 1 parameter, 20 % scored Category I in 2, and 25 % did not score Category I in any parameter. Furthermore, Figure 25 illustrates the impact of the four parameters. Of the total 602 measured classrooms, the numbers represent the classrooms where the TAIL quality of the corresponding parameter was the worst, thus the imposed parameter. The number at the intersection of each ellipse indicates the number of classrooms where that combination of parameters was equally bad. Results show that CO_2 and $PM_{2.5}$ were the two most impactful parameters among the four parameters. In 25 % and 17 % of classrooms, CO_2 and $PM_{2.5}$, respectively, were the worst-scored parameters. Furthermore, in 37 % of classrooms, these two parameters were equally poor and thus imposed on the TAIL IAQ rating. Moreover, in another 8 % of classrooms, these two parameters and another parameter were equally inadequate.

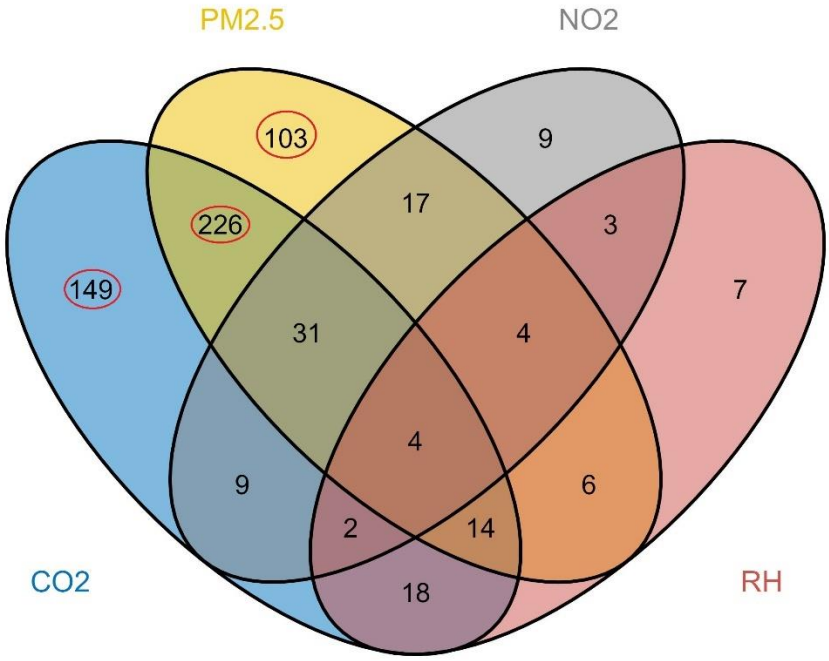


Figure 25: Venn diagram representing the impact of the four IAQ parameters, on the classroom scale (n = 602)

IV.3.3.2. TAIL IAQ rating on the school scale

Table 25 presents the TAIL classification of the seven parameters in the IAQ and the overall classification of the 308 schools. Results show that more than 90% of the schools achieved at least a category II rating of benzene, formaldehyde, and mold. Thus, once again the analysis will be focused on the other four parameters, where more schools achieved only a category III or IV rating: 34% of schools for the relative humidity, 83% of schools for the CO_2 concentration, 76% of schools for the $PM_{2.5}$ concentration, and 13% of schools for the NO_2 concentration.

Table 25: TAIL-rating of the indoor air quality on the school scale, calculated by averaging the TAIL IAQ classrooms' ratings (n = 308)

TAIL IAQ rating	Category I	Category II	Category III	Category IV	Missing data

Benzene	80.2 % (247)	17.2 % (53)	0.0 % (0)	1.0 % (3)	1.6 % (5)
CO_2	1.0 % (3)	8.1 % (25)	21.8 % (67)	61.1 % (213)	0.0 % (0)
Formaldehyde	76.9 % (237)	23.1 % (71)	0.0 % (0)	0.0 % (0)	0.0 % (0)
NO_2	65.0 % (200)	21.7 % (67)	0.0 % (0)	13.0 % (40)	0.3 % (1)
$PM_{2.5}$	0.3 % (1)	22.1 % (68)	0.0 % (0)	75.6 % (233)	2.0 % (6)
Relative humidity	14.3 % (44)	50.3 % (155)	28.2 % (87)	6.2 % (19)	1.0 % (3)
Visible mold	94.2 % (290)	5.5 % (17)	0.0 % (0)	0.0 % (0)	0.3 % (1)
Overall IAQ	0.0 % (0)	1.6 % (5)	5.2 % (16)	93 % (287)	0.0 % (0)

Table 26 describes the overall classification of the TAIL IAQ in the 308 measured schools, defined by the worst individual TAIL classrooms' IAQ rating of the school. Regarding the overall IAQ rating, two schools were demoted from the Category III to the Category IV rating.

Table 26: TAIL-rating of the indoor air quality on the school scale, defined by the worst TAIL IAQ classrooms' rating of the school (n = 308)

TAIL IAQ rating	Category I	Category II	Category III	Category IV	Missing data
Benzene	79.6 % (245)	17.2 % (53)	0.0 % (0)	1.6 % (5)	1.6 % (5)
CO_2	1.0 % (3)	3.5 % (11)	21.4 % (66)	74 % (228)	0.0 % (0)
Formaldehyde	75.9 % (234)	24.1 % (74)	0.0 % (0)	0.0 % (0)	0.0 % (0)
NO_2	64.3 % (198)	21.4 % (66)	0.0 % (0)	13.9 % (43)	0.3 % (1)
$PM_{2.5}$	0.3 % (1)	21.4 % (66)	0.0 % (0)	76.3 % (235)	2.0 % (6)
Relative humidity	13.9 % (43)	49.6 % (153)	28.2 % (87)	7.1 % (22)	1.0 % (3)
Visible mold	94.2 % (290)	5.5 % (17)	0.0 % (0)	0.0 % (0)	0.3 % (1)

Overall IAQ	0.0 % (0)	1.6 % (5)	4.5 % (14)	93.8 % (289)	0.0 % (0)

IV.3.3.3. Data interpretation

The following analysis focused more on the four parameters: relative humidity, CO_2, NO_2, and $PM_{2.5}$. Starting with the relative humidity, Table 27 presents the results of its TAIL-rating in schools, according to the previously defined different variables of the schools' characteristics.

Table 27: TAIL-rating of the relative humidity in different groups of schools (n = 308)

Variables	**TAIL – RH quality**				
	Category I	**Category II**	**Category III**	**Category IV**	**Not available**
Type of school					
Nursery	17 % (27)	54 % (85)	25 % (39)	4 % (6)	1% (1)
Elementary school	11 % (17)	47 % (70)	32 % (48)	9 % (13)	1 % (2)
Surrounding environment					
Rural	16 % (22)	54 % (72)	24 % (32)	6 % (8)	0 % (0)
Suburban	14 % (15)	47 % (52)	32 % (36)	6 % (7)	1 % (1)
Urban	11 % (7)	49 % (31)	30 % (19)	6 % (4)	3 % (2)
Climatic zone					
H1a	17 % (13)	49 % (38)	25 % (19)	6 % (5)	3 % (2)
H1b	10 % (4)	56 % (22)	26 % (10)	8 % (3)	0 % (0)
H1c	8 (15%)	34 (62%)	13 (24%)	0 % (0)	0 % (0)
H2a	9 % (2)	41 % (9)	41 % (9)	9 % (2)	0 % (0)

H2b	19 % (7)	46 % (17)	30 % (11)	5 % (2)	0 % (0)
H2c	13 % (4)	52 % (16)	26 % (8)	10 % (3)	0 % (0)
H2d	15 % (2)	31 % (4)	54 % (7)	0 % (0)	0 % (0)
H3	12 % (4)	45 % (15)	27 % (9)	12 % (4)	3 % (1)
Measured season					
Heating	16 % (38)	54 % (129)	24 % (58)	5 % (12)	1% (1%)
Non – heating	9 % (6)	37 % (26)	41 % (29)	10 % (7)	3 % (2)

Relative humidity is the second parameter to be measured and assessed continuously throughout a time series of measurement instances, following the same principle as the assessment of the air temperature. The assessment hours remain the same, Monday to Friday, from 09h00 to 17h00, for a total of 40 hours, or 240 measurement points. As a reminder, the assessment principle can be found in Figure 7.

As shown in Table 27, no significant difference between the distributions of the TAIL rating of the relative humidity can be spotted across the different school's characteristics. Further analysis can be made by plotting the evolution of the RH in a classroom, using the same earlier approach to the air temperature. Figure 26, Figure 27, Figure 28, and Figure 29 represented the minimal, median, and maximal values of measured RH in classrooms that obtained categories I, II, III, and IV during the heating season. Colored portions of the figures correspond to the values of the threshold used to determine the TAIL RH rating.

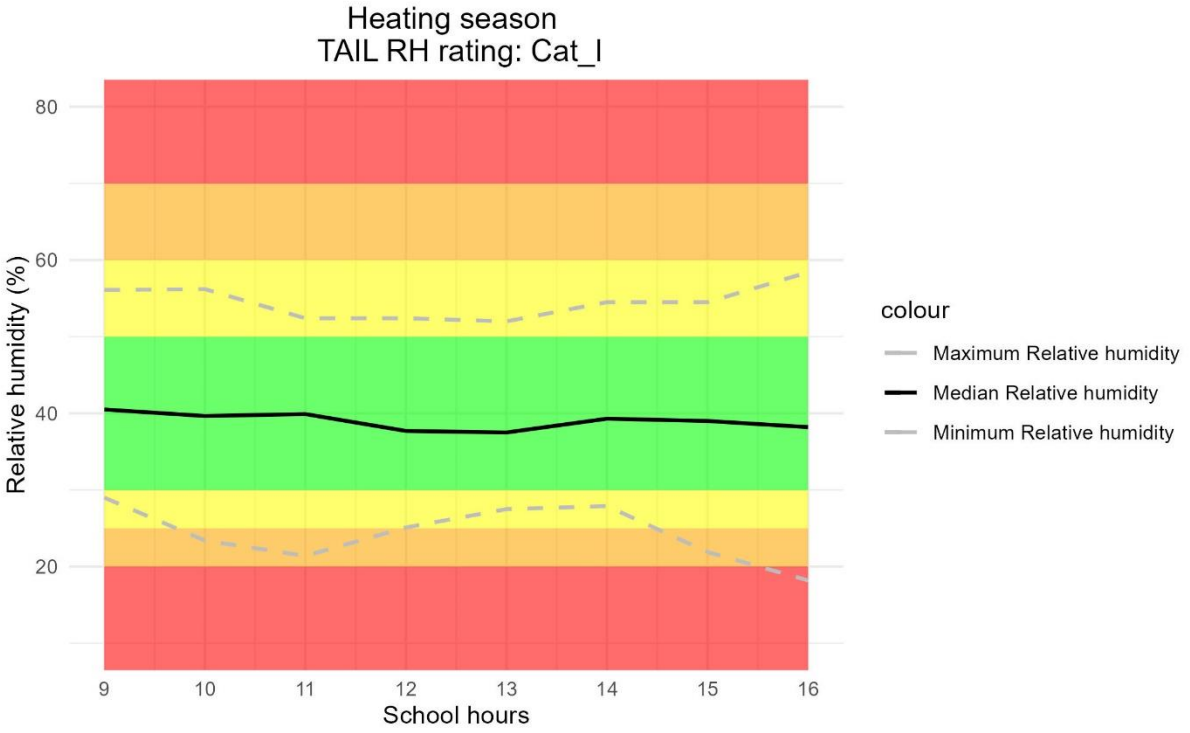


Figure 26: Evolution of the relative humidity measured during a school day, in category I TAIL RH classrooms, during the heating season.

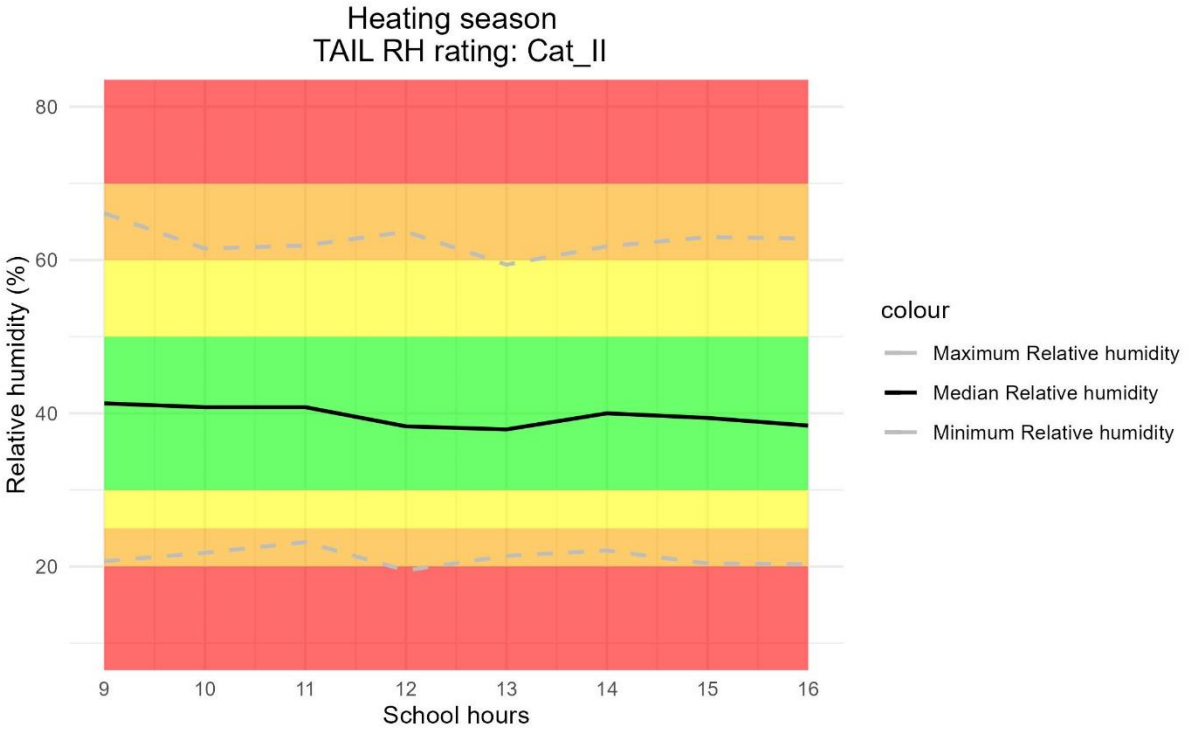


Figure 27: Evolution of the relative humidity measured during a school day, in category II TAIL RH classrooms, during the heating season.

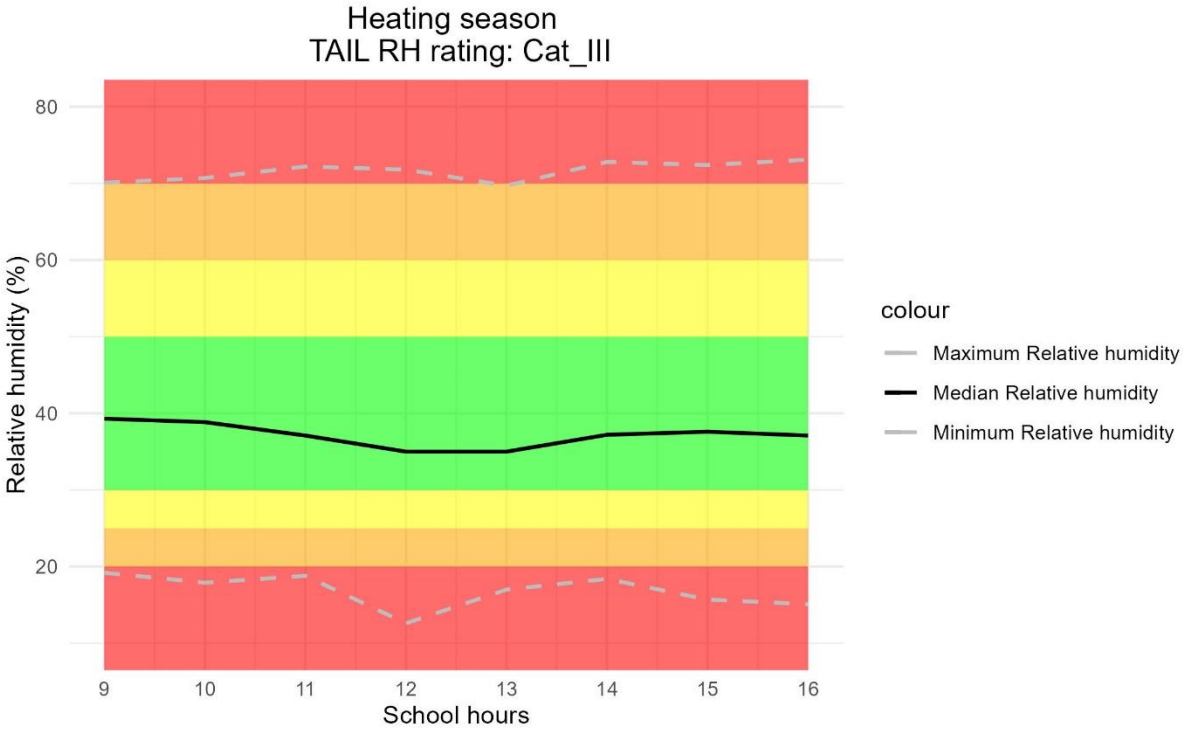


Figure 28: Evolution of the relative humidity measured during a school day, in category III TAIL RH classrooms, during the heating season.

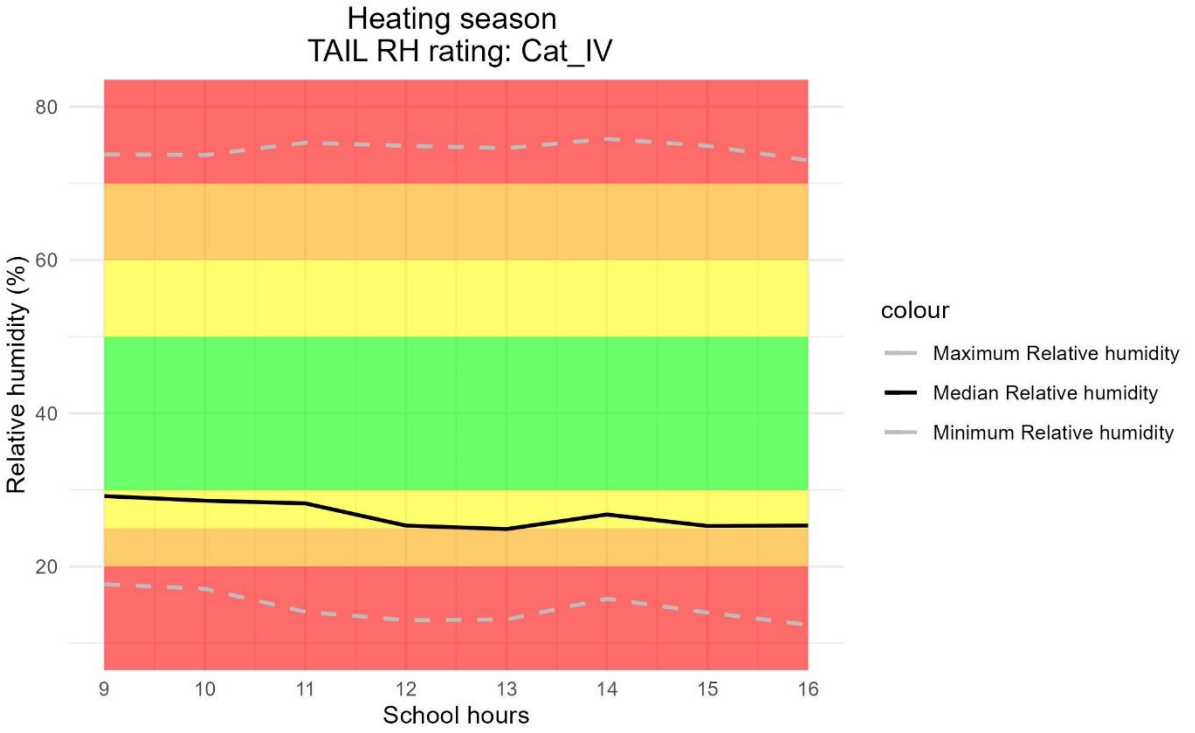


Figure 29: Evolution of the relative humidity measured during a school day, in category IV TAIL RH classrooms, during the heating season.

Across the four figures, the dotted gray lines represent the minimum and maximum values further apart from classrooms with a TAIL RH rating of category I to category IV. Consequently, this means a larger dispersion was observed in classrooms with a poor TAIL RH rating. Contrarily, the black lines that represent the median values stayed relatively constant in each plot. However, compared to the Categories I and II classrooms, the median of RH in Category III classrooms was lower and further reduced in Category IV classrooms. This indicates a dryer air trend in poorer TAIL RH classrooms measured in the heating season.

Moreover, Figure 30, Figure 31, Figure 32, and Figure 33 represent the minimal, median, and maximal values of measured RH in classrooms that obtained categories I, II, III, and IV during the non-heating season.

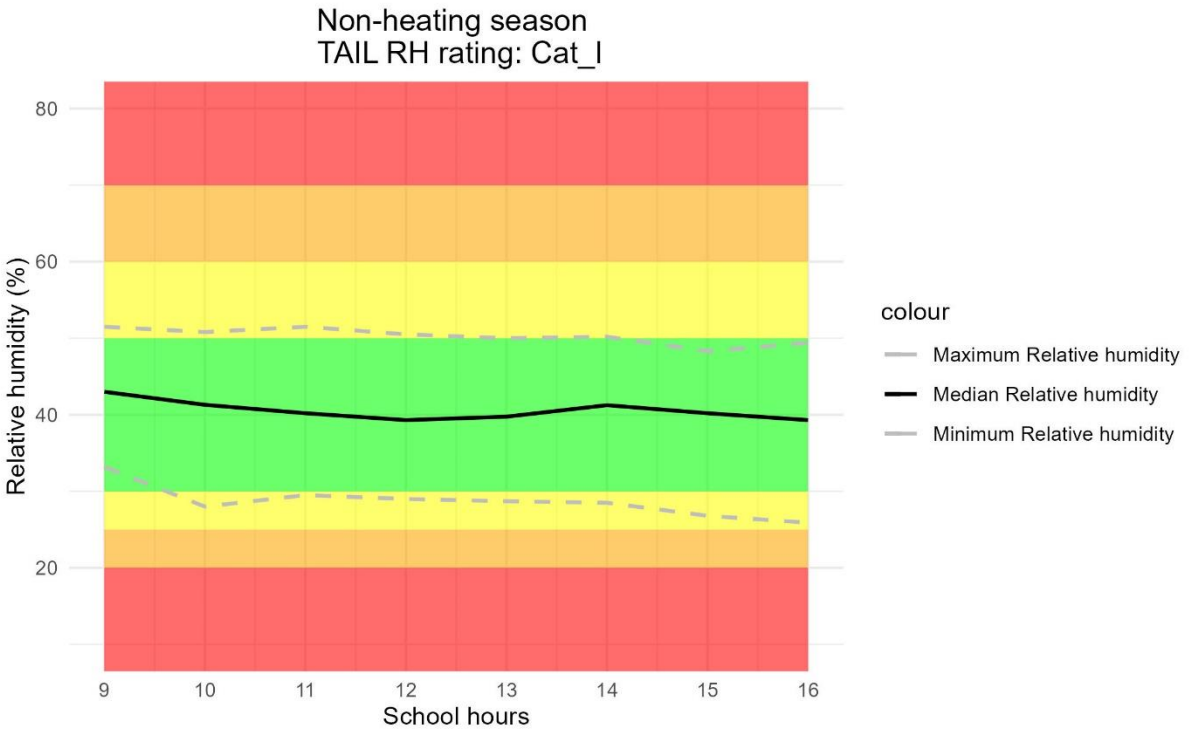


Figure 30: Evolution of the relative humidity measured during a school day, in category I TAIL RH classrooms, during the non-heating season.

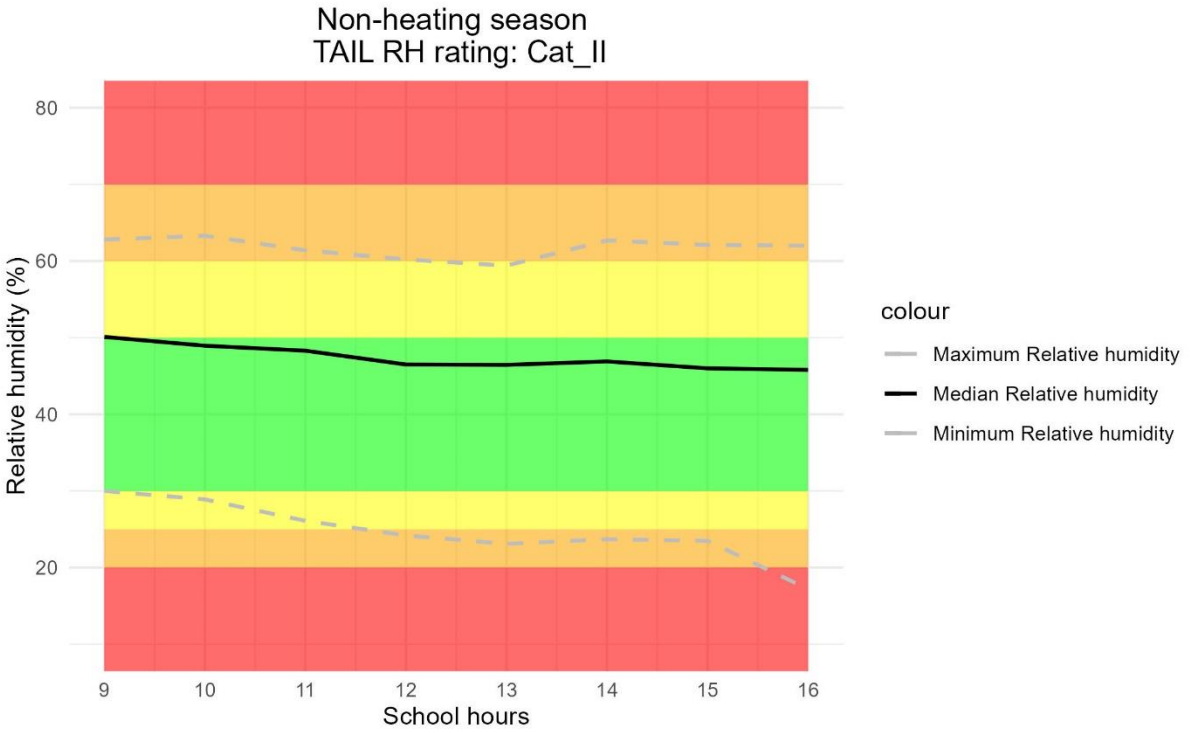


Figure 31: Evolution of the relative humidity measured during a school day, in category II TAIL RH classrooms, during the non-heating season.

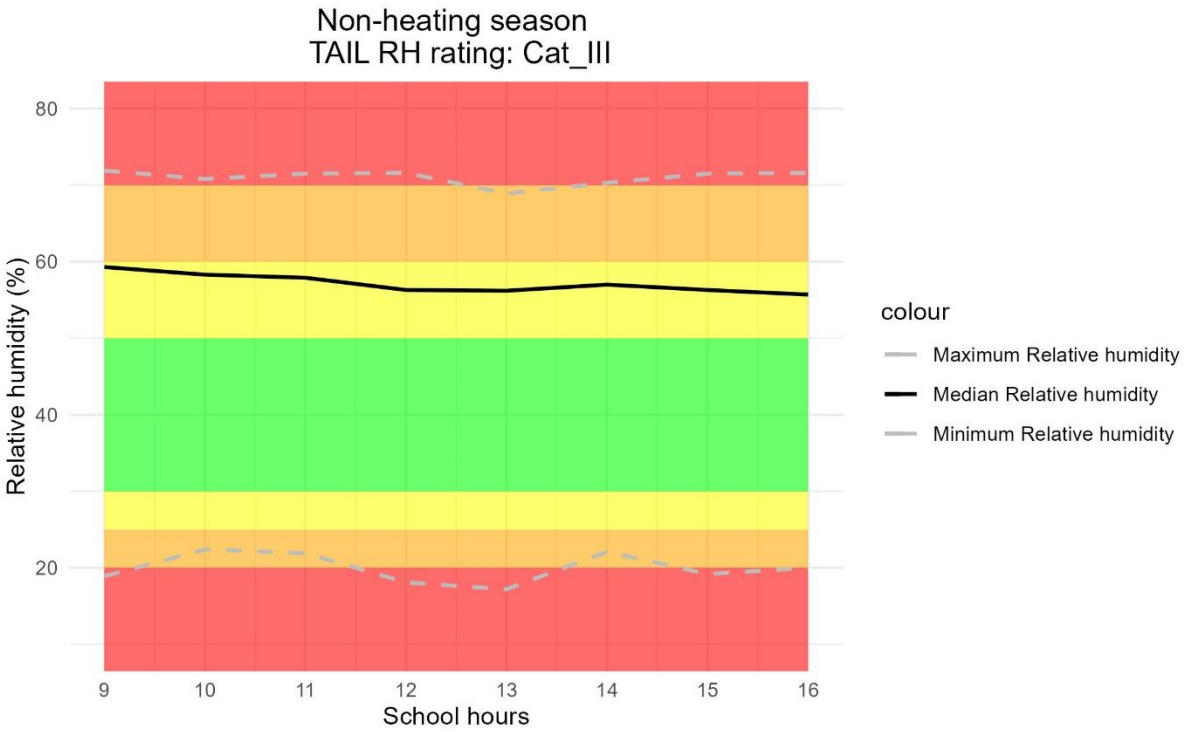


Figure 32: Evolution of the relative humidity measured during a school day, in category III TAIL RH classrooms, during the non-heating season.

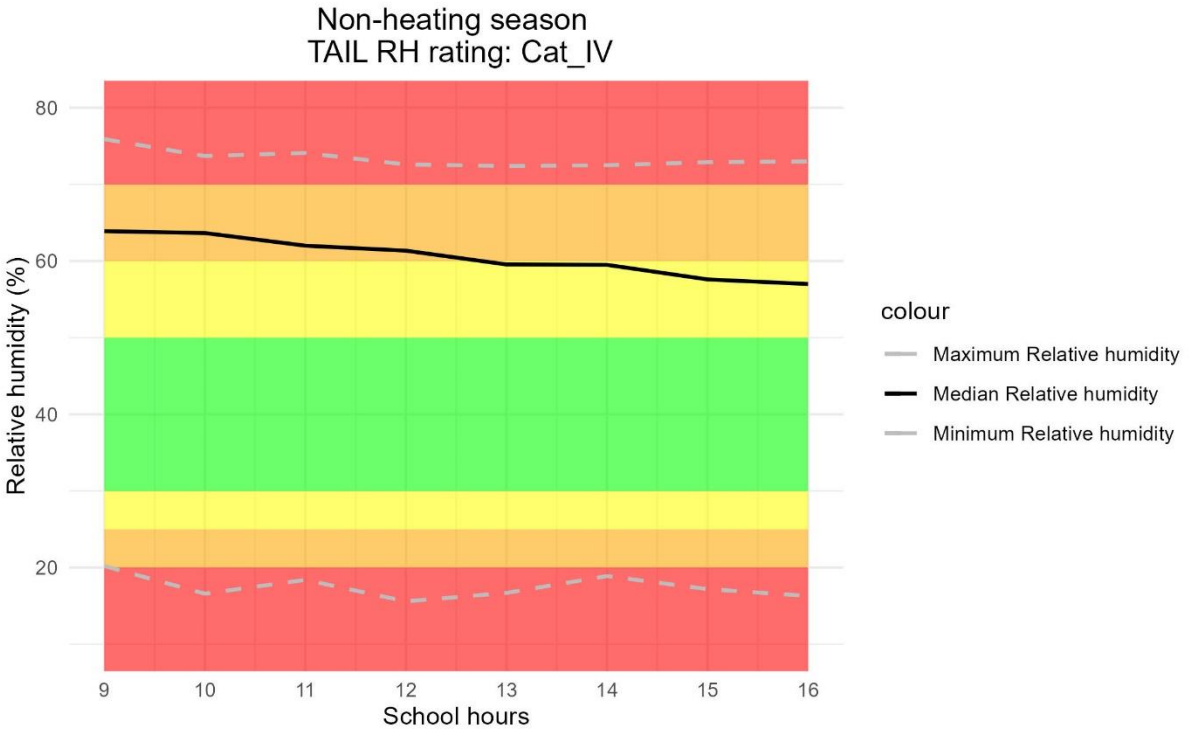


Figure 33: Evolution of the relative humidity measured during a school day, in category IV TAIL RH classrooms, during the non-heating season.

Similar to classrooms measured during the heating season, a larger dispersion can be observed when comparing classrooms with a category I to category IV TAIL RH rating. However, in an opposite and much more significant manner, the black lines representing the median values increased when comparing classrooms with a category I to category IV TAIL RH rating. Consequently, this indicated more humid air in poorer TAIL RH classrooms during the non-heating season.

The second analysis consists of the concentration of CO_2. Table 28 presents the results of the TAIL-rating of the measured concentration of CO_2 in schools, according to different variables.

Table 28: TAIL-rating of the CO_2 quality in different groups of schools (n = 308)

Variables	**TAIL – CO_2 quality**				
	Category I	**Category II**	**Category III**	**Category IV**	**Not available**
Type of school					
Nursery	1 % (2)	12 % (19)	32 % (50)	55 % (87)	0 % (0)
Elementary school	1 % (1)	4 % (6)	11 % (17)	84 % (126)	0 % (0)
Surrounding environment					
Rural	1 % (1)	13 (10%)	28 (21%)	92 (69%)	0 % (0)
Suburban	1 % (1)	6 % (7)	27 % (30)	66 % (73)	0 % (0)
Urban	2 % (1)	8 % (5)	14 % (9)	76 % (48)	0 % (0)
Climatic zone					
H1a	0 % (0)	4 % (3)	16 % (12)	81 % (62)	0 % (0)
H1b	3 % (1)	5 % (2)	31 % (12)	62 % (24)	0 % (0)
H1c	2 % (1)	13 % (7)	29 % (16)	57 % (32)	0 % (0)
H2a	0 % (0)	5 % (1)	27 % (6)	68 % (15)	0 % (0)

H2b	0 % (0)	0 % (0)	14 % (5)	86 % (32)	0 % (0)
H2c	0 % (0)	6 % (2)	6 % (2)	87 % (27)	0 % (0)
H2d	0 % (0)	23 % (3)	38 % (5)	38 % (5)	0 % (0)
H3	3 % (1)	21 % (7)	27 % (9)	48 % (16)	0 % (0)
Measured season					
Heating	0.3 % (1)	7 % (16)	21 % (51)	71 % (170)	0 % (0)
Non – heating	3 % (2)	13 % (9)	23 % (16)	61 % (43)	0 % (0)

There was a significant difference in the distribution of the TAIL CO_2 rating in the two groups of variables. Figure 34 presents the distribution of the TAIL CO_2 rating in nursery and elementary schools. The TAIL CO_2 rating in elementary schools was more inadequate than in nurseries. It could be due to different classroom characteristics, e.g., occupied density, classroom usage, activity, and ventilation practice. Figure 35 presents the distribution of the TAIL CO_2 rating in schools from different climate zones. Three groups can be observed based on the percentage of TAIL CO_2 category IV rating schools. Group 1 consists of schools from the H2d and H3 zones, where less than 50% of schools achieved a category IV TAIL CO_2 rating. Group 2 consists of schools from the H1b, H1c, and H2a, where less than 70% of schools achieved a category IV TAIL CO_2 rating. Finally, group 3 consists of schools from the H1a, H2b, and H2c, where more than 80% of schools achieved a category IV TAIL CO_2 rating. The difference can be due to the randomness of not having a consistent number of measured schools in each group. However, it could also be linked to the usage of the classrooms, ventilation practice, and the specificity of the building's design for adaptation to its specific climate zone.

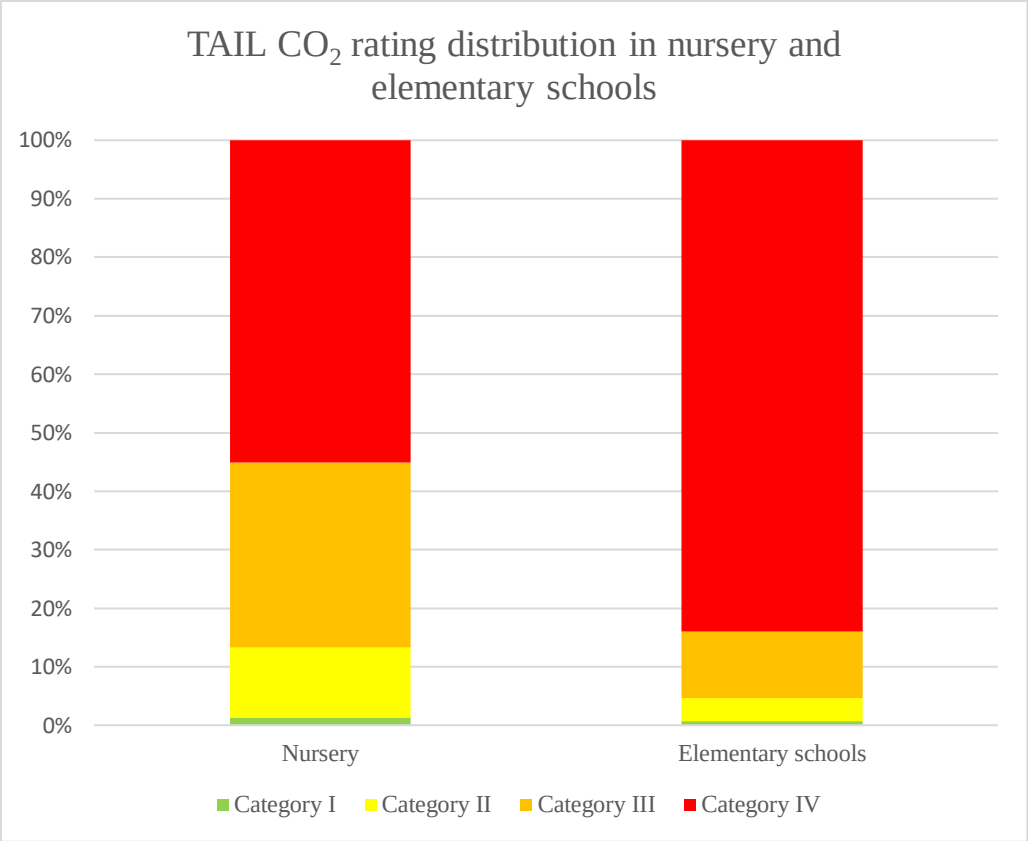


Figure 34: Distribution of the TAIL CO_2 rating in nursery and elementary schools

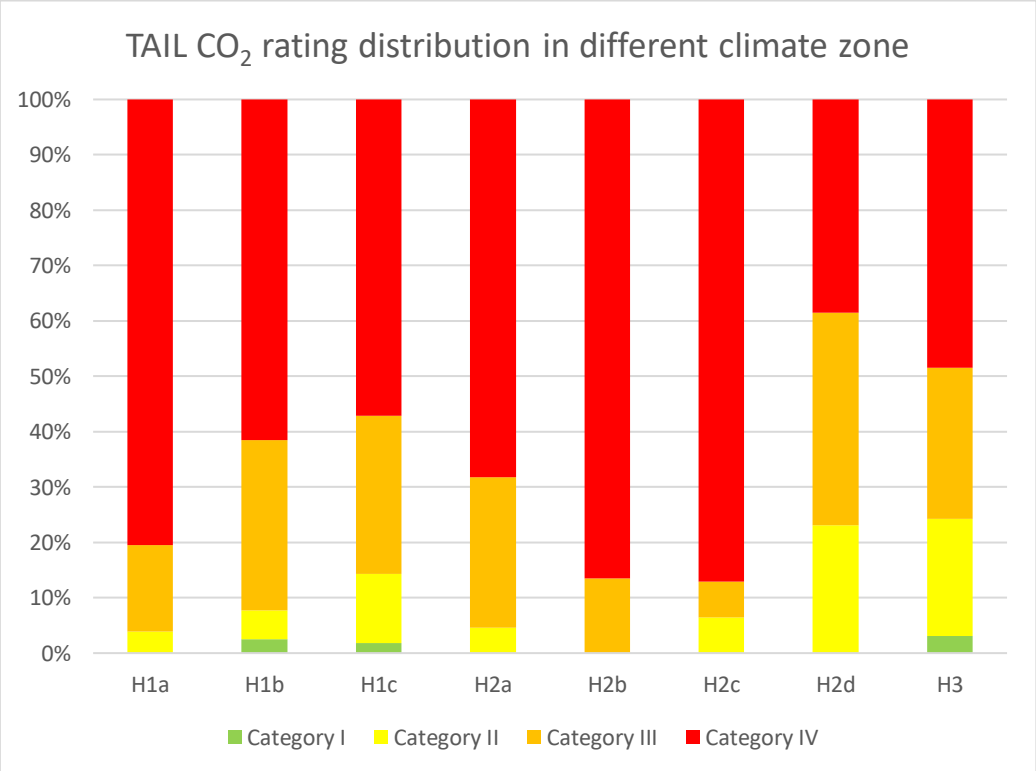


Figure 35: Distribution of the TAIL CO_2 rating in schools from different climate zone

CO_2 is the last of the three parameters where the assessment of a time series of measurement points was required, with air temperature and RH the other two. As a reminder, a flow chart illustrating the rating principle can be found in Figure 8. The only difference in the assessment of the CO_2 concentration compared to the other two aforementioned parameters is that there is only one upper limit for each quality category. As an illustration, the following Figure 36, Figure 37, Figure 38, and Figure 39 present the evolution of the measured CO_2 concentration during a day in classrooms measured during heating season, with categories I, II, III, and IV TAIL CO_2 ratings, respectively. From every classroom that achieved the corresponding TAIL CO_2 rating, the minimal, median, and maximal CO_2 concentration from each measured day were plotted to represent a random school day. The dotted gray line represents the minimal and maximal CO_2 concentration, while the continuous black line represents the median CO_2 concentration. The colored area represents the corresponding portion of the threshold values used to determine the TAIL CO_2 category.

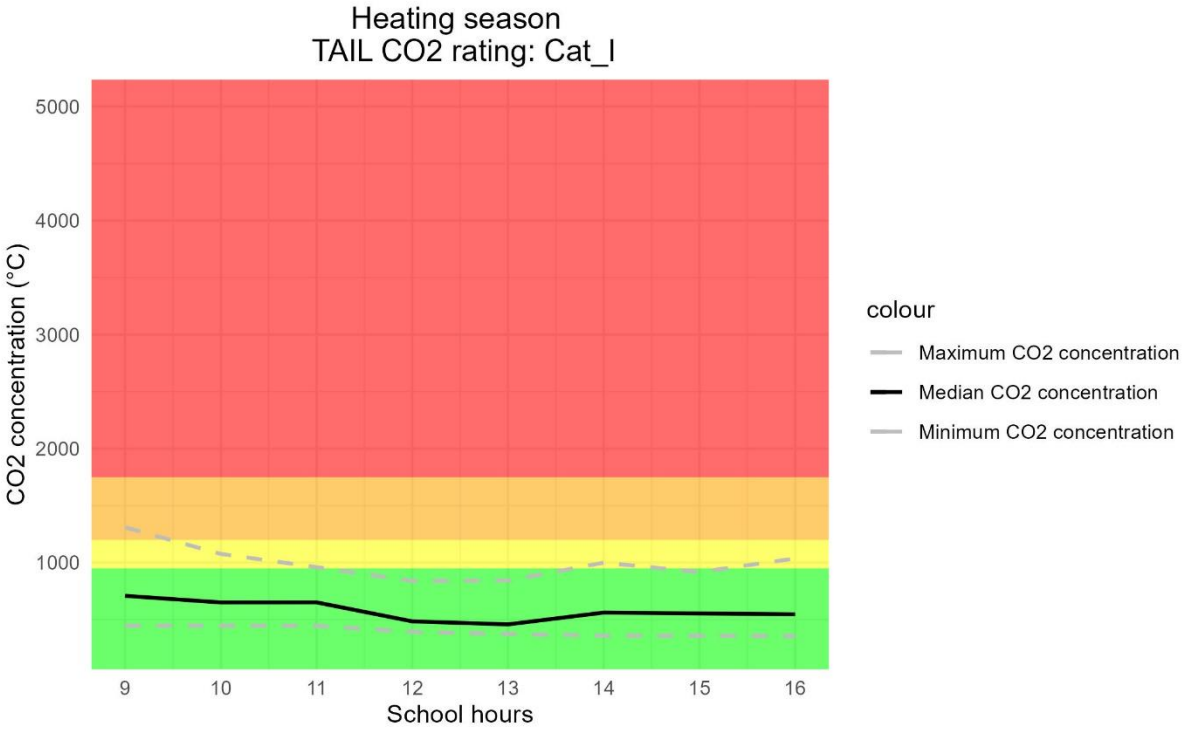


Figure 36: Evolution of the CO_2 concentration measured during a school day, in category I TAIL CO_2 classrooms, during the heating season

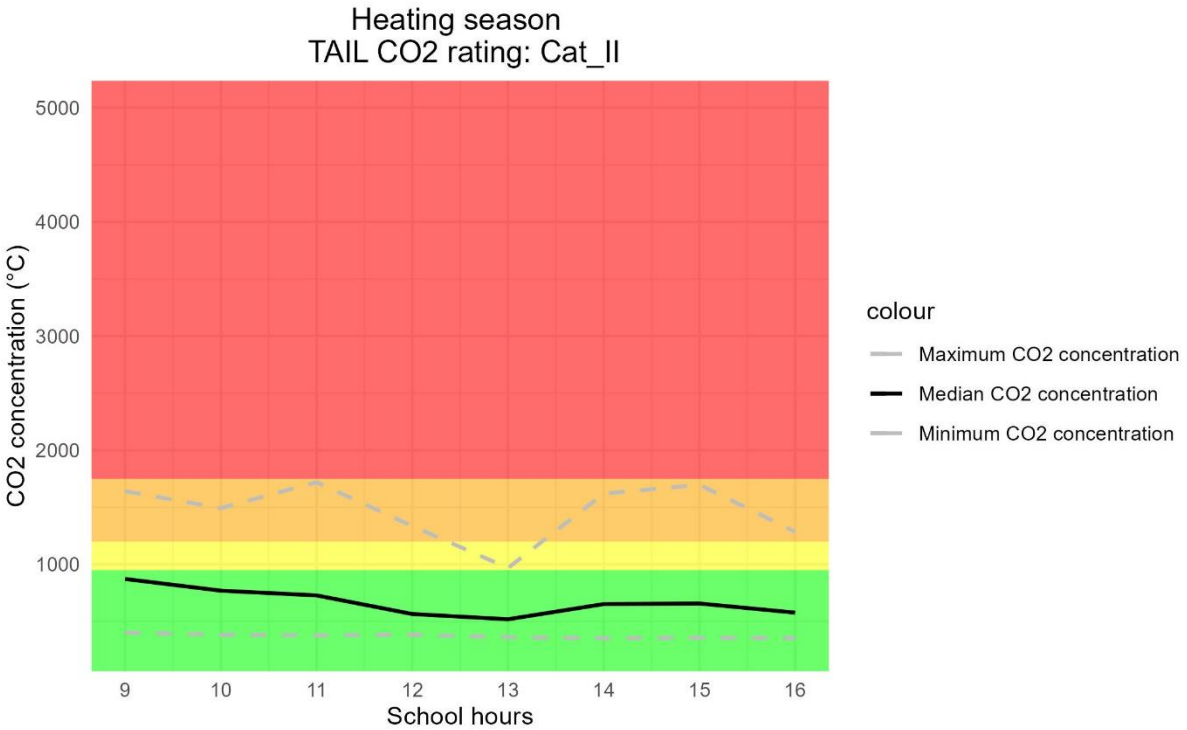


Figure 37: Evolution of the CO_2 concentration measured during a school day, in category II TAIL CO_2 classrooms, during the heating season

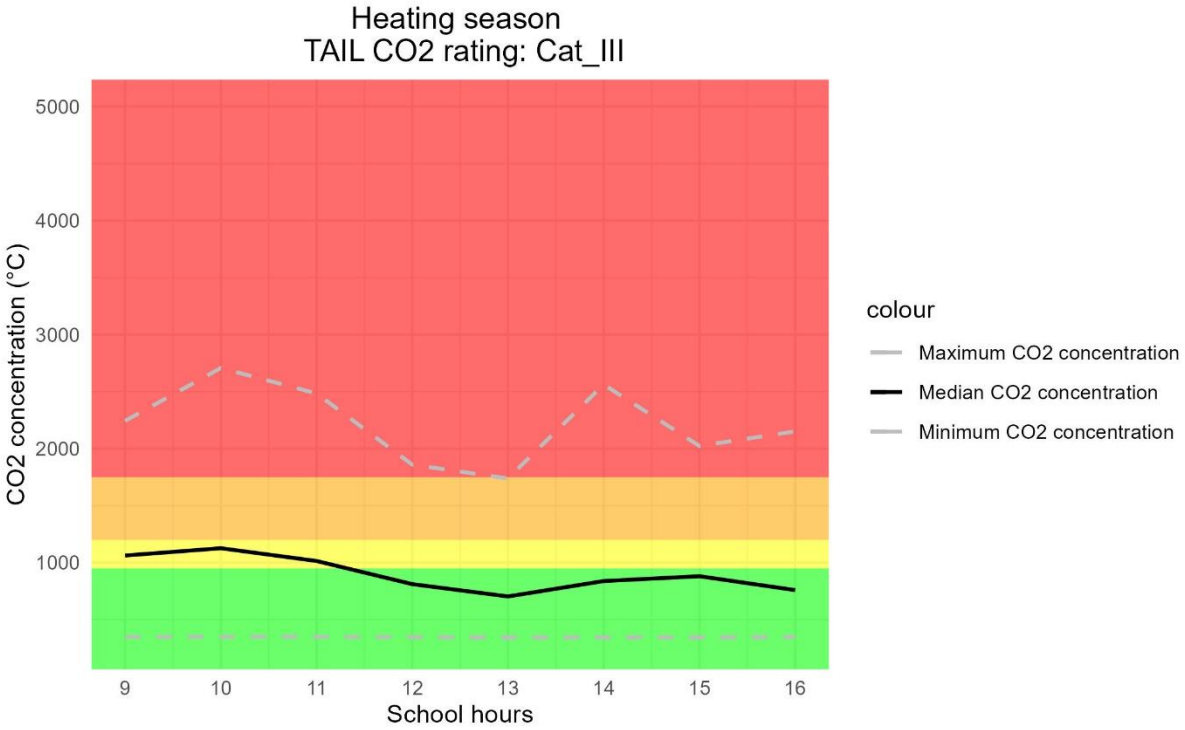


Figure 38: Evolution of the CO_2 concentration measured during a school day, in category III TAIL CO_2 classrooms, during the heating season

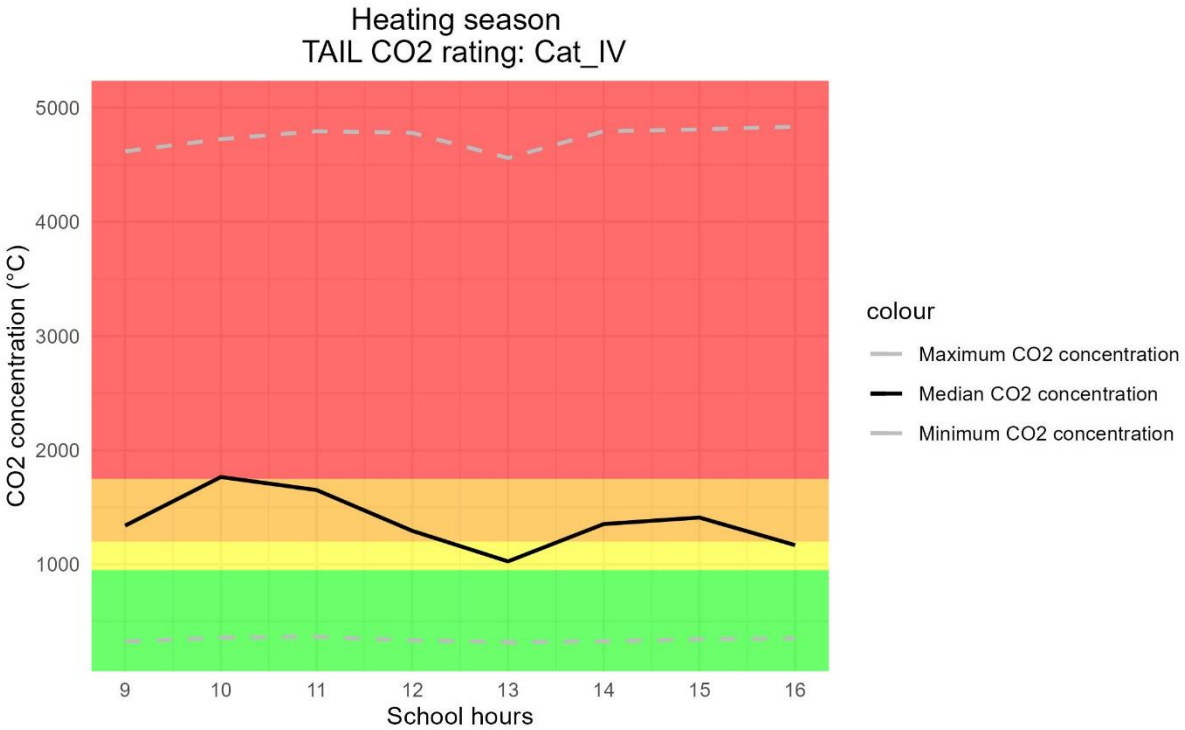


Figure 39: Evolution of the CO_2 concentration measured during a school day, in category IV TAIL CO_2 classrooms, during the heating season

Consistently, the dotted line representing the minimal and maximal values of measured CO_2 grew further apart as the TAIL CO_2 rating of the classrooms went from category I to IV. This indicated a larger dispersion in classrooms with a more inadequate TAIL CO_2 rating. The minimal values line stayed unchanged, regardless of the time of the day and the TAIL CO_2 rating of the classrooms. The median values lines of classrooms with a category I and II TAIL CO_2 rating stay entirely in the category I values, so the exceeded allowance time must be the factor separating these classrooms. As anticipated, the median lines rise higher in classrooms with a category III and IV TAIL CO_2 rating.

Following the same principle, the Figure 40, Figure 41, Figure 42, and Figure 43 illustrate the evolution of the CO_2 concentration measured in classrooms during the non-heating season.

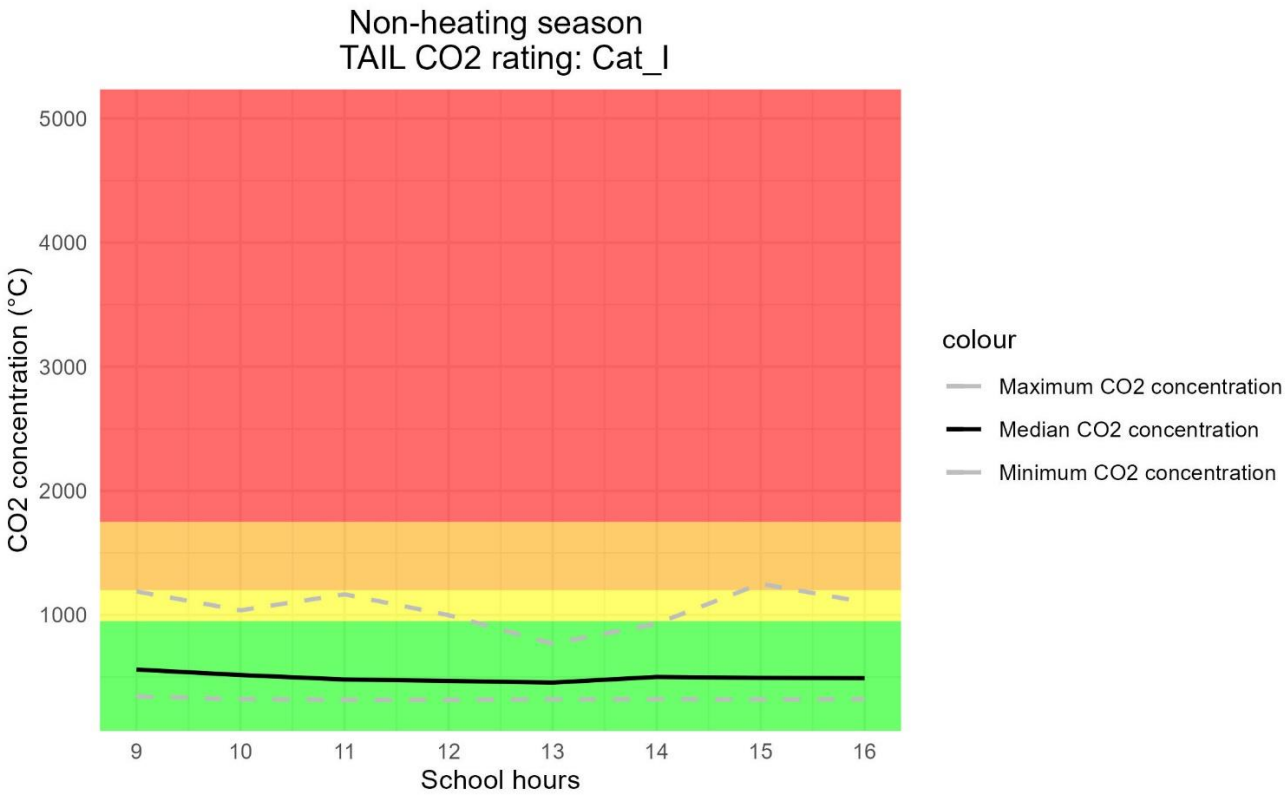


Figure 40: Evolution of the CO_2 concentration measured during a school day, in category I TAIL CO_2 classrooms, during the non-heating season

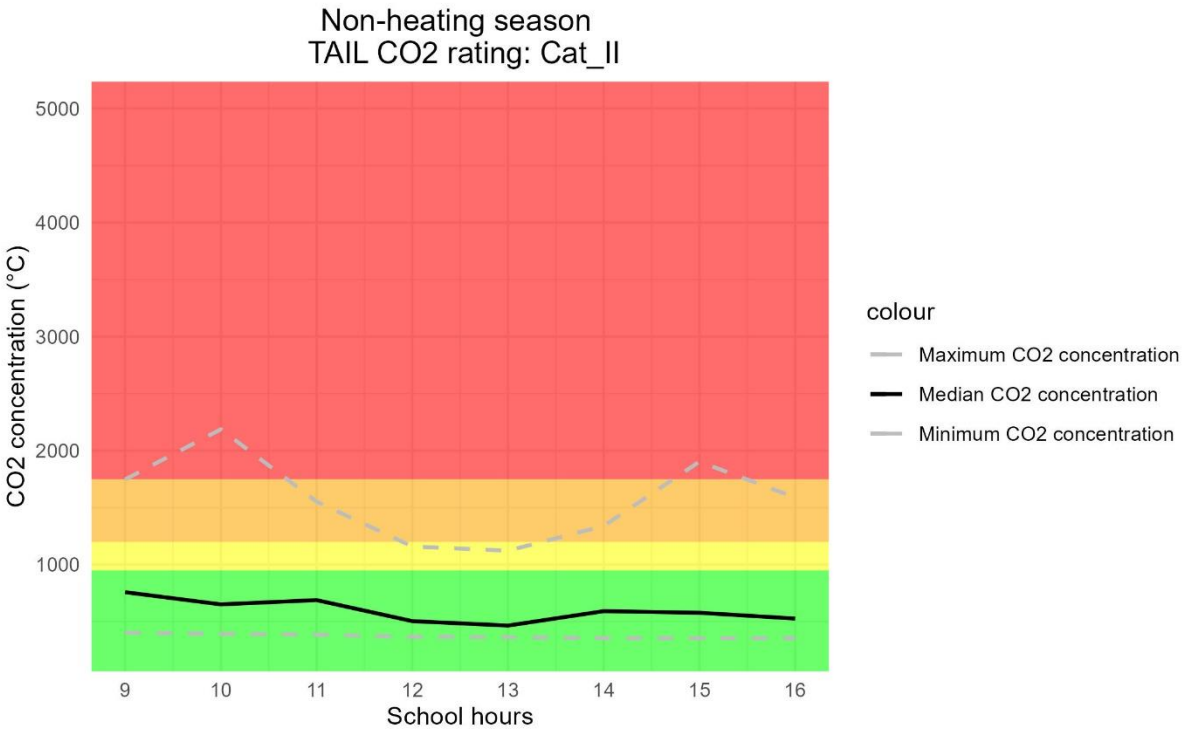


Figure 41: Evolution of the CO_2 concentration measured during a school day, in category II TAIL CO_2 classrooms, during the non-heating season

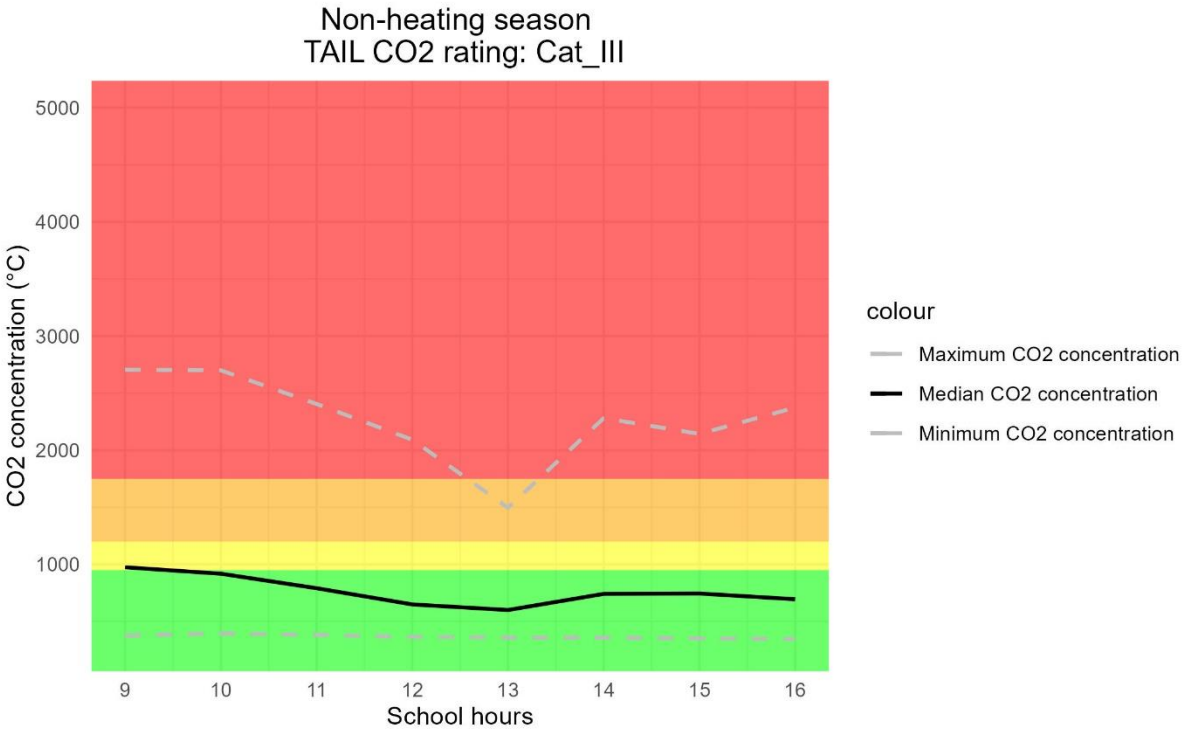


Figure 42: Evolution of the CO_2 concentration measured during a school day, in category III TAIL CO_2 classrooms, during the non-heating season

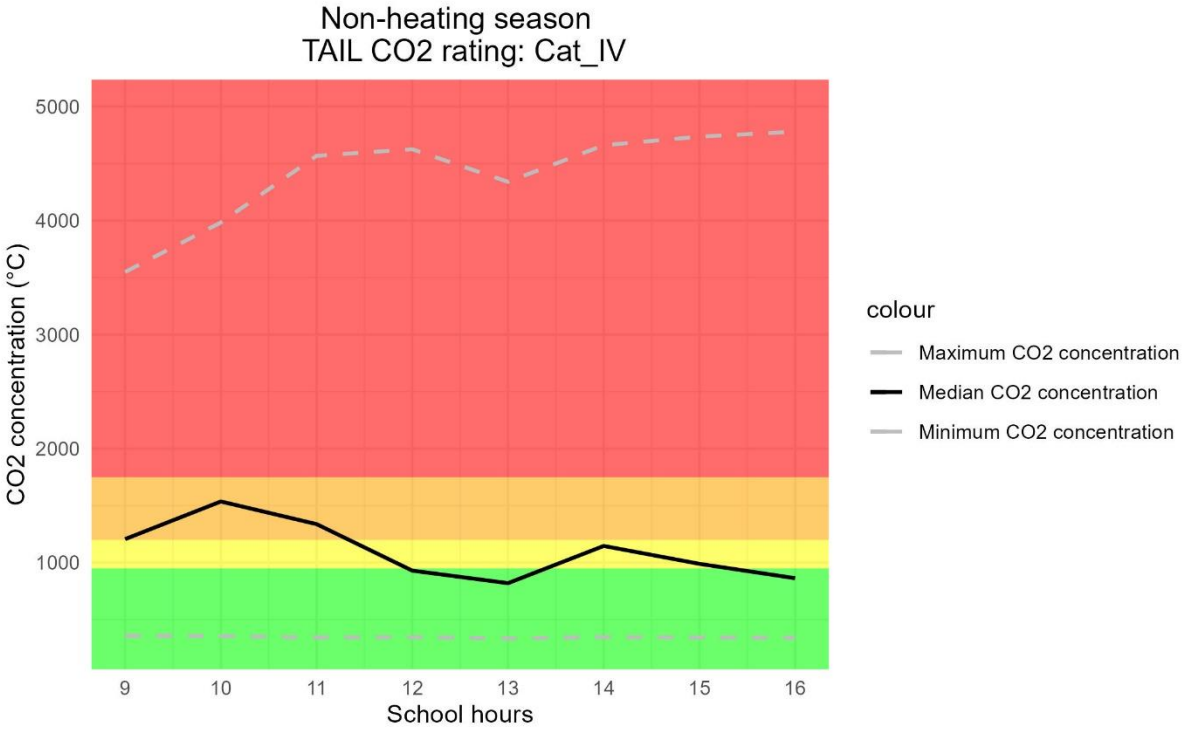


Figure 43: Evolution of the CO_2 concentration measured during a school day, in category IV TAIL CO_2 classrooms, during the non-heating season

Once again, a larger dispersion was observed in poorer TAIL CO_2 rating classrooms. The dotted minimal values remain unchanged in all four graphs, regardless of the measured time. The black line represents the median values for the CO_2 concentration in Category I and II classrooms, which once again stayed entirely within the Category I values and increased in Category III and IV classrooms.

Continuing with the assessment of the $PM_{2.5}$ parameter, Table 29 presents the results of the TAIL-rating of the measured concentration of $PM_{2.5}$ in schools, according to different variables used to stratify the schools' sample.

Table 29: TAIL - rating of the $PM_{2.5}$ quality in different groups of schools (n = 308)

Variables	**TAIL – IAQ quality**				
	Category I	**Category II**	**Category III**	**Category IV**	**Not available**
Type of school					

Nursery	1 % (1)	23 % (37)	0 % (0)	75 % (119)	1 % (1)
Elementary school	0 % (0)	21 % (31)	0 % (0)	76 % (114)	3 % (5)
Surrounding environment					
Rural	0 % (0)	19 % (26)	0 % (0)	78 % (104)	4 (3%)
Suburban	1 % (1)	31 % (34)	0 % (0)	68 % (75)	1 % (1)
Urban	0 % (0)	13 % (8)	0 % (0)	86 % (54)	2 % (1)
Climatic zone					
H1a	0 % (0)	19 % (15)	0 % (0)	77 % (59)	4 % (3)
H1b	0 % (0)	31 % (12)	0 % (0)	67 % (26)	3 % (1)
H1c	0 % (0)	27 % (15)	0 % (0)	73 % (41)	0 % (0)
H2a	0 % (0)	27 % (6)	0 % (0)	68 % (15)	5 % (1)
H2b	0 % (0)	19 % (7)	0 % (0)	81 % (30)	0 % (0)
H2c	0 % (0)	26 % (8)	0 % (0)	71 % (22)	3 % (1)
H2d	0 % (0)	0 % (0)	0 % (0)	13 (100%)	0 % (0)
H3	3 % (1)	15 % (5)	0 % (0)	82 % (27)	0 % (0)
Measured season					
Heating	0.3 % (1)	23 % (54)	0 % (0)	75 % (178)	2 % (5)
Non – heating	0 % (0)	20 % (14)	0 % (0)	79 % (55)	1 % (1)

Regarding the type of schools measured and its measured season, no significant differences were observed in the distribution of the TAIL rating in schools, where more than 75 % of schools only achieved a Category IV rating. However, there was a significant difference in the

distribution of the TAIL $PM_{2.5}$ rating in the two other variables. Figure 44 represents the distribution of the TAIL $PM_{2.5}$ rating by their surrounding environment, where more than 80 % of schools from the urban area were rated Category IV. Figure 45 represents the distribution of the TAIL $PM_{2.5}$ rating by their climate zone, where 100 % of schools (13 schools) from the H2d zone were classified as Category IV. As a reminder, the H2d zone represents the zone with an influence mainly from the oceanic climate and higher mean temperature in the summer compared to other zones. These differences could be due to the usage of the classrooms' equipment, different indoor and outdoor sources, and teachers' ventilation practices. Nevertheless, TAIL has proven its usefulness in differentiating the levels of $PM_{2.5}$ in these schools.

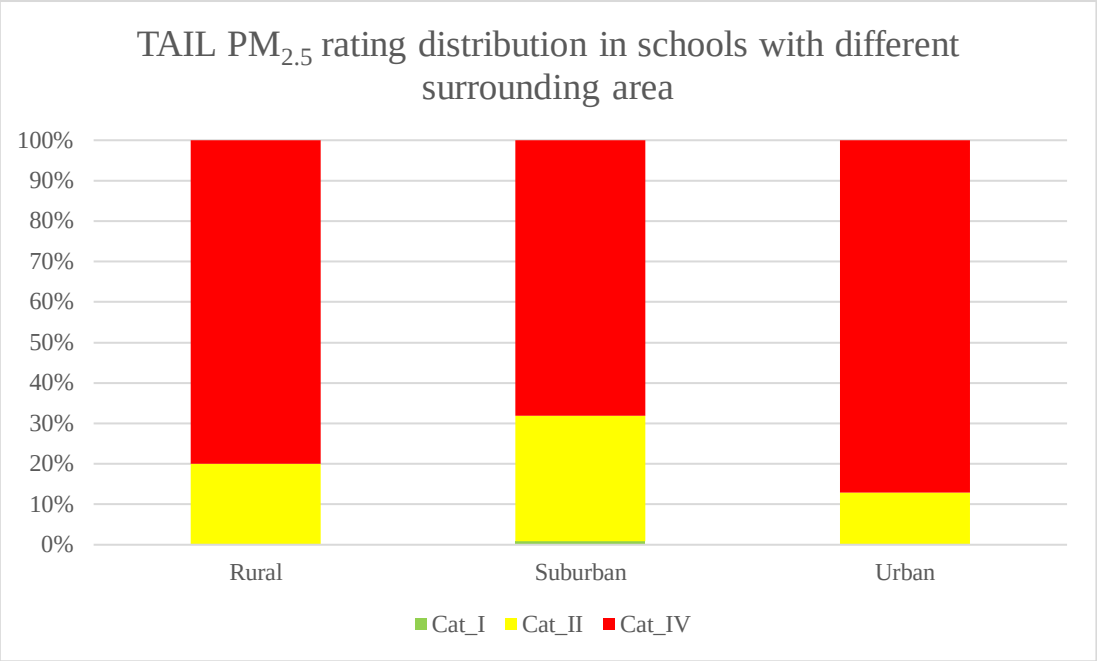


Figure 44: Distribution of the TAIL $PM_{2.5}$ rating in schools from different surrounding area

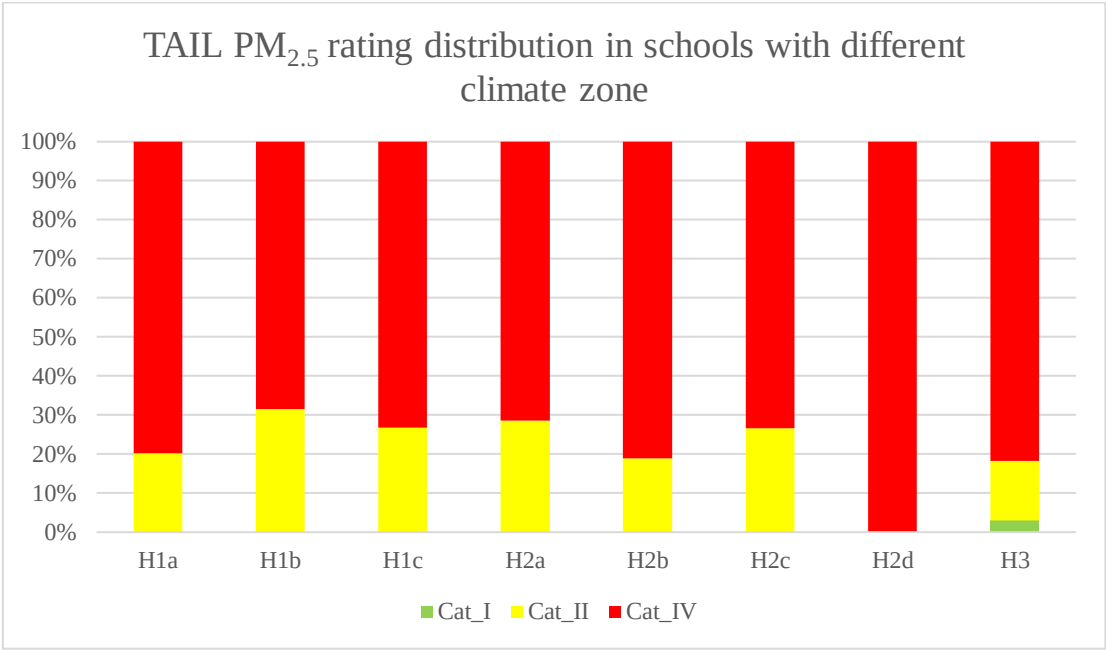


Figure 45: Distribution of the TAIL $PM_{2.5}$ rating in schools from different climate zone

Finally, it is the assessment of the TAIL NO_2 rating. Table 30 presents a closer look at the distribution of the TAIL-rating for the NO_2 quality in schools, according to different schools' variables.

Table 30: TAIL-rating of the NO_2 quality in different groups of schools (n = 308)

Variables	TAIL – NO_2 quality				
	Category I	**Category II**	**Category III**	**Category IV**	**Not available**
Type of school					
Nursery	66 % (104)	20 % (32)	0 % (0)	14 % (22)	0 % (0)
Elementary school	64 % (96)	23 % (35)	0 % (0)	12 % (18)	1 % (1)
Surrounding environment					
Rural	87 % (117)	11 % (15)	0 % (0)	1 % (2)	0 % (0)
Suburban	70 % (78)	19 % (21)	0 % (0)	11 % (12)	0 % (0)
Urban	8 % (5)	49 % (31)	0 % (0)	41 % (26)	2% (1)
Climatic zone					
H1a	47 % (36)	29 % (22)	0 % (0)	23 % (18)	1 % (1)
H1b	79 % (31)	15 % (6)	0 % (0)	5 % (2)	0 % (0)
H1c	66 % (37)	23 % (13)	0 % (0)	11 % (6)	0 % (0)
H2a	86 % (19)	14 % (3)	0 % (0)	0 % (0)	0 % (0)
H2b	81 % (30)	19 % (7)	0 % (0)	0 % (0)	0 % (0)
H2c	74 % (23)	19 % (6)	0 % (0)	6 % (2)	0 % (0)
H2d	77 % (10)	23 % (3) (23%)	0 % (0)	0 % (0)	0 % (0)

H3	42 % (14)	21 % (7)	0 % (0)	36 % (12)	0 % (0)
			Measured season		
Heating	65 % (154)	22 % (53)	0 % (0)	13 % (30)	0.3 % (1)
Non – heating	66 % (46)	20 % (14)	0 % (0)	14 % (10)	0 % (0)

Similar to the TAIL $PM_{2.5}$ rating, there was no difference in the distribution of the TAIL NO_2 rating from the different types of schools and the measured season. However, as shown in Figure 46, a significant difference can be observed between rural and urban schools. More than 80 % of schools in rural areas achieved a Category I TAIL NO_2 rating, while less than 10 % of schools in urban areas achieved a Category IV rating. Regarding Category IV, there was a significant increase, from 1 % of schools in the rural area to 41 % of schools in the urban area. As NO_2 sources are mainly combustion, outdoor traffic can be a possible explanation for this difference. Furthermore, in urban areas with a higher-density population, a significant increase in outdoor traffic led to this contrary distribution of the TAIL NO_2 rating.

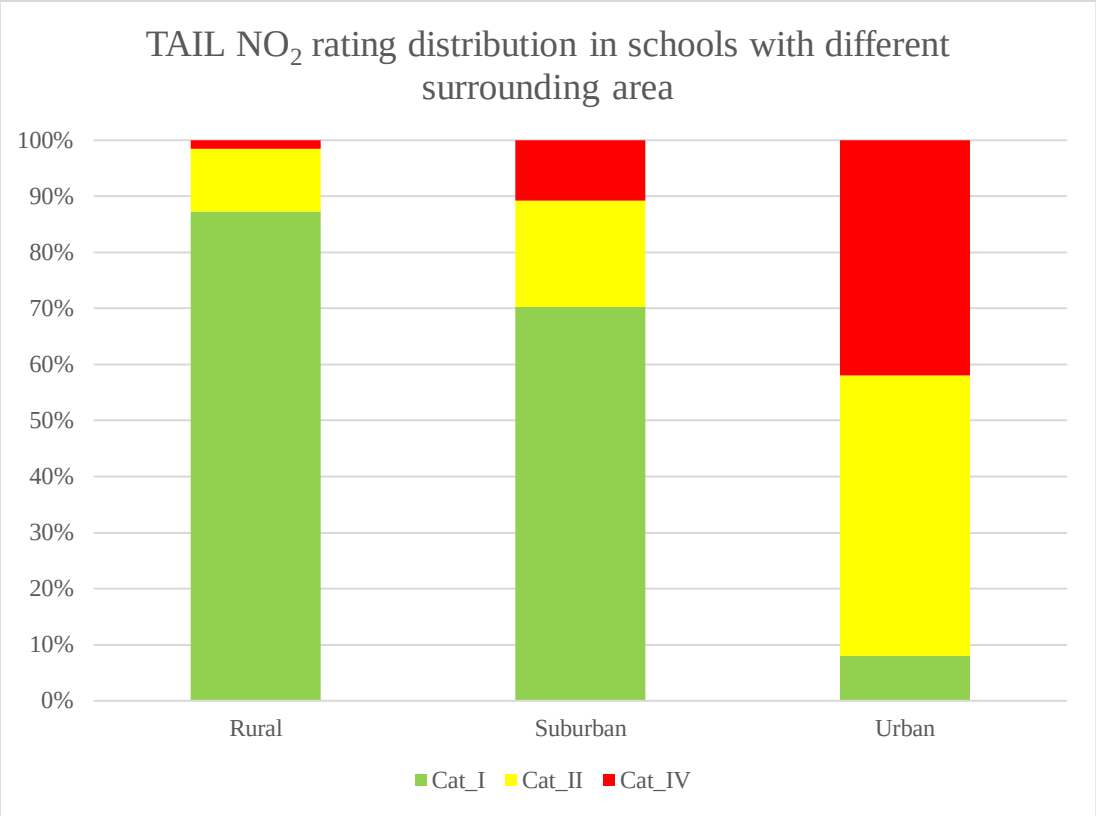


Figure 46: Distribution of the TAIL NO_2 rating in schools from different surrounding area

The difference between the distribution of the TAIL rating of $PM_{2.5}$ and NO_2 can be illustrated with the following two maps. Figure 47 and Figure 48 represent all the 308 schools measured during the campaign; each school was represented by a colored circle, where the color would represent the corresponding TAIL rating of the $PM_{2.5}$ and NO_2. These two maps provided an overview of the TAIL rating from all measured schools. Interactively, a comparison can quickly be made for schools in the same zone or with similar characteristics. It is an advantage of TAIL, where inter-comparison of schools can be made simple by just adding a color representation. Consequently, these two maps will offer quick and direct access to the TAIL rating, thus aiding every IEQ improvement action, from the local to the regional/national level.

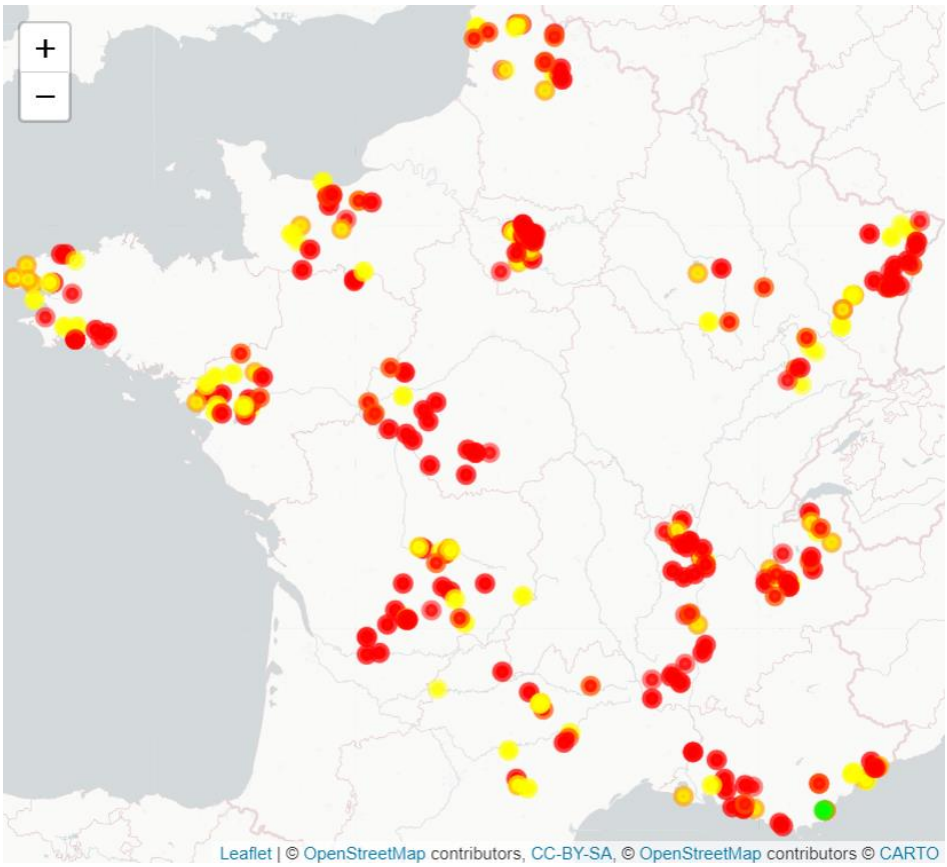


Figure 47: Visualization of the TAIL rating of $PM_{2.5}$ in schools assessed in the feasibility test

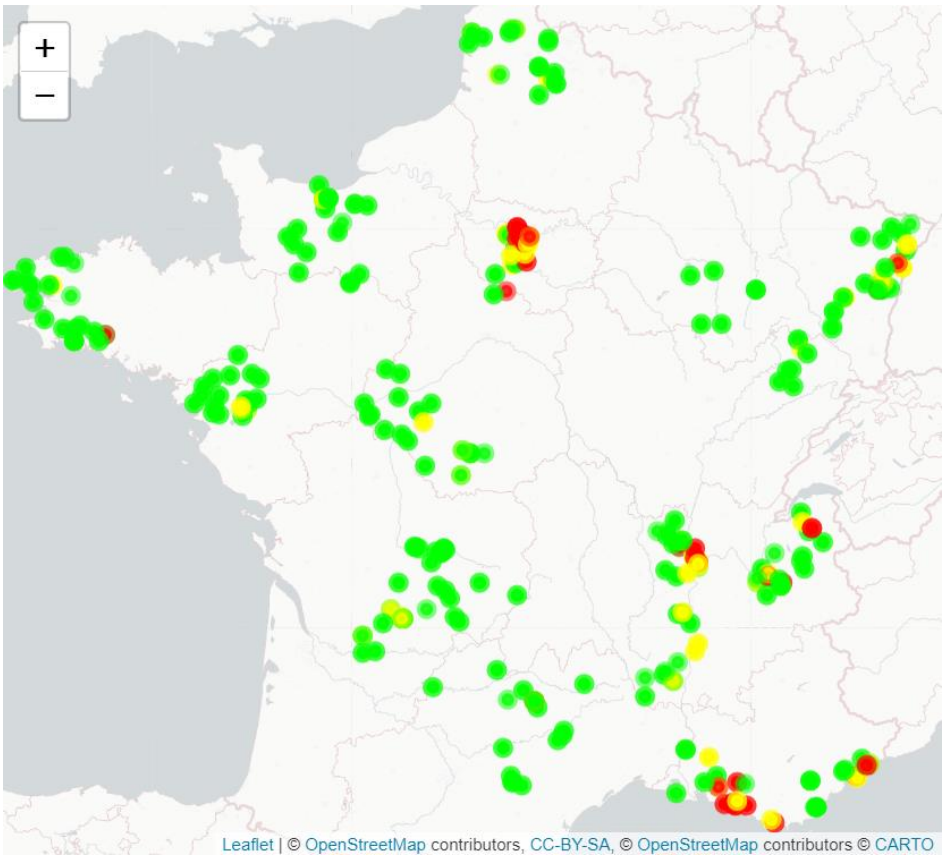


Figure 48: Visualization of the TAIL rating of NO_2 in schools assessed in the feasibility test

IV.3.4. Luminous environment

IV.3.4.1. TAIL luminous on the classroom scale

The fourth component of the TAIL-rating scheme for schools is the luminous environment. As mentioned above, no assessment of the daylight factor of schools was made during the campaign. Consequently, the TAIL rating of the luminous environment would only be evaluated by artificial lighting. As presented in Table 14, the field technician measured the artificial lighting in schools in the early morning, with all solar protection closed, to ensure only an assessment of the artificial lighting. Furthermore, artificial classroom lighting was assessed on horizontal surfaces (students' tables) and vertical surfaces (writing boards). In line with the TAIL rating principle, the luminous rating of a classroom was imposed by the more unfavorable rating of the two, horizontal surfaces (students' tables) or vertical surfaces (writing boards). Table 31 presents the TAIL of the luminous environment on the classroom scale. In half of the measured classrooms, the measured artificial lighting only achieved Category IV quality.

Table 31: TAIL-rating of the luminous environment on the classroom scale (n = 602)

Quality category	Category I	Category II	Category III	Category IV	Missing data
Number of classrooms	3.5 % (21)	18.9 % (114)	26.7 % (161)	49.7 % (299)	1.2 % (7)

IV.3.4.2. TAIL luminous on the school scale

Table 32 presents the results of the TAIL classification of the luminous environment, on the school scale. In nearly half of the schools assessed during the campaign, artificial lighting only achieved a TAIL category IV quality, and only one school achieved the category I quality.

Table 32: TAIL-rating of the luminous environment on the school scale, calculated by averaging the TAIL luminous classrooms' ratings (n = 308)

Quality category	Category I	Category II	Category III	Category IV	Missing data
Number of schools	1.0 % (1)	18 % (56)	31 % (97)	49 % (151)	1.0 % (3)

Table 33 describes the overall classification of the TAIL luminous environment in the 308 measured schools, defined by the worst individual TAIL classrooms' luminous rating of the school. 22 schools got demoted from the Category II rating, and 42 schools got demoted to the Category IV rating, representing 14 % of measured schools.

Table 33: TAIL-rating of the luminous environment on the school scale, defined by the TAIL worst luminous classrooms' rating of the school (n = 308)

Quality category	Category I	Category II	Category III	Category IV	Missing data
Number of schools	1.0 % (1)	11 % (34)	25 % (77)	63 % (193)	1.0 % (3)

Table 34 provides a closer analysis of the lighting in schools under different variables. No significant differences in terms of the TAIL-rating category quality in schools can be observed.

Table 34: TAIL-rating of the visual environment in different groups of schools (n = 308)

Variables	TAIL – IAQ quality				
	Category I	**Category II**	**Category III**	**Category IV**	**Not available**
Type of school					
Nursery	1 % (1)	14 % (22)	26 % (41)	58 % (91)	2 % (3)
Elementary school	0 % (0)	23 % (34)	37 % (56)	40 % (60)	0 % (0)
Surrounding environment					
Rural	1 % (1)	21 % (28)	30 % (40)	48 % (64)	1 % (1)
Suburban	0 % (0)	16 % (18)	32 % (36)	50 % (56)	1 % (1)
Urban	0 % (0)	16 % (10)	33 % (21)	49 % (31)	2 % (1)
Climatic zone					
H1a	0 % (0)	18 % (14)	32 % (25)	47 % (36)	3 % (2)

H1b	0 % (0)	21 % (8)	28 % (11)	51 % (20)	0 % (0)
H1c	0 % (0)	18 % (10)	32 % (18)	50 % (28)	0 % (0)
H2a	5 % (1)	27 % (6)	14 % (3)	55 % (12)	0 % (0)
H2b	0 % (0)	19 % (7)	35 % (13)	46 % (17)	0 % (0)
H2c	0 % (0)	6 % (2)	32 % (10)	58 % (18)	3 % (1)
H2d	0 % (0)	15 % (2)	31 % (4)	54 % (7)	0 % (0)
H3	0 % (0)	21 % (7)	39 % (13)	39 % (13)	0 % (0)
Measured season					
Heating	0.3 % (1)	18 % (43)	32 % (76)	49 % (117)	0.3 % (1)
Non – heating	0 % (0)	19 % (13)	30 % (21)	49 % (34)	3 % (2)

IV.3.4.3. Data interpretation

As explained earlier, the TAIL visual environment consisted only of the assessment of the measurement of the lighting level and, as the daylight factor was not evaluated. The artificial lighting was measured both horizontally (on students' tables) and vertically (on writing' board), and the overall TAIL illuminance classification was imposed by the worst scoring rating between the two. Table 35 presents the differences between the TAIL results applied to illuminance in both directions. The results show that while in more than half of the schools, lighting on students only achieved a category III or IV, it was worse on writing boards, as more than 73% of the schools only achieved a category III or IV. Additionally, in only one school from a total of 308 schools, where both artificial lighting on students' tables and on writing boards achieved a Category I TAIL luminous rating, therefore a Category I TAIL luminous rating.

Table 35: Differences between the TAIL results of artificial lighting horizontally and vertically

	Artificial lighting	Horizontal on students' tables	Vertical on writing boards	Overall TAIL artificial lighting
TAIL visual quality category	Category I	6.8 % (21)	4.2 % (13)	0.3 % (1)
	Category II	37.3 % (115)	19.2 % (59)	18.2 % (56)
	Category III	31.2 % (96)	30.2 % (93)	31.6 % (97)
	Category IV	23.8 % (73)	43.2 % (133)	49.0 % (151)
	Missing data	0.9 % (3)	3.2 % (10)	0.9 % (3)

Figure 49 and Figure 50 represent the measured illuminance levels at all measured points on students' tables and teachers' boards, respectively. The colored portion represents the threshold levels used to assess the luminous environment. Once again, the results show that the illuminance level on the teachers' boards was poorer than on the students' tables.

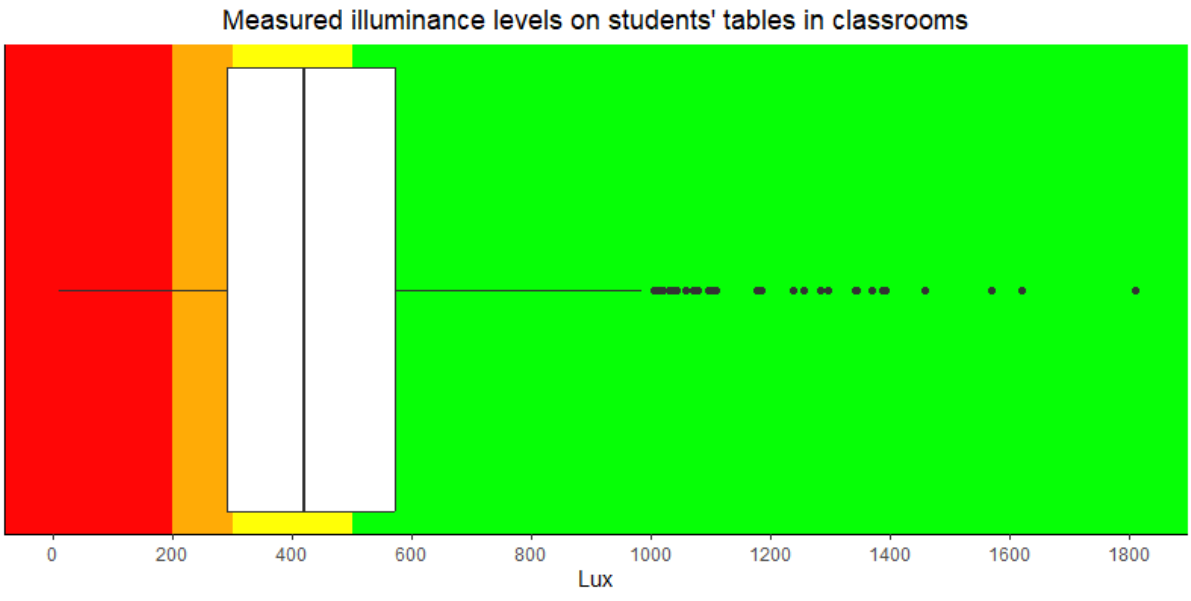


Figure 49: Measured illuminance on students' tables in classrooms and the respective threshold level used in the assessment of the luminous environment

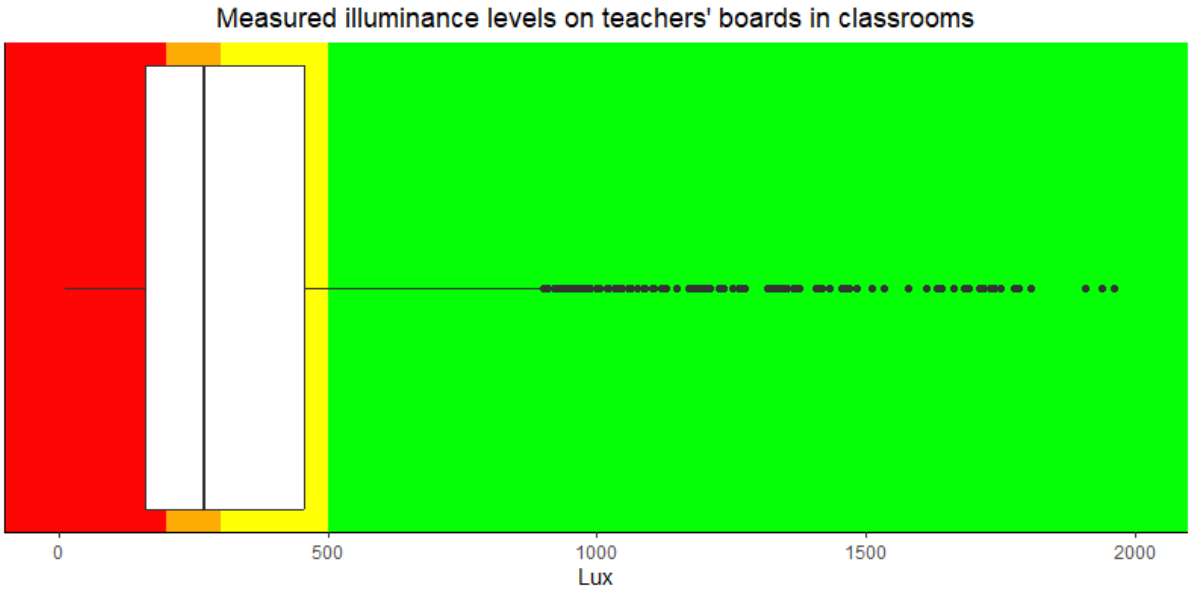


Figure 50: Measured illuminance on teachers' boards in classrooms and the respective threshold level used in the assessment of the luminous environment

The TAIL feasibility test results show that schools struggle to achieve adequate lighting quality on students' tables and teachers' writing boards. Nevertheless, in some schools, natural light is the predominant lighting source, and artificial lighting is only a substitute when natural lighting cannot be used. Consequently, this partial feasibility test on artificial lighting only assessed a half-picture. In future studies, a complete test of the luminous environment with an assessment of the daylight factor and artificial lighting will thoroughly evaluate the visual environment.

IV.3.5. Overall TAIL classification

IV.3.5.1. TAIL overall rating on the classroom scale

Finally, the overall TAIL rating aims to provide an assessment of the performance of the IEQ in the measured classroom. Table 36 presents the distribution of the overall TAIL rating, in the classroom scale. No measured classroom achieved a Category I or II TAIL.

Table 36: The overall TAIL-rating on the classroom scale (n = 602)

Overall TAIL	Category I	Category II	Category III	Category IV	Missing data
Number of classrooms	0 % (0)	0 % (0)	3.6 % (22)	96.4 % (580)	0 % (0)

IV.3.5.2. TAIL overall rating on the school scale

Table 37 presents the overall TAIL rating applied to the sample of 308 schools in the campaign. Once again, no school has achieved category II or I quality; and 99 % of the schools were only able to achieve category IV.

Table 37: TAIL-rating of the overall IEQ on the school scale, calculated by averaging the overall TAIL rating of the classrooms (n = 308)

Overall TAIL	Category I	Category II	Category III	Category IV	Missing data
Number of schools	0 % (0)	0 % (0)	1 % (5)	99 % (303)	0 % (0)

Table 38 describes the classification of the overall TAIL rating in the 308 measured schools, defined by the worst overall individual TAIL classroom rating of the school. There was only one minor change: one school was demoted from Category III to Category IV rating.

Table 38: TAIL-rating of the overall IEQ on the school scale, defined by the worst overall classrooms' TAIL rating of the school (n = 308)

Overall TAIL	Category I	Category II	Category III	Category IV	Missing data
Number of schools	0 % (0)	0 % (0)	1 % (4)	99 % (304)	0 % (0)

IV.3.5.3. Data interpretation

The worst scoring component always defined the overall TAIL rating scheme. Over the 303 Category IV schools, there were schools for which all four components scored a category IV, or even one and two components scored a category I. Table 39 represents these different groups, from the total of 303 Category IV TAIL schools.

Table 39: Distribution of the different types of Category IV TAIL-schools (n = 303)

Schools that had Category IV in all 4 components	12

Schools that had 0 category I component	195
Schools that had 1 category I component	92
Schools that had 2 category I components	4

Only 4 % of schools scored category IV in all four components. 64 % of schools did not score category I in any of the four components, and 31 % of schools scored category I in at least one component. Once again, the rating principle has enforced the holistic and equitable contribution of the four IEQ components, as these schools could achieved a higher overall IEQ score with another rating calculation process.

Finally, what has been the most impactful IEQ component? Figure 51 illustrates the impact of the four components, with the numbers representing the schools where the corresponding component was the worst scored, and the intersection between the ellipses meant the corresponding components were equally poor. Results show that in 25 % of schools, the thermal environment and the IAQ were equally poor; in 20 % of schools, the luminous environment and the IAQ were equally poor; and in 18 % of schools, the IAQ was the worst component.

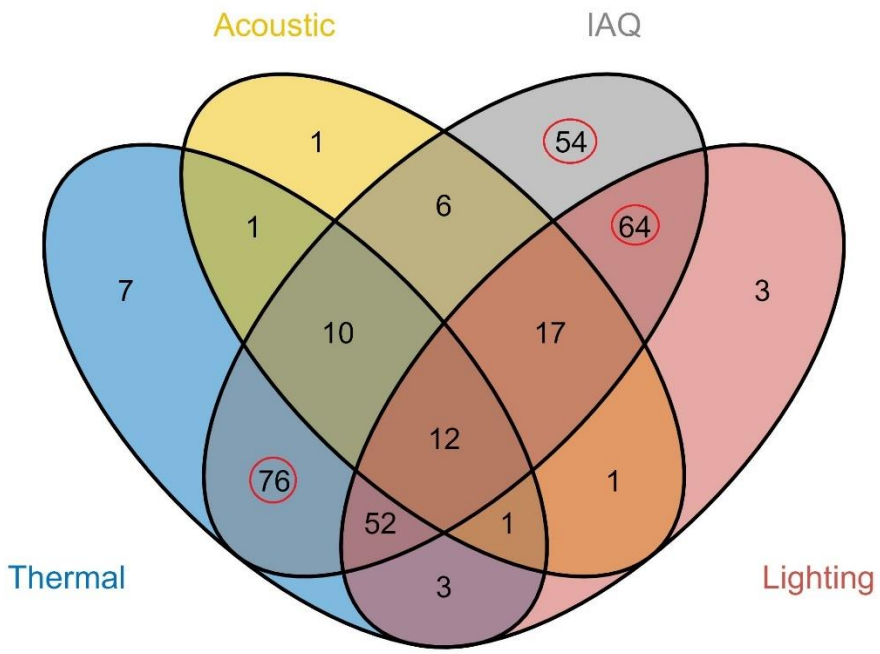


Figure 51: Impact of the four IEQ components on the school scale (n = 308).

IV.4. Discussion and perspective

The feasibility test of the TAIL rating scheme has been performed, using the dataset coming from the National School IEQ Survey from France. The rating scheme has demonstrated its ability to effectively separate the different IEQ quality categories, in schools with different characteristics. Regarding individual IAQ parameters, there were two groups with contrary results. Benzene, formaldehyde, and mold all showed favorable results, with very few schools achieving category IV quality. However, other parameters, i.e. relative humidity, CO_2, $PM_{2.5}$, and NO_2 show much more unfavorable results. Some tendencies were also observed, e.g., higher dispersion of measurement of air temperature and relative humidity in schools with the worst TAIL-rating and worst TAIL classification in schools situated in urban areas compared to rural and suburban areas. In some cases, improper utilization of classrooms can be noticed, e.g., a maximal indoor air temperature of 33 °C was recorded in a classroom during the heating season, suggesting an overheating coming from heating devices, or inadequate artificial lighting on writing boards compared to students' tables.

Overall, the rating assigned by TAIL is less discriminating, as 98% of the schools evaluated obtained a Category IV, with the remaining 2% obtaining a Category III rating. As a reminder, the objective of the feasibility test is not to rate the schools' IEQ but rather an application of the TAIL rating scheme for demonstration. Nevertheless, the TAIL rating scheme has shown that schools struggled with the IAQ component compared to the other three. Furthermore, in the IAQ component, the concentration of CO_2 or $PM_{2.5}$ imposed the rating in most cases.

A prominent feature of the TAIL rating scheme is the inter-comparison between different schools. By comparing the different characteristics, equipment, and occupants' usage in schools with different TAIL quality categories, schools with poor TAIL ratings can learn from schools with good TAIL ratings, and vice versa. Consequently, the rating scheme provides additional information to the school administration to aid them with any mitigation solution or IEQ improvement decision. Similar to the maps of the TAIL $PM_{2.5}$ and the TAIL NO_2 results (Figure 47 and Figure 48), the following Figure 52 shows the map of the overall TAIL rating of the 308 assessed schools in the feasibility test. Although the results here seem dire, with only five orange circles representing the five Category III schools and the 303 rest only achieving a Category IV rating, the TAIL rating scheme can provide much information at a local, regional, national, and even international scale. With this information, school administrations can make more informed decisions to improve the IEQ in their schools or classrooms.

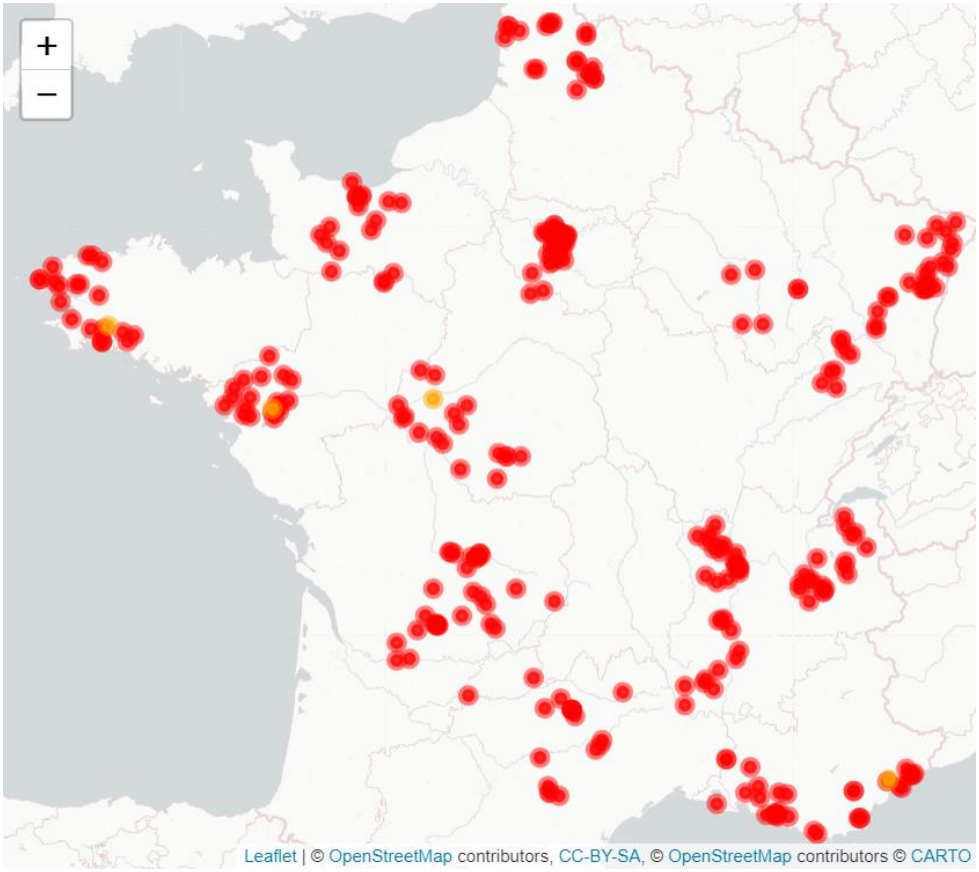


Figure 52: Visualization of the overall TAIL rating in the 308 schools assessed in the feasibility test

Regarding any modification of the rating principle, a discussion about the rating principle of the three-time series parameters (the air temperature, the relative humidity, and the concentration of CO_2) can be raised. As shown and analyzed in their three corresponding flow charts of classification (Figure 11, Figure 23, Figure 24), across all three parameters, a similar total of only 4 % of classrooms was demoted from their original rating. Thus, this could be evaluated as a stringent feature of the rating scheme. Furthermore, for a classroom to be classified in Category I or II, the total measured time could not exceed more than 1 % of the time in Category III or IV, respectively. In a typical assessment school week of 48 hours, this would represent only 28 minutes, which could be much too strict. However, more tests are required to evaluate whether or not revisions of this principle are needed.

However, there are some limitations to the feasibility test. Firstly, of the 14 parameters included in the school TAIL-rating scheme, only ten were measured during the campaign. Thus, it is only a partial test. It has been an impactful compromise for assessing the luminous environment,

as with the lack of assessment of the daylight factor, only artificial lighting was evaluated. Consequently, the results did not fully represent the classrooms' lighting conditions. Secondly, the measurement of some parameters during the campaign did not follow the suggestion in the TAIL-rating scheme, as they were measured before the inception of the rating scheme. It mainly affected the assessment of the acoustic environment, where only the background noise level during the weekend was assessed, once again leading to a relatively representative assessment of the noise-exposed by the children. Nevertheless, the objective of the feasibility test is to demonstrate the principle of the TAIL rating scheme. While it is only a partial test and some compromises, the capacity to discriminate the state of IEQ in different schools has been demonstrated. Future studies intend to use the TAIL rating scheme and are welcome to employ the entire rating scheme, which will offer further development.

IV.5. Conclusion

This chapter focuses on the application test of the TAIL-rating schemes for schools, using the dataset of measured IEQ parameters during the France National Schools survey. Multiple IEQ parameters were measured in 602 classrooms in 308 schools in mainland France. The application tests ten of the 14 parameters in the rating scheme. However, the objective of the test is not to rate the IEQ in these schools using the TAIL rating scheme but rather to demonstrate the capacity of the TAIL rating scheme.

Results show the TAIL's potential as an overall indicator of IEQ in schools. From the measurement of IEQ parameters, abnormal conditions in classrooms were revealed, e.g., high air temperature (more than 33 °C) even in classrooms measured during the heating season and insufficient lighting on teachers' writing boards. IAQ was identified as the most influential of the four IEQ components with its intrinsic rating principle. Furthermore, CO_2 and $PM_{2.5}$ were the most influential of the seven assessed IAQ parameters. Additionally, a potential future revision of the rating principle of time-series parameters (air temperature, relative humidity, CO_2) can be raised, albeit with more application to another dataset. Nevertheless, from this experiment, future studies with an appreciation of the rating scheme should design the measurement protocol using the suggestion in the TAIL to assess all aspects of the rating scheme thoroughly.

The success of the feasibility test provides positive feedback for the construction of the TAIL rating scheme. It is a further step towards establishing an IEQ indicator that will provide

streamlined information to school administrators, aiding them with any IEQ improvement decision in schools.

V. Relations between TAIL, buildings characteristics and occupants' perception

V.1. Context and objectives

The feasibility test of the TAIL rating for schools demonstrated its capacity to classify the different quality levels of IE in different classrooms and schools. Consequently, a measurement-based rating scheme can be considered as an objective assessment tool for rating IEQ in schools. However, a debate can be raised on whether the occupants' feedback on the classrooms' IEQ can be predicted by the assessment using the TAIL rating scheme. Occupants' feedback consists of their overall perception, satisfaction with the classroom, and their sensation of a specific stimulus or condition in the classroom. An exploratory test on a dataset of objective assessment and subjective responses to the condition in the classrooms will further complete the existing literature and provide necessary perspectives for future studies.

The opportunity presented itself during the measurement period of the IEQ survey; occupants' feedback on the different components of the IEQ was recorded. From this context, our research aims to explore the existence of a relationship between the TAIL rating and the occupant's perception of the classroom and, if not, the occupants' sensation of a specific condition in the classroom. This consists of analyzing the difference in answers to questions given to occupants from classrooms, respective of their classifications of the different components of TAIL. Accordingly, it can be translated into a statistical question: "Would the TAIL classification predict the occupants' responses to perception or sensation questions about the classrooms' IEQ?" Interpreting the existence or absence of a correlated relationship will provide opportunities for revising or modifying the IEQ assessment in the TAIL rating scheme.

The following subsections are organized as follows. Subsection V.2 provides details of the dataset and outlines the statistical test. Subsection V.3 presents the statistical test results for each TAIL component, subsection V.4 discusses obtained results and their impact, and subsection V.5 concludes.

V.2. Research setting

V.2.1. Perception data available

For every measured classroom, every presented teacher was given a self-administrated questionnaire on their perception of the classrooms, which teachers were free to answer at any time during the school week being evaluated. During the campaign, there were some cases where multiple teachers gave answers to the questionnaire in the same room. They each received their questionnaire and responded with their responses. Each set of responses was treated independently, and no average was made for teachers in the same classrooms. A total of 711 teachers had responded, of which 16 were unusable, resulting in 695 sets of treatable responses. These 695 teachers originated from 599 classrooms, where in 503 classrooms, there was only one teacher; in 95 classrooms, there were two teachers; and in one classroom, there were three teachers.

The questionnaire consists of five questions depicting four components of the IEQ in classrooms. Details on these five sets of questions can be found as follows, and the complete list of questions and responses can be found in the corresponding table in the annex:

- Thermal perception (5 questions): Table A 2
- Acoustic perception (19 questions): Table A.3
- Quality of air perception (3 questions): Table A.4
- Olfactory perception (4 questions): Table A.5
- Visual perception (23 questions): Table A.6

The teachers' perception of the overall IEQ in the classrooms was not recorded. Thus, no correlation test was performed with the overall TAIL rating classification. Furthermore, the third and fourth sets of questions addressed the IAQ condition in the classroom, with emphasis on the aspect of the IAQ and related to odors in the classrooms, respectively. Thus, the correlation test of these two sets of questions was performed with the classification of the TAIL IAQ component. Details on the statistical test performed can be found below (subsection V.2.2).

V.2.2. Statistical analysis

The objective of the statistical test is to analyze the correlation between the classified results of a component of TAIL at the classroom scale and teachers' responses to the corresponding set of questions. Regarding the questions used, for the 5th set of questions on visual perception, there were 13 questions on natural lighting and 10 on artificial lighting. Since the TAIL assessment of the feasibility test only evaluates the quality of the artificial light, as no measurement of the daylight factor was made, the statistical test was only performed on the questions concerning the quality of artificial light.

Furthermore, the test can be separated into two parts: the assessment of the correlation between the TAIL component's category and teachers' responses to questions on their overall perception and satisfaction of the corresponding IEQ component in their classroom. Each of the five sets of questions contained a specific question to assess the teacher's overall satisfaction with that component of IEQ. Table 40 provides details of the five questions. There were seven answers to each question, ranged: 1 – very unpleasant, 2, unpleasant, 3 fairly unpleasant, 4 neutral, 5 – fairly pleasant, 6 – pleasant, 7 – very pleasant.

Table 40: List of perception questions on the IEQ components asked of the teachers

IEQ component	Questions
Thermal environment	Over the past three months or since the start of the school year, how would you rate the air temperature in your classroom?
Acoustic environment	Over the past three months, or since the start of the school year, how do you feel about the overall sound environment in your classroom?
Indoor air quality	Over the past three months or since the start of the school year, how would you rate the overall air quality in your classroom?
Perception of the odors	In case odors were detected over the past three months or since the start of the school year, do these odors bother you?

Luminous environment	If you have used artificial lighting, how would you rate the lighting atmosphere in the classroom induced by its use of artificial lighting?

The chosen statistical test for this analysis was Pearson's chi-squared test to ascertain the potential disparities in the proportions of responses provided by teachers across classrooms associated with different TAIL scores. An indicative p-value of 0.05 was chosen, where a p-value less than 0.05 indicates a statistically significant relationship and a higher than 0.05 p-value indicates a statistically non-significant relationship. Consequently, teachers' responses were treated as categorical variables, and the chi-square test was deemed appropriate for assessing any variations of answers among groups of teachers. While the responses could alternatively be analyzed as ordinal variables, especially in satisfaction questions, considering they were structured on a 7-point scale ranging from 1 to 7, employing tests like analysis of variance (ANOVA) could be a viable alternative. ANOVA is an extension of the t-test, which compares the difference in mean results of more than two groups. However, the decision to opt for the chi-square test was primarily driven by the data distribution and the categorical nature of the responses, ensuring a more robust analysis of the observed differences without assuming the underlying data distribution to be normally distributed, as ANOVA does. All statistical analyses were carried out using R software version 4.1.2. Figure 53 illustrates the statistical test.

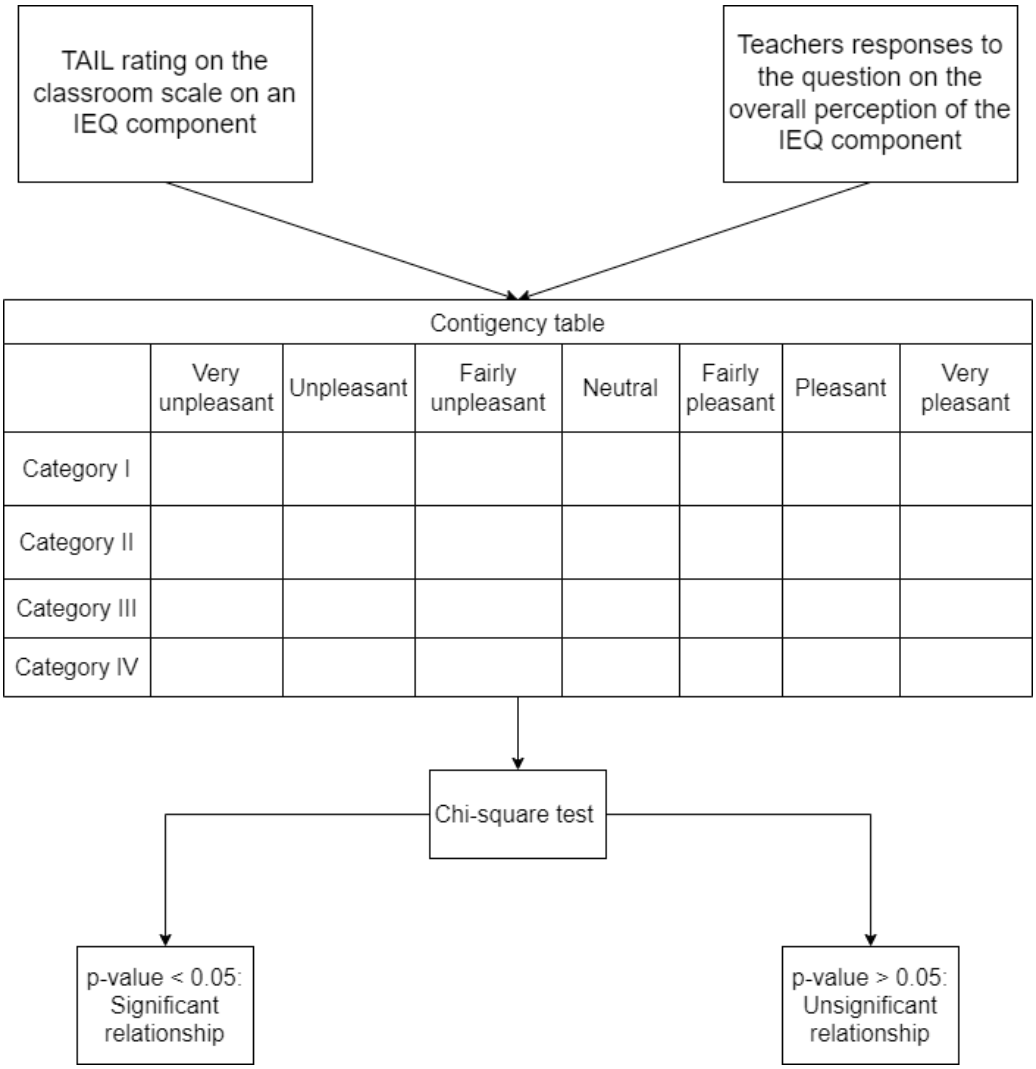


Figure 53: Flow chart describing the statistical test between the TAIL IEQ classroom rating and teachers' responses to perception questions

The second part of the statistical test applied the same principle as the first, with the assessed questions the only difference. These are now questions regarding a specific sensation of the classrooms. Table 41, Table 42, Table 43, Table 44, and Table 45 detail all these recorded questions. For more details, including the questions, all modalities of answers, and the number of teachers and their given responses, consult Table A 2, Table A.3, Table A.4, Table A.5, and Table A.6 in the Appendix. In total, there were four questions addressed the thermal environment, 18 questions addressed the acoustic environment, two questions addressed the indoor air quality, three questions addressed the sensation of the odors, and five questions addressed the sensation of the luminous environment.

Table 41: Questions addressing different sensation to the thermal environment (695 teachers from 308 schools)

Questions
Question 1 - Over the past three months or since the start of the school year, how would you rate the air temperature in your classroom? (N = 695)
Question 2 - Over the past three months or since the start of the school year, do you feel that the air temperature in your classroom varies over the course of the day? (N = 695)
Question 3 - In the last three months or since the start of the school year, have you experienced draughts in your classroom? (N= 695)
Question 4 - If yes, how do you rate them? (N = 261)

Table 42 : Questions addressing different sensation to the acoustic environment (695 teachers from 308 schools)

Questions
Question 1 - Can you hear the voices of teachers and/or children in adjacent classrooms (right next door) or on the floor above or below? (N = 695)
Question 2 - If yes, are you bothered, disturbed or perturbed by these voices? (N = 246)
Question 3 - Do you hear noise from chairs or tables in adjoining classrooms (right next door) or on the floor above? (N=695)
Question 4 - If yes, are you bothered, disturbed or perturbed by these noises? (N = 192)
Question 5 - Do you hear noise from people in the hallway or in a common circulation area on the same floor as your classroom? (N=695)
Question 6 - If yes, are you bothered, disturbed or perturbed by these noises? (N = 358)
Question 7 - Do you hear noise from people in the corridor or in a shared circulation area on the upper or lower floor? (N=695)
Question 8 - If yes, are you bothered, disturbed or perturbed by these noises? (N = 118)

Question 9 - Do you hear noise from sanitary installations (WC, toilet flushing)? (N=695)
Question 10 - If yes, are you bothered, disturbed or perturbed by these noises? (N = 163)
Question 11 - Do you hear noise from outside the building when the windows are closed? (N=695)
Question 12 - If yes, are you bothered, disturbed, or perturbed by these noises? (N = 332)
Question 13 - Do you hear noise from outside the building when the windows are open? (N=695)
Question 14 - If yes, are you bothered, disturbed, or perturbed by these noises? (N = 578)
Question 15 - Do you hear other noises coming from outside the classroom? (N=695)
Question 16 - If yes, are you bothered, disturbed, or perturbed by these noises? (N = 145)
Question 17 - Is there a controlled mechanical ventilation system in your classroom? (N=695)
Question 18 - If yes, are you bothered, disturbed, disrupted by this system? (N= 118)

Table 43: Questions addressing different sensation to the indoor air quality (695 teachers from 308 schools)

Questions
Question 1 - Over the past three months or since the start of the school year, how do you rate the air in your classroom? (dry/humid) (N = 695)
Question 2 - Over the past three months or since the start of the school year, how do you rate the air in your classroom? (stuffy/freshness) (N = 695)

Table 44 Questions addressing different sensation to the perception of the odors (695 teachers from 308 schools)

Questions
Question 1 - Over the last three months or since the start of the school year, on the whole, do you smell odors in the classroom? (N = 695)

Question 2 - If yes, where do odors come from (N = 329)
Question 3 - If yes, odors are generally (N = 329)

Table 45: Questions addressing different sensation to the luminous environment (695 teachers from 308 schools)

Questions
Question 1 - Since the start of the school year or in the last three months, have you used artificial lighting in your classroom? (N = 695)
Question 2 - If you have used artificial lighting, how does it disturb you? (N = 691)
Question 3 - If you have used artificial lighting, do you have any problems with legibility (e.g. of written documents)? (N = 691)
Question 4 - If you have used artificial lighting, regarding glare, how would you find the state of artificial light (N = 691)
Question 5 - If you have used artificial lighting, do you feel that the lighting ambience in the classroom induced by its use faithfully reproduces the colors? (N = 691)

Figure 54 describes the statistical test performed between responses to questions about a specific sensation and the TAIL rating of the components of the classrooms associated with the teachers. The number of answers varied from question to question, thus explaining the unspecific answers in the contingency table in the figure. No change was made to the indicative value 0.05 of the p-value, and all statistical analyses were carried out using R software version 4.1.2.

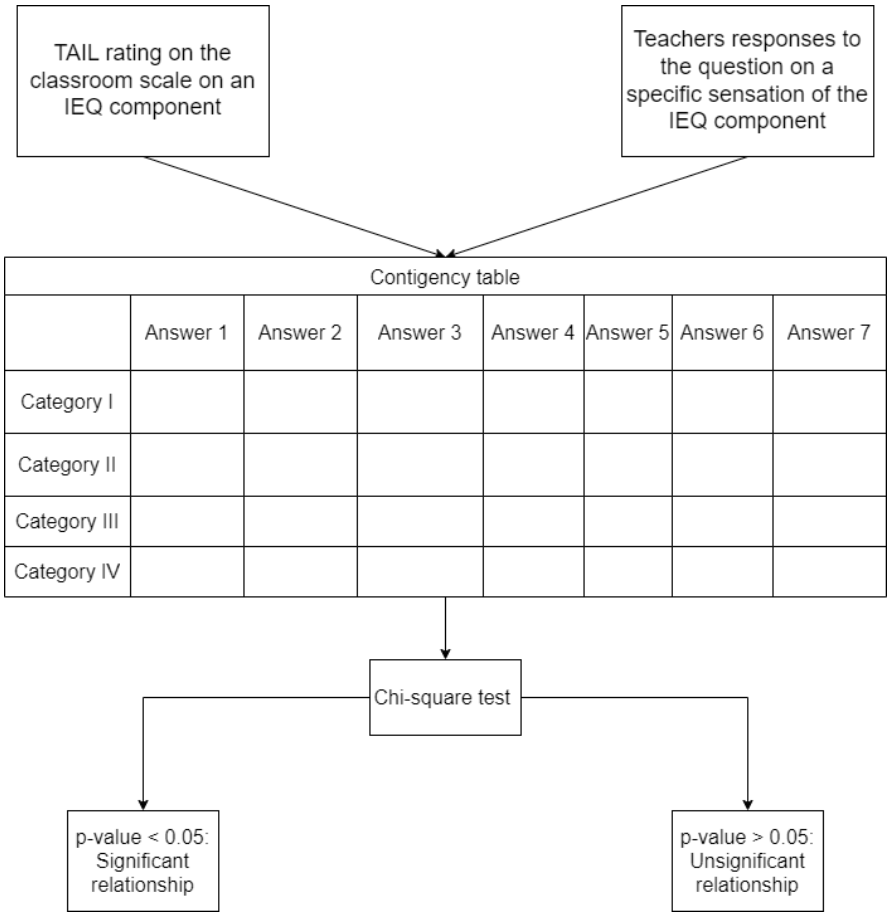


Figure 54: Flow chart describing the statistical test between the TAIL IEQ classroom rating and teachers' responses to questions on their sensation to a specific condition

The following section, V.3, describes the results obtained from the statistical test for each question set. The relationship, significant or not, between the TAIL IEQ component and the teachers' responses to their overall satisfaction question was first addressed in every subsection. Secondly, the relationship between the TAIL IEQ component and the teachers' responses to all perception questions was presented and analyzed.

V.3. Results

V.3.1. Responses about the thermal environment

From the total number of 695 teachers that have provided answers, only 680 responses were reported from a classroom with a TAIL classification of the thermal environment. There were

42 teachers associated to a classroom with a Category I quality, 114 teachers associated to a classroom with a Category II quality, 218 teachers associated to a classroom with a Category III quality, and 306 teachers associated to a classroom with a Category IV quality. In this subsection, the relationship between the TAIL thermal rating and the overall thermal satisfaction will be assessed first, then follows the assessment of the relationship between the TAIL thermal rating and the three questions on the teachers' thermal perception.

V.3.1.1. Relationship between the TAIL thermal rating and the overall thermal satisfaction

The first relationship tested was between the teachers' overall satisfaction with the ambiance temperature in their assigned classroom. Figure 55 presents details of this statistical analysis. In each category, the total length of the bar represents the teachers' given answers in classrooms associated with the corresponding TAIL thermal rating, and different colored portions represent the corresponding given answers. Furthermore, each bar was always centered around the neutral response, aiding the comparison between the two types of responses (from "very unsatisfied" to "fairly unsatisfied" and from "fairly satisfied" to "very satisfied").

First and foremost, the associated p-value of the chi-square test to this relationship was 0.27. Thus, the relationship between the TAIL thermal rating and the teachers' overall thermal satisfaction was insignificant. Regardless of the TAIL thermal rating, there was no observed difference between the distribution of teachers' thermal satisfaction. However, across all four TAIL thermal categories, the proportion of teachers who were satisfied with the thermal environment was always larger than those who were unsatisfied with the thermal environment in their classrooms.

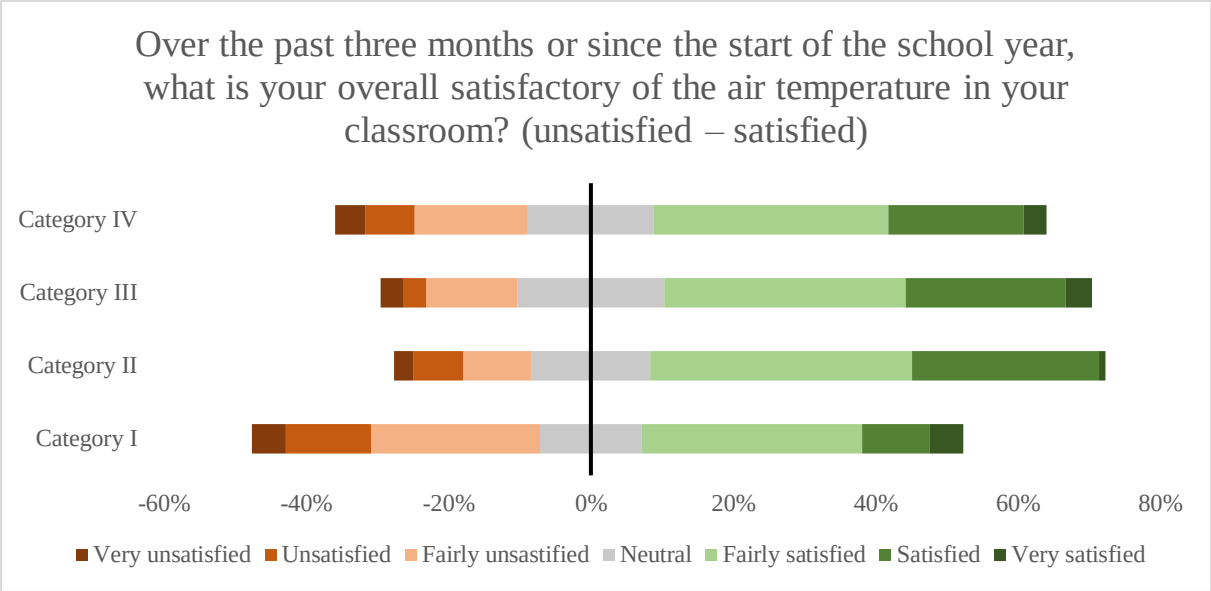


Figure 55: Distribution of teachers' answers to the overall satisfaction of the thermal environment, separated by the different TAIL thermal rating (n = 680 teachers)

V.3.1.2. Relationship between the TAIL thermal rating and the other questions on the thermal perception

Between the TAIL thermal rating and the three questions on the thermal perception of the teachers, three potentially significant relationships can be formed. However, the statistical test only yielded one significant relationship. It was between the TAIL thermal rating and the teachers' perception of the ambiance air temperature, whether it was cold or hot. Figure 56 plotted the teachers' answers to this question. Once again, for each TAIL thermal category, the neutral answer was centered, aiding any comparison between "cold" and "hot" answers. The associated p-value of the relationship was $13.\ 10^{-8}$.

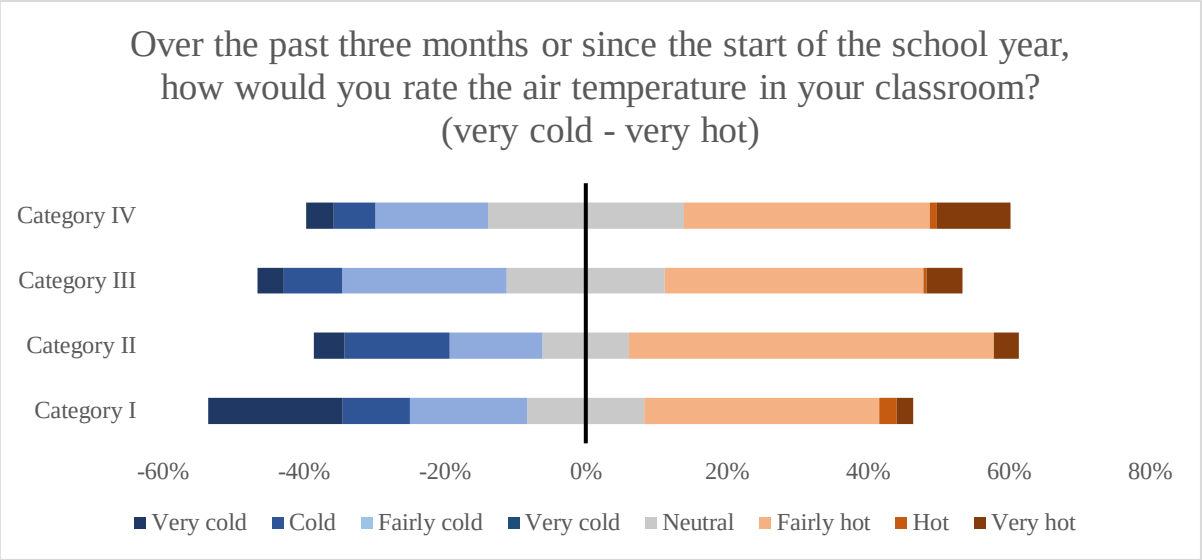


Figure 56: Distribution of teachers' answers to their sensation of the air temperature in the classrooms, separated by the different TAIL thermal rating (n = 680 teachers)

Firstly, there is an increase of answers on the right side, the "hot" side going from Category I to Category IV, from 38 % in Category I classrooms to 55 % in Category II classrooms, and from 42 % in Category III classrooms to 46% in Category IV classrooms. There is also a slight increase in teachers who were given a "neutral" answer, from 16 % in Category I classrooms and 12 % in Category II classrooms, to 22 % and 27% in Category III and Category IV classrooms. Consequently, there is a decrease in the percentage of teachers answered "cold", from 45 % and 24 % in Category I and Category II classrooms, to 35 % and 25 % in Category III and Category IV classrooms.

An interpretation into these results could be made that in Category I classrooms, there were more teachers who answered that the air temperature was from "very cold" to "fairly cold", compared to teachers in classrooms with a poorer TAIL result. Furthermore, in classrooms with a TAIL thermal result of Category II, III and IV, there were more teachers who answered from "fairly hot" to "very hot". These indicated that in these poorer TAIL thermal rated classrooms, teachers were able to perceive a high temperature, based on their answers. In addition, a higher portion of teachers answered: "fairly satisfied" to "very satisfied" compared to teachers who answered "very unsatisfied" to "fairly unsatisfied", even in Category III and IV classrooms. This indicates that even if more teachers answered that they felt hot in poorer TAIL-rated classrooms, more teachers also answered "satisfied" about the air temperature in the classrooms. Nevertheless, the statistical test did not observe significant differences in the

proportion of satisfactory answers about the thermal environment from teachers in different TAIL thermal-rated classrooms.

V.3.2. Responses about the acoustic environment

Out of a total of 695 teachers who provided responses, only 619 came from a classroom with an acoustic environment classified by TAIL. There were 401 teachers in classrooms with a Category I quality, 168 teachers in classrooms with a Category II quality, 32 teachers with a Category III quality, and 18 teachers with a Category IV quality. In this section, first the assessment between the TAIL acoustic rating and the overall acoustical satisfaction will be present, then follow the assessment of the relationship between the TAIL acoustical rating and the 18 questions on the teachers' acoustical perception.

V.3.2.1. Relationship between the TAIL acoustic rating and the overall acoustical satisfaction

Firstly, did the teachers in classrooms with a different TAIL acoustic classification have different answers regarding their overall satisfaction? Figure 57 presents details of this statistical analysis. Once again, in each category, the total length of the bar represents the teachers' given answers in classrooms associated with the corresponding TAIL acoustic rating, and different colored portions represent the corresponding given answers. Furthermore, each bar was always centered around the neutral response, aiding the comparison between the two types of responses (from "very unsatisfied" to "fairly unsatisfied" and from "fairly satisfied" to "very satisfied").

The associated p-value of the chi-square test to this relationship was 0.84. Thus, the relationship between the TAIL acoustic rating and the teachers' overall acoustic satisfaction was insignificant. Regardless of the TAIL-acoustical rating, there was no observed difference between the distribution of teachers' acoustical satisfaction. However, across all four TAIL acoustic categories, the proportion of teachers who were satisfied with the acoustical environment was always larger than those who were unsatisfied with the acoustical environment in their classrooms.

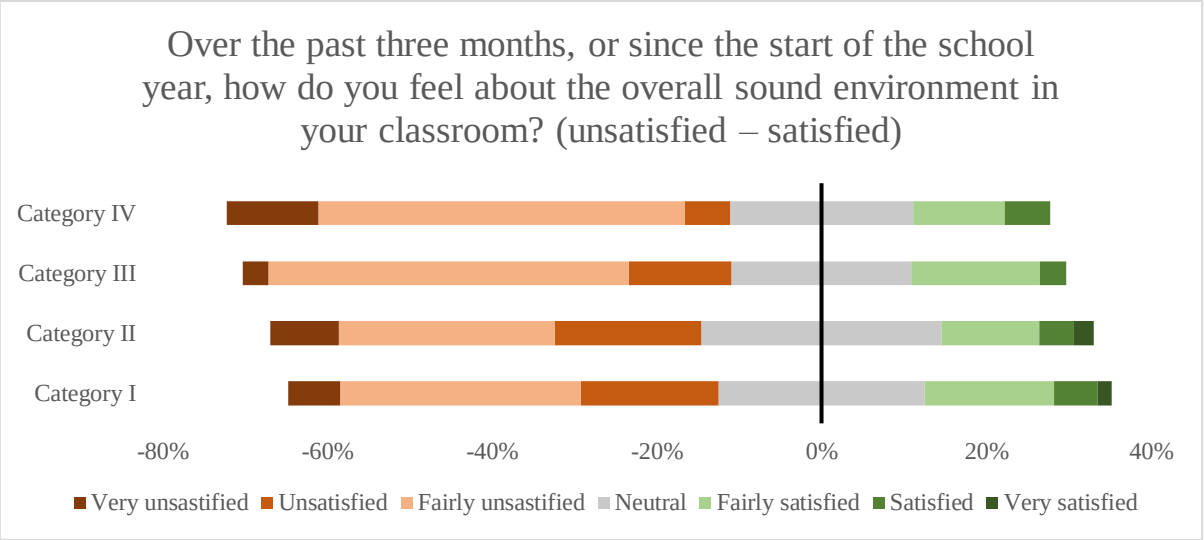


Figure 57: Distribution of teachers' answers to the overall satisfaction of the acoustic environment, separated by the different TAIL acoustic rating (n = 619 teachers)

V.3.2.2. Relationship between the TAIL acoustic rating and the other questions on the acoustic perception

This section discusses the relationship between the TAIL acoustic rating and the teachers' acoustic perception. From a total of 19 relationships to be assessed, significant relationships were found between the TAIL acoustic rating and three questions.

Figure 58 presents the distribution of responses from teachers in classrooms with different TAIL acoustic ratings, where the associated p-value was 0.0086, meaning that a significant relationship has been found. 168 teachers out of 619 were asked to give their perception when they detected noises from chairs or tables in adjoining classrooms (right next door) or on the floor above. The figure shows that the percentage of undisturbed teachers by the detected noise reduced from 38% in Category I and 29% in Category II classrooms to 10% in Category III before rising again to 33% in Category IV. Furthermore, only a small percentage of teachers answered: "extreme disturbance", and they were always from classrooms with Category I and Category II acoustic ratings (0.9 % from Category I classrooms and 8.5 % in Category II classrooms). An interpretation reads that in a lower background noise level, teachers were more disturbed by noise from chairs or tables in adjoining classrooms (right next door) or on the floor above.

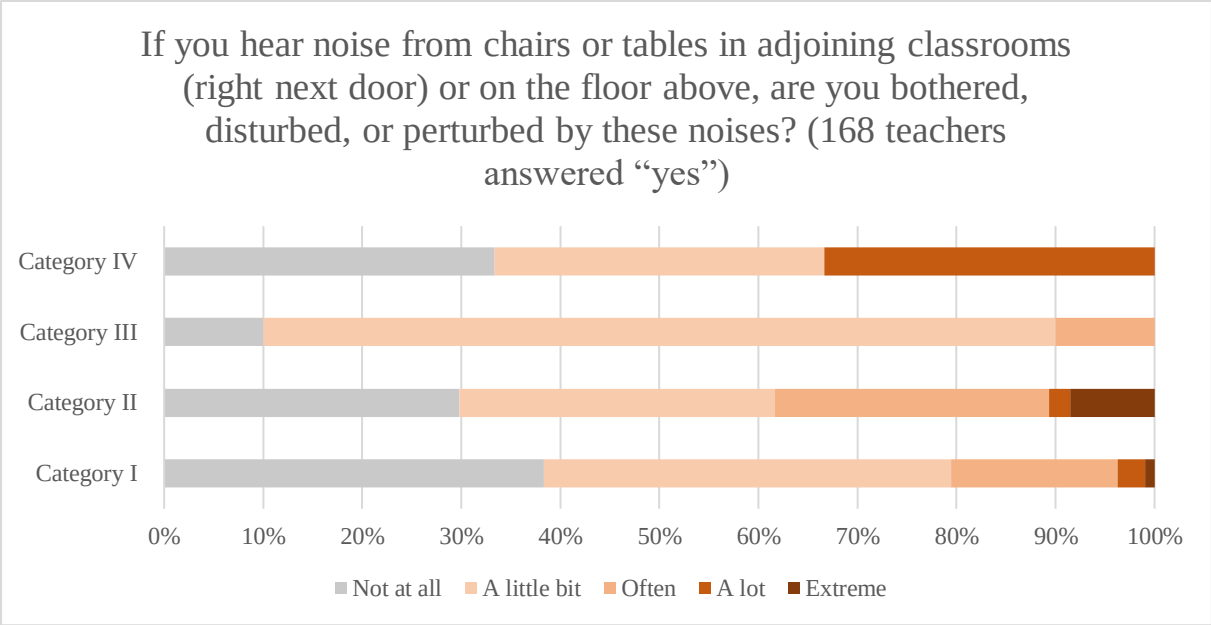


Figure 58: Distribution of teachers' answers to their disturbance in presence of the small furniture noise in adjoining classrooms, separated by the different TAIL acoustic rating (n = 168 teachers)

The second significant relation was between the TAIL acoustic rating and the teachers' disturbance to noise from people in the corridor or a shared circulation area on the upper or lower floor, with a p-value of 0.00012. Figure 59 presents the distribution of responses to this question from 101 teachers who detected these noises in their classrooms, separated by the TAIL acoustic rating of their classrooms. Similar to the previous question, only a small percentage of teachers answered: "a lot of disturbance" and "extreme disturbance," and they were always from classrooms with a TAIL acoustic rating of Category I and Category II (5.1 % in Category I classrooms and 24 % in Category II classrooms°. Once again, this indicates that in a low background noise classroom, teachers were more likely to be disturbed by small noises outside the classrooms.

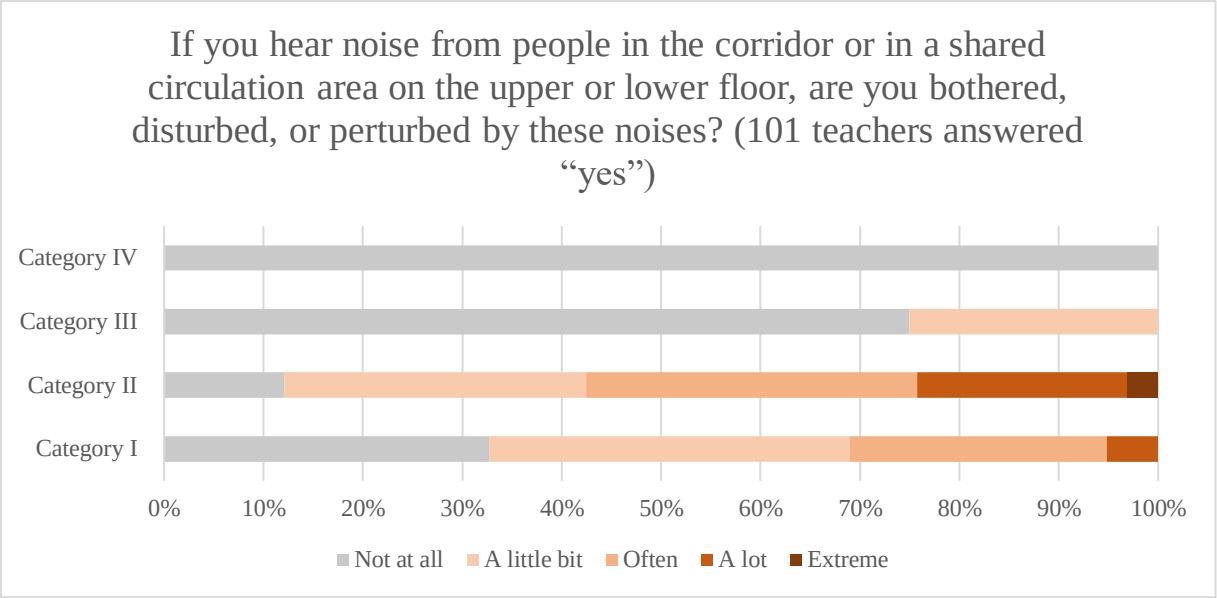


Figure 59: Distribution of teachers' answers to their disturbance in presence of the people noise from adjoining spaces, separated by the different TAIL acoustic rating (n = 101 teachers)

Finally, the third significant relation concerns the presence of a controlled mechanical ventilation system in the classroom, with an associated p-value of 0.028. Figure 60 presents teachers' answers, separated based on the TAIL acoustic rating of the classrooms. 613 out of 619 teachers (99%) provided an answer. Results show that more teachers reported the presence of controlled mechanical ventilation in the classrooms with a poor TAIL acoustic rating. Specifically, the percentage increased from 14% in Category I classrooms and 20% in Category II classrooms to 21% in Category III classrooms and 38% in Category IV classrooms.

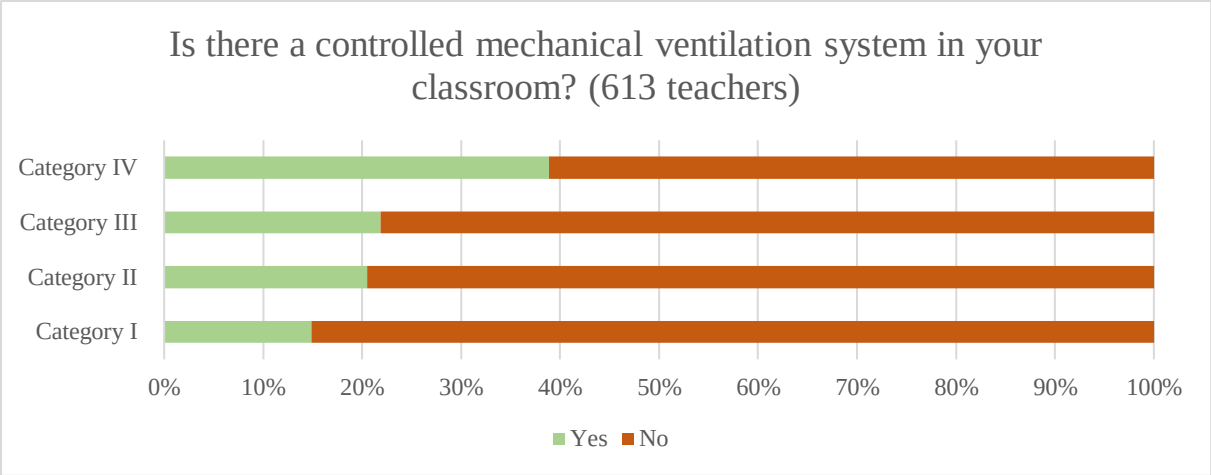


Figure 60: Distribution of teachers' answers to the presence of a mechanical ventilation system in their classrooms, separated by the different TAIL acoustic rating (n = 613 teachers)

V.3.3. Responses about the indoor air quality

Of a total of 695 teachers who provided responses, only 685 were from classrooms with IAQ TAIL rating. In this subsection, first the assessment of the relationship between the TAIL IAQ rating and the teachers' overall IAQ satisfaction was presented, then followed by the assessment of the relationship between the TAIL IAQ rating and the teachers' perception of the IAQ.

V.3.3.1. Relationship between the TAIL IAQ rating and the overall IAQ satisfaction

The statistical test between the TAIL IAQ rating and the overall IAQ satisfaction yielded a significant relationship, with an associated p-value of 0.00045. The result indicates that teachers gave significantly different answers in classrooms with a different TAIL IAQ rating. Figure 61 presents the distribution of answers to this question from 685 teachers. As there were no category I TAIL IAQ-rated classrooms, only three horizontal bars were in the figure. Results showed that no teachers gave an "unsatisfactory" answer in Category II classrooms. Additionally, there is an increase in "unsatisfactory" answers in Category III and IV classrooms (7.8 % in Category III classrooms and 12 % in Category IV classrooms). Interestingly, while there is a decrease in the percentage of "satisfactory" teachers from Category II to Category IV classrooms (76 % in Category II classrooms, 65 % in Category III, and 56 % in Category IV classrooms), more than half of the teachers were still "satisfactory" with the classrooms' IAQ.

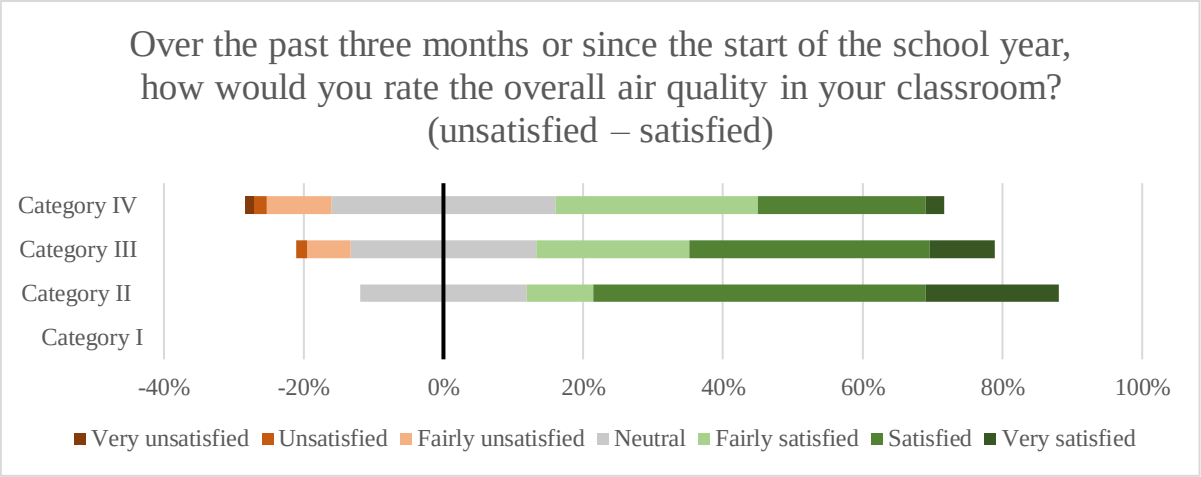


Figure 61: Distribution of teachers' answers to the overall satisfaction of the indoor air quality, separated by the different TAIL IAQ rating (n = 685 teachers)

V.3.3.2. Relationship between the TAIL IAQ rating and the other questions on the IAQ perception

The second part assesses the relationship between the TAIL IAQ rating and the teachers' responses to IAQ perception questions. Only one significant relationship was observed between the TAIL IAQ rating and the perception of stuffiness or freshness of the classrooms' air, with an associated p-value of 0.011. Figure 62 presents the distribution of teachers given answers, separated by their classrooms' associated TAIL IAQ rating. Once again, there were no Category I TAIL IAQ-rated classrooms. Thus, there were only three horizontal bars.

The percentage of teachers with an answer from "1 – very stuffy" to "3 – fairly stuffy" increases from 14% and 15% in Category II and III classrooms to 36% in Category IV classrooms. On the contrary, the percentage of teachers with an answer from "5 – fairly fresh" to "7 – very fresh" dropped from 57% in category II classrooms to 51% and 40% in category III and IV classrooms. However, the percentage of teachers who answered "fresh" was still relatively high, even in Category IV classrooms (40 %).

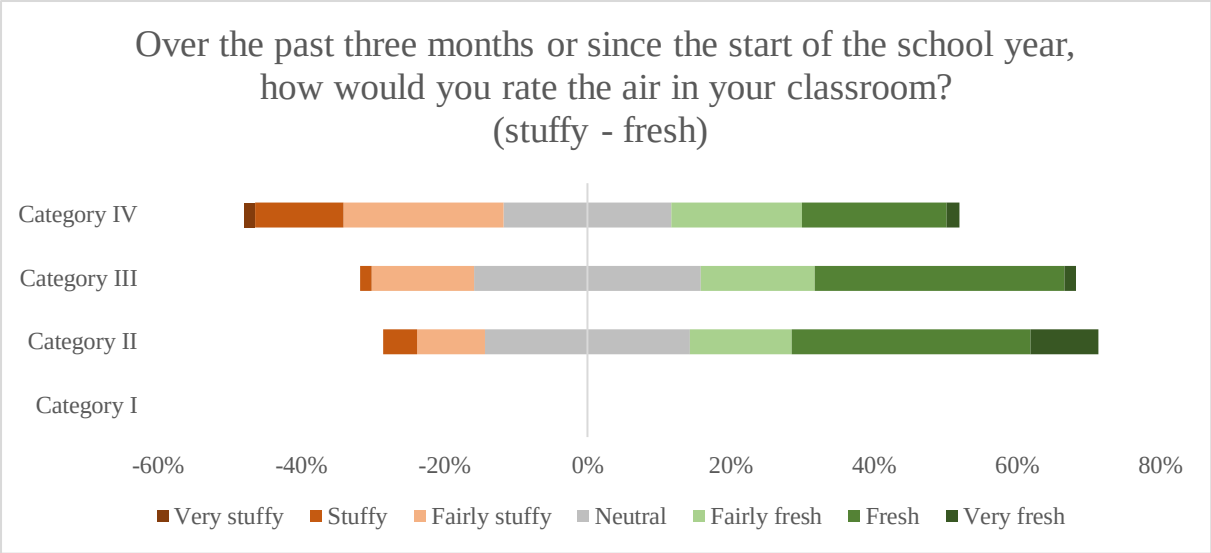


Figure 62: Distribution of teachers' answers to the stuffiness-freshness perception of the indoor air quality, separated by the different TAIL IAQ rating (n = 682 teachers)

V.3.4. Responses about odors and the indoor air quality

Out of 695 teachers who have provided answers, only one teacher did not respond to any question regarding olfactory perception. Thus, 694 responses were reported from classrooms with an IAQ TAIL classification. In this subsection, first, an assessment of the relationship between the teachers' overall satisfaction with detected odors and the TAIL IAQ rating was presented, followed by the determination of existing relationships between the TAIL IAQ rating and other questions on the teachers' odors perception.

V.3.4.1. Relationship between the TAIL IAQ rating and the overall satisfaction of odors

The relationship between the TAIL IAQ rating and the teachers' overall satisfaction with odors was only assessed by 328 teachers, as only these teachers detected an odor in their classrooms. With an associated p-value of 0.063, the difference was not significant. Figure 63 details the teachers' responses to this question, separated by their classrooms' TAIL IAQ rating.

Regardless of the significance of the relationship, the results reveal some interesting interpretations. First, there is an increase in teachers who answered "unsatisfied" with the detected odors going from Category II to Category IV classrooms. No teachers answered "satisfied" with the detected odors in Category II classrooms. However, some were in Category III and IV classrooms (9.7 % in Category III and 1.4 % in Category IV classrooms). Further investigation, especially on the nature of the detected odors, should be done, as in the poor TAIL IAQ-rated classrooms, detected odors could be a satisfactory factor to the teachers.

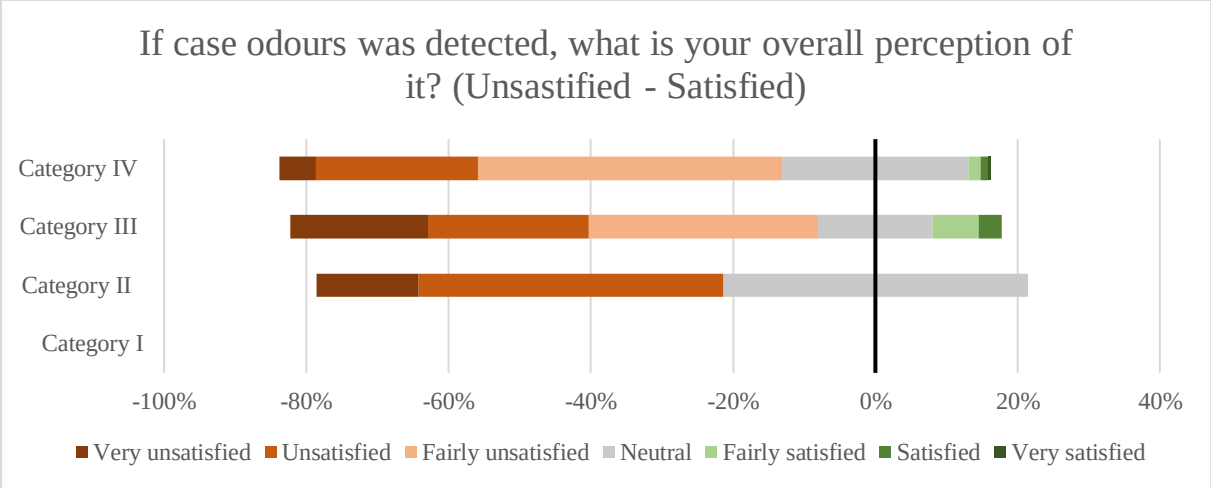


Figure 63: Distribution of teachers' answers to the overall satisfaction of the detected odors, separated by the different TAIL -IAQ rating (n = 328 teachers)

V.3.4.2. Relationship between the TAIL IAQ rating and the other questions on the perception of odors

From the three questions on the teachers' perception of the odors in classrooms, only one significant relationship with the TAIL IAQ rating was found, with an associated p-value of 0.02. It was the question of the location of the detected odors, from inside of the classroom, outside of the classroom, or outside of the building. 329 teachers answered the question. Figure 64 details on the results. In Category II TAIL IAQ classrooms, all teachers answered that the detected odors were coming from the inside the classrooms, and in poorer TAIL IAQ classrooms, more sources were added, from both outside of the classroom, and outside of the building.

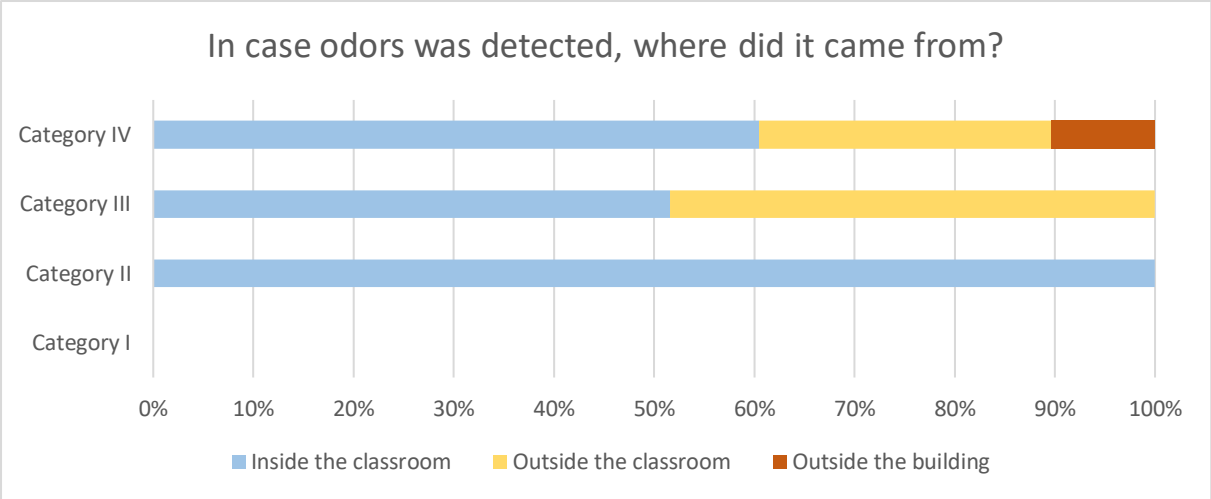


Figure 64: Distribution of teachers' answers to the location of the detected odors in the classroom, separated by the different TAIL IAQ rating (n = 329 teachers)

V.3.5. Responses about the luminous environment

Of the 695 teachers who have provided answers, 682 answered the luminous questionnaires. First, this subsection assesses the relationship between the teachers' overall visual satisfaction with the TAIL luminous, followed by the determination of existing relationships between the TAIL luminous rating and other questions on the teachers' visual perception.

V.3.5.1. Relationship between the TAIL luminous rating and the overall lighting satisfaction

The statistical test between the TAIL luminous rating and the teachers' overall satisfaction with the luminous environment yielded a significant relationship, with an associated p-value of 0.044. Figure 65 presents the distribution of the teachers' answers to the question, separated by their associated classroom's TAIL luminous rating.

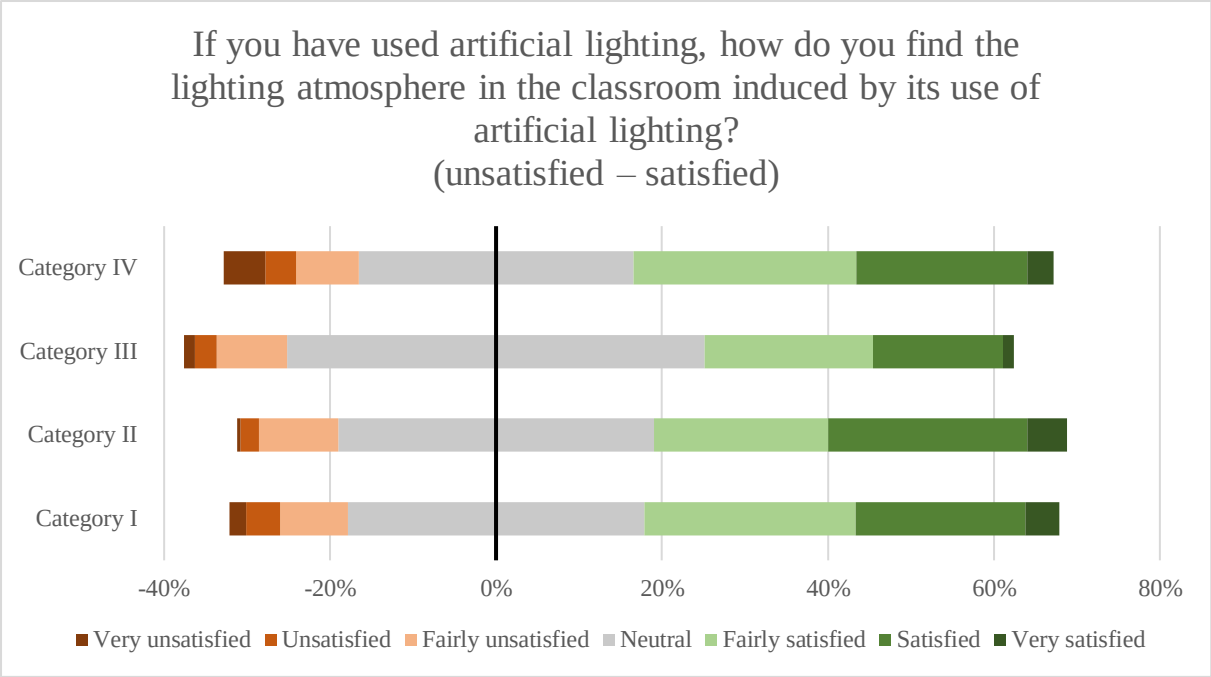


Figure 65: Distribution of teachers' answers to the overall satisfaction of the luminous environment, separated by the different TAIL luminous rating (n = 682 teachers)

While there are significant differences between teachers' answers from different TAIL rating classrooms, as evidenced by a p-value of less than 0.05, the visual representation of these differences may appear subtle or challenging to discern. The "neutral" answers stayed relatively unchanged, at 40 % in every TAIL luminous category, except for Category III classrooms, at 50 %. Furthermore, there was a slight increase in the percentage of "unsatisfied" answers, going from 14 % in Category I to 16 % in Category IV classrooms. Nevertheless, the percentage of "satisfied" teachers remained high, with over half in Category I, II, and IV classrooms and 37 % in Category III classrooms.

V.3.5.2. Relationship between the TAIL luminous rating and the other questions on the lighting perception

The assessment of the relationship between the TAIL luminous rating and the other five questions on the lighting perception did not return any significant relationship.

V.4. Discussion and perspectives

Based on results obtained from the feasibility test of the TAIL rating scheme for IEQ in schools, a statistical test has been conducted to examine the association between the classified TAIL results and the given answer of the teachers on both their satisfaction and perceptions of the individual IEQ component. Any correlations observed will provide suggestions and possible revision discussion of the TAIL rating scheme for schools. Table 46 below summarizes the observations from this statistical test.

Table 46: Summary table of the significant relationships between the TAIL IEQ rating and the teachers' perception questions

IEQ component	Satisfaction	Perception
Thermal	No significant differences observed	Significant differences with the hot – cold perception of the air temperature
Acoustic	No significant differences observed	Significant differences with: - Disturbance by furniture and people's noise from outside of the classroom - Presence of a mechanical ventilation system
Indoor air quality	Significant differences observed	Significant differences with the stuffiness – freshness of the air
Indoor air quality – Olfactory	No significant differences observed	Significant differences with the location of the odors detected
Luminous	Significant differences observed	No significant differences observed

A significant difference was not observed between the overall satisfaction and the TAIL thermal rating for the thermal environment. However, a significant difference was observed between the hot or cold perception of the air temperature and the TAIL thermal rating, and more teachers feel "hot" with a poorer TAIL thermal rating (Categories III and IV), correlated with findings on measured air temperature in classrooms earlier in the feasibility study. Nevertheless, with more than half of the teachers answering "satisfied" with the air temperature regardless of the

TAIL thermal rating, this indicates that a high temperature was the thermal preference of most teachers.

No significant difference was observed between the overall satisfaction and the TAIL acoustic environment for the acoustic environment. However, a significant difference was observed between the disturbance with furniture and people's noise from outside of the classrooms and the presence of a mechanical ventilation system in the classroom. In classrooms with a low background noise, teachers were more disturbed by outside noises. More classrooms with a poor TAIL acoustic rating (Categories III and IV) were equipped with a mechanical ventilation system. However, teachers were not disturbed by the noises from this system in different TAIL acoustic-rated classrooms, as no significant difference was observed in that question. Nevertheless, more than half of teachers were "unsatisfied" with the classroom's acoustical performance, regardless of the TAIL acoustic rating. A possible explanation could be that during school hours, with the presence of students, classroom background noise levels can rise very high and become unpleasant for teachers.

For the IAQ, a significant difference was observed in teachers' responses on their overall satisfaction with the classroom's air in different TAIL IAQ-rated classrooms. In poorer TAIL IAQ classrooms (Categories III and IV), more teachers were "unsatisfied" with the air than in Category II classrooms. However, the percentage of "satisfied" teachers was higher than 50 %, regardless of TAIL IAQ rating. Another significant difference was observed between teachers' answers to the stuffiness–freshness of the air and different TAIL IAQ classrooms. Once again, more teachers answered "stuffiness" in poorer TAIL IAQ classrooms, but most still answered "freshness", even in category IV IAQ. These results indicate that most teachers did not perceive the poor air quality, even in classrooms with a TAIL IAQ rated III or IV.

Secondly, for the IAQ, there was another set of related questions focused on the olfactory. No significant differences were observed between the TAIL IAQ rating of the classrooms and the teachers' overall satisfaction in case odors were detected. Nevertheless, regardless of the TAIL IAQ rating, most teachers answered "unsatisfied" with the odors. However, the minority of "satisfied" answers were associated with Category III and IV classrooms. A significant difference was observed between the TAIL IAQ of the classrooms and the location of the detected odors, with a homogeneous answer "inside the classroom" for Category II TAIL IAQ classrooms and more locations for other TAIL IAQ quality classrooms. These results indicate that odor sources are mainly indoors. Finally, while odors were mainly "unpleasant," the nature

of the odors should be examined, as they could also be “pleasant,” even in poorer TAIL IAQ classrooms.

Only one significant difference was observed between the TAIL luminous and the teachers’ overall satisfaction with the luminous environment. However, this difference remains challenging to assess visually. Nevertheless, the results contradicted the TAIL luminous classification, where half of the teachers were “satisfied” with the luminous condition, whereas the TAIL luminous classification suggested otherwise.

In summary, a different TAIL classification of the individual IEQ component can lead to different responses to some satisfaction or perception answers, particularly the perception rather than the overall satisfaction. Interpreting these perception results gives more understanding of teachers’ conditions in the classrooms. Additionally, the satisfaction of the IEQ component was more complicated to distinguish by the TAIL rating scheme. Furthermore, the teachers’ overall satisfaction with the individual IEQ was often contradicted by the TAIL rating scheme, where most teachers gave a “satisfied” answer, even in poor TAIL quality classrooms. Nevertheless, it was not the objective of the TAIL rating scheme to predict the teachers’ satisfaction. In future development, the rating scheme could be calibrated to better reflect the teachers’ overall satisfaction, but it is not the current focal point.

In view of this work, certain limitations were encountered during statistical testing that need to be overcome.

Firstly, in the distributed questionnaire, there was a lack of a question on the satisfaction of the overall IEQ of the classrooms. Consequently, in this exploratory test, the TAIL IEQ rating of the individual component was tested against the corresponding IEQ questionnaire. Future studies that want to replicate this research setting should deploy a question on the overall satisfaction of the overall IEQ of the classrooms.

Many discussions have been raised about the inclusion of the students' perceptions. In this dataset, as the destined schools were nurseries and elementary schools, the inclusion of the students' perceptions has been refrained, as it will further complicate the task given to the field technician and the teachers. Another debate can be raised about students, especially pupils or infants, on their understanding of IEQ comfort and other concepts. Future studies should

envision all these tasks and deploy detailed explanations on every question, mainly if the occupants are students or younger audiences.

Additionally, each individual is unique. Consequently, any personal information, such as age, gender, and background information, will influence the occupants' perception of the IEQ. In perspective, a more complex model, e.g., multivariate logistic regression, should be used to fully understand the association between the occupants' perception and the TAIL-rating classification.

Finally, in the research setting of this exploratory test, there were only a few associated teachers in each classroom, resulting in a small number of non-repetitive occupants across all the different classrooms. Consequently, intercomparison between different classrooms should be made with reservations. Another approach that future studies could envisage is using a fixed panel, as used by the BSI standard [39]. The fixed panel size should be determined in the conception phase, as this decision will indeed be reflected in the cost of the studies. Nevertheless, a panel of unchanged people allows more consistent results on occupants' satisfaction or perception of different classrooms.

V.5. Conclusion

Along with the TAIL classification from the feasibility study, the teachers' overall satisfaction and perception of the IEQ in the classrooms was also recorded during the measurement of the French National school's campaign. Thus, a statistical study was performed to explore the possible correlation between the TAIL classification and the teachers' answers on their IEQ satisfaction and perception of each of the four IEQ components.

More significant differences were observed between the different TAIL IEQ ratings and the teachers' answers to perception questions than teachers' answers to satisfaction questions. In observed correlated perception questions, notable results showed that more teachers feel "hot" in poorer TAIL thermal-rated classrooms, and more teachers were disturbed by outside noise in better TAIL-classified classrooms. Furthermore, classrooms with a mechanical ventilation system were classified with a poorer TAIL acoustic rating. However, there was no significant difference in the disturbance caused by this system.

In addition to the lack of significant differences observed between the TAIL rating and the teachers' answers to the IEQ's satisfaction, the results often do not fully represent the TAIL rating. Most teachers were "satisfied" with the thermal, IAQ, and luminous ratings, whereas the TAIL thermal, IAQ, and luminous were poor in most classrooms. An interpretation reads that occupants' satisfaction only partially correlated with the classrooms' IEQ TAIL rating. Calibration can be made in future developments to reflect the occupants' satisfaction better. However, it is not the current priority of the rating scheme.

VI. Discussion and perspective

With the aim and perspective of characterizing IEQ in schools in a referenced manner, as well as providing an aid to any future IEQ mitigation and improvement actions in schools, the objective of the thesis was to develop an IEQ rating scheme destined to be used in schools' environment, called the TAIL rating scheme for schools. This section discusses methods, findings, and limitations encountered while developing the TAIL rating scheme for schools.

First developed as a work package in the European project ALDREN, the TAIL rating scheme in hotels and offices aimed at evaluating the IEQ before renovations and suggesting renovations to improve the IEQ while gaining energy performance. Following a verified feasibility test, the TAIL rating scheme in hotels and offices was confirmed to be able to discriminate between the IEQ in different buildings. In perspective, this work presents a possible adaptation of the TAIL rating scheme to the school environment, called the TAIL rating scheme for schools.

However, the premises of this adaptation differed from the original TAIL rating scheme for hotels and offices. In this version for schools, the aim is to develop an overall rating scheme that makes comparisons of the IEQ in different schools possible. The starting point was a literature review of 88 studies that measured IEQ parameters in schools. It was conducted to gather all pertinent IEQ parameters for school measurement. A list of 32 parameters that characterized the IEQ in schools has been collected, emphasizing their measurement method and their ranges of results. This database will serve as the starting point for the future development steps of the rating scheme and any future studies. In a post-analysis context, the literature review process could be done more comprehensively, compared to only selecting studies from Europe and North America, as in the current state, there is a gap in IEQ studies in schools coming from other parts of the world.

The following steps of adapting the TAIL rating scheme involve selecting IEQ parameters to be assessed. Keeping the continuity from the original TAIL for hotels and offices, the original 12 IEQ parameters were kept in the school's TAIL rating scheme. Additionally, new parameters were selected, as the objective of the rating is to be an overall assessment of the IEQ in schools. New parameters were selected based on three criteria from the earlier list of pertinent parameters. The first criterion was that the IEQ parameter possessed documented impacts on children's health and well-being. By selecting parameters that impact children's health and well-being, the TAIL rating scheme will thoroughly assess the children's condition and exposure in

the classroom, considering every harmful parameter holistically. The second criterion was the practicality of their measurement protocol, especially in a wide-scale study. This criterion suggests that none of the selected parameters in the rating scheme will discourage schools from being measured on either the economic or the technical aspect. The rating scheme should incentivize schools to use it voluntarily. The third criterion was the availability of guidelines and values in international standards or regulations. Logically, in order to be able to set up multiple quality levels in the TAIL rating scheme, included parameters should all possess guidelines levels in referenced documents from renowned institutions or regulation parties.

After the screening of new parameters, two parameters were added. These two new parameters underline the evolution of the TAIL rating scheme and the objective of being an overall marker of the IEQ in schools.

In schools, verbal communication between teachers and students is essential, especially for younger students, whose vocabulary and expression skills are still being developed. Thus, the assessment of speech intelligibility was determined to be necessary. However, as observed in the literature review, the measurement protocol of this parameter is complicated and costly; furthermore, there is a lack of guideline values in standards and regulations for speech intelligibility. Conveniently, speech intelligibility depends on the RT, and this parameter satisfied all three selection criteria.

The occupants in schools consist mainly of children, whose activities during the day and physical and metabolic characteristics differ from adults. NO_2 poses a greater risk to children than adults, as respiratory rates are higher than adults. Thus, they are more exposed to this asthma exacerbation factor. The screening process against the two other criteria also returned satisfactory results. Thus, NO_2 was also included in the TAIL rating scheme for schools.

There were 14 parameters to be measured in the TAIL rating scheme for schools. As mentioned above, new parameters should be added when all three criteria are met for all future developments of the school TAIL rating scheme. As scientific results on the influence of IEQ parameters on children's health and well-being continue to expand, so does the technical capacity to measure those parameters. In future iterations of TAIL, it will be considered a success if previously deemed to be "not enough scientific proof", "complicated to measure", or "guidelines value nonexistent" parameters can be added, as it signals a leap in both scientific understanding and technical measurement protocol. Some examples were the operative

temperature, speech intelligibility, PM_{10}, SVOCs, or glare assessment. These parameters significantly impact children's health, well-being, and cognitive performance. However, their measurement protocols are not economically viable, especially on wide-scale studies. Consequently, it will further discourage schools from measuring and monitoring the IEQ. The 14 IEQ parameters included in the TAIL rating scheme for schools represent an adequate blend between the characterization of the IEQ in schools and other factors, e.g., economics and logistics. At any significant development, scientific or technical, new IEQ parameters should be included to maintain the relevancy and prominence of the rating scheme. Consequently, it means the TAIL rating has taken one step closer to fully representing the exposed environment that children experience.

The critical talking point is how the overall rating of the IEQ of the schools was determined from the measurement of multiple parameters in each IEQ component and from multiple measured classrooms in each school. In the TAIL rating scheme for hotels and offices, starting with measuring each parameter in multiple rooms throughout the buildings, the rating of each parameter will then be averaged to obtain a TAIL rating at the building level. Afterward, the rating of each component will be determined by its worst scoring parameter. Only then will the overall TAIL rating of the building be determined by the worst scoring component (see Figure 9). However, in the TAIL rating scheme for schools, the order started with measuring IEQ parameters in classrooms and then determining the TAIL rating for each component and the overall TAIL rating at the classroom level. Afterward, by averaging the TAIL rating of each component and the overall TAIL from every classroom, the TAIL rating of each component and overall, at the schools' level can be obtained (see Figure 10). By reversing the calculation order, all classrooms now possess their TAIL rating based on their own measurement data. These small changes allow schools to act or decide on any IEQ-related mitigation or renovation at the classroom level to improve the IEQ in each classroom, therefore improving the IEQ at the school level. The primary subject of discussion is the intrinsic principle of the TAIL rating scheme, where the worst scoring IEQ parameter imposed the rating of the IEQ component, and the worst scoring IEQ component imposed the overall rating. Giving every parameter in each IEQ component an equal weight and every IEQ component an equal weight in the overall TAIL rating seems arbitrary since this allows the school to trade off a worst-performing parameter against a better one, resulting in a higher overall score. The TAIL rating principle incentivizes schools to raise the performance of every parameter and every component equally to obtain a high overall score.

Having finalized the TAIL rating scheme for schools, the next step is to perform a feasibility test to determine whether the rating scheme can discriminate different IEQs in different schools. Advantageously, a dataset consisting of various IEQ parameters and measured in numerous schools existed. From 2013 to 2017, the “Observatoire de la qualité de l'air intérieur” (OQAI) conducted a national campaign, called the National Schools’ Survey, to describe the IEQ in classrooms in mainland France. To better understand children's exposure to a large number of pollutants never or rarely measured before in classrooms, as well as the ambient conditions to which they are exposed. Measurement was made in 602 classrooms or 308 schools. However, as the measurements during the campaign were made before the concretization of the TAIL rating scheme, not every parameter was measured, and the measurement protocols of various parameters were not matched. Nevertheless, a partial test of 10 out of 14 parameters regarding the feasibility test was performed, and some compromises were made to account for the differences between the measurement protocols of the two. With the benefit of hindsight, future studies should perform a complete test, following the TAIL-suggested measured protocol. In addition, tests in another region will broaden the range of the rating scheme and provide more vision for any eventual evolution.

Results of the overall TAIL rating seem dire, with 96 % of classrooms rated Category IV and 99 % of schools rated Category IV. However, looking at each component's TAIL rating and each parameter's TAIL rating, it becomes clearer that TAIL can differentiate the IEQ performance in each classroom and school. Results showed that schools had few problems with several parameters (i.e., formaldehyde, benzene, and visual mold), as in more than 90% of schools, their TAIL results were classified in high or medium levels (Category I and II). On the contrary, the results for other parameters were more inadequate (e.g., air temperature, CO_2, $PM_{2.5}$, and artificial lighting), as in more than 75% of schools, only moderate or low levels (Category III and IV) were achieved.

The general trend of specific parameters was also noted and thus provides further interpretation. For example, regardless of the TAIL thermal quality, there is an increase in air temperature throughout the day, indicating heat buildup during standard classroom usage. However, classrooms with a Category I or II TAIL thermal rating did a better job keeping the air temperature inside the threshold values throughout the day. In some cases, classroom air temperature could reach a high level (more than 33°C) in heating and non-heating seasons. This indicates an overheated classroom during the heating season, and mitigation action can be taken

quickly. Between different parameters in the IAQ component, there are also interpretations to be made. No notable differences were observed between the TAIL rating of CO_2 and $PM_{2.5}$, where more than 75% of schools achieved only moderate or low levels (Category III and IV). However, for the TAIL rating of NO_2, there is a significant difference between schools in rural and urban areas, where 1 % and 41 % of schools were rated Category IV, respectively. Finally, for the luminous environment, the assessment made by TAIL shows that keeping an adequate artificial lit writing board was more challenging than keeping an adequate artificial lit students' table.

As mentioned earlier, the overall TAIL rating seems one-sided, with most schools only achieving a Category IV result. However, it shows that, in one classroom, it is complicated to achieve good IEQ performance across all parameters. In most schools, IAQ and thermal were the standalone culprits that lowered the overall TAIL rating. Furthermore, in the IAQ component, CO_2 and $PM_{2.5}$ were the most decisive parameters. Nevertheless, a good IEQ in schools means all parameters are taken into account, as they all contribute to the environment that children are experiencing. Consequently, the measurement-based TAIL rating scheme provides all schools' stakeholders with the needed insights for targeted interventions, in a holistic manner.

In perspective, this feasibility test has also raised numerous points of further development for the TAIL rating scheme. First, the rating principle of the three time-series parameters (air temperature, RH, and CO_2), in particular "the total exceeding time" principle. In order to be classified Category I, at least 94 % of measured time has to be in the Category I threshold levels, less than 5 % of measured time has to be in the Category II threshold levels, and less than 1 % of measured time has to be in the Category III threshold. For an assessment time of 1 school week, 1% of the measured time corresponds to only 20 minutes. This means a classroom with the measured air temperature in Category I for 45 hours (94%) will be demoted to Category II if the air temperature was in Category III for 20 minutes (c.f. Figure 11). In the feasibility test, this only affected a small number of classrooms, less than 5 % across all three parameters. Nevertheless, tests on other datasets are needed before discussing any change to the calculation method.

In its current version, the TAIL rating scheme offers only a snapshot of what was measured at a particular instance. It can compare schools in different areas, even in an illustrative approach, such as the three earlier presented maps (Figure 47, Figure 48, and Figure 52). Prospectively,

if the technical capacities allow, the TAIL rating scheme should offer a real-time assessment of the IEQ. On the classroom scale, a real-time indicator should alarm all occupants if IEQ parameters exceed a certain threshold; thus, quick mitigation can be done. On the school scale, it will be an insight for all stakeholders to make IEQ improvement renovation. On a larger scale, regional, national, or even international, a real-time IEQ indicator is invaluable for any regulation-wise decision that requires any oversight over a large area.

Having performed the feasibility test, it is worthwhile to examine whether the TAIL rating can predict the occupants' IEQ satisfaction and perception. The opportunity arises, as during the IEQ measurement of the campaign, teachers were asked to document their satisfaction and perception of the IEQ in their classrooms. Therefore, the decision was made to explore whether there is a significant difference in teachers' responses in classrooms with different TAIL ratings. As the teachers were not asked about their overall satisfaction with the overall IEQ of the classrooms, only the TAIL rating of each IEQ component of each classroom was used to test against the questions corresponding to that component. Teachers were associated with the classrooms and, therefore, with their corresponding TAIL IEQ component rating. For each component, the relationship between the TAIL rating and teachers' satisfaction was tested, followed by the relationship between the TAIL rating and other perceptions questions. In perspective, it would be more comprehensible to document teachers' satisfaction with the overall IEQ of the classroom regarding all four IEQ components. Moreover, to make results between different classrooms more comparable, a better practice would be to use a constant panel of teachers to document their satisfaction and perception in every classroom, as each person has his/her preferences regarding IEQ.

Regarding IEQ satisfaction, a significant difference in teachers' responses was observed in different TAIL-rated IAQ classrooms and in different TAIL-rated luminous classrooms. Albeit significantly, the difference in teachers' satisfaction responses in different TAIL-rated luminous classrooms remained challenging to interpret visually. In different TAIL rating IAQ classrooms, there was an increase in "unsatisfied" teachers going from Category II to Category IV classrooms and a decrease in "satisfied" teachers, respectively. However, most teachers were still "satisfied" with the IAQ in their classrooms, even in poorly rated TAIL IAQ classrooms (Categories III and IV). This trend was also observed in the TAIL thermal rating, albeit the differences in responses between different TAIL thermal-rated classrooms were not significant. This indicates that occupants' satisfaction varies from individual to individual, and the TAIL

rating scheme could not predict the teachers' satisfaction for all four IEQ components. The rating scheme could be calibrated to represent the occupants' satisfaction better; however, it is not the current priority.

Regarding teachers' IEQ perception, significant differences in teachers' responses were observed in all components except for the luminous environment. For the thermal environment, more teachers feel "hot" in poorer TAIL thermal-rated classrooms. This was in line with previous results, as the air temperature was higher in poorer TAIL thermal-rated classrooms (Categories III and IV). For the acoustic environment, in categories I and II acoustic-rated classrooms, with low background noise, any noises outside the classrooms cause more disturbance to teachers than in categories III and IV classrooms, where a higher background noise could already mask these noises. For the IAQ, more teachers feel that the air was "stuffy", going from Category II to Category IV classrooms. These results have further contributed to the understanding of occupants' perception of the IEQ and also given insight into the general preferences of the IEQ in teachers' classrooms.

With retrospective analysis, there were some interesting perspectives. Firstly, considering the majority of occupants in the school, children, their satisfaction, and perception of the IEQ should also be documented. However, this requires further planning and development, as the concept of satisfaction and perception in children are still not fully understood. Secondly, as mentioned above, the preference of the IEQ varied from individual to individual. It combines results from each background information, e.g., age, gender, and health. It is intriguing to investigate this dataset and future studies using a multivariate model, considering all the factors that could influence occupants' satisfaction and perceptions of the IEQ.

VII. Conclusion

This thesis aimed to develop an Indoor Environmental Quality (IEQ) rating scheme tailored for schools, termed the TAIL rating scheme. Originating from the ALDREN project's TAIL scheme for hotels and offices, this adaptation provides a comprehensive assessment of school IEQ. The scheme seeks a delicate balance between scientific rigor, technical feasibility and economic viability, thus encouraging schools to use it. The main takeaways from this adaptation are as follows:

- A literature review of 88 studies on IEQ parameters in schools was conducted, resulting in a list of 32 pertinent parameters. This literature review database is a foundation for future TAIL rating scheme development and similar studies.
- Two new parameters, reverberation time and nitrogen dioxide, were added based on criteria related to health impact, practicality, and international standards.
- The TAIL rating scheme for schools calculates ratings at the classroom level, allowing for targeted improvements, even at the classroom level. Nevertheless, the intrinsic principle of worst-scoring parameters and components influencing overall ratings was kept, thus incentivizing schools to address every aspect of IEQ comprehensively.

The feasibility test, utilizing data from the National Schools' Survey, carried out between 2013 and 2017 in 602 classrooms and 308 schools in mainland France, demonstrated the scheme's ability to differentiate IEQ performance within classrooms and schools. While overall ratings may suggest challenges, detailed component and parameter assessments reveal nuanced insights for targeted interventions. The main results are as follows:

- The TAIL scheme effectively categorizes IEQ quality in schools with varying characteristics, highlighting disparities in IAQ parameters.
- TAIL ratings of the thermal environment show problems with overheating and high air temperature variability in classrooms.
- TAIL ratings of the acoustical environment show little interpretation due to the measurement performed during the weekend.
- TAIL ratings demonstrate schools' struggles with IAQ, mainly due to CO_2 and $PM_{2.5}$ concentrations.

- TAIL ratings of the luminous environment show that illuminance on teachers' boards was poorer than on students' tables.

An opportunity arises to explore the correlation between the TAIL ratings and the teachers' satisfaction and perceptions of each individual component of the IEQ. The main takeaways from this exploratory test are as follows:

- Regarding teachers' satisfaction with the classrooms' IEQ, significant differences in teachers' answers in different TAIL-IEQ classified classrooms were observed only for the IAQ and visual environment. However, the percentage of teachers who gave a "satisfied" answer remains high, even in category III or IV classrooms.
- More significant differences were observed regarding other questions on teachers' perceptions, meaning more teachers could notify changes to specific classroom IEQ conditions. Nevertheless, this experiment shows that occupants' perception and satisfaction are unreliable tools for characterizing IEQ.
- In addition, a more robust statistical model can be used to complete the experiment, such as a multi-logistical regression model that considers every factor that impacts occupants' satisfaction and perception of the IEQ.

Further perspectives include the exploration of real-time IEQ assessments and the potential to predict occupants' satisfaction and perceptions. The analysis of teachers' responses provided valuable insights. However, the TAIL rating scheme only partially predicted teachers' satisfaction. Nevertheless, it is not the current priority of the rating scheme.

To conclude, the TAIL rating scheme was developed to assess the IEQ in schools. By providing an overall rating score, the rating scheme simplifies the assessment of the IEQ. It communicates the result directly and in an intelligible manner to all schools' stakeholders. As demonstrated in the explanatory test regarding the perception, teachers' perception of the thermal environment and the air quality were not strongly associated with its measured quality. Therefore, they should be informed of its inadequate quality.

Consequently, all concerned parties should be encouraged to take action to improve the inadequate IEQ in schools. The TAIL-rating scheme helps render visible the invisible – IEQ in schools – and provides much-needed aid to all concerned parties. Ultimately, children deserve the best school conditions, and we should do everything possible to achieve that. The thesis sets

the foundation for ongoing developments and underscores the importance of adapting methodologies to capture the diverse perspectives within different schools better.

VIII. List of publications

Journal papers

- Tran, M.-T.; Wei, W.; Dassonville, C.; Martinsons, C.; Ducruet, P.; Mandin, C.; Héquet, V.; Wargocki, P. Review of Parameters Measured to Characterize Classrooms' Indoor Environmental Quality. *Buildings* **2023**, DOI: https://doi.org/10.3390/buildings13020433.
- Tran, M.-T.; Wei, W.; Dassonville, C.; Martinsons, C.; Ducruet, P.; Derbez, M.; Mandin, C.; Héquet, V.; Wargocki, P. Adaptation of the TAIL rating scheme to enable assessing indoor environmental quality in elementary schools. *To be submitted*

Conference papers

- Tran, M.-T., Wei, W., Dassonville, C., Mandin, C., Wargocki, P., & Hequet, V. Development of the TAIL rating scheme for indoor environmental quality in schools. *CLIMA 2022 Conference.* **2022,** DOI: https://doi.org/10.34641/clima.2022.244
- Tran, M.-T.; Wei, W.; Dassonville, C.; Martinsons, C.; Ducruet, P.; Mandin, C.; Héquet, V.; Wargocki, P. Indoor environmental quality in schools what are the main indicators? *Conference Indoor Air 2022.*
- Tran, M.-T.; Wei, W.; Dassonville, C.; Martinsons, C.; Ducruet, P.; Derbez, M.; Mandin, C.; Héquet, V.; Wargocki, P. Applicability and sensitivity of the TAIL rating scheme using data from the French national school survey *Conference AIVC 2023.*

Conference summary paper

- Minh-Tien Tran, Jean-Marie Alessandrini, Bernard Collignan, Ambre Delater, Virginie Desvignes, Corinne Mandin, Aya Mansouri, Pierre Martinache, Mélanie Nicolas, Frédéric Thévenet, Liselotte Tinel, David Umba, Marie Verriele, Wenjuan Wei. Conférence " Indoor Air ", 12 au 16 juin 2022, Kuopio, Finlande. *Environnement, Risques & Santé.* **2023**;22(1):66-71. DOI: doi:10.1684/ers.2023.1701

Internal presentation

- "Journée des Doctorants ADEME": 2021, 2022, 2023
- "Journée des Doctorants CSTB": 2023 (Ma thèse en 180 secondes)
- GEPEA seminar: 2022

External presentation

- Indoor Air 2022, Kuopio, Finland.

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X. Appendix

Table A.1: Measurement made in the French National IEQ survey

Parameters	Measurement device	Model	Measurement principle	Measurement protocol	Range of measurement
Air temperature	Thermo-hygrometer	Rotronic / Hygrolog HL 20-D	Platinum probe 100 Ω Capacitive sensor +/-1 %	Measurement on continuous in 4.5 days; Time interval = 10 minutes	-10 °C to 50 °C 0 to 100 %
Relative humidity					
CO_2	NDIR sensor	CSTB/Lumair	NDIR sensor	Measurement on continuous in 4.5 days; Time interval = 10 minutes	0 to 5000 ppm
Background noise level	Sound meter + Calibration unit	Cirrus / Optimus Red class 2 Calibrator	Electret microphone	Measurement on continuous in 7 days; Time interval = 2 seconds	20 to 130 dB
Total particles count	Optical particle counter	GRIMM/ G1.08	Light diffraction 15 particle size channels (from 0.3 to 20 µm)	Measurement on continuous in 4.5 days; Time interval = 10 minutes	0 to 2000000 particles per liter

Artificial light	Lux meter	Konica Minolta / T10	Silicon photocell	Spot measurement 1 or 2 boards and 5 tables 9 measurements per board and 5 measurements per table	0.1 to 999999 lux
Lead in paintworks	X-ray fluorescence device	Niton XL XLP	X-ray fluorescence	Spot measurements 15 minimum	0 to 80 mg/cm2
Volatile organic compound (VOC)	Passive tube	Radiello® carbograph 4	Adsorption of VOCs on carbograph 4	Continuous 4.5-day sampling	N/A
Aldehyde	Passive tube	Radiello® DNPH	Reaction of aldehydes with 2,4-DNPH to form 2,4-DNPHydrazone	Continuous 4.5-day sampling	N/A
Nitrogen dioxide (NO_2)	Passive tube	Tube PASSAM Ag®	Radial diffusion of NO_2 in a tube containing triethanolamine	Continuous 4.5-day sampling	N/A
Semi volatile organic compound (SVOC), gas phase	Pumping system + URG cartridge	Sensidyne/Gil'Air 3 SKC/AirChek 3000 Battery eliminator	SVOC recovery on PUF foam and particulate SVOC recovery on quartz filter	Continuous sampling over 4.5 days by active pumping 2 L/min	N/A
$PM_{2.5}$ particulate matter by mass	Pumping system	SKC/AirChek 3000 Battery eliminator/ Impacteur PM2,5/ Teflon filter	Gravimetric	Continuous sampling over 4.5 days by active pumping 1,8 L/min	N/A

Semi volatile organic compound (SVOC), in settled dust	Vacuum cleaner + specific Teflon sampling head (CSTB)	Siemens / CSTB	Collection of dust deposited on the ground (at least 10 m2) Laboratory analysis of deposited dust	Punctual sampling	N/A
Lead	Lead-free, detergent-free pre-saturated wipes	EMS®	Recovery of dust deposited on the ground Analysis of dust deposited in the laboratory	Punctual sampling	N/A
Other metals	Vacuum cleaner + specific sampling head (CSTB)	Siemens / CSTB	Recovery of dust deposited on the ground Analysis of dust deposited in the laboratory	Punctual sampling	N/A
Dust mite allergens	Mitest® vacuum cleaner + cartridge and collector	Indoor Biotechnologies	Recovery of dust deposited on dormitory mattresses Laboratory analysis of deposited dust	Punctual sampling	N/A

Table A 2: Distribution of answers to questions in the thermal perception questionnaire (695 teachers from 308 schools)

Questions	Number of responses	%
Question 1 - Over the past three months or since the start of the school year, how would you rate the air temperature in your classroom? (N = 695)		
1 = very cold	5	0.70%

2 = cold	33	4.64%
3 = fairly cold	59	8.30%
4 = either cold either hot	266	37.41%
5 = fairly hot	124	17.44%
6 = hot	157	22.08%
7 = very hot	49	6.89%
Not specified	2	0.28%
Question 2 - Over the past three months or since the start of the school year, do you feel that the air temperature in your classroom varies over the course of the day? (N = 695)		
1 = never	126	17.72%
2=sometimes	337	47.40%
3=often	181	25.46%
4=all the time	49	6.89%
Not specified	2	0.28%

Question 3 - Over the past three months or since the start of the school year, how do you rate the air temperature in your classroom? (N = 695)		
1 = very unsatisfied	25	3.52%
2 = unsatisfied	42	5.91%
3 = fairly unsatisfied	99	13.92%
4 = neutral	127	17.86%
5 = fairly satisfied	232	32.63%
6 = satisfied	145	20.39%
7 = very satisfied	23	3.23%
Not specified	2	0.28%
Question 4 - In the last three months or since the start of the school year, have you experienced draughts in your classroom? (N = 695)		
1 = never	432	60.76%
2 = sometimes	198	27.85%
3 = often	47	6.61%

4 = all the time	16	2.25%
Not specified	2	0.28%
Question 5 - If yes, how do you rate them? (N = 261)		
1 = very unpleasant	22	8.40%
2 = unpleasant	54	20.61%
3 = fairly unpleasant	82	31.30%
4 = neutral	69	26.34%
5 = fairly pleasant	23	8.78%
6 = pleasant	6	2.29%
7 = very pleasant	3	1.15%
Not specified	2	0.76%

Table A.3: Distribution of answers to questions in the acoustic perception questionnaire (695 teachers from 308 schools)

Questions	Number of responses	%
Question 1 - Over the past three months, or since the start of the school year, how do you feel about the overall sound environment in your classroom? (N = 695)		
1 = very noisy	47	6.61%
2 = noisy	117	16.46%
3 = fairly noisy	201	28.27%
4 = neutral	182	25.60%
5 = fairly calm	98	13.78%
6 = calm	36	5.06%
7 = very calm	13	1.83%
Not specified	1	0.14%
Question 2 - Can you hear the voices of teachers and/or children in adjacent classrooms (right next door) or on the floor above or below? (N = 695)		
1 = yes	246	34.60%

2 = no	407	57.24%
3 = no respond	39	5.49%
Not specified	3	0.42%
Question 3 - If yes, are you bothered, disturbed or perturbed by these voices? (N = 246)		
1 = not at all	116	47.15%
2 = a little bit	83	33.74%
3 = often	39	15.85%
4 = a lot	5	2.03%
5 = extreme	3	1.22%
Not specified	0	0.00%
Question 4 - Do you hear noise from chairs or tables in adjoining classrooms (right next door) or on the floor above? (N = 695)		
1 = yes	192	27.00%
2 = no	459	64.56%

3 = no respond	42	5.91%
Not specified	2	0.28%
Question 5 - If yes, are you bothered, disturbed or perturbed by these voices? (N = 192)		
1 = not at all	68	35.42%
2 = a little bit	80	41.67%
3 = often	34	17.71%
4 = a lot	5	2.60%
5 = extreme	5	2.60%
Not specified	0	0.00%
Question 6 - Do you hear noise from people in the hallway or in a common circulation area on the same floor as your classroom? (N = 695)		
1 = yes	358	50.35%
2 = no	308	43.32%
3 = no respond	26	3.66%

Not specified	3	0.42%
Question 7 - If yes, are you bothered, disturbed or perturbed by these voices? (N = 358)		
1 = not at all	108	30.17%
2 = a little bit	159	44.41%
3 = often	69	19.27%
4 = a lot	18	5.03%
5 = extreme	4	1.12%
Not specified	0	0.00%
Question 8 - Do you hear noise from people in the corridor or in a shared circulation area on the upper or lower floor? (N = 695)		
1 = yes	118	16.60%
2 = no	417	58.65%
3 = no respond	159	22.36%
Not specified	1	0.14%

Question 9 - If yes, are you bothered, disturbed or perturbed by these voices? (N = 118)		
1 = not at all	34	28.81%
2 = a little bit	41	34.75%
3 = often	29	24.58%
4 = a lot	12	10.17%
5 = extreme	2	1.69%
Not specified	0	0.00%
Question 10 - Do you hear noise from sanitary installations (WC. toilet flushing)? (N = 695)		
1 = yes	163	22.93%
2 = no	500	70.32%
3 = no respond	30	4.22%
Not specified	2	0.28%
Question 11 - If yes, are you bothered, disturbed or perturbed by these voices? (N = 163)		

1 = not at all	70	42.94%
2 = a little bit	59	36.20%
3 = often	17	10.43%
4 = a lot	11	6.75%
5 = extreme	6	3.68%
Not specified	0	0.00%
Question 12 - Do you hear noise from outside the building when the windows are closed? (N = 695)		
1 = yes	332	46.69%
2 = no	361	50.77%
3 = no respond	0	0.00%
Not specified	2	0.28%
Question 13 - If yes, are you bothered, disturbed or perturbed by these voices? (N = 332)		
1 = not at all	81	24.40%

2 = a little bit	126	37.95%
3 = often	89	26.81%
4 = a lot	30	9.04%
5 = extreme	6	1.81%
Not specified	0	0.00%
Question 14 - Do you hear noise from outside the building when the windows are open? (N = 695)		
1 = yes	578	81.29%
2 = no	115	16.17%
3 = no respond	0	0.00%
Not specified	2	0.28%
Question 15 - If yes, are you bothered, disturbed or perturbed by these voices? (N = 578)		
1 = not at all	146	25.26%
2 = a little bit	159	27.51%

3 = often	165	28.55%
4 = a lot	83	14.36%
5 = extreme	25	4.33%
Not specified	0	0.00%
Question 16 - Do you hear other noises coming from outside the classroom? (N = 695)		
1 = yes	145	20.39%
2 = no	544	76.51%
3 = no respond	0	0.00%
Not specified	6	0.84%
Question 17 - If yes, are you bothered, disturbed or perturbed by these voices? (N = 145)		
1 = not at all	22	15.17%
2 = a little bit	43	29.66%
3 = often	43	29.66%

4 = a lot	26	17.93%
5 = extreme	9	6.21%
Not specified	2	1.38%
Question 18 - Is there a controlled mechanical ventilation system in your classroom? (N = 695)		
1 = yes	118	16.60%
2 = no	571	80.31%
Not specified	6	0.84%
Question 19 - If yes, are you bothered, disturbed or perturbed by these voices? (N = 118)		
1 = not at all	86	72.88%
2 = a little bit	13	11.02%
3 = often	6	5.08%
4 = a lot	7	5.93%
5 = extreme	5	4.24%

Not specified	1	0.85%

Table A.4: Distribution of answers to questions in the quality of air questionnaire (695 teachers from 308 schools)

Questions	**Number of responses**	**%**
Question 1 - Over the past three months or since the start of the school year, how would you rate the overall air quality in your classroom? (N = 695)		
1 = very unsatisfied	7	0.98%
2 = unsatisfied	12	1.69%
3 = fairly unsatisfied	60	8.44%
4 = neutral	214	30.10%
5 = fairly satisfied	190	26.72%
6 = satisfied	176	24.75%
7 = very satisfied	26	3.66%
Non specified	10	1.41%

Question 2 - Over the past three months or since the start of the school year, how do you rate the air in your classroom? (dry/humid) (N = 695)		
1 = very dry	12	1.69%
2 = dry	112	15.75%
3 = fairly dry	98	13.78%
4 = neutral	396	55.70%
5 = fairly humid	54	7.59%
6 = humid	12	1.69%
7 = very humid	1	0.14%
Non specified	10	1.41%
Question 3 - Over the past three months or since the start of the school year, how do you rate the air in your classroom? (confined/renewed) (N = 695)		
1 = very confined	9	1.27%
2 = confined	76	10.69%
3 = fairly confined	145	20.39%

4 = neutral	166	23.35%
5 = fairly renewed	122	17.16%
6 = renewed	150	21.10%
7 = very renewed	14	1.97%
Non specified	13	1.83%

Table A.5: Distribution of answers to questions in the olfactory perception questionnaire (695 teachers from 308 schools)

Questions	**Number of responses**	**%**
Question 1 - Over the last three months or since the start of the school year, on the whole, do you smell odors in the classroom? (N = 695)		
1 = never	365	51.34%
2 = sometimes	329	46.27%
Not specified	1	0.14%
Question 2 - If yes, do odors come from (N = 329)		

1 = from inside the classroom	199	60.30%
2 = from outside the classroom	100	30.30%
3 = from outside the building	30	9.09%
Not specified	0	0.00%
Question 3 - If yes, odors are generally (N = 329)		
1 = very unpleasant	22	6.67%
2 = unpleasant	76	23.03%
3 = fairly unpleasant	134	40.61%
4 = neutral	84	25.45%
5 = fairly pleasant	7	2.12%
6 = pleasant	4	1.21%
7 = very pleasant	1	0.30%
Not specified	1	0.30%

Question 3 - If yes, over the past three months or since the start of the school year, do these odors bother you? (N = 329)		
1 = never	92	27.88%
2 = a few	143	43.33%
3 = often	64	19.39%
4 = very	28	8.48%
5 = extreme	2	0.61%
Not specified	0	0.00%

Table A.6: Distribution of answers to questions in the visual perception questionnaire (695 teachers from 308 schools)

Questions	Number of responses	%
Question 1 - How do you like the view from your classroom windows? (N = 695)		
1 = very unpleasant	22	3.09%
2 = unpleasant	14	1.97%

3 = rather unpleasant	48	6.75%
4 = either unpleasant either pleasant	243	34.18%
5 = rather pleasant	152	21.38%
6 = pleasant	125	17.58%
7 = very pleasant	89	12.52%
Not specified	2	0.28%
Question 2 - In the last three months or since the start of the school year or when you are in the classroom, please specify how natural light or direct sunlight bother you (N=695)		
1=not at all	213	29.96%
2=a little bit	208	29.25%
3=often	177	24.89%
4=all the time	81	11.39%
5 = extreme	13	1.83%
Not specified	3	0.42%

Question 3 - If natural light or direct sunlight bothers you, please specify the time of day (N = 479)		
1 = rather in the morning	208	43.42%
2 = rather in the afternoon	210	43.84%
3 = all day long	61	12.73%
Not specified	0	0.00%
Question 4 - If natural light or direct sunlight bother you, do you have problems with legibility? (N= 479)		
1 = never	154	32.15%
2 = sometimes	236	49.27%
3 = often	80	16.70%
4 = all the time	9	1.88%
Not specified	0	0.00%
Question 5 - In the last three months, or since the start of the school year, have you used movable solar protection (curtains, shutters, blinds, sliding panels)? (N = 695)		
1 = never	110	15.47%

2 = sometimes	213	29.96%
3 = often	238	33.47%
4 = all the time	130	18.28%
Not specified	4	0.56%
Question 6 - If you have used them, how satisfied were you with their effectiveness? (N = 581)		
1 = very unsatisfied	24	4.12%
2 = unsatisfied	18	3.09%
3 = rather unsatisfied	59	10.12%
4 = neutral	44	7.55%
5 = rather satisfied	174	29.85%
6 = satisfied	169	28.99%
7 = very satisfied	92	15.78%
Not specified	1	0.17%

Question 7 - If you have not used them, was “no need” the reason? (N = 110)		
1 = yes	75	68.18%
2 = no	34	30.91%
Not specified	1	0.91%
Question 8 - If you did not use them, was “lack of protection” the reason? (N = 110)		
1 = yes	32	29.09%
2 = no	77	70.00%
Not specified	1	0.91%
Question 9 - If you have not used them, was “blocked mechanism” the reason? (N = 110)		
1 = yes	3	2.73%
2 = no	106	96.36%
Not specified	1	0.91%
Question 10 - If you did not use them, was “inaccessible mechanism” the reason? (N = 110)		

1 = yes	0	0.00%
2 = no	108	98.18%
Not specified	2	1.82%
Question 11 - If you did not use them, was “insufficient protection” the reason? (N = 110)		
1 = yes	0	0.00%
2 = no	108	98.18%
Not specified	2	1.82%
Question 12 - If you did not use them, was there another reason? (N = 110)		
1 = yes	3	2.73%
2 = no	105	95.45%
Not specified	2	1.82%
Question 13 - Specify the other reasons (N = 3)		
Text	3	100.00%

Not specified	0	0.00%
Question 14 - Since the start of the school year or in the last three months, have you used artificial lighting in your classroom? (N = 695)		
1 = never	2	0.28%
2 = sometimes	40	5.63%
3 = often	313	44.02%
4 = all the time	338	47.54%
Not specified	2	0.28%
Question 15 - If you have used artificial lighting, how does it disturb you? (N = 691)		
1 = not at all	519	75.11%
2 = a little bit	82	11.87%
3 = often	64	9.26%
4 = all the time	20	2.89%
5 = extreme	5	0.72%

Not specified	1	0.14%
Question 16 - If you have used artificial lighting, do you have any problems with legibility (e.g. of written documents)? (N = 691)		
1 = never	531	76.85%
2 = sometimes	139	20.12%
3 = often	17	2.46%
4 = all the time	3	0.43%
Not specified	1	0.14%
Question 17 - If you have used artificial lighting, do you find the lighting atmosphere in the classroom induced by its use of artificial lighting (N = 691)		
1 = very unpleasant	14	2.03%
2 = unpleasant	20	2.89%
3 = rather unpleasant	60	8.68%
4 = either unpleasant either pleasant	272	39.36%
5 = rather pleasant	158	22.87%

6 = pleasant	143	20.69%
7 = very pleasant	24	3.47%
Not specified	0	0.00%
Question 18 - If you have used artificial lighting, regarding glare, how would you find the state of artificial light (N = 691)		
1 = not at all glare	481	69.61%
2 = a little bit glare	129	18.61%
3 = often glare	70	10.10%
4 = all the time glare	10	1.44%
5 = extreme glare	1	0.14%
Not specified	0	0.00%
Question 19 - If you have used artificial lighting, do you feel that the lighting ambience in the classroom induced by its use faithfully reproduces the colors? (N = 691)		
1 = yes	522	75.54%
2 = no	52	7.53%

3 = no information	117	16.93%
Not specified	0	0.00%
Question 20 - If you did not use artificial lighting in the classroom, was “sufficient natural light” the reason? (N = 2)		
1 = yes	2	100.00%
2 = no	0	0.00%
Not specified	0	0.00%
Question 21 - If you did not use the artificial lighting in the classroom, was “malfunction” (e.g. flickering. noise) the reason? (N = 2)		
1 = yes	0	0.00%
2 = no	2	100.00%
Not specified	0	0.00%
Question 22 - If you did not use artificial lighting in the classroom, was there other reasons (N = 2)		
1 = yes	1	50.00%
2 = no	1	50.00%

Not specified	0	0.00%
Question 23 - Specify the other reasons (N = 1)		
Text	1	100.00%
Not specified	0	0.00%

COLLEGES SCIENCES
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LOIRE ET LE NUMERIQUE

IMT Atlantique
Bretagne-Pays de la Loire
École Mines-Télécom

Titre : Construction d'un indicateur agrégé de la qualité de l'environnement intérieur dans les écoles

Mots clés : thermique, acoustique, qualité de l'air intérieur, visuel, indice

Résumé : Après la maison, l'école est le milieu de vie le plus fréquenté par les enfants. Les écoles sont des environnements intérieurs spécifiques en termes de qualité de l'air intérieur. La densité du mobilier, l'utilisation de produits pour les activités (par exemple, colles, peintures, feutres) et le nettoyage fréquent des locaux peuvent avoir diverses répercussions sur la qualité de l'air intérieur et constituent des spécificités de ces bâtiments par rapport aux habitations. Par conséquent, une évaluation plus large de la qualité de l'environnement intérieur (QEI) dans les écoles est nécessaire. Dans ce contexte et sur la base de l'indicateur TAIL (pour Thermique, Acoustique, qualité de l'air Intérieur et Luminosité) précédemment développé pour les bureaux et les hôtels, ce travail vise à étudier la possibilité et la pertinence d'un indicateur global de la qualité de l'environnement intérieur dans les écoles. Ainsi l'indice TAIL a été défini pour les écoles. Il comprend 14 paramètres de QEI et une évaluation globale en quatre catégories peut être fournie pour chaque école. Les 4 niveaux de catégories correspondent à I pour un niveau souhaité, II pour un niveau convenable, III pour un niveau non adapté et IV indésirable. Un test de faisabilité a été réalisé à partir des données issues de l'enquête nationale française sur la qualité de l'environnement intérieur réalisées dans les écoles entre 2013 et 2017. Les résultats montrent que l'indice d'évaluation TAIL permet d'identifier clairement les paramètres pour lesquels des actions d'amélioration seraient nécessaires. Enfin, une analyse explicative de la relation entre la perception des occupants et la classification TAIL est effectuée. En conclusion, ce travail met en évidence la pertinence de l'outil d'évaluation TAIL pour les écoles afin d'assurer la conformité de la qualité de l'environnement intérieur et d'aider les parties prenantes à prendre des décisions pour améliorer la qualité de l'environnement intérieur.

Title: Construction of an Aggregate Indicator of Indoor Environmental Quality in Schools

Keywords: thermal, acoustic, indoor air quality, lighting, index

Abstract: After home, the school is the environment where children spend most of the time. Schools are specific indoor environments in terms of indoor air quality. The density of occupation, the density of furniture, the use of products for activities (e.g. glues, paints, felt-tip pens), and the frequent cleaning of the premises can have various repercussions on indoor air quality and are specific features of these buildings compared with homes. Consequently, a special assessment of indoor environmental quality (IEQ) dedicated for school buildings is necessary. In this context, and based on the TAIL rating scheme for thermal, acoustic, indoor air quality, and lighting parameters previously developed for offices and hotels, this work aimed at studying the possibility and relevance of a global indicator of indoor environmental quality in schools, called the TAIL rating scheme or schools. The rating comprises fourteen IEQ parameters, rating of each component of IEQ and the overall rating of IEQ for a school building. Four levels of IEQ are defined as I - a desirable level, II - a suitable level, III - low level and IV - an unsuitable level. A feasibility test of the rating scheme was conducted using the data from French national survey on indoor environmental quality in schools carried out between 2013 and 2017. The results showed that the TAIL rating scheme can discriminate the specific IEQ levels. An explanatory analysis was also made using IEQ evaluations of teachers; they were compared with the TAIL rating schemes and showed agreements with regards to sensations but not perceptions. In conclusion, this work highlights the relevance of the TAIL rating scheme for schools to ensure iIEQ compliance and provide an aid to the school stakeholders when decisions to remediate IEQ are taken.