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Thermal Conditions in Indoor Environments: Exploring the Reasoning behind Standard-Based Recommendations

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Abstract: Professionals in the building design and operation fields typically look at standards and guidelines as a reliable source of information and guidance with regard to procedural, contractual, and legal scope and requirements that are relevant to accountability issues and compliance necessities. Specifically, indoor environmental quality (IEQ) standards support professionals to bring about comfortable thermal, air quality, acoustic, or visual conditions in buildings. In this context, it appears essential to regularly examine the IEQ standards' applicability and scientific validity. The present contribution focuses on common thermal comfort standards in view of the reasoning and includes evidence behind their recommendations and requirements. Thereby, several international and national thermal comfort standards are examined via a structured matrix to assess basic parameters, design and performance variables targeted by the standards, suggested value ranges, and both general and specific evidence from the scientific literature. Finally, this paper discusses findings and points to the identified gaps in the chain of evidence from the results of scientific studies and the recommendations included in the thermal standards. As such, the present contribution has the potential to inform future developments regarding transparent and evidence-based thermal standards.

Keywords: indoor environmental quality; thermal comfort; standards and guidelines; evidence

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1. Introduction

1.1. General Reflections on Thermal Conditions in Indoor Environments and the Associated Impact on Occupants' Health and Well-Being

The importance of the indoor thermal experience is inarguably significant for the human species. The ability to create and control fire provided Homo sapiens with the means to optimize their living conditions in caves, a skill they exercised despite the impact it had on indoor air quality and their health [1]. This survival instinct still drives, to an extent, the environmental adjustments instantiated by humans in their built environment. However, contemporary scientific evidence also shows how indoor thermal experiences may affect—in isolation or in combination with other environmental factors—people's behavior and comfort perception [2–5], their performance or productivity [6,7], and their health and well-being [8,9]. Amongst the various strands of the indoor environmental experience, the thermal is the most methodically studied [2,10], which potentially indicates that it is dominant within the overall environmental perception. However, defining and delivering optimum thermal conditions is not just aimed at maximizing occupant satisfaction or well-being. Prolonged exposure to specific indoor environmental conditions has been shown to shift people's thermal preferences and influence their potential to adapt to thermal variations [11–17]. Moreover, it has been suggested that exposure to a wider range of temperatures outside the thermal comfort range may have health benefits [18]. This highlights the importance of standardization of criteria as well as testing and rating systems for thermal environments in buildings.

1.2. Thoughts on the General Role of the Standards in the Building Delivery Process

The European Committee for Standardization (CEN) describes standards as "technical documents" aimed to act as "rule(s), guideline(s), or definition(s)" [19]. The American Society of Heating Refrigerating and Air-Conditioning Engineers (ASHRAE) specifies that standards and guidelines often entail "uniform methods of testing for rating purposes, describe recommended practices in designing and installing equipment and provide other information to guide the industry" [20]. The British Standards Institution (BSI) describes the purpose of standards as providing a "reliable basis" for users that share "the same expectations" for a product or service [21], with attention drawn to the importance of standardization for ensuring quality, safety, and proper costing of the processes concerned.

A definition given by Batik in his guide to standards [22] is one that drew on the important role of consolidating "scientific and technical knowledge" to bring "the benefits of scientific research into widespread application", something which is very much reflected in the definitions given now by the CEN. Furthermore, the International Organisation for Standardisation (ISO) and the BSI also share a definition for standards being exactly that, i.e., "the distilled wisdom of people with expertise in their subject matter" [21,23], whereby CEN names "manufacturers, consumers and regulators" as possible creators of standards developed within their remit. Therefore, the scope of standards is seen as sharing of and capitalizing on scientific and technological progress, which evolves via research, development, and application.

1.3. Should Thermal Standards Provide Arguments for the Validity of Their Recommendations?

For standards to be seen as vehicles for translating research into mainstream knowledge and application, they must draw findings from research in a way that is traceable and transparent to both researchers and the public. This is in line with what the CEN describes as the end-product of standardization, i.e., a "consensus-built, repeatable way of doing something" [19]. Meticulous referencing of original information sources is fundamental to good research, not just to give due credit but also to encourage attention to detail, which further enhances scientific thought and reporting [24]. This is a fundamental prerequisite for the recording and dissemination of scientific findings and one embedded in the peer-review system for scientific publications. The ASHRAE draws on the tangible implications of standards' use in establishing "conditions . . . that are seen as acceptable" [20]. This translates into an intended perception that standards convey factual information that may be seen by some audiences as fundamentally accurate and unquestionable until new evidence proves otherwise.

In standards dedicated to the thermal environment, the typical approach has been to firstly establish evaluation methods, and secondly specify values for direct application to specific projects or designs [25]. This order of priority recognizes that the actual outputs of these evaluation methods are very much dependent on the context within which they are applied, a circumstance that has been also translated into the concept of classes or categories, which are relevant to the targeted indoor environmental conditions, occupant types, and climatic variations. Despite the fact that international or European standards may not be prescribing parameters or indices for controlling the quality of the thermal environment, they are often directly linked to the creation of national rules that do so. This points to the considerable influence of the guidelines beyond mere technical specifications. Given the open-ended nature of the scientific discovery process, one should expect that our standardization and regulatory systems would catch up with scientific advances, update their documentation, and maintain consistency across multiple parts and versions [26–28]. This paper focuses on the aspect of traceability [26], which, despite its strong bearing on this expectation, to our knowledge, has not been either directly or sufficiently addressed in the previous literature.

2. Approach

2.1. Overview

Given the key importance typically attributed to national and international standards as reliable tools that support decision-making in a variety of fields, the approach implemented in this paper involves the specific assessment of selected standards. Up-to-date standards indeed represent, in the authors' opinion, effective vehicles for implementing research results into mainstream knowledge and practice. Standards can support the process of designing and controlling comfortable and sustainable buildings. As there are continuous advances in the scientific state of knowledge in this domain, the present contribution focuses on the critical review and discussion of the aforementioned selection of standards. The objective of the assessment is to encourage a deeper discussion of the standards' potential to support professionals and other stakeholders in providing and maintaining high-performance indoor environments.

2.2. Selection of Standards

It is important to understand that the selection process of the analyzed standards for this contribution was not intended to generate an exhaustive list of all relevant sources in the thermal comfort domain. Rather, the intention was to identify a set of well-known and frequently referenced national and international standards with topical links to thermal comfort considerations in indoor environments. This process was aided by the authors' awareness of technical papers related to thermal comfort that make references to applicable standards. All identified sources were assessed as reported in the following Section 2.3. Thereby, key elements of the selected standards (technical content and specific recommendations) were extracted in a structured manner in order to provide a high-level perspective and facilitate the comparison of standards on a larger scale.

2.3. Standards Assessment Matrix

To facilitate the assessment of the selected standards, a specific matrix was developed. Key criteria embedded in this matrix emerged logically from the purpose of the assessment, which is the inquiry regarding the evidentiary basis of the standards' mandates. Hence, the explicitly stated independent variables in the standard (i.e., indicators of indoor environmental conditions) had to be identified together with their mandated value ranges. Additional criteria were taken into consideration based on general quality criteria as applicable to the practical role of standards in the professional community. These criteria included attributes such as usability, which is an important factor for the practical applicability and effectiveness of the standards.

The standard assessment matrix is composed of four parts, addressing (I) basic information about the standards, (II) design and performance variables targeted by the standards, (III) scientific evidence for the set of specifications, and (IV) the level of usability of the standards.

The elements of Part I of the matrix are reported in Table 1. In particular, the 'Target IEQ-domain(s)' were used to identify the IEQ domains (e.g., thermal comfort, IAQ (indoor air quality), acoustic comfort, visual comfort) addressed by the standards, since some of these are dedicated to more than one domain. In that case, it was evaluated whether a combined effect of multiple domains is considered. Finally, the 'Scope' refers to the subject and purpose of the standard.

Table 1. Part I of the standards assessment matrix.

Basic Parameters							
Full title	Abbreviation	Year	Geographic coverage	Target IEQ domain(s)	Combined effect	Relevant building type(s)	Scope

In Part II of the matrix (Table 2), the authors considered both the design and performance specifications targeted by the standard, in particular by specifying the variables concerned, the values set, and the classes defined (if any). Note that the rows of the matrix are dedicated each to different design and/or performance variables, as a standard might set, for example, different design specifications for air temperature and vertical air temperature difference (spatial dimension).

Table 2. Part II of the standards assessment matrix.

Target Design and Performance Variables					
Design variables	Design variables values	Design classes/ categories	Performance variables	Performance variables values/ranges/functions	Performance classes/ categories

Part III of the matrix was dedicated to reporting the scientific evidence in support of each specification (Table 3). Thus, as described before, the authors used each row to report the evidence for each different specification. The authors first verified whether direct evidence is available, for example in terms of a dataset directly referred to in the standard. Next, a search was conducted for general and/or specific references to other standards in support of the given specifications. General and/or specific references to the technical literature (e.g., scientific/technical papers, reports, studies) were also identified in the standard and reported. Finally, a column of the matrix was dedicated to potential other evidence for the standard's requirements, which is not referred to in the standard itself.

Table 3. Part III of the standards assessment matrix.

Evidence					
Direct evidence for the requirements	General reference to other standards	Specific reference to other standards	General reference to technical literature	Specific reference to technical literature	Potential other evidence

The last part (Part IV) of the matrix consisted of a subjective evaluation of the effectiveness, efficiency, and satisfaction with the standard by expressing the level of agreement on a different set of statements (Table 4) based on a 4-point Likert scale ('Fully agree', 'Somewhat agree', 'Somewhat disagree', 'Strongly disagree'). This query was conducted by the team of authors to obtain a first impression of how the collected standards (and the level of transparency underlying their specifications) would be perceived by potential stakeholders using them. Needless to say, given the small number of the members and the subjective component of the query, the results are not suggested to be either conclusive or definitive.

Table 4. Part IV of the standards assessment matrix.

Effectiveness	Efficiency	Satisfaction
• This standard is generally highly effective. • This standard states the design/performance criteria in a clear and unambiguous manner. • This standard encourages the flexibility toward identifying creative and effective solutions through its entailed requirements. • This standard reflects the latest state of domain knowledge and technology.	• The relevant information is easily found in this standard. • The language/material of this standard is easily accessible. • The requirements of this standard are easily complied in specific projects.	• This standard is highly motivational and inspires the development of good solutions. • Agenda, other than the objective criteria, is pursued in this standard. • Studying, using, and working with this standard is a positive experience.

2.4. Selection of Technical Literature

As outlined before, Part III of the standards assessment matrix is used to identify references underpinning the different requirements set by the standard. These references have been searched for both directly in the text and indirectly by looking at the bibliography of the standard. Most standards were scrutinized twice as they were themselves referenced in other standards. The authors also included papers not directly referred to in the standards but that were thought of as being potentially relevant to one or more requirements set by the standards. Here, again, the selection of this additional set of references was not intended to be exhaustive, but was rather based on the authors' judgment, informed by their prior knowledge and expertise.

2.5. Evaluation of the Strength of the Provided Evidentiary Material

In the process of reviewing and assessing relevant technical literature as identified in the studied standards (see Section 2.4), the strength of the provided material was evaluated. Thereby, the authors developed an additional matrix to assess relevant information stated in the provided evidentiary material. This assessment matrix included, in the first part, general information with regard to:

- Arguments for selection (i.e., type of reference (general/specific), design and performance variables for which the reference is relevant);
- Basic information (i.e., method of the study, physical and climatic context, date/duration of the study);
- Participant information (i.e., number, gender, age of participants, cultural/ethnic background);
- Collected data (i.e., IEQ data, occupant-related data, outdoor conditions data as well as respective quality/resolution of the provided data);
- Data analysis (i.e., data processing method, clarity of the results and interpretation).

In the second part of the assessment matrix, respective columns were included to evaluate the evidence strength (see Table 5). Thereby, the following three categories were considered:

(i) Data reliability;
(ii) Consistency of the results with related requirements in the standard;
(iii) Argumentation/reasoning for the evaluation of the results' consistency.

Table 5. Assessment categories with regard to the evaluation of evidence.

Data Validation	Evaluation of Evidence	
Were the results validated with reference to other/similar studies in the relevant domain?	Are the results consistent with related requirements in the standard?	Argument(s)/reasoning for your choice stated in the previous column

3. Findings

3.1. Overview on the Selected Standards, Guidelines, or Regulations and Referenced Technical Literature

Initially, a total of 17 documents (7 standards, 2 guidelines, 1 national regulation, 2 commercial certification schemes and 5 technical reports), including 8 international and 9 national/European instances, were reviewed according to the approach described in Section 2.3 [29–45].

The majority of the reviewed documents are advisory in nature, with the exception of ASR A3.5 [44], which is a German Technical Rule for Workplaces that mandates the requirements regarding indoor temperature at workplaces, and the German standard DIN 4108-2 [34], which specifies requirements regarding cold and warm season thermal protection. The two documents WELL v2 and Passive House set the criteria for building certification and are, therefore, entirely optional [39,45]. The CIBSE documents (guides and technical memorandums) offer guidance only [40–43,46]. The reviewed European standards [29,30,38] are treated differently in the member countries with respect to the degree to which they are legally binding or of advisory nature, for example, within the frame of the Energy Performance of Buildings Directive (EPBD) [47].

The reviewed ISO standards [35–37] are also voluntary as indicated in the foreword to all ISO standards [48], and are often included as part of private legal agreements in the construction process. In the introduction of the BSI version of the European standards, a clear distinction is made between standards and regulations in the sense that "compliance with a standard cannot confer immunity from legal obligations" [21]. However, the development of European standards is largely aimed at harmonizing processes that support key EU policies and directives [49]. In the case of the EPBD, EU member states are expected to consider adopting the standards it supports and to enforce their content (e.g., requirements or calculation methods) by the national building regulations. Similarly, the ASHRAE standards are also voluntary and are often designed to be used in conjunction with rules and codes, in case of enforcement by local or national jurisdiction (refer to [50] and the 'special note' included in the reviewed ASHRAE standards [31–33]).

In this review process, general (indirect) and specific (direct) references to other standards as well as general (indirect) and specific (direct) references to the technical literature were identified. Thereby, several documents were identified that could potentially provide direct or indirect evidence for performance variables (e.g., PMV) and design variables (e.g., indoor air temperature) that are referred to in the respective documents.

The majority of the reviewed documents (87%) provide general (i.e., bibliographic) and/or specific references to other standards. Most of the reviewed documents (73%) provide general reference to the technical literature, in most cases in the form of a bibliography at the end of the document. About half of the reviewed documents (60%) provide specific references to the technical literature.

Table 6 gives an overview of the basic information of the reviewed documents, such as publication year, geographic coverage, relevant building types, mentioned IEQ environments, and scope. Note that the publication dates given in this table refer to the document version reviewed (in certain cases, more recent versions of a standard might have been issued since the writing of this paper). Table 7 provides information on the documents' target design and performance variables. It has to be noted that in about half of the reviewed documents, more than one IEQ domain is mentioned.

Table 6. Overview of assessed standards, guidelines, national regulation, commercial certification schemes, and technical reports—Part 1.

Standard	Year	Geographic Coverage	Relevant Building Type(s)	Mentioned IEQ Environment	Scope
EN 16798-1 [29], CEN/TR 16798–2 [30]	2019	European	Residential and non-residential	Thermal environment, IAQ, visual environment, acoustic environment	The standard specifies requirements for indoor environmental parameters for the thermal environment, indoor air quality, lighting, and acoustics, as well as how to establish these parameters for building system design and energy performance calculations.
ASHRAE Standard 55 [31]	2020	US/International	Residential and non-residential	Thermal environment	The standard specifies the combinations of indoor thermal environmental factors and personal factors that provide acceptable thermal environmental conditions.
ASHRAE Guideline 10 [32]	2016	US/International	All indoor enclosed spaces except spaces primarily for manufacturing, parking garages, storage spaces, other spaces not designed primarily for human occupancy	Thermal environment, IAQ, acoustic environment (sound and vibration), visual environment (non-ionizing electromagnetic radiation including visible light)	The guideline provides guidance regarding IEQ factors and their interaction applicable to several space types and to the design, construction, commissioning, operation, and maintenance of buildings.
ANSI/ASHRAE/ USGBC/IES Standard 189.1 [33]	2009	US/International	Non-residential, residential above three stories, does not apply to buildings that do not use electricity, fossil fuels, or water	Thermal environment, IAQ, visual environment (daylighting), acoustic environment	The standard targets high-performance green buildings (site sustainability, water use efficiency, energy efficiency, IEQ, atmospheres, materials, resources), design, construction and operation of new buildings and their systems, new portions of buildings and their systems, and equipment in existing buildings.
DIN 4108-2 [34]	2013	National (Germany)	Residential and non-residential	Thermal environment (minimum requirements to thermal protection)	The standard describes the design of minimum thermal protection of buildings and building elements, among others warm season prevention from overheating. It includes a simple compliance method and advanced simulation method, and a procedure providing detailed simulation boundary conditions to determine the frequency of room temperatures.
ISO 7730 [35]	2005	International	Residential and non-residential	Thermal environment	The standard presents methods for predicting the general and local thermal sensation of people exposed to moderate thermal environments.

Table 6. *Cont.*

Standard	Year	Geographic Coverage	Relevant Building Type(s)	Mentioned IEQ Environment	Scope
ISO 17772-1 [36]	2017	International	Residential and non-residential (offices, schools)	Thermal environment, IAQ, visual environment (lighting), acoustic environment	The standard defines IEQ ranges to be used as input for building energy calculation and long-term evaluation of the indoor environment.Note that the standard provides empty tables (Annexes A-G) suitable for national implementation, if values differ from those shown in ISO 17772-1:2017.
ISO/TR 17772-2 [37]	2018				The technical report explains how to use ISO 17772-1 for specifying IEQ parameters for building system design and energy performance calculations. It also outlines new possibilities to improve the IEQ and reduce the energy use of buildings (e.g., personalized systems, air cleaning technologies, consideration of adapted persons).
EN 14501 [38]	2018	European	Not specified (non-residential and residential)	Thermal environment, visual environment	The standard specifies prescriptive building measures for controlling solar gains by providing reference parameters for glazing and shading devices.
WELL v2 [39]	2020	International	Residential and non-residential environments	Thermal environment, IAQ, visual environment, acoustic environment	The commercial certification scheme includes a set of strategies around ten concepts, namely air, water, nourishment, light, movement, thermal comfort, sound, materials, mind, and community. The thermal comfort concept considers, among other aspects, general thermal comfort, local (dis)comfort, and control over the thermal environment.
CIBSE Guide A [40]	2021	National (UK)	All types	Thermal environment, IAQ, visual environment, acoustic environment	The guideline provides a set of criteria for the building environmental design regarding indoor environment (thermal, visual, and acoustic) and health (IAQ, mold growth) as well as methods of calculations (e.g., thermal comfort evaluation, energy demand).

Table 6. *Cont.*

Standard	Year	Geographic Coverage	Relevant Building Type(s)	Mentioned IEQ Environment	Scope
CIBSE TM40 [41]	2020	National (UK, extension to Australia)	All types except healthcare buildings	Thermal environment, IAQ, visual environment (daylighting), acoustic environment, other (land-scape/vegetation, electromagnetic fields, water)	The technical report provides guidance on the relevance of health and well-being strategies for building services. It concerns key environmental parameters that impact well-being in the design, construction, and operation of buildings, including indoor environment and further areas.
CIBSE TM52 [42]	2013	National (UK) /European	Non-residential	Thermal environment (overheating in the warm season)	The technical report provides a series of criteria by which the risk of overheating can be assessed or identified.
CIBSE TM59 [43]	2017	National (UK)	Residential (new or refurbishment)	Thermal environment (overheating in the warm season)	The technical report provides a design methodology for the assessment of overheating in homes based on the use of dynamic thermal modelling.
ASR A3.5 [44]	2010	National (Germany)	Non-residential (workplaces, rooms for work breaks, sanitary, canteen)	Thermal environment (occupational safety and health: sufficient room temperature at the workplace)	The rule specifies mandatory minimum requirements for the room temperature of workplaces specifying the general requirements of the German Ordinance of Workplaces (under the German Safety and Health at Work Act) as well as basic occupational safety obligations of the employer, obligations and rights of employees, and the monitoring of occupational safety.
Passive House [45]	2015	International	All types	Thermal environment and IAQ in the context of energy use compliance	The commercial design and certification scheme concerns ultra-low-energy buildings.

Table 7. Overview on assessed standards, guidelines, national regulation, commercial certification schemes, and technical reports—Part 2.

Standard	Targeted Variables	
	Design Input	Performance
EN 16798-1 [29], CEN/TR 16798–2 [30]	Input parameters for the design of building envelope, heating, cooling, ventilation, and lighting, operative temperature range for assumed space types, presence/no presence of heating/cooling systems, radiant temperatures, air speed, air temperature, floor surface temperature	Performance criteria are defined in CEN/TR 16798–2, categories (PMV, temperature ranges, radiant temperature asymmetry, draft, vertical temperature gradient, floor temperature), long-term evaluation of IEQ based on post-occupancy studies or simulations

Table 7. *Cont.*

Standard	Targeted Variables	
	Design Input	Performance
ASHRAE Standard 55 [31]	Air temperature, radiant temperature, indoor air humidity, air speed	PMV, indoor operative temperature, long-term evaluation of the general thermal comfort conditions
ASHRAE Guideline 10 [32]	-	-
ANSI/ASHRAE/USGBC/IES Standard 189.1 [33]	Thermal environmental conditions for human occupancy: refers to ANSI/ASHRAE Standard 55 (Section 6.1 "Design")	Thermal environmental conditions for human occupancy: refers to ANSI/ASHRAE Standard 55 (Section 6.2 "Documentation")
DIN 4108-2 [34]	Envelope/space properties with regard to thermal protection in the cold and warm season (minimum requirements)	Operative temperature reference values and maximum degree hours for acceptable overheating in the advanced compliance method
ISO 17772-1 [36]	Air temperature, mean radiant temperature, floor surface temperature, operative temperature, air speed, air humidity	PMV, draft rate, vertical air temperature difference, warm and cool floors, radiant asymmetry
ISO/TR 17772-2 [37]		
EN 14501 [38]	Total energy transmittance g_{tot}, secondary heat dissipation $q_{i,tot}$, perpendicular transmittance $T_{e,n\text{-}n}$, out of scope visual variables	Operative temperature
WELL v2 [39]	-	PMV, indoor operative temperature, % satisfied (survey), measurements: dry-bulb temperature, relative humidity, air speed (only for projects that use elevated air speed method), and mean radiant temperature
CIBSE Guide A [40]	Air temperature, radiant temperature, indoor air humidity, air speed	Acceptable temperature bands, acceptable temperature, acceptable temperature drift during a day/over several days, radiant temperature asymmetry, overheating risk-assessment, combination of (high) relative humidity (RH) and (high) temperature, relative humidity, minimum acceptable air temperature, combination of indoor RH, air temperature, and fresh air supply
CIBSE TM40 [41]	Air temperature, mean radiant temperature, wind speed, solar gains, etc. (all relevant environmental parameters of PMV model), physiological and behavioral/adaptive mechanism (implicating 'clo' and 'met' of PMV model), adaptive opportunities, social/cultural conditions (e.g., perceptions of sweating)	PMV, operative temperature (link to CIBSE Guide A), running mean of outdoor temperature (link to CIBSE TM52, TM59)
CIBSE TM52 [42]	Air temperature, radiant temperature, humidity, air speed, clothing, and activity level	PMV, operative temperature, upper limit temperature
CIBSE TM59 [43]	Design condition to find cost-effective options to limit overheating risk whilst also delivering all the other aspects occupants look for in their homes (e.g., daylight, insulation, view, etc.)	Includes combination of design aspects that contribute to overheating risk, i.e., windows and door openings, exposure time, infiltration and mechanical ventilation, air speed assumption, blinds and shading devices, communal corridor

Table 7. *Cont.*

Standard	Targeted Variables	
	Design Input	**Performance**
ASR A3.5 [44]	-	Requirements towards room temperature represented by the air temperature depending on activity and body posture and partly depending on outdoor temperature. Qualitative descriptions of how to protect against excessive solar radiation, examples are given
Passive House [45]	Operative temperature, minimum thermal protection, building and primary energy use	Frequency of overheating, frequency of high humidity incidence and occupant satisfaction, standard allows designers an alternative pathway to proving thermal comfort if adherence to DIN EN ISO 7730 is demonstrated

In a second step, the identified technical literature is assessed according to the developed matrix. Thereby, a total of 39 technical publications are reviewed in detail in order to evaluate the entailed evidentiary material, if any. In the end, a total of 21 papers were found to provide some form of direct or indirect evidentiary material [14–17,51–67]. Table 8 provides information on the evidentiary material included in the selected standards [29–31,36,37]. Thereby, it has to be noted that all selected standards include references to other standards (between 7 and 38 links) and to technical reports (2 to 7 links). While EN 16798-1 [29] and ISO 17772-1 [36] do not include any link to research publications, CEN/TR 16798-2 [30], ISO/TR 17772-2 [37], and ASHRAE Standard 55 [31] include between 23 and 75 links to research publications. Specific references related to thermal comfort are rarely included (for instance four references are included in CEN/TR 16798-2 and ISO/TR 17772-2 [30,37]).

Table 8. Analysis of selected standards (note that ST refers to standard, TR to technical reports, and RP to research publication).

Standard	Year	References ST/TR/RP
ASHRAE Standard 55 [31]	2020	4/2/75
EN 16798-1 [29]	2019	Overall: 38/6/0, related to thermal environment: 7/1/0
CEN/TR 16798-2 [30]	2019	Overall: 35/3/23, related to thermal environment: 7/1/4
ISO 17772-1 [36]	2017	Overall: 37/7/0, related to thermal environment: 7/2/0
ISO/TR 17772-2 [37]	2018	Overall: 7/2/23, related to thermal environment: 1/0/4

The following section (Section 3.2) provides a summary of the overall evaluation of the strength of the evidentiary material in the standards. The subsequent section (Section 3.3) discusses the evaluation of the perceived usability of the standards.

3.2. Summary of Findings

This section is structured along thermal comfort models, namely *(i)* exemplary evidence in support of the variables related to the PMV model of thermal comfort, *(ii)* exemplary evidence in support of adaptive model-based thermal comfort criteria, and further criteria regarding *(iii)* exemplary evidence related to local discomfort and overheating. Our intention is merely to evaluate the traceability of thermal environment-related evidence in standards, guidelines, national regulation, commercial certification schemes, and technical reports to their research basis.

ISO 7730 [35], ASHRAE Standard 55 [31], and EN 16798-1/ISO 1777-1 [29,36] include the PMV model predicting people's sensation, which was developed based on the human body's thermal balance under steady-state ambient conditions by Fanger [51,68]. For example, ISO 7730 [35] and ASHRAE Standard 55 [31] generally reference this work [51]. However, detailed reference to specific parts of the work is not provided in the standards. With regard to recommended criteria for the thermal environment for mechanically cooled and heated buildings, EN 16798-1 [29] refers specifically in Appendix A.2.1/B2.1 to ISO 7730 [35]. ISO 17772-1 [36] also refers to ISO 7730 [35] in its bibliography, but references specifically to this standard only in the introduction. ISO/TR 17772-2 [37], (p. 4) specifically names ISO 7730 [35] in the text about the criteria for mechanically heated or cooled buildings and states that typical values for activity and clothing insulation could be found in the stated references. However, this standard (and its title) is not listed in the bibliography. Furthermore, the standard is not listed as the source for a detailed description of the PMV method. ISO 7730 [35] refers generally to Fanger's work [68] but does not mention it in the text. Only experts can relate the standardized method for general thermal sensation to the original work and supplementary later work.

Going deeper into ISO 7730 (p. 3, [35]), the standard states that "the index should only be used for values of PMV between −2 to +2 [...]" which is in accordance with Fanger [51,68]. Looking at the tables in Appendix E of ISO 7730 [35], this recommendation was considered. The ranges of the variables given in the appendix tables (metabolic rate: 0.8–4 met, clothing insulation 0–2 clo, ambient temperature −10 to 34 °C, air velocity < 0.1–1.0 m/s, and a relative humidity of 50%) are in accordance with the ranges for the application of the PMV method given in the method description of ISO 7730 (metabolic rate: 0.8–4 met, clothing insulation 0–2 clo, air temperature 10–30 °C, mean radiant temperature 10–40 °C, air velocity 0–1 m/s, and partial vapor pressure 0–2700 Pa), though they deviate from Fanger's tables in [51,68]. Fanger [51,68] compares the heat balance equation with empirical data and states that it "must [...] be remembered that only 'spot' comparisons are possible, since the results of the 'empirical' studies apply only at one constant value of each of the four variables" ([68] last paragraph of Chapter 2). Similar remarks follow in the chapter in which the PMV as the thermal index is developed [51,68]. In Fanger's own experiments, which were accomplished by earlier studies by Nevins [52,69], a single clo value of 0.6 clo was tested and operative temperature values were tested (air temperature and mean radiant temperature) that included a range of 18.9–32.2 °C. Overall, the PMV index development and the related empirical studies provide, first of all, an excellent example of good documentation, and since the standard developed as a follow up from this piece of research [51,68], overall, there is a good representation, documentation, and transparency given. Apart from this, extensions or adjustments to the original method carried out in the course of the standardization would benefit from direct references.

Adaptive thermal comfort models represent an empirical field-study-based thermal comfort model approach that is included in many standards and guides internationally: among others, ASHRAE Standard 55 [31], EN 16798-1 [29], ISO 17772-1/2 [36,37], CIBSE Guide A, CIBSE TM52, CIBSE TM 59, and CIBSE TM40 [40–43]. There are other adaptive comfort standards, for instance the Indian standard [70], which we do not elaborate further on here. The adaptive thermal comfort approach states that adaptive thermal comfort models relate indoor operative temperatures ranges to outdoor temperature conditions including the recent history of the course of the outdoor temperature (running mean outdoor air temperature). ASHRAE Standard 55 in 2004 was the first to include an adaptive thermal comfort model in a standard based on evidence given from ASHRAE RP 884 and a proposal worked out by de Dear and Brager [57]. While in the original work ASHRAE RP 884, the outdoor thermal conditions were represented by the mean monthly outdoor effective temperature, the outdoor thermal conditions as implemented in the first version of ASHRAE 55 (2004) were represented by the mean monthly outdoor air temperature [16]. Only later were the thermal conditions represented by the running mean outdoor air temperature as in the current version [31].

The second standard that included an adaptive thermal comfort model was EN 15251 [71] (the precursor of EN 16798-1 [29]) in 2007, based on evidence from the European project SCATs [72] and a proposal by McCartney and Nicol [56] for the inclusion into a European standard. In addition, a large number of publications in relation to these two main research projects, on which the American and the European adaptive models are based, have been published and cannot be mentioned here.

ASHRAE Standard 55 [31] includes the adaptive thermal comfort model as the method to determine "Acceptable Thermal Conditions in Occupant-Controlled Naturally Conditioned Spaces" in its normative Section 5.4. informative Appendix I, which explains the application of the method in more detail. However, no references to the research literature in Appendix L are established, which contains the main reference ASHRAE RP 884 and a related publication [17] as well as one further research publication related to the adaptive thermal comfort approach.

EN 16798-1 Annex B2.2 [29] and ISO 17772-1 Annex B.2 [36], which address the adaptive thermal comfort model approach, do not contain any references. Likewise, paragraph 6.2.2 in [29] only contains one cross-reference to a method to evaluate the long-term performance of the thermal environment. CEN/TR 16798-2 [30] and ISO/TR 17772-2 [37] are the technical reports to EN 16798-1 [29] and ISO 17772-1 [36]. They aim to explain "how to use EN 16798-1 for specifying indoor environmental parameters for building systems design and energy performance calculations". In both documents' sections on the thermal environment, there are four relevant research-related publications [73–75], of which one relates to the ASHRAE RP 884 project by de Dear and Brager, and three relate to the summarized research work by Humphreys and Nicol, also covering the SCATs project [72]. However, these research publications are exclusively mentioned in the bibliography. Neither Annex B2.2 and B.2, respectively, nor the respective Paragraph 6.3.2 in both documents mention any of these references, though they are supposed to explain the respective sections in the standard EN 16798-1 [29] and ISO 17772-1 [36]. It is not possible to locate the related references to the topic of thermal environment in the text.

CIBSE Guide A [40] uses specific references directly in the text. With regard to the adaptive thermal comfort model, Section 1.4.1 refers to examples of the origin of the approach [73,76,77]. Section 1.5.2 in [40] introduces the adaptive model's relation of comfort temperatures and outdoor temperature referencing directly to related SCATs data [56,78] and related studies supporting the choice of specific parameters, for example, the constant α [79] used to determine the running mean outdoor temperature in the adaptive model. The text in Section 1.4.1 explicitly names a publication by Humphreys et al. 2013 [14] to support the mentioned sufficient amount of occupant control to adjust the temperature in a range of $+/-$ 2 K. A related technical paper that has been directly referenced by CIBSE Guide A [40] is a study by Humphreys et al. [15]. The results of this study are cited in CIBSE Guide A as the evidence base for the acceptable temperature drift during a day of $+/-$ 1K.

Draft is unwanted local cooling caused by air movement [31,55] and is a phenomenon of local discomfort that is relevant mainly for a close to neutral overall thermal sensation. Draft sensation, according to Fanger, depends on the local air temperature, local mean air velocity, and local turbulence intensity, and is applicable to light sedentary work activity with the whole body thermal sensation close to neutral [35]. It is addressed, among others, in ISO 7730 [35], EN 16798-1/2 [29,30], and ASHRAE Standard 55 [31]. Fanger et al. [55,80] laid the foundation to the method and validity range of draft rate model included in those standards.

ISO 7730 [35] lists 10 references in the bibliography which are related to draft in close to neutral environments. None of them are directly referenced in the text, which makes it challenging to follow up on the results. The method presented in Section 6.2 of ISO 7730 [35] presents the formula from [55] and its application for predicting draft at the neck for people at light sedentary activity. Proposed adjustments and extensions of the model by a wider range of air temperatures and activity levels as, for example, by Griefhahn et al. [81] seem not to be considered, though the reference is mentioned in the bibliography. ISO 7730 [35] makes another indirect reference to a technical paper [62]. The paper makes an argument for considering airflow direction when assessing draft. Even though the paper is referenced, ISO 7730 [35] does not consider airflow direction as an evaluation criterion. The following quotation (p. 6, [35]) could be regarded as a representation of both references in this standard: "At the level of arms and feet, the model could overestimate the predicted draught rate. The sensation of draught is lower at activities higher than sedentary (>1.2 met) and for people feeling warmer than neutral."

EN 16798-1 [29] lists requirements for the draft rate in Table B.3 in its Annex B, otherwise the standard refers in Section 6.2.1.2 to its technical report [30] which provides few introductory explanations and otherwise repeats the content of ISO 7730 [35] without providing direct references. ISO 7730 [35] is referenced in the bibliography as the only reference related to draft.

ASHRAE Standard 55 [31] indirectly provides references to 13 research publications on the effect of air movement on thermal comfort. It also refers to the original work by Fanger et al. [55,80] on the draft rate model. Related regulative content does not precisely represent the results insofar as ASHRAE Standard 55 describes draft sensation as being dependent on the air speed, the air temperature, the activity, and the clothing, but does not mention turbulence intensity. Furthermore, it provides one maximum value for limited air speed below the operative temperatures of 22.5 °C of 0.15 m/s. According to ASHRAE Standard 55 [31] "sensitivity to draft is greatest where the skin is not covered by clothing, especially the head region comprising the head, neck, and shoulders and the leg region comprising the ankles, feet, and legs". This seems to represent the results presented in Toftum [62], which are referenced in the bibliography, though it refers to a different publication by Toftum [62] on air flow direction than ISO 7730 [35]. It needs to be mentioned that ASHRAE Standard 55, beyond addressing the potential of air movement to cause local discomfort, also considers the importance of air movement for local convective cooling in warm conditions contributing to improving comfort perception, also referenced indirectly in its bibliography. However, we do not elaborate further on this here.

All mentioned standards use different classes A, B, C [35] or categories I, II, III [29,30,36,37] and assign different levels of predicted dissatisfaction to these categories or classes (Table 9). No information can be found on why these assigned levels differ between general and local discomfort and why they differ between the domains of local discomfort. ASHRAE Standard 55 [31] uses just one category for acceptable general thermal comfort (analytical method: equaling PPD 10%; adaptive model: 80% acceptability) and local thermal discomfort (Table 9). Systematic analyses from three databases (among others, ASHRAE Database I and SCATs [72]) showed that "no relative satisfaction benefit to individuals or to realistic building occupancies" [82] can be found for class A compared to class B and C buildings. Likewise, in the recent ASHRAE Database II [83], real-world data analyses do not provide support to the hypothetical satisfaction benefit of such classes [84].

Table 9. Maximum predicted levels of dissatisfaction assigned to the categories in selected standards. ASHRAE's requirements for general (PMV) and local thermal comfort are marked in bold.

Categories ISO 7730	Categories EN 16798-1/2 ISO 17772-1/2	General Thermal Comfort—PMV	Draft	Vertical Air Temperature Difference	Warm/Cold Floors	Radiant Temperature Asymmetry
A	I	<6	<10	<3	<10	<5
B	II	**<10**	**<20**	**<5**	**<10**	**<5**
C	III	<15	<30	<10	<15	<10
	IV	<25				

The German Rule on Workplace Temperature ASR A3.5 [44] contains a section on allowed temperatures in the case of elevated outdoor temperature (>26 °C) and defines a step model of how to act in case of room temperatures above 26 °C and above 30 °C. It refers to five technical documents, of which four are occupational safety and health guidelines of OSH insurance organizations. It does not reference any research publications. In connection with the development of the rule, experiments were carried out investigating performance, perception of thermal environment, and, for example, drinking behavior with subjects. The experiments serve as one basis for the revised rule containing a stepwise action model. The experiments' results are documented in a report [85]. More details about the considerations when developing the rule are described in a research publication [67]. However, none of the publications are referenced in the rule, which is one of the general approaches when developing those mandatory rules as described and discussed in [26] for the case of the German Rule on Workplace Ventilation.

Overall, it appears that the referencing of the scientific literature in standards is inconsistent, with no clear distinction or definition of direct and indirect references. Some standards use in-text citations in the relevant sections, while others just mention the papers in a general bibliography, or some not at all.

3.3. Usability

As described in Section 2.3, a subjective evaluation of the standards' effectiveness, efficiency, and satisfaction is performed in the course of assessing the standards. Thereby, the researchers involved in the present effort expressed the level of agreement with a set of different statements in view of the following three aspects: effectiveness (indicated in terms of Part A in Figure 1), efficiency (indicated in terms of Part B in Figure 1), and satisfaction (indicated in terms of Part C in Figure 1). The evaluation results of the standards' usability are presented in Figure 1 and discussed in the following.

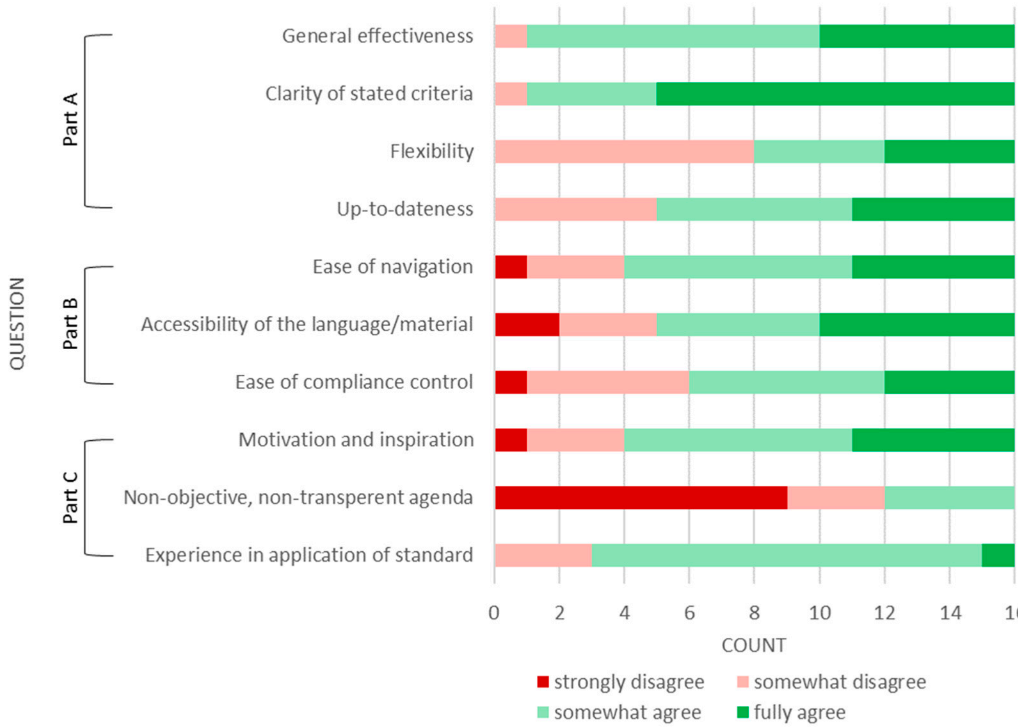

Figure 1. Evaluation of standard's usability in view of effectiveness (**Part A**), efficiency (**Part B**), and satisfaction (**Part C**).

On the one hand, opinions differ with regard to the standards' flexibility. About half of the assessors disagree that the standards encourage flexibility toward identifying creative and effective solutions within the respective requirements. On the other hand, most agree in terms of the general effectiveness of the standard as well as on the clarity of the stated criteria, such as that the performance and design variables are stated in a clear and unambiguous way. Moreover, about one third of the assessors disagree with the statement that the standard reflects the latest state of the domain knowledge and technology. This impression is also in line with the overall statistics in Section 3.1, which identifies the average publication year of the included references as the year 1996.

While there is agreement that relevant information is easily found and that the included language and material are easily accessible, about one third of the assessors disagree that the requirements of the standard are/can be easily complied with in specific projects.

The majority perceive working, studying, and applying the standards as a positive experience. A likewise positive impression is perceived in terms of motivation and inspiration characteristics of standards towards encouraging good solutions. In contrast to this, standards are not found to entail non-objective and non-transparent agendas.

4. Discussion

The analysis of exemplary thermal comfort standards shows that it can be challenging to trace the origin or evidentiary basis of specific evaluation criteria or design values/methods because of often missing direct references. Especially for those who were not involved in the development process of standards, guidelines, codes, or regulations (e.g., practitioners or young researchers), it is often difficult to understand why a specific requirement is included or whether evaluation criteria or design values are fully supported by acknowledged evidence such as peer-reviewed research publications.

Those involved in the standardization processes may be more aware of the fact that, in certain instances, research results are provided in a form that cannot be easily mapped onto practice-oriented design requirements or evaluation criteria. It may be that available research does not cover the desired scope completely, or that not all relevant cases were investigated, or that a research work refers to a variable which does not match with the variable that is mostly used or easily available (or measurable) in professional practice (e.g., outdoor air temperature instead of outdoor effective temperature [16]). Research is subject to funding and, therefore, standardization committees cannot simply "order" research that completely closes knowledge gaps or conclusively substantiates necessary simplifications and transformations of available knowledge to workable guidelines.

Discussions within standardization committee meetings may be documented in terms of meeting minutes, but such minutes are typically not accessible to those who apply standards or conduct research. In fact, internal decision-making processes cannot be retraced by others after the publication of the standard. On the other hand, there is a need to translate research results into practice instead of waiting until the last missing piece of information is provided, since standards, guidelines, codes, or regulations still intend to reflect the technology and thinking currency of standards, guidelines, codes, or regulations. Therefore, it is paramount to follow a transparent process when developing standards. Thereby, it must be ensured that new knowledge supporting the standards' recommendations is continuously embedded in the standards in a traceable manner. This can be stated in the case for the inclusion of the general thermal comfort requirements and models into standards.

Documentation related to standards has sometimes been published in terms of papers by participants (authors, researchers) involved in the standardization processes. As mentioned in Section 3.2, one example is the contribution by de Dear and Brager [16] regarding the change from outdoor effective temperature to mean monthly outdoor air temperature. However, such documentation can only target specific issues or changes in standards and guidelines. In some countries (e.g., Germany), the parties involved in the development processes of a rule, guideline, or standard publish comments on the standards that entail deeper explanations or reasonings for various criteria, requirements, or values. An example is the description of the development of the summer overheating requirements for ASR A3.5 [44] by Hellwig et al. [67]. However, it is not possible to include all aspects, requirements, and past and current developments in such publications, nor would practitioners be able to easily access those publications (for instance, in terms of linked open-access documents related to the relevant standards).

ASHRAE Standard 55 [31] includes a reporting of the development process by documenting the publication history of the standards´ follow-up versions. A summary of major changes is included in the addenda as well as a detailed description of changes in the relevant sections in its appendix ("Informative Appendix M—Addenda Description"). A reasoning for the changes is sometimes provided. Since 2004, ASHRAE has used a continuous maintenance procedure whereby the addenda to the standards are publicly available on the ASHRAE website [86]. Thereby, changes or corrections that have been included in follow-up versions of the standard are documented and traceable.

5. Recommendations for Future Standardization Efforts and Conclusions

The quality of indoor environments in general and thermal conditions in particular represent major indicators of buildings' performance. In this context, related standards play a major role. It is generally assumed that standards translate the results of disciplinary knowledge (in this case, appropriate thermal comfort conditions for human occupancy) into specific requirements (typically, values of specific performance indicators that are treated as proxies of people's perception of thermal conditions). Thus, the standards have the potential to act as the source of reliable information for the professionals involved in the building design and operation process. Moreover, they can be also relied upon in regulatory processes pertaining, for instance, to building certification and compliance checking. Given the significance of the standards' role in the building delivery process, it seems appropriate to regularly examine the consistency and up-to-dateness of their content and the degree to which such content is supported by actual evidence. The present contribution provided a preliminary effort in this direction. Thereby, the intention was not to offer exhaustive coverage, but to point to certain common observations that could contribute to the continued development and further improvement of standards in this area. A number of such observations may be briefly recapitulated for the area of thermal comfort as follows:

- The reviewed thermal standards include both general (i.e., bibliographic) and specific references to other standards.
- Likewise, many standards include general references to the technical literature. About 60% of the thermal standards refer specifically to the technical literature (i.e., scientific/technical papers, and reports).
- In case of some standards, several indirect pieces of evidence are stated in the bibliography section that seem to provide evidence, but these sources are not clearly stated or referred to with regard to the standards' specific mandates.
- The origin of thermal comfort methods that have been incorporated into standards decades ago (e.g., PMV model, draft rate model, adaptive model) is, in principle, traceable. However, the evidence and traceability of some details is not fully given in all cases. Directly referencing would improve this considerably.
- The referenced literature per se, even if inconsistently quoted, does in the majority entail empirical studies with consistent findings. Some of the references in the bibliographies report on findings which seem to have not made their way into the standards.
- The reasoning of included classifications in the selected standards is not found in the standards or their related technical reports.

It is important to note at this point what the above critical observations intend and what they do not. The intention is not at always to derogate the considerable effort and legacy involved in the development of standards. Specifically, thermal comfort standards have, in general, played and still play an important and constructive role in raising awareness and sensitivity to a very critical purpose of building activity, namely occupants' health and well-being. Hence, pointing to existing shortcomings is intended to contribute to continuous improvement and enlightened application of the standards in practice. The findings of the present effort imply the need for further efforts in at least two directions:

- On the one side, the quality of standards needs to be improved vis à vis multiple criteria, including transparency, clarity, consistency, communication effectiveness, documentation of the underlying reasoning, traceable logic, and rules in provision of evidence and referencing, explicit declaration of gray areas of knowledge and uncertainties, and most importantly, perpetual updating in the context of emerging new understanding and knowledge.
- On the other side, the scientific community cannot expect the standardization bodies to single-handedly sift through the vast and rather inhomogeneous body of research in this area. Such bodies have to engage in much complex and consensus-oriented deliberations involving multiple—at times conflicting—interests that are not solely technical and domain-specific, but originate from industry, commerce, and policy. Consistent science-based formulations of the state of the art in the pertinent domain (in this case, thermal comfort) is a task best performed by the pertinent scientific community.

In order to increase the transparency and traceability of standard-based criteria, including their evidentiary basis, the following key recommendations appear justified:

Writing and communication:

- Specific approaches, criteria, or values in standards and guidelines should provide direct references to the original research that forms their evidentiary basis.
- The users of standards would benefit from a consistent and clearly communicated referencing method and style. Abiding by such an approach across multiple standards (i.e., not only thermal but also related to other IEQ domains) would facilitate a more productive application of standards.

Standardization process:

- A systematic documentation of the standardization process would be beneficial (beyond minutes or work documents with tracked changes). Such documentations should also be accessible to the users of standards and guidelines (see for instance ASHRAE's continuous maintenance procedure).
- The above-mentioned documentation of the standardization process should provide detailed information and arguments for the evaluation criteria, models, and design recommendations.
- Reports, publications, or other materials that provide the evidentiary basis should be preserved along with the standard and preferably published as open-source documents also accessible to non-academic stakeholders.
- If extensions, supplements, and transformations of the standards were made based on the updated state of knowledge, then the respective adjustments or additions need to be highlighted in a transparent manner. If no evidentiary basis is provided for such extensions, supplements, and transformations, then arguments must be given as to why they were implemented.
- Such documentation and reasoning are also necessary when changes to standards are implemented.

Publication:

- Standards, guidelines, or codes, as well as their revisions, should be supplemented with a technical document containing (*i*) direct reference to the evidentiary research and (*ii*) the argumentation for the development or transformation process.

An essential recommendation for future standardization processes is to solve the lack of detailed documentation and transparent traceability, for instance, via platforms for knowledge management. Anyone accessing or obtaining a standard should be provided in the process with information and access to documentation of the evidentiary basis of that standard's key mandates.

Future standards would benefit from applying agreed-upon across-the-board rules in referencing and citations. Future research could also profit from such documentation practices as the existing gaps in the state of the scientific understanding of the relevant subject could be more readily recognized. As such, research funding organizations could be provided with more solid and objective grounds to support new research endeavors and enhance technical research protocols.

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