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What is a safety 'control'? A systematic review of the lexicon of safety controls for defense and prevention

Yaqoob Raheemy [a,*], Fred Sherratt [b,1], Matthew Hallowell [c]

[a] Dept. of Civil, Environmental, and Architectural Engineering, University of Colorado, Boulder, 1111 Engineering Drive, UCB 428, Boulder, CO 80309, USA
[b] Construction Safety Research Alliance, University of Colorado Boulder, 1111 Engineering Drive, UCB 428, Boulder, CO 80309, USA
[c] K. Stanton Lewis Professor of Construction Engineering, and Executive Director, Construction Safety Research Alliance, Dept. of Civil, Environmental, and Architectural Engineering, Boulder, 1111 Engineering Drive, UCB 428, Boulder, CO 80309, USA

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ABSTRACT

Introduction: The concept of control has been central to safety management, evolving from early machine-guarding statutes to a key role in accident prevention and risk science. Interestingly, it now underpins the modern view that safety is the presence of controls rather than the absence of injury. More importantly, poorly defined or insufficient controls remain a routine root cause of accidents, yet the term still lacks a shared, accepted definition. *Method:* To this end, we conducted a PRISMA-guided systematic review of peer-reviewed and gray literature, asking: (1) what definitions of control exist? (2) what categories or types are proposed? and (3) how is control effectiveness evaluated? The review was limited to documents discussing controls as preventive or defensive measures, under specific inclusion and exclusion criteria. *Results:* In the corpus examined, the study identified no single, agreed-upon definition of control. Terms such as barriers, defenses, and safeguards are frequently conflated, and, notably, even the widely referenced term barrier is used inconsistently in the literature and standards. Additionally, although multiple classification schemes exist, none provides a validated framework for categorization or adequacy assessment, leaving systems vulnerable under abnormal conditions. The Hierarchy of Controls, dominant in safety standards, rests more on professional consensus than on empirical evidence and therefore warrants further scrutiny. Energy-based safety thinking, particularly the notions of direct control and high-energy thresholds, offers a promising path for defining and evaluating controls. *Practical Applications:* The practical application of this work lies in its potential to support a more precise and consistent understanding of what constitutes a safety control. Addressing current ambiguity enables practitioners to better design, implement, and assess effective controls in high-risk environments, thereby strengthening interventions and advancing more informed decision-making across research and practice.

1. Introduction

The concept of control has played a fundamental role in safety management throughout its history (De Ruijter & Guldenmund, 2016; Dekker, 2019; Li & Guldenmund, 2018). Indeed, the earliest mention of control with regards to safety legislation can be found in the UK's Factory and Workshop Act of 1878, which explicitly states the need for machine guarding as the first control legally required in the mills and factories following the first industrial revolution (Sherratt, 2016). Yet despite such early inclusion, and the subsequent extensive research of controls as preventative measures for occupational safety (Selleck et al., 2023; Squillante et al., 2021; Zhang et al., 2019), the fatality rate in high-risk industries, such as construction, still remains worryingly high.

Controls have a longer and more complex relationship with safety management than might be expected. They have been an enduring part of the lexicon, but their consideration has taken, and continues to take, various forms depending on context and operationalization. Controls can be conceptualized as a process, a systemic or operational control found within SMS (Hudson, 2001) an example being the use of gateways for planning and project progress. Alternatively, and very differently, their close links to accident prevention (Li & Guldenmund, 2018) have seen them also positioned as tangible interventions and preventative strategies, to varying foci such as high-energy or dynamic interactions (Ahmadi et al., 2021).

* Corresponding author.
E-mail addresses: mohammadyaqoob.raheemy@colorado.edu (Y. Raheemy), fred@nemesisv.co.uk (F. Sherratt), matthew.hallowell@colorado.edu (M. Hallowell).
[1] Formerly affiliated with the Construction Safety Research Alliance, University of Colorado Boulder, USA, at the time this research was conducted.

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The prominence of controls within safety management is indubitably and mainly intertwined with the way in which accidents and incidents have been theorized, conceptualized, and investigated in practice (Bellamy, 2015; Mohammadi et al., 2018; Zhang et al., 2019). Early models, such as Heinrich's (1931) Domino Theory, conceptualized accidents as a sequence of events, where controls acted as interventions to prevent unsafe acts and conditions (Kjellén & Adinyira, 2017). Bird (1974) expanded this view, framing 'lack of control' as the initial cause of accidents, emphasizing its preventive role within organizational frameworks. As industrialization introduced new risks, models evolved to address these complexities. Energy models, developed by Gibson (1961) and Haddon (1973), identified uncontrolled energy transfer as a root cause of injuries, prompting controls designed to manage energy flow and prevent harm (Swuste et al., 2014). Further advancements questioned the linearity of earlier models, especially for complex sociotechnical systems (Leveson, 2004). Systemic models emerged, viewing accidents as the result of non-linear interactions within organizational, social, and technical systems. Here, controls focus on managing dynamic interactions and feedback loops to ensure system stability (Altabbakh et al., 2014; Zhang et al., 2022).

This complex and broad application of controls within the safety space has created an impression of a shared understanding of the concept. As a result, there is often no perceived need to seek clarification when discussing safety controls. This presumption of shared understanding permeates many standards and scholarly literature, which frequently fail to provide a consistent definition or conceptualization of controls (Roelen et al., 2018). Such ambiguity presents a significant challenge for those striving to optimize safety controls. As Selleck et al. (2023, 2022) argue, controls are often undefined, ineffective, and inadequate (Lingard et al., 2021; Winge & Albrechtsen, 2018). They emphasize the necessity of redirecting attention toward enhancing the reliability and effectiveness of controls, recognizing these efforts as pivotal to preventing fatalities and advancing in safety practices. Achieving this, however, demands a more nuanced understanding of how controls are conceptualized in both research and practice. On the other side, with the modern perspective defining safety as the presence of controls rather than the absence of injuries (Conklin, 2019), the impetus to explore this concept becomes even more compelling.

Ideally, such work will also contribute to the establishment of agreed definition for control, a gap that the field suffers from. Agreed definitions form the cornerstone of every scientific discipline and absence of a precise definition significantly hampers the scientific community, obstructing the testing of hypotheses, replication of research protocols, and constructive debate on conclusions (Raheemy et al., 2025; Abbott, 2002). As Kaplan (1990, cited in Sklet, 2006, p. 495) aptly noted, "When words are used sloppily, concepts become fuzzy, thinking is muddled, communication is ambiguous, and decisions and actions are suboptimal, to say the least." Conversely, clear and accepted definitions bring precision and clarity to language, facilitating unambiguous communication of ideas and concepts (Abbott, 2002). More importantly, they enable research to be approached from diverse perspectives and through various methodological lenses, ultimately aggregating knowledge to enhance the practical application of controls in the field.

Therefore, this paper seeks to respond positively to the arguments of Selleck et al. (2022, 2023) and make a contribution to the wider literature on this topic, presenting a robust systematic literature review of safety controls that remains agnostic in its content to support further research within specific applied fields. Specifically, this study seeks to address the following questions:

What are the various definitions of controls?
What are the different categories or types of controls?
How is the performance or effectiveness of controls evaluated?

2. Method

A systematic literature review (SLR) was undertaken to collect, evaluate, synthesize, and present findings from multiple research studies related to controls as measures for prevention and defense. An SLR is a structured and reproducible approach for compiling existing relevant research or evidence on a particular topic or research question (Lame, 2019). An SLR ensures a thorough assessment of the quality and scope of existing evidence relating to the research topic, providing a more accurate and comprehensive understanding than traditional literature reviews (Araújo et al., 2020; Kitchenham & Charters, 2007; Pati & Lorusso, 2018). In particular, Preferred Reporting Items for Systematic Reviews (PRISMA) guidelines were followed to conduct the SLR. PRISMA provides a structured framework that assists in explicitly collecting and analyzing data through identifying, selecting, evaluating, and reviewing relevant studies (Nair et al., 2013). A mapping of the PRISMA process as followed for this study can be found in Fig. 1.

2.1. Data search

A comprehensive search was undertaken to collect relevant peer-reviewed data on the topic of 'control' using the online databases: EBSCO, Web of Science, PubMed, IEEE Xplore, Google Scholar, and Scopus. The following search string (or keywords) was employed to retrieve the sources:

["Safety Control" OR "Safety Controls" OR "Control Measures" OR "Control Strategies" OR "Controls" OR "Control" AND ["Accident Models" OR "Accident Model" OR "Safety Management"]

Additionally, this paper sought data from gray literature. Grey literature refers to documents that are not commercially published and typically lack formal bibliographic control or peer review, such as reports, theses, conference papers, and government documents (Schöpfel et al. (2010)). Including gray literature in systematic reviews is important because it can provide unique insights to a broader range of studies, often addressing niche or practical issues that peer-reviewed literature might overlook (Adams et al., 2016).

To capture gray literature, this study also included any search resulted from Google Scholar, Scopus, PubMed, and IEEE Xplore search. The following health and safety institutions' websites were also searched to obtain relevant data from this study: National Institute for Occupational Safety and Health (NIOSH), Occupational Safety and Health Administration (OSHA), Health and Safety Executive (HSE), and Canadian Centre for Occupational Health and Safety (CCOHS).

2.2. Inclusion criteria

We specifically focused on controls as a form of prevention or defense in this systematic review. In simple terms, the study included papers that discussed safety-related controls designed to protect against hazards and prevent injuries. Additionally, only English-language publications with full-text access were considered. The full inclusion criteria for this study are detailed in Table 1.

Although the primary search term was "control," records using conceptually equivalent terminology such as "barrier," "defense," or "safeguard" were eligible when these terms referred to deliberate preventive or defensive measures that met the predefined inclusion criteria presented in Table 1.

2.3. Exclusion criteria

The term control is widely used across various contexts in the safety domain, often carrying different meanings depending on the application. To maintain the conceptual and analytical focus of this review, particularly with respect to identifying and evaluating preventive safety controls (as defined in RQ 1–RQ 3), the following exclusion criteria (EC)

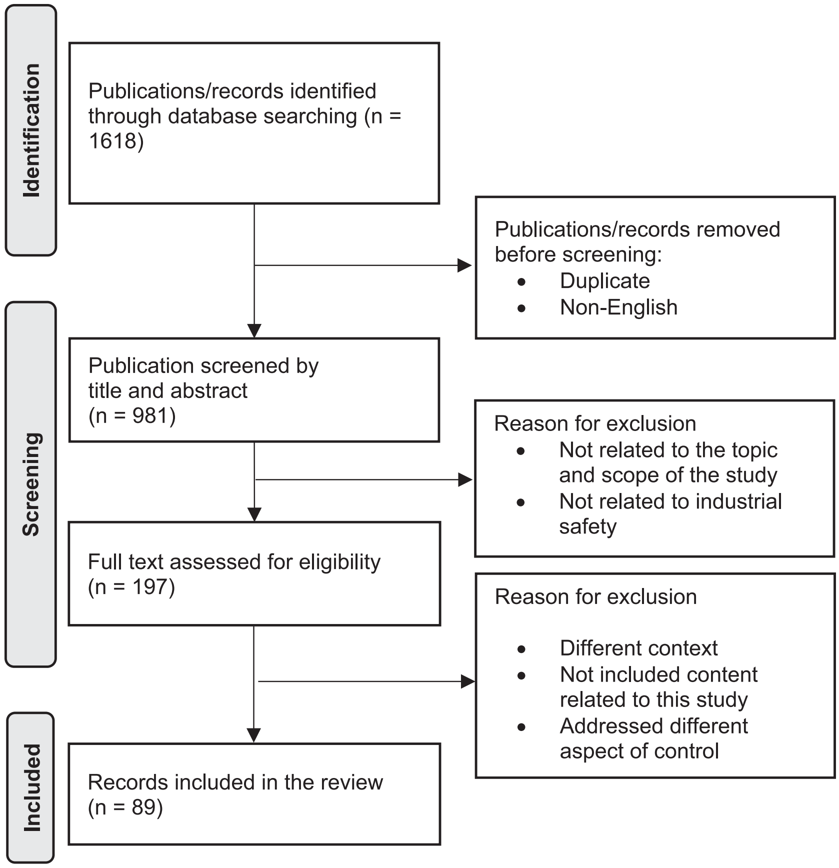

Fig. 1. PRISMA Flowchart.

Table 1
Inclusion criteria.

Criterion	Description
Language and access	Full text available in English
Publication status	Peer-reviewed journal article, peer-reviewed conference paper, doctoral thesis, or grey-literature report issued by a recognized safety authority (listed in section 2.1).
Conceptual focus	The paper discusses safety controls, defined as deliberate measures whose primary purpose is to prevent or mitigate accidents, injuries, or hazardous energy releases in occupational or industrial settings. Such measures may be physical, procedural, or organizational, but they must be explicitly framed as preventive or defensive.
Topical scope	The preventive measure is analyzed in the context of accident models, accident investigation, or safety-management systems, matching at least one term from the "context" block of the search string.
Relevance to at least one research question (RQ)	The paper provides empirical data or conceptual clarification that informs at least one research question: RQ 1: definitions or conceptualizations of controls; RQ 2: categories, types, or taxonomies of controls; RQ 3: assessment of control performance, reliability, or effectiveness.
Industrial or occupational domain	The setting is industrial, occupational or infrastructure safety (e.g. construction, mining, oil & gas, manufacturing, or process industries). Food-hygiene, consumer-product and environmental studies were excluded.

were applied:

- **EC-1:** Superficial mention of search terms. Papers in which the relevant terms (e.g., safety control) appeared only in passing, without substantial discussion or conceptual treatment, were excluded. Example: Liu et al. (2020) referenced safety control but primarily discussed the integration of indoor positioning systems with Building Information Modeling. The term was not elaborated upon in a way relevant to this review's objectives.
- **EC-2:** Focus on control mechanisms unrelated to preventive safety barriers. Publications that addressed controls as project-specific procedures, technical parameters, or monitoring schemes, without framing them as preventive barriers against hazards, were excluded. Examples: Tian et al. (2019) discussed geotechnical safety criteria in coal mining, focusing on structural design thresholds, not conceptual controls.
- **EC-3:** Different terminological meanings. In some papers, the term control was used in contexts that diverged from the safety control concept entirely (e.g., computational models, optimization techniques, or managerial feedback systems). These uses were excluded as semantically incompatible with the scope of this review. Example: Ning et al. (2018) applied control to describe a site layout optimization model, without addressing hazard mitigation or injury prevention.
- **EC-4:** Domain mismatch. Finally, papers that discussed control in non-industrial contexts, such as food safety or public health, were excluded. These works, while relevant to other safety fields, do not contribute conceptually or empirically to the occupational hazard control literature targeted here. Example: Gowen et al. (2007) focused on food-quality monitoring in agri-food processing, which lies outside the review's scope.

These exclusion criteria were designed to grind the conceptual focus of the review and ensure that only studies relevant to the research questions were included. To clarify the scope and application of the exclusion criteria, Table 2 provides a detailed set of exclusion examples,

Table 2
Example of exclusion decisions.

No	Title of excluded paper	Reference	Exclusion Criteria	Explanation
1	Decision Support Analysis for Safety Control in Complex Project Environments Based on Bayesian Networks	(Zhang et al., 2013)	EC-2	The paper focuses on a decision-support or monitoring tool and does not contribute to the research questions.
2	Disaster-Inducing Mechanism in a Roadway Roof and Its Safety-Control Criteria	(Tian et al., 2019)	EC-2	The paper discusses geotechnical stability limits for coal-mine roofs. No relevance to the research questions.
3	Construction Safety Control and Management on Extra-Large Underwater Caisson in the Taizhou Bridge	(Liu et al., 2013)	EC-2	The paper describes project-specific engineering steps.
4	Construction-Site Safety Control with Medium-Accuracy Location Data	(Edrei and Isaac, 2017)	EC-2	RTLS-based alert or surveillance system; does not discuss control as a prevention or defense mechanism.
5	A tri-objective ant colony optimization based model for planning safe construction site layout	(Ning et al., 2018)	EC-3	Uses “control” for layout-optimization.
6	Conceptual Framework for Computer-Based Construction Safety Control	(Stanton & Willenbrock, 1990)	EC-3	Frames an MIS or feedback loop; no relevance to the RQs.
7	Application of Information Technology in Active Safety Control for Construction Machine	(Liu & Hu, 2017)	EC-2	Sensor or PLC detection–reaction focus.
8	Identification of Construction Safety Risks Based on Text Mining and LIBSVM Method	(Xu et al., 2020)	EC-1	Pure risk-identification study; “control” appears only tangentially—no content for any RQ.
9	Proactive Construction Safety Control: Measuring, Monitoring, and Responding to Safety Leading Indicators	(Hallowell et al., 2013)	EC-2	Treats “control” as a leading-indicator monitoring scheme; hence irrelevant to RQ 1–3’s
10	Study on Safety Control for Wuhan Metro Construction in Complex Environments	(Ding et al., 2011)	EC-2	Geotechnical isolation piles and diaphragm walls for metro works—engineering context outside the review’s occupational-control scope (no RQ 1–3 value).
11	Study on Improving the Safety Training Effect of Safety-Control Staff in Highway and Waterway Construction	(Sun et al., 2012)	EC-3	Focuses on staff training; does not touch RQ 1–3.
12	Safety Prediction of Shield Tunnel Construction Using Deep Belief Network and Whale Optimization Algorithm	(Ge et al., 2022)	EC-2	Predictive ML model; “control indices” are forecast outputs, not hazard-intercepting measures—no relevance to RQ 1–3.
13	Hyperspectral Imaging — An Emerging Process Analytical Tool for Food Quality and Safety Control	(Gowen et al., 2007)	EC-4	Focuses on food-quality or food-safety monitoring in agri-food processing; offers no data for occupational preventive controls

illustrating each criterion with multiple cases and explaining why the excluded studies offered no substantive contribution to the three research questions.

2.4. Data selection process

The process followed for data extraction and selection is shown in Fig. 1 and outlined below:

- The search string described in Section 2.1 was applied to all chosen electronic databases and specialist websites.
- Redundant records and non-English sources were excluded.
- Titles and abstracts were screened against the predefined inclusion and exclusion criteria. A record was considered irrelevant when the inclusion criteria were not met—that is, when the abstract offered no discussion of any measure intended to prevent or defend against accidents or hazardous events and any mention of control related solely to quality, statistical, process or other non-safety contexts. Such records were removed.
- Full texts of the remaining records, along with any that were ambiguous at the title-abstract stage, were critically reviewed. When an abstract was unclear, the main text was examined to confirm whether preventive or defensive controls were discussed before a final decision was recorded.

The keywords for this search were selected through a pilot search on safety controls, which allowed the focus to be refined in alignment with the study's objectives. The refined keywords were then used by the lead researcher to conduct a systematic search across relevant databases. To provide more clarity, Table 3 provides examples that illustrate the data selection process, taking into account the inclusion and exclusion criteria.

To ensure the reliability and consistency of the screening procedure, Reviewer 1 screened a random sample of 161 titles and abstracts (about 10% of the database; Mak & Thomas, 2022) against the predefined inclusion and exclusion criteria. After a three week interval (Marx et al., 2003), considered sufficient to minimize recall bias, Reviewer 1 reevaluated the same sample; concordance between the two assessments yielded Cohen’s $\kappa = 0.83$, indicating substantial intra rater agreement (Nichols et al., 2010). To ensure consistency, Reviewer 2 conducted a subsequent review of the same set of records. While we did not conduct a formal interrater reliability test, this additional round of validation confirmed substantial agreement with Reviewer 1′s assessment. Only a few minor discrepancies were identified, leading to clarifications of the exclusion criteria. After this validation step, Reviewer 1 proceeded to screen the remaining records, referring any doubtful cases to Reviewer 2 for joint adjudication.

Table 3
Data selection examples.

Paper Title	*Control* term in abstract?	Mentions prevention or defense?	Decision	Reason
Determining the Reliability of Critical Controls in Construction Projects	yes ("critical controls")	yes	Included	Studies how specific controls avert major events.
Application and Modification of the Tripod Beta Method for Analyzing the Causes of Oil and Gas Industry Accidents	Although the abstract does not directly use the term 'control,' the paper discusses different types of prevention and control.	yes	Included	Abstract explains how the method traces failures of preventive measures
Exploring the Relationship between Major-Hazard, Fatal and Non-Fatal Accidents through Outcomes and Causes	Although the abstract does not directly use the term 'control,' the paper discusses different types of prevention and control.	yes	Included	Compares how preventive measures fail across severity bands.
Errors, Defects and Safety Control at Construction Stage	The title and abstract include the term 'control,' but it is used in the context of quality control, not defense.	no	Excluded	Uses *control* purely for quality-inspection; no accident-prevention content.

2.5. Data sorting and management

A data sorting template was developed using a Microsoft Excel spreadsheet to organize bibliographic information (title, author, and year) and the relevant content related to this review, including the definition and/or conceptualization, type, and classification of controls. A full list of all included studies, along with indications of which studies are pertinent to each section, is provided in a table and can be found in the supplementary materials available at the following link: List of Data.

2.6. Synthesis of results

The final results obtained from the study encompassed diverse aspects of how safety controls were explored, resulting in inherently heterogeneous data. Consequently, a narrative synthesis was employed to systematically summarize and interpret the findings. A narrative synthesis approach is particularly suited to contexts where heterogeneity in study design, methodologies, and outcomes makes *meta*-analysis inappropriate (Kruse et al., 2017). Unlike a simple descriptive summary of the included studies, narrative synthesis involves a deeper analytical process. It enables the identification of similarities and differences across studies, exploration of relationships within the data, and evaluation of the strength of the evidence (Lisy & Porritt, 2016).

The synthesis was conducted in two layers (Guise et al., 2014). In the first stage, every included article was read in full and the relevant data were captured in a structured tabular format which included the bibliographic information (Paper Title, Author(s), and Year), Definition or Overview of Control, Types or Classification of Control, Cause of Accident (where discussed) and Control Mechanism or Intervention; an additional column recorded brief notes on theoretical lineage or contextual relevance. It ensured that each study could be compared directly on the attributes most pertinent to the research questions.

In the second stage, all entries linked to a single research question were gathered in one worksheet and reread as a corpus, where an inductive thematic analysis was carried out. Thematic analysis included identifying, listing, and tabulating themes for each research question, allowing patterns across the included studies (Popay et al., 2006). Short descriptive codes were applied line-by-line; related codes were reviewed continuously and merged into broader concepts, which were refined iteratively until each theme was internally coherent and externally distinctive.

For each theme a concise narrative summary was prepared and recorded in the Excel extraction sheet, setting out in a few sentences what the theme encompassed and identifying two or three studies that illustrated it most clearly. This approach allows clear visibility of both the scope of each theme and the evidence supporting it. Every paper in the review appears under at least one theme and is cited in the relevant results subsection, ensuring that the entire evidence base is represented. Where papers adopted opposing positions, for example some treating safeguards as a subset of barriers while others viewing defense and safeguard as distinct concepts, and others classifying controls into passive, active and procedural categories in contrast to hierarchies that place elimination and substitution at the top, these differences were flagged during coding and are discussed explicitly in the corresponding sections rather than blended into a single conclusion.

3. Findings

The following sections present the findings of this study. For each study question, the results are first summarized in a table and then explored through a more detailed narrative that discusses key themes. The content or examples shown in Tables 4, 5, 6, and 10 are selected based on their direct contribution to the core themes of the study. Specifically, entries are included if they explicitly address at least one of the study's questions. Studies that provided more contextual information or helped strengthen the discussion are explored in greater depth within the narrative.

3.1. Definitions and conceptualizations of 'Control'

The concept of 'control' in safety management literature reflects a diverse range of interpretations and terminology. Based on the records identified in this study, no common or consistent definition of the term controls could be identified; however, some prominent themes do emerge.

3.1.1. Control as measures to manage hazardous energy and prevent accidents

Despite the absence of a consistent and commonly accepted definition, a recurring theme in the literature identifies control as measures or strategies for managing energy (as a source of harm) to prevent accidents or injuries. Table 4 summarizes the findings of this study, presenting controls through the lens of this perspective. For example, as described by Pasman et al. (2018), controls are perceived as measures to prevent or manage energy sources or events that might lead to hazardous releases, typically resulting in fatalities or other forms of damage. Similarly, Yuebing et al. (2011) describe controls as mechanisms that ensure the normal flow of energy, preventing accidents by shielding targets from hazardous exposures.

This conceptual understanding is further supported by studies that define accidents as the uncontrolled release or transfer of hazardous energy leading to injury or damage (Ge et al., 2022; Hoffman & Wilkinson, 2011; Pasman et al., 2018; Rahimi, 1986; Rasmussen & Grønberg, 1997; Squillante et al., 2021). For example, the U.S. Department of Energy (DOE) defines an accident as the "unwanted transfer (or release) of energy that, due to the absence or failure of barriers and controls, results in injury, property damage, or reduced production output" (DOE 1999, p. 1112; Saleh et al. 2010).

Table 4
Definition of controls as measures to manage hazardous energy and prevent accidents.

Definition and/or Conceptualization of Control	Source
Controls are depicted as a set of countermeasures (including barriers) that address unwanted transfers or releases of energy to prevent injuries and property damage.	(Squillante et al., 2021)
Controls are perceived as measures to prevent or manage energy sources or events that might lead to hazardous releases, typically resulting in fatalities or other forms of damage.	(Pasman et al., 2018)
Controls are viewed as barriers positioned between a threat and the top event, designed to either prevent the threat (energy hazard) from occurring or stop its escalation to the point where it becomes a top event.	(Mulcahy et al., 2017)
Controls are described as a set of barriers designed to prevent or mitigate the harmful effects of energy sources.	(Swuste et al., 2014)
Controls serve as strategies to prevent injuries by effectively managing or limiting the flow of unwanted energy.	(Khanzode et al., 2012)
Controls are measures to separate or shield targets from hazardous energies.	(Appicharla, 2011)
Controls aim to ensure that the energy of direct hazards flows through normal channels.	(Yuebing et al., 2011)
Controls are described as measures that manage the flow of energy and prevent accidents.	(Shahrokhi & Bernard, 2010)
Control involves managing energy sources through the implementation of appropriate barriers, work methods, and competent personnel for the activities undertaken.	(Joy, 2004)
Controls involve a range of strategies designed to manage and mitigate risks associated with energy flows, aiming to prevent accidents and reduce their impact on vulnerable targets.	(Rasmussen & Grønberg, 1997)
Controls are described as a set of countermeasures used to restrict, reduce, block, or alert against potential unwanted energy flow (PUE) to humans or other parts of the system.	(Rahimi, 1986)

This way of conceptualizing control can be traced back to Haddon's (1973, 1968) energy theory. Haddon argued that injuries result from the fundamental cause of hazardous energy—its release and subsequent contact with an individual. Haddon proposed that to prevent injuries or accidents, hazardous energy must be effectively controlled, supported by countermeasures aimed at mitigating or redirecting this energy (these countermeasures are discussed in detail in section 3.2).

While this perspective on control is evident across multiple studies, it is important to acknowledge the diversity in how the term is conceptualized and applied. Although energy management emerges as a recurring theme, the study did not identify a consistent definition of control from this viewpoint.

3.1.2. *Definition of control through its synonyms*

The SLR identified other terms with interpretations similar to controls, such as barriers, defenses, and safeguards. Notably, these terms are equally ambiguous, with no common accepted definitions (Roelen et al., 2018; Sklet, 2006). Table 5 summarizes studies where these terms (barrier, defense, or safeguard) were used either in a similar meaning or interchangeably with the term control. The following sections discuss the differences, overlaps, and interchangeable use of terms like control, safeguard, and barrier, as well as instances where their distinctions have been explored.

3.1.2.1. Concept of barrier. The terms control and barrier are often interpreted in similar ways, and in some studies, they are even used interchangeably (e.g., De Ruijter & Guldenmund, 2016). Yet, there is no commonly agreed-upon definition of barrier in the literature or in regulations and standards (Shahrokhi & Bernard, 2010; Sklet, 2006).

The conceptual overlap between barriers and controls arises from their shared role as preventive measures against accidents or injuries.

Table 5
Control, barrier, defense, or safeguard.

Definition and/or Conceptualization	Source
Controls and barriers are used similarly and are described as measures for effectively managing the flow of energy by restricting or stopping it.	(Ge et al., 2022)
The terms barriers, controls, and administrative functions are used similarly to discuss safety measures aimed at preventing accidents. Barriers and controls are described as measures used to prevent or mitigate energy sources or events that could lead to hazardous releases, potentially resulting in fatalities and other forms of damage.	(Pasman et al., 2018)
Control is perceived as preventive barriers, positioned between a threat and the top event, and are designed to either prevent the threat from occurring or stop the escalation of a threat to the point where it becomes involved in a top event.	(Mulcahy et al., 2017)
The terms control and barrier are used interchangeably and are interpreted as elimination or prevention barriers that are placed between the threat and the top event.	(De Ruijter & Guldenmund, 2016)
The terms controls, safeguards, and barriers are used interchangeably to denote preventive or mitigative measures against hazards. These are mechanisms that prevent, restrict, or protect against the pathway of hazard or risk.	(Pitblado et al., 2015)
Barriers are regarded as a type of control and are used to manage and prevent the flow of energy (hazard source). Controls encompass a broader range of measures; however, administrative controls and procedural barriers are used similarly. No clear distinction is made between controls and barriers, as both serve the common purpose of reducing risk by mitigating or preventing hazards.	(Swuste et al., 2014)
Barriers and controls are interchangeably used as measures to separate or shield targets from hazardous energies.	(Appicharla, 2011)
Defense and barriers are used interchangeably, though there is no universally accepted definition of barriers. It has been emphasized that defense/barrier tactics may be utilized to reduce energy damage, according to Haddon's descriptions of barriers as strategic measures for damage reduction, also known as energy barriers.	(Winge, 2019; Sklet, 2006; Haddon, 1973)

For instance, Sklet (2006) defined a barrier as a means to prevent accidents or events, while controls are similarly understood as measures aimed at preventing accidents or injuries. The occurrence of accidents is frequently attributed to the absence or inadequacy of such controls (Ahmadi et al., 2021; Ahmadi et al., 2023; Appicharla, 2011; Hoffman & Wilkinson, 2011; Joy, 2004; Pitblado et al., 2015; Saleh et al., 2010; Squillante et al., 2021). This convergence in the interpretation and application of barriers and controls is evident in various accident prevention models such as MORT, Bowtie, HFACS, STAMP, and so on.

MORT, developed by Johnson (1973), represents accident causation as a hierarchical fault tree that traces individual component failures or unsafe acts back to systemic weaknesses in the organization's control structure. The Bowtie model, developed in the process industries during the 1990 s (Visser, 1998), visualizes a single "top event" positioned between arrays of preventive and mitigative barriers, making the presence or absence of controls explicit. HFACS, derived from Reason's Swiss-cheese metaphor (Shappell & Wiegmann, 2000), classifies the breakdown of controls across four nested levels of unsafe acts, preconditions for unsafe acts, supervisory factors and organizational influences. Finally, STAMP reconceptualizes safety as a problem of system control and feedback. More specifically, accidents are viewed as the result of inadequate enforcement of constraints within sociotechnical control loops rather than the failure of individual components (Leveson, 2016). Although their analytical foci differ, each of these and other similar models embeds the idea that barriers or controls constitute the primary defense against the propagation of hazardous phenomena

(Altabbakh et al., 2014; Fu et al., 2020).

For example, Fig. 2 illustrates a bow-tie diagram depicting the arrangement of controls implemented to tackle the threat or its consequence (i.e., to prevent accidents or its consequence). Conversely, Fig. 3 presents a similar bow-tie diagram that uses barriers to achieve the same goal of preventing unwanted events from occurring.

Alternatively, barriers are also explained as mechanisms to manage the flow or release of hazardous energy to prevent accidents (Harms-Ringdahl, 2004; Pasman et al., 2018; Squillante Jr et al., 2021; Swuste et al., 2014). For example, Kjellén and Adinyira (2017, p. 130) defined a barrier as:

> "A set of system elements (human, technical, organizational) that as a whole provide a barrier function with the ability to intervene in the energy flow to change its intensity or direction."

As discussed earlier (Section 3.1.1), control has also been interpreted from this perspective, providing another rationale for the intrinsic relationship between control and barrier.

The concept of a barrier is closely tied to Haddon's energy theory, which played a significant role in its emergence. Among the ten countermeasures Haddon proposed to mitigate energy hazards and prevent injuries (see section 3.2.1), countermeasure six specifically emphasized "separating the energy being released from the susceptible structure by interposition of a material barrier of energy." The term 'material barrier' is used to separate energy from potential contact. Some authors argue that this concept left considerable room for interpretation, leading to the development of a diverse genealogy of barriers (Bellamy et al., 2007). Although the concept of a barrier is widely used in the safety domain (Hollnagel, 2016, 1999), a consistent or common definition for the term remains absent.

3.1.2.2. Concept of defense and safeguard. Another term identified through the SLR, which has also been employed in a manner similar to control and barrier, is that of 'defense.' Reason (1997) introduced this concept, defining it as:

> "Various means by which the goal of ensuring the safety of people and assets can be achieved" (Harms-Ringdahl, 2004, p. 354).

As discussed earlier, control and barrier are both viewed as measures to prevent accidents or injuries, and insufficient or inadequate implementation of these measures can lead to adverse outcomes. In a similar vein, Reason argues that accidents occur due to the lack or inadequacy of defenses. Specifically, Reason (1997, p. 2) states:

> *"All organizational accidents entail the breaching of the barriers and safeguards that separate damaging and injurious hazards from vulnerable people or assets—collectively termed 'losses.' This is in sharp contrast to individual accidents where such defenses are often either inadequate or lacking."*

Fig. 4 illustrates this principle, showing the role of defenses in preventing losses.

In addition to Reason's work, other studies have invoked the notion of defense in a way that parallels the usage of barrier (e.g., Qiao et al., 2022). Like control and barrier, no common accepted definition for defense emerged from the SLR. Although no studies were found that explicitly distinguish defense from control or barrier, Harms-Ringdahl (2009) contends that the concept of defense is broader than that of a barrier. According to his argument, 'hard defenses' correspond to physical barriers, while 'soft defenses' extend beyond tangible barriers to encompass regulations, procedures, and training. However, no further definitions were provided to delineate physical from non-physical barriers in detail.

This distinction likely stems from the use of barriers as physical entities designed to interrupt hazardous energy release and thus protect against critical events and their consequences (Johnson, 1973). Over time, the barrier concept expanded to include non-physical elements, leading to the introduction of various barrier types in occupational safety literature. Despite this evolution, some authors still exclude non-physical elements from their barrier definitions (Holland, 1997; Mulcahy et al., 2017; Sklet, 2006), indicating that the practical focus on material barriers proposed by Haddon (1973) has persisted.

Additionally, some studies have applied the term 'safeguard' in a manner similar to control, barrier, or defense (e.g., Pitblado et al., 2015; Hoffman & Wilkinson, 2011), however yet again no commonly accepted definition emerged for safeguard from within the data.

3.1.2.3. Controls, barriers, and safeguards – What is the difference?. The term control, and similar terms, have been widely applied in the safety space with no commonly accepted definition. Sklet (2006) studied the concept of safety barrier and argued that this, and similar words – such as defense (in-depth), layer of protection, safety (critical) function, safety critical element, and safety system – are even applied in regulations, standards, and the scientific literature with no commonly accepted definition established. This has resulted in a highly diverse and cluttered space of interpretation, which is arguably problematic for understanding as well as application.

The Chartered Institute of Ergonomics and Human Factors (CIEHF) seeks to provide clarification in differentiating controls, safeguards, and barriers (McLeod, 2017; McLeod & Randle, 2017). According to CIEHF, controls encompass both barriers and safeguards. Barriers are defined as specific types of controls designed to independently prevent harmful events. They can therefore be considered "hard defenses" and include physical objects or systems used as intervention form in preventing the

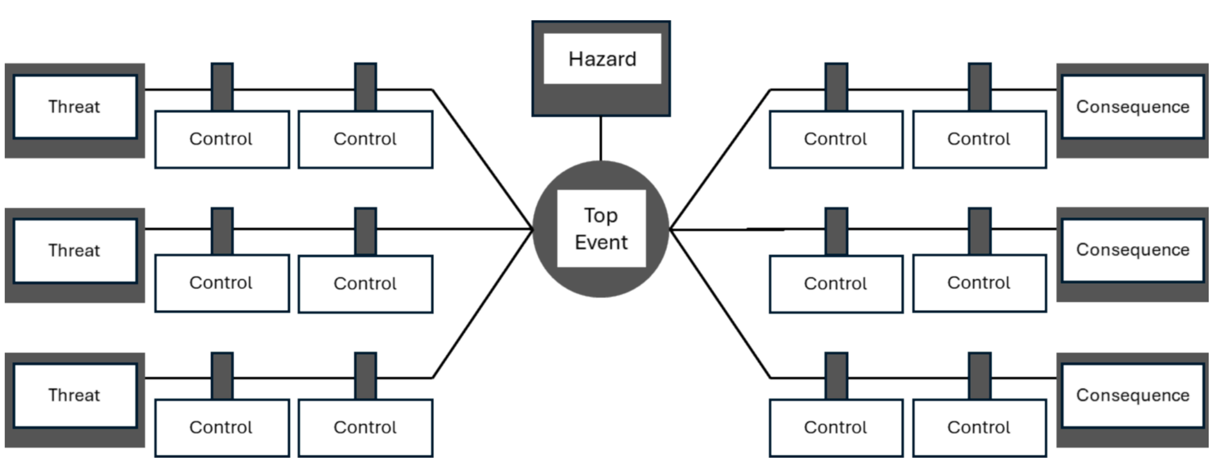

Fig. 2. Control in a generic bowtie diagram; adopted from Mulcahy et al. (2017).

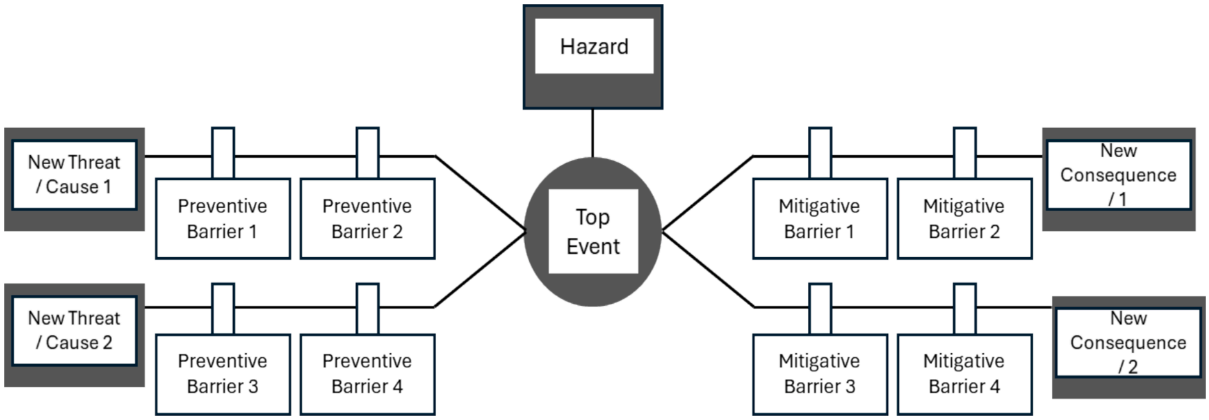

Fig. 3. Barrier in a generic bowtie diagram; adopted from Pitblado et al. (2015).

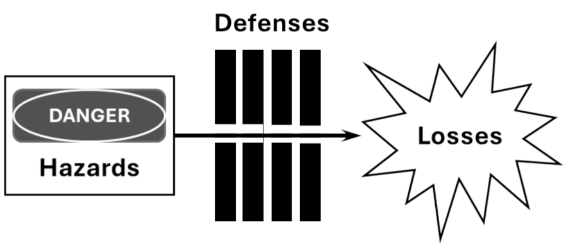

Fig. 4. The role of defense in preventing loss; adopted from Reason (1997).

release of hazardous energy. In contrast, safeguards are supportive measures that enhance barriers but do not meet the criteria to be primary controls, examples of safeguards being procedures, warning signs, operating procedures and cross-checking practices, and training.

CIEHF provides the following definitions for control, barrier, and safeguard:

> *"The term 'control' means measures expected to be in place to prevent incidents. Controls comprise barriers and safeguards."*
> *"The term 'barriers' means controls that are assessed as being sufficiently robust and reliable that they can be relied on as primary control measures against incidents."*
> *"The term 'safeguards' means controls that support and underpin the availability and performance of barriers but that cannot meet the standards of robustness or reliability to be relied on as a full barrier."*

Although the above may seem a straightforward differentiation between terms, some blurry aspects remain. For example, while the difference between a barrier and a safeguard is described as being based on their level of robustness and reliability, the CIEHF do not also establish a clear threshold for what constitutes sufficient robustness and reliability for a safeguard to qualify as a barrier. In other words, it remains unclear what specific criteria a safeguard must meet to transition into being considered a barrier. Furthermore, the differentiation between these two concepts is also linked to the organization's ability to implement and maintain them. This implies that a measure classified as a barrier in one organization might only be treated as a safeguard in another, depending on the level of effort and resources the organization is willing or able to invest.

The SLR did not identify any other study that sought to explain the difference between controls and similar terminologies. However, this study revealed an interplay among the terms control, barrier, defense, and safeguard in the literature, as summarized in Fig. 5.

3.2. Classifications of controls

The absence of an accepted definition of control has given rise to multiple classification frameworks—many of which are vague and inconsistently applied. Although the present study did not identify a consistent framework of categorizing controls, several prominent classification themes emerged, as described in the following sections.

3.2.1. Classification of control from the lens of energy theory

Table 6 summarizes various studies that categorize controls based on how they manage or mitigate hazardous energy. Although no study was found through this SLR that adopted a consistent classification throughout, Haddon's energy theory played a pivotal role in shaping these approaches.

Early accident-causation models often attributed injury severity to random chance, suggesting that accidents were both inevitable and unmanageable in their outcomes (Heinrich, 1931; Khanzode et al., 2012). Challenging this perspective, Haddon (1968) proposed a scientific framework centered on causative factors—specifically the role of hazardous energy in injury causation—thus moving away from the idea that accidents and their outcomes are purely coincidental. This paradigm shift laid the groundwork for a more systematic, etiologically driven approach to injury prevention (Haddon, 1965).

In his seminal work, *Energy Damage and Ten Countermeasure Strategies*, Haddon (1973) detailed a set of interventions designed to reduce losses by controlling energy hazards. These countermeasures are outlined in Table 4, which presents 10 strategies for preventing, limiting, or otherwise managing hazardous energy.

Building on Haddon's energy theory, later on, Johnson (1973) developed the 'energy and barrier tree' model, which is also known as the Management Oversight and Risk Tree (MORT) and proposed other controls measures shown in Table 5. Johnson distinguished these controls into two categories: (1) energy barriers and (2) paper barriers. Energy barriers refer to physical interventions, whereas paper barriers encompass procedural or administrative measures, such as documentation, policies, and standard operating procedures. In MORT, both types of barriers function to direct or manage hazardous energy and mitigate the risk of unintended releases. There are many accident models developed based on energy theory (Li & Guldenmund, 2018), none of which carry a consistent classification of controls.

From Table 7 and Table 8, it is evident that these classification methods are rooted in Haddon's work on energy and control. However, notable variations exist in how different authors approach these classifications.

A number of authors argue that Haddon's energy theory, especially his Energy Damage and Ten Countermeasures (Haddon, 1973), substantially influenced the development of numerous hierarchical hazard-control strategies. These include Johnson's (1973) MORT, Jensen's (2007) Three-Level Hierarchy of Controls, Manuele's (2013) hazard-control strategies, and, perhaps most notably, the widely recognized hierarchy of controls (Jensen, 2007; Lyon & Popov, 2019).

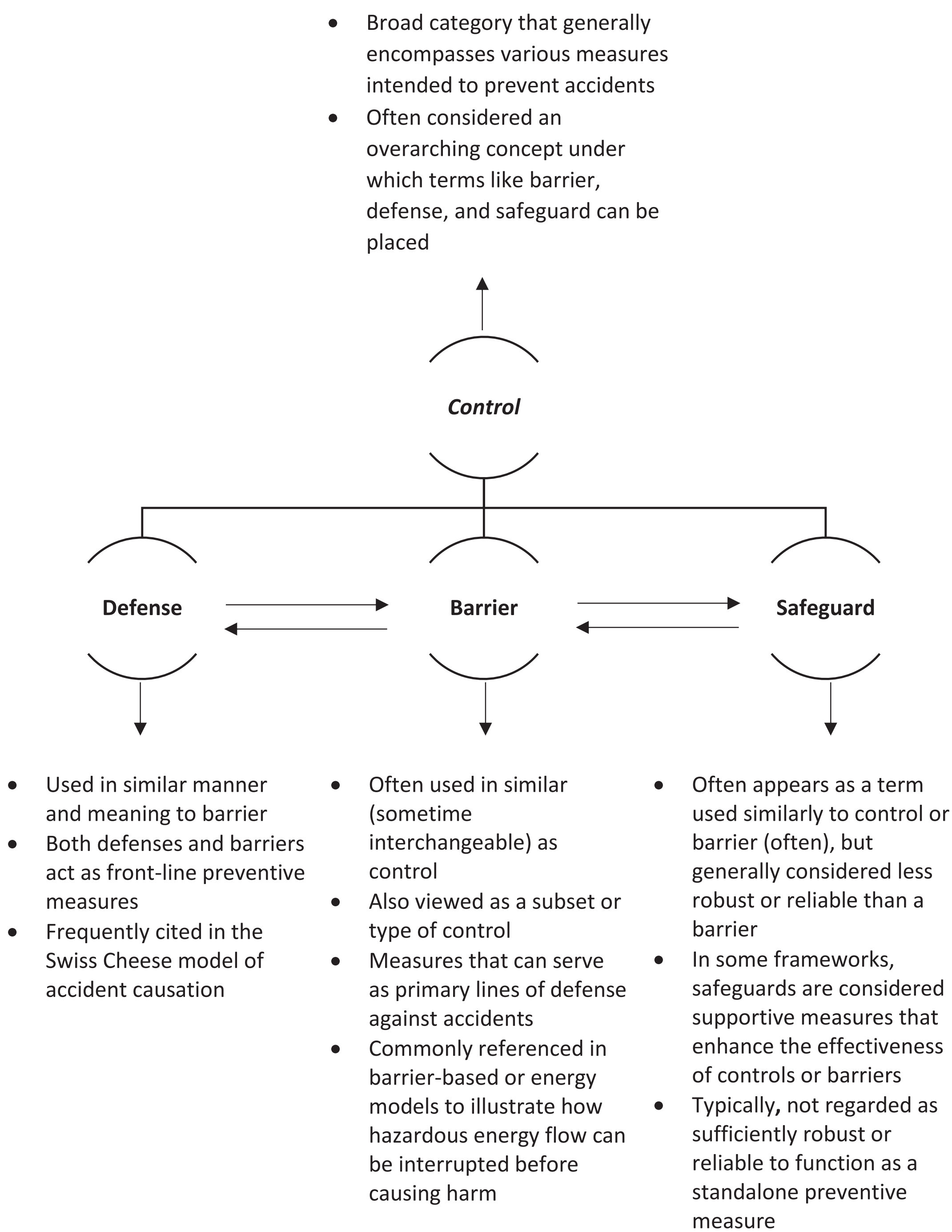

Fig. 5. Interplay between control, barrier, defense, and safeguard.

3.2.2. *The Hierarchy of controls*

Arguably, the most prominent practical application and classification of controls is found within the Hierarchy of Controls (HOC), which has been extensively applied across various fields and is frequently cited in numerous regulations and standards. For example, in the United States, NIOSH (2022) and OSHA (2024) all recommend the use of the HOC as part of hazard prevention and control strategies. Also, in the UK, the Health and Safety Executive also incorporates a HOC in its recommended risk assessment and management processes (HSE, 2024).

The common framework of the HOC, from most to least protective, is discussed below and shown in Fig. 6 (Deziel et al., 2022; NIOSH, 2022):

a. **Elimination:** making sure the hazard no longer exist by removing the hazardous substance or process entirely. For example, doing work at ground level rather than at heights.
b. **Substitution:** changing out a material or process to reduce hazard; replacing it with a less hazardous alternative. For example, switching to a less hazardous material.
c. **Engineering controls:** reducing exposure by preventing hazards from coming into contact with workers; using technology to limit the hazard's release or intensity. For example, using noise enclosures.
d. **Administrative controls:** change the way work is done or give worker more information by providing worker with relevant training, warnings, or procedures.

Table 6
Classification of control from the lens of energy theory.

Classification of Controls	Description	Source
1. Prevention of the energy build-up 2. Change the energy emission 3. Separation of potential victims from the energy source 4. Create barrier between victims and energy source 5. Care of victims	No explicit explanation or definition is provided. However, the controls are presented hierarchically, from most to least effective.	(Swuste et al., 2014)
1. Isolating the source of energy release 2. Separating the source and the user in time–space 3. Providing protecting envelope around the user 4. Providing instruction and information necessary to enable the users to operate rationally in the presence of energy release	The first three measures are interpreted as engineering controls similar to prevention through design, which involves redesigning jobs to control hazards. The last measure relates to education (training) and regulations (safety rules) aimed at modifying behavior to reduce the risk of energy or hazard exposure. The study does not explicitly discuss the hierarchy or effectiveness of these controls; however, it mentions that enforcement control assessments are rarely studied.	(Khanzode et al., 2012)
Energy elimination Energy release minimization Energy isolation Protection through safety gear and emergency systems	No explicit explanation or definition was provided.	(Joy, 2004)
1. Relocating vulnerable objects 2. Altering energy paths 3. Containing energy sources	No explicit explanation or definition was provided.	(Rasmussen & Grønberg, 1997)
1. Eliminating energy source 2. Reducing energy source levels 3. Blocking energy transfer 4. Alerting operators	No explicit explanation or definition was provided.	(Rahimi, 1986)

Table 7
Haddon's Energy Control Measures (Haddon, 1973).

No	Control
1	To prevent the initial marshalling of the form.
2	To reduce the amount of energy marshalled.
3	To prevent the release of energy.
4	To modify the rate of spatial distribution of release of energy from its source.
5	To separate in space or time the energy being released from the susceptible structure.
6	To separate the energy being released from the susceptible structure by interposition of a material barrier of energy.
7	To modify the contact surface, subsurface, or basic structure which can be impacted.
8	To strengthen the living or nonliving structure which might be damaged by the energy transfer.
9	To move rapidly in detection and evaluation of damage and to counter its continuation and extension.
10	All those measures which fall between the emergency period following the damaging energy exchange and the final stabilization of the process (including intermediate and long-term reparative and rehabilitative measures).

e. **Personal protective equipment (PPE):** providing clothing and devices to protect workers. For example, using safety glasses or hardhats.

The HOC originated from the field of occupational health and industrial hygiene as a strategy to reduce hazards to workers (Deziel et al., 2022). Initially, the principle was to control hazards as close to the source as possible, with engineering controls as the preliminary measure and PPE as the second option (Lyon & Popov, 2019). One of the earliest formalizations of this concept appeared in the National Safety Council's (NSC) Accident Prevention Manual, third edition, published in 1955. The manual outlined a three-step "order of effectiveness and preference" (Manuele, 2014):

Table 8
Johnson's Energy Control Measures (Johnson, 1973).

No	Control
1	Limit the energy (or substitute a safer form).
2	Prevent the build-up.
3	Prevent the release.
4	Provide for slow release.
5	Channel the release away – that is, separate in time or space.
6	Put a barrier on the energy source.
7	Put a barrier between the energy source and men or objects.
8	Put a barrier on the man or object – block or attenuate the energy.
9	Raise the injury or damage threshold.
10	Treat or repair.
11	Rehabilitate

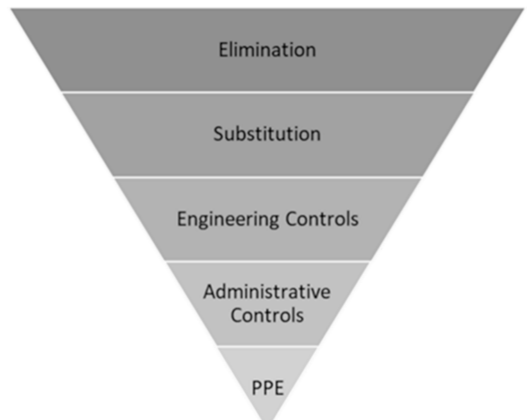

Fig. 6. Hierarchy of Controls; adapted from NIOSH (2022)

- Elimination of the hazard from the machine, method, material, or plant structure.
- Guarding or minimizing the hazard at its source if elimination was not feasible.
- Protecting the operator through PPE if the hazard could neither be eliminated nor adequately guarded at the source.

The HOC has been incorporated into various standards and regulations, becoming an integral part of many safety frameworks (Manuele, 2014). However, the HOC itself has been the subject of criticism, not least because it is constructed primarily from consensus and professional judgments, rather than empirical scientific evidence (Ajslev et al., 2022; Barnett, 2020; Barnett & Brickman, 1986). Indeed, Barnett (2020) conducted a comprehensive study on safety hierarchies, analyzing 66 publications since 1952, including 21 different versions of the HOC, and concluded that generally such hierarchies lack a scientific foundation. Each hierarchy has primarily resulted from consensus or speculation, including the order of use of the components contained therein, without supporting justification from scientific research (Barnett, 2020; Lyon & Popov, 2019).

Additionally, although the concept of HOC is widely applied and used in the safety space, what the HOC comprises is not consistent, and many variations exist. Variation in HOCs can be seen in the differing versions found in NIOSH framework and ANSI standards (e.g., NIOSH, 2022; ANSI Z10-2012 (R2017), ANSI B11.0-2020). For instance, the

HOC in NIOSH includes five steps, as discussed above; however, the ANSI version includes warnings as a control level before administrative controls, making it a six-level hierarchy.

Studies have emphasized that there is a need for more rigorous scientific research and a reevaluation of the HOC to ensure its principles are scientifically sound and consistently applied (Ajslev et al., 2022; Barnett, 2020).

3.2.3. Controls designed for preventing fatalities

Another classification approach identified in this SLR involved categorizing controls based on their focus on addressing serious injury and fatality (SIF) risks versus non-SIF risks. Recent studies emphasize the importance of distinguishing between controls designed for general hazard and those specifically aimed at mitigating or eliminating hazards that could result in SIF. These distinctions are further discussed in the following sections.

3.2.3.1. The notion of critical control. A notable example is provided by Selleck et al. (2023, 2022) and the International Council on Mining and Metals (ICMM), who distinguish between SIF and non-SIF categories of controls. The ICMM defines control as:

> *"an act, object (engineered), or system (combination of act and object) intended to prevent or mitigate an unwanted event"* (ICMM, 2015, p. 5).

Notably, the ICMM framework excludes procedural elements, such as management plans, risk-assessment techniques, and behavior-based safety tools, from its definition of controls. Instead, controls are expected to have a direct and observable impact on safety outcomes. They must be specific, actionable, and verifiable measures capable of directly preventing an incident or reducing its severity when it occurs.

To draw a clear distinction, the ICMM (2015, p.5) defines what it terms *critical* controls as:

> *"A control that is crucial to preventing the event or mitigating the consequences of the event. The absence or failure of a critical control would significantly increase the risk despite the existence of the other controls. In addition, a control that prevents more than one unwanted event or mitigates more than one consequence is normally classified as critical."*

Critical controls are designed to address material unwanted events (MUEs)—those with the potential to result in SIFs, or significant property and environmental damage. Unlike controls that are designed for mitigating general hazards, critical controls are indispensable for preventing such catastrophic outcomes or mitigating their consequences. According to the ICMM, the failure or absence of a critical control significantly increases risk, even if other controls remain operational.

The ICMM outlines clear frameworks for distinguishing controls from critical controls, but the process is subjective and heavily reliant on varying risk assessment methodologies. Identifying critical controls depends on defining MUEs, which are informed by historical and foreseeable events, input from experienced personnel, and data from site-specific, company-wide, and industry-level incident histories. In general, the approach lacks a scientific methodology and relies on qualitative judgment and organizational priorities, which can make it challenging sometimes to differentiate between critical controls and controls.

3.2.3.2. Direct control. The concept of a direct control represent another categories of controls specifically designed to prevent or mitigate SIFs. Drawing on energy-based safety principles, Hallowell (2023, p.11) defines a direct control as follows:

1) *Specifically targeted at mitigating a high-energy source.*
2) *Effectively reduces exposure to the hazard when properly installed, verified, and used (i.e., serious injuries or fatalities should not reasonably occur if these conditions are met).*
3) *Remains effective even in the presence of unintentional human error during work, provided the error is unrelated to the installation or functionality of the control.*

To qualify as a direct control, all of the above three criteria must be met.

Direct controls derive their conceptual foundation from empirically validated relationships between energy magnitude and injury severity (Hallowell et al., 2017). Put simply, higher energy levels are associated with greater potential harm. According to Hallowell et al. (2017), energy levels around 500 J typically correlate with first-aid injuries, levels from 500 to 1,500 J are linked to medical cases, and levels exceeding 1,500 J—categorized as 'high-energy'—are often associated with SIFs. The definition of direct control is therefore specifically designed and intended to eliminate or mitigate high-energy hazards in order to prevent SIFs.

Direct controls are categorized into the following types:

- **Absolute:** These types of direct controls completely eliminate exposure to high-energy hazards when properly installed, verified, and used. Examples include de-energization, LOTO systems, or machine guarding.
- **Mitigating:** These types of direct controls reduce energy exposure to below the 500-ft-lbs threshold but do not eliminate exposure entirely. Examples include thermal insulation barriers that reduce heat exposure from pipes, fall protection systems that limit free-fall distances, or airbags and seat belts that reduce the impact of motor vehicle collisions.

3.2.4. Other lines of classification of controls

In addition to the previous classification frameworks, other categorization frameworks for controls could also be identified yet were less prominent in the data. These are summarized in Table 9. No consistent classification framework was observed across the reviewed studies, nevertheless, notable similarities emerged, which are summarized as follow:

3.2.4.1. Prevention and protection. This way of classifying controls was observed across several studies; however, the definitions of these types varied. For example, preventive controls were described as measures designed to avert the occurrence of hazardous events or reduce their probability. These controls aim to address potential risks before they materialize, thereby minimizing the likelihood of accidents and injuries. Conversely, protection or reactive controls were described as measures focusing on alleviating the consequences of an event after it has occurred, with examples including emergency response plans, first aid kits, and fire suppression systems.

Rathnayaka et al. (2012) and Yuebing et al. (2011) defined prevention or elimination controls as measures aimed at preventing the release of energy hazards and effectively eliminating the source of potential harm. They cited engineering controls as examples, such as removing or substituting hazardous materials or processes (Puisa et al., 2021). On the other hand, mitigative controls were described as measures implemented after the release of an energy hazard to reduce the severity of its consequences. This classification approach is particularly evident in bowtie models (Lyon & Popov, 2019), which visually map hazard management pathways by linking preventive measures with mitigative responses.

3.2.4.2. Physical and non-physical. Physical controls are characterized by tangible elements such as fences, barricades, and PPE. These controls are sometimes referred to by synonymous terms like hard defenses, hard engineering barriers, and control barriers. In contrast, non-physical controls encompass intangible measures, including procedural guidelines, documentation, and training programs (Hollnagel, 1999). These

Table 9
Other lines of classification of controls.

Types/Classification	Source
• Proactive/preventive: controls that prevent the occurrence of the hazardous event or reduce the occurring probability.The above mentioned barriers can be of different types such physical, non-physical, technical or operational. • Reactive barriers/mitigation: controls that alleviate the consequence of the event.	(Squillante et al., 2021)
• Hard: controls that are physical such as alarms, PPE, or barriers • Soft: controls that are process based and are not physical such as legislation, training, or procedures.	(Winge, 2019)
• Passive barriersNo specific definition were provided. However, it was mentioned that barrier analysis are required to the energy sources and determine effective controls to prevent an accident. • Active barriers • Procedural	(Pasman et al., 2018)
Various types of control were used. No consistent framework were mentioned. • Preventive barriers: controls that limit the extent and/or duration of spreading of material or energy. • Passive and active: controls that limit the dispersion of hazardous energy. • Physical barriers: controls that are activated on demand to prevent an accident from escalating further.	(Rathnayaka et al., 2012)
• Hard engineering barriers: controls that are designed to withstand intense conditions, and • Soft barriers: controls that consist of interactions between people and process such as procedure or permit.	(Hoffman & Wilkinson, 2011)
Controls are divided into: • Hard defenses like physical barriers and alarms • Soft defenses such as regulatory and training measures	(Harms-Ringdahl, 2009)
No specific classification system has been used, but the following prevention or protection types are mentioned without definition or explanation: social barriers, organizational barriers, hardware barriers, cultural barriers, behavioral barriers, human barriers, etc. However, the barrier types (described as prevention or protection measures) are classified by function in the following ways: • Physical barriers: systems of controls or barriers that prevent the transport of a hazard from release to intrusion, e.g., restricted physical access. • Functional barriers: systems of controls or barriers that prevent movement or action, e.g., locks, mechanical interlocking, etc. • Symbolic barriers: systems of controls or barriers that counter, prevent, or thwart actions, e.g., warnings and labels. • Incorporeal barriers: intangible systems of barriers that require or promote conformity, e.g., rules, laws, regulations, etc.	(Hollnagel, 2016; 2008; 1999)
Controls are divided into: • Passive barrier: controls that perform their function without intervention such as crash barriers. • Active barriers: controls that require activation to become functional such as interlocks and automatic shutdown systems. • Behavioral barrier: controls that involve some kind of human intervention such as observations or instrument readings or warnings.	(Bellamy et al., 2007)
Control types include: • Passive barriers: controls that are always in functioning and do not need human action such as physical barrier (e.g., wall) or permanent barriers. • Activated barriers. Controls that have set up preconditions that need to be met before the action can be carried out. • Human action: controls that their effectiveness are relied on the knowledge of the operator in order to reach the purpose such as observations, communication, or rules. • Symbolic barriers: controls that need an interpretation by a person in order to achieve their purpose such as passive warnings or prohibited areas.	(Dedianous & Fievez, 2006)
Control types include: • Barrier: ways in which hazards are countered to ensure a top event does not occur. • Management controls: ways in which defense is exercised by trainings, procedures etc. • Design and engineering control: ways in which preventive and mitigative measures are built into the system.	(Hudson, 2001)

are alternatively termed procedural or management controls (Hudson, 2001), behavioral controls, soft barriers, and soft defenses, emphasizing their reliance on processes and human factors rather than physical structures.

3.2.4.3. Active and passive. Passive controls are defined as barriers that function autonomously without requiring human intervention or activation. Examples include crash barriers, physical walls, and permanent installations that provide continuous protection. On the other hand, active controls necessitate activation to become operational, often involving automatic systems or human actions. Examples of passive controls include interlocks, automatic shutdown systems, and activated alarms, which engage in response to specific triggers or events.

Although these classifications were observed across studies (see Table 6), the definitions of the types of controls within these frameworks varied significantly among the studies. This variation is highlighted in the summary provided in Table 6.

3.3. Effectiveness of controls

Selleck et al. (2023, 2022) suggest that a focus on the reliability and effectiveness of safety controls in the field would yield useful research findings able to enhance performance in practice. However, this SLR found that the analysis of the performance of controls is not a straightforward topic. Although no consistent framework for the analysis of controls was found in this study, more general considerations of performance tended to emerge from two different perspectives (Sklet, 2006): (1) accident investigation; (2) proactive risk analysis and control.

From the perspective of accident investigations, the analysis of controls seeks to elucidate several aspects after an incident occurred (Sklet, 2004):

Controls that were applied and how they performed.
Controls that were in place but not used.
Controls that were needed but were not in place.
Controls that were in place but were not adequate.

There are a vast array of accident investigation techniques and approaches found throughout occupational safety management (Dien et al., 2012; Li & Guldenmund, 2018; Sklet, 2004). However, the analysis of controls is most commonly found within barrier-based accident models, whereby barriers are primarily used as forms of control to manage the flow of energy and prevent the hazard of energy from reaching the target (Harms-Ringdahl, 2009; Hoffman & Wilkinson, 2011; Sklet, 2004; Svenson, 1991; Trost & Nertney, 1985). In such cases, there are numerous and various criteria proposed for evaluating the quality or performance of barriers. Review studies conducted by Qiao et al. (2022) and Sklet (2006) provides the criteria as shown in Table 10 for analyzing and applying barriers, which also serve as controls for managing energy or preventing events.

Conversely, the analysis of controls through the lens of proactive risk analysis and control is somewhat different and rather more challenging.

Table 10
Criteria for the evaluation of controls (Hollnagel, 1999; 2008; 2016; Sklet 2006).

Attribute	Description
Functionality/ Effectiveness	The ability of a barrier to perform a specified function under given technical, environmental, and operational conditions.
Reliability/Availability	The ability of a barrier to perform a function with actual functionality and response time while needed, or on demand.
Response Time	The time from when a deviation occurs that should have activated a safety barrier, to the fulfillment of the specified barrier function.
Robustness	The ability of a barrier to resist given accident loads and function as specified during accident sequences.
Triggering Event or Condition	The event or condition that triggers the activation of a barrier.

Complexity arises from the entanglement between accident investigation and risk analysis (Harms-Ringdahl, 2004), as well as the dependency on selecting and applying controls based on the analysis of various hazards and accident scenarios (Sklet, 2006).

A wide variety of risk assessment methods are available, including quantitative, semi-quantitative, and qualitative approaches (e.g., Khan et al., 2015), with commonly cited methods including bowtie analysis, fault and event tree analysis, barrier analysis, layer of protection analysis (LOPA), and layers of mitigation analysis (LOMA) (Lyon & Popov, 2020, 2016). These models typically define risk as the product of an incident's frequency or probability and the severity of its potential outcome. In these models, controls are identified and implemented as part of risk reduction strategies to mitigate risks to an acceptable level (Bowles, 2003; Floyd, 2015), with their performance evaluated based on whether they are sufficiently effective in achieving this level of risk mitigation. This acceptable level is commonly defined using the principle of 'As Low as Reasonably Practicable' (Dedianous & Fievez, 2006; Hourtolou et al., 2004; Lyon & Popov, 2020). ALARP refers to the "level of risk that can only be further reduced by an increase in resource expenditure that is disproportionate to the resulting decrease in risk" (ANSI/ASSE, 2011; Manuele, 2010, p. 3). However, the determination of the ALARP threshold is inherently subjective (Jones-Lee & Aven, 2011; Melchers, 2001), making the evaluation of control performance reliant on subjective judgment and contextual interpretation. Similarly, some studies have argued that the performance of controls is often influenced by human and organizational factors, such as group dynamics, psychological biases, consensus-based decision-making, and the normalization of warnings (Lingard et al., 2021; Li et al., 2020; McLeod, 2017; Winge & Albrechtsen, 2018).

While existing methods are generally effective in identifying controls for common risk scenarios, they often fall short in preventing fatalities from abnormal or unexpected situations (Selleck et al., 2023, 2022). More notably, no publication was found that sought to examine the reliability or sufficiency of controls used to manage construction-related fatality risks (Selleck et al., 2022). In addition, while a substantial body of research identified through this SLR emphasizes that accidents often result from the absence or inadequacy of controls (Ahmadi Rad et al., 2023; Ahmadi et al., 2021; Squillante et al., 2021 Appicharla, 2011; Hoffman & Wilkinson, 2011; Pitblado et al., 2015; Saleh et al., 2010; Joy, 2004;), despite this, this literature only found frameworks developed that judges judge a control sufficient once it achieves the risk-reduction factor implied by an ALARP, a threshold that remains based on subjective judgment than a fixed benchmark.

4. Discussions

Definitions lie at the core of every scientific discipline. When key terms are clear and shared, researchers can test hypotheses, replicate findings, and debate conclusions on common ground. When definitions diverge, knowledge fragments and practice become inconsistent.

This review shows that safety science has yet to reach consensus on the definition of control. Authors shift among the labels barrier, defense, safeguard and the tiers of the Hierarchy of Controls, creating a thicket of overlapping concepts. Although these labels share some common ground, the resulting diversity obscures more than it clarifies and hampers both rigorous research and coherent application. One visible symptom is the existence of more than 66 versions of the Hierarchy of Controls (Barnett, 2020), each reflecting a different implicit judgment about what counts as a control and how effective one control is relative to another.

Such variability has real consequences for risk mitigation. Because each definition assigns different attributes to a control, the very same measure can be judged essential in one framework and peripheral in another. A permit-to-work, for instance, is classed as an administrative paper barrier in one taxonomy, a lower-tier safeguard in another, a soft defense in a third, and is omitted entirely from critical control schemes. By contrast, based on the definition of high energy and direct control (Erkal & Hallowell, 2023, 2017), a permit-to-work, whether used alone or alongside other administrative measures, does not qualify as a direct control; it may support safe practice, yet it cannot be deemed sufficient for eliminating or mitigating high-energy hazards. The lack of a common definition therefore leaves practitioners to decide whether a measure, such as a permit-to-work, is the primary line of protection, a minor adjunct, or no control at all, an uncertainty that significantly undermines consistent, reliable decision-making.

Amid the confusion, this review identifies four features that consistently characterize a control. First, it is intentional and hazard specific, meaning it is deliberately selected to manage a defined hazard, such as machine guarding designed to prevent contact with a rotating shaft or a trench shield installed to prevent trench collapse during excavation. Second, it acts directly on hazardous energy, eliminating, isolating, dissipating, or reducing the energy below a harmful threshold, such as de-energization that prevents electrical exposure or pressure relief that reduces stored energy. Third, its presence and correct function are verifiable, for example through inspection of a physical guard or functional testing of an interlock or emergency stop circuit. Fourth, it remains effective even when human error occurs, such as fixed guards that protect regardless of worker attention, interlocked access doors that prevent operation unless closed, or a fall arrest system that limits the consequences of a misstep even when a worker slips or loses balance. Though seldom stated explicitly, these features recur throughout the literature and offer a foundation on which a shared definition could be built.

Recent developments suggest movement toward that foundation. Critical control in mining industry holds that a control must interrupt energy hazards without relying on flawless human performance, be verifiable in the field, and carry clear accountability for upkeep. The definition of direct control in construction sets similar requirements and, crucially, ties inclusion to an empirically validated relationship between energy magnitude and injury severity: exposures above roughly 1500 J correlate with fatalities (Hallowell et al., 2017; Bayona et al., 2024), so measures that reliably remove or limit such energies become indispensable for preventing serious injuries or fatalities.

Progress now depends less on coining new labels than on subjecting those already in use to rigorous evaluation and disciplined refinement. Future work should first forge a scientifically grounded, commonly agreed definition of control and develop a concordance showing how barriers, safeguards, defenses and related terms, including control classifications, map onto that core concept. Such a shared vocabulary will sharpen conceptual clarity, reduce duplication of effort and guide standards bodies, regulators and scholars toward consistent usage.

In addition, researchers should tie control performance to objective criteria, such as scientifically defined energy thresholds, to build an empirical basis for deciding what constitutes an adequate control in practice. Moreover, the HOC, while widely recognized, lacks a solid empirical foundation. Future work is needed to either validate the existing HOC through scientific research, evaluating the relative effectiveness of the different levels of control, or to develop a new model grounded in scientific evidence.

More fundamentally, as safety is increasingly framed as the presence of controls rather than simply the absence of injury, converging on a precise shared understanding of control has become an essential prerequisite for credible research and impactful practice. This study offers a structured foundation on which future work can build more reliable, comparable and ultimately more effective safety controls, particularly where control sufficiency remains uncertain.

4.1. Limitations and future research

As with any research, this review is subject to limitations that warrant acknowledgment. One key limitation is selection bias (Drucker et al., 2016), as the review relied on specific keywords and search terms to identify relevant studies. Although these terms were carefully selected through a pilot search and refined to align with the study's scope, they may have inadvertently excluded relevant studies that did not use this terminology. Furthermore, because the review focused on studies that explicitly use the term safety-related control, the concept's varied labels across sectors mean that papers describing equivalent measures under different terms may have been overlooked.

Second, the scope of the review was limited to studies addressing controls within occupational and industrial safety contexts, focusing on measures whose primary purpose is to prevent or mitigate accidents, injuries, or hazardous energy release. In this context, control is predominantly conceptualized as interrupting the event pathway (e.g., the release of hazardous energy). Emerging forms of risk, such as psychosocial, cyber, and artificial intelligence (AI) risks, extend beyond the empirical scope of this review and were not systematically represented in the corpus. Nevertheless, these risk domains are conceptually important because they can challenge the conceptualization of control and shift attention toward interventions that act on information flows, decision processes, and organizational conditions rather than directly on the release of hazardous energy (Hollnagel, 2018; Leveson, 2016).

For example, psychosocial risks such as work-related stress, excessive or insufficient job demands, poor supervisory practices, and moral injury do not map neatly onto controls that act on hazardous energy. Instead, controls for these risks often need to be considered and designed at the level of work design, staffing, leadership behavior, and organizational culture (Kjærgaard et al., 2025). Similarly, AI can add to the complexity of the notion of control. AI can be used both as an object of risk (e.g., automated decision-making) and as a control measure (e.g., AI-enabled monitoring, predictive analytics, and decision support for hazard detection and exposure control) (Jetha et al., 2025). In this context, controls act by modifying information, decisions, and workflows rather than directly intervening on hazardous energy. These approaches still speak of controls, but the mechanisms are different. Future research should therefore examine how these emergent risks affect the concept of control, including definitions and classifications.

Additionally, future work should explore the development of empirically validated definitions and classifications of control using the attributes identified in this review and examine their applicability across diverse safety domains. Systematic *meta*-analyses could assess how different control types perform under varying operational conditions and how their effectiveness can be evaluated. Such work would advance both the conceptual and practical understanding of safety control as a foundational construct within safety science.

5. Conclusion

This review provides the first systematic synthesis of how safety control is defined, classified, and evaluated within the safety literature. According to the corpus included in this review, the findings show no common accepted definition of control exists and that related terms such as barrier, defense, and safeguard are often used interchangeably, inconsistently, or without explicit conceptual justification. This study systematically maps the definitional, classificatory, and evaluative dimensions of control and shows that existing frameworks are fragmented and overlapping. The Hierarchy of Controls, in particular, remains grounded largely in professional consensus rather than empirical validation.

In addition, this work disentangles the conceptual overlap among control, barrier, defense, and safeguard and establishes a coherent terminological foundation that clarifies their relationships and functional distinctions. The analysis identifies four recurring attributes that characterize a control: it is intentional and hazard specific; it acts directly on hazardous energy by eliminating, isolating, dissipating, or reducing it below a harmful threshold; its presence and correct function are verifiable; and it remains effective in the presence of human error. These features create a pathway toward a scientifically grounded and operationally meaningful definition of control.

Whereas previous systematic reviews have focused exclusively on barriers, this study extends the scope to the underlying concept of control itself, strengthening theoretical consistency and advancing terminological precision across safety literature. The clarification provided here enhances the conceptual integrity of safety science and supports the development of standardized approaches for defining, designing, and assessing controls in both research and practice. In doing so, it contributes an essential step toward establishing a shared lexicon capable of aligning scholarship, regulation, and professional application around control.

CRediT authorship contribution statement

Yaqoob Raheemy: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Fred Sherratt:** Writing – review & editing, Supervision, Investigation, Conceptualization. **Matthew Hallowell:** Writing – review & editing, Resources, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

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

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Yaqoob Raheemy is a Graduate Research Assistant at the Construction Safety Research Alliance based at the University of Colorado Boulder. He earned a BS in Civil Engineering and MS in Construction Project Management. He is currently completing his PhD in Construction Engineering and Management with focus on Construction Safety.

Dr Fred Sherratt was former Associate Director of Research at the Construction Safety Research Alliance based at the University of Colorado Boulder. She is a Chartered Builder and Chartered Building Engineer, with over ten years of experience working for a large contractor in the United Kingdom. Fred has also worked as a Professor of Construction Sociology in the UK, and her research prioritizes the wellbeing of construction workers and specifically the elimination of serious injuries and fatalities in the construction industry.

Dr. Matthew Hallowell is a President's Teaching Scholar and Endowed Professor of Construction Engineering at the University of Colorado Boulder. He earned a BS and MS in Civil Engineering and a PhD with a focus on Construction Engineering and Occupational Safety and Health. Before his academic career, he worked in construction as a laborer, project engineer, and quality inspector. Dr. Hallowell specializes in construction safety research and has pioneered leading indicators, hazard recognition programs, safety risk assessment, and precursor analysis. He has published over 100 peer-reviewed papers and has overseen over $3 million in external funding. For his research, he has received the National Science Foundation CAREER Award and the Construction Industry Institute Outstanding Researcher Award.