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Scientometric Analysis and Review of Safety in Design in AEC Industry

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Abstract:
Safety in design (SiD), is a new paradigm for managing workers safety in architecture, engineering, and construction (AEC) sector. However, there is a lack of a holistic mapping on the SiD research in a global range. To explore the advancement and sketch the panorama of SiD research, this research investigates SiD research through a scientometric review. A total of 199 bibliographic records from Web of Science, Scopus, and Engineering Village were retrieved and analysed.

Results show that the most distinguished countries where SiD research have been undertaken are the USA, UK, and China. Major studies fields concentrated on engineering and technology; however, studies on electrical, ergonomics, building information modelling, decision making, equipment, and education are emerging. In addition, the paper presents a framework genialised from several key themes, revealing the focal points and trends of SiD research over time. This review provides a comprehensive understanding of SiD research word wide, contributing to the existing knowledge in safe design and has laid a solid foundation for future research that look into the detailed design features for improving SiD implementation in the construction projects.

Keywords:
Safety in design, scientometric review, architecture, engineering, and construction (AEC) sector

1 Introduction

Compared to other sectors, the construction sector has not been pictured as a safe workplace for workers, with significant fatalities annually (Jaselskis et al., 1996; Martinez et al., 2020; Tam et al., 2004). Because of the complex nature of construction projects, long schedule, harsh working conditions with dangerous hazards involved, addressing construction safety has always been a challenging issue in the sector. Previously, the contractors have been responsible for the safety on site. Safety in design (SiD), however, has changed the roles and responsibility distribution among construction project participants, prescribing safety consideration in the design phase (Gambatese et al., 2005). Design suggestions and strategies have been collected, assisting designers in recognising the hazards and understanding SiD , such as “Design for Construction SafetyToolBox”, a computer program composing the design suggestions for the best practice (Gambatese et al., 1997). To faciliate SiD, visualisation technology such as Building Information Modeling (BIM) has been leveraged to improve the productivity and safety of workers (Golabchi et al., 2018).

There are a number of studies in literature that are focused on reviewing and implementing SiD. For example, (Adaku et al., 2021) developed a theoretical framework aimed at advancing PtD in improving organisational capability. Reviews have been extended to understand SiD knowledge, skills, and experience needed that can significantly contribute to improve design practice and provide competency assessment for PtD implementation. Moreover, Hardison and Hallowell (2019) conducted a review with an analysis of aspects of feasibility, implementation, and designed instruments of SiD.

However, the knowledge of what, precisely, encapsulates broader and diverse research aspects in the SiD fields have not been reached. There has been currently little literature review generalising SiD and its applications in different types of construction projects and in different geographical areas. The evolution, trends, gaps and also future directions available to the entire research community also are yet to be uncovered.

To fill this research gap, the authors employ the scientometric review approach to the SiD body of knowledge. The findings are expected to provide researchers with a comprehensive understanding of the state quo of SiD by exploring the trends and prototypes of SiD, highlighting research themes, the areas for future studies. The findings will serve as a start point for new research in investigating the specific design features under the SiD approach.

2 Research method

Scientometric analysis is a quantitative study that contributes to a comprehensive understanding of a specific scientific field, and could be presented by bibliographic records based on previous publications (Vinkler, 2010). This scientometric review involves three stages, namely research question formation, bibliometric searching, scientometric analysis. Figure 1. shows an overview of the review process.

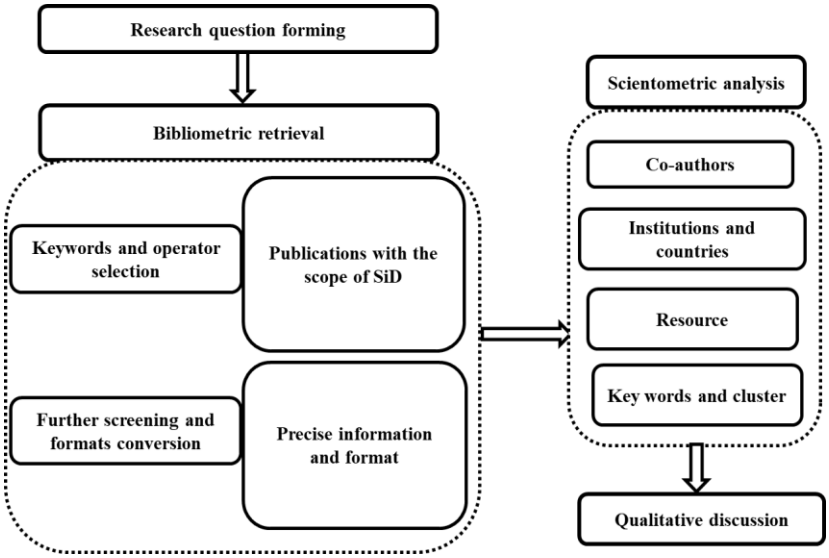

Figure 1. The procedures of the scientometric review

2.1 Formation of research questions

We have formulated the following questions in order to obtain a full picture of the SiD research. This has been done in accordance with previous scientometric reviews:

(1) Who are the key researchers, institutions and regions contributing to SiD research?
(2) What are the valuable sources including high cited journals and articles?
(3) Where are the advancements and trends in SiD research?
(4) What are potential areas for future research?

2.2 Bibliography searching

After determining the research questions, we accessed eligible resources. Articles from a certain time range, including books, journals, and conference proceedings, were considered to extract information. Three databases were used to search articles: Scopus, Web of Science, and Engineering Village. The searching strategies are indicated in Figure 2.

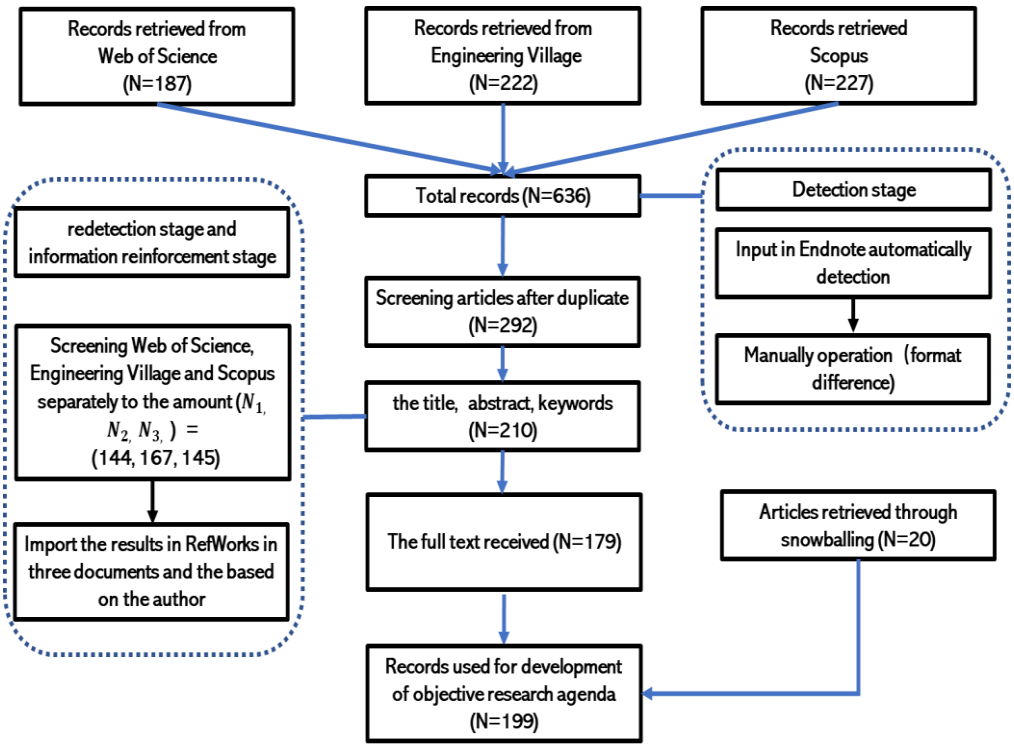

Figure 2. The search strategy and processing of the resource

2.2.1 The Level of Sub-section Nesting

Authors are not advised to use more than three levels of sub-section nesting. The use of too many nesting levels will reduce clarity and may be confusing for the readers of your article.

3 Scientometric analysis results

This section describes results visualised in the science mapping, with network of the authors, institutions and countries, references, and key words.

3.1 Co-author network

A co-author network was generated through nodes and links. The node presents the author, and the link shows the cooperation in the form of publications. Figure 3 shows the author's information with the node indicating the amount of the publications and colour differentiating the groups cooperating on SiD research. The top contributors information, institutions and countries/regions and contributions to the SiD field are listed in Table 1.

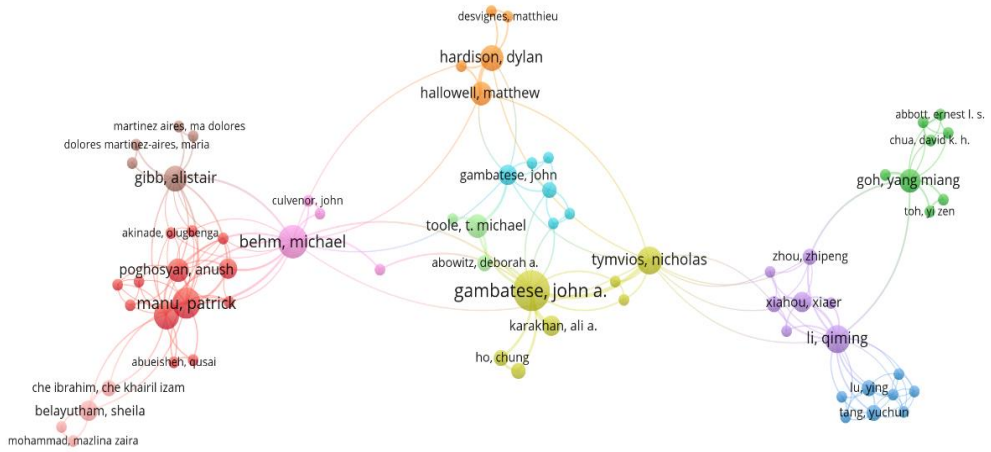

Figure 3. The authors information regarding the SiD reseach

Table 1. The top ten productive researchers on PtD

Author	University	Country/region	Number of papers
John A. Gambatese	Oregon State University	USA	14
Michael Behm	East Carolina University	USA	8
Patrick Manu	University of Wolverhampton	UK	7
Li Qiming	Southeast University	PR China	6
Abdul-Majeed Mahamadu	Univ. of the West of England	UK	6
Nicholas Tymvios	Bucknell University	USA	6
Sunwook Kim	Virginia Tech Blacksburg	USA	5
Maury A. Nussbaum	Virginia Tech Blacksburg	USA	5
Alistair Gibb	Loughborough University	UK	5
Hardison, Dylan	East Carolina University	USA	5

3.2 Network of institutions and countries

This section identifies the institutions and countries that contribute to SiD research.A network generated from the retrieved bibliography data was analyzed to find the contributions. Detailed information for countries is shown in Table 2.

3.3 Source analysis

3.3.1 journals analysis

As summarized in Table 3, the top 10 journals including SiD studies were investigated according to statistical analysis in Vosviewer. Safety Science had 29 publications (14.5%), taking the top position among all the sources, followed by the Journal of Construction Engineering and Management (15 articles) and Automation in Construction (10 articles). Half of the numbers of the journals are in the USA.

3.3.2 Top cited articles analysis

According to (Small, 1973), the recurrence with which two reports are referred to is characterised as co-citation, another kind of archive coupling. Two papers' co-citation recurrence can be determined by contrasting how records are referred to in the Science Citation Index and tallying indistinguishable sections. The number of references referred to by distributions can be determined using record co-citation analysis (Zhao, 2017), thereby can be used for community's general knowledge and evaluation. The network constituted 621 nodes and 1943 links with modularity (0.8813) and meant silhouette (0.9278). A network's modularity refers to complexity breaking down into components or modules, and the metric serves as a benchmark for the overall clarity of a network decomposition. Its silhouette value [-1, 1] measures a clustering configuration's efficiency (Chen, 2016). The top10 documents that were selected for the recommendation to new researchers of SiD are listed in Table 4.

Table 2. Top institutions in the SiD research

Institution	country	documents	Citations	Link strength
University of Oregon	USA	17	560	8
East Carolina University	USA	12	547	12
Virginia Tech	USA	12	145	1
West England University	UK	7	31	9
University of Colorado	USA	7	79	5
Hanyang University	South Korea	6	396	0
National University of Singapore	Singapore	6	286	1
Southeast University	China	6	189	2
Bucknell University	USA	6	176	7
University of Manchester	UK	5	22	8
RMIT University	Australia	5	127	1

3.4 Keywords and cluster analysis

Keywords are extracted from the paper abstract and main content. This resulted in 360 nodes representing keywords, and 1,529 links presented in Figure 6. The keyword nodes are then placed on a timeline for those terms that are most prevalent. It was found that "Safety", "prevention", and "design" occurred with a maximum frequency in the keywords and clusters analysis. Management, ergonomics, and system have emerged as new trends. Virtual reality (VR) technology and construction processes were the heated topics, significantly influencing the advancement of BIM research.

According to the timeline, around 1998, the primary nodes (high frequency) were on VR, hazards recognition, design process, and methodology. After that, VR and the construction process became dominant. Electrical/electronics, equipment, and ergonomics had centrality around 2008. Around 2004, computer-aided simulation started to be applied in SiD research. Safety standards, innovation models, and ergonomics appeared in the research field around 2007. Building information modelling (BIM), learning, accident analysis, best practice, communication, attitude, game, and e-competence have increased since then.

Table 3. The top source journals in SiD

Source journal	Host country	Journal impact factor (2021)	Number of articles	Citations	Totally link
Safety Science	Netherland	6.392	29	1055	2264
Journal of Construction Engineering and Management	USA	5.292	15	472	1251
Automation in Construction	Netherland	10.517	10	697	1294
Journal of Safety Research	USA	4.262	4	225	352
Engineering Construction and Architectural management	USA	3.385	3	17	760
Journal of Professional Issues in Engineering Education and Practice	USA	1.667	3	94	433
Practice Periodical on Structural Design and Construction	USA	1.59	3	9	597
Architecture Engineering and Design Management	United Kingdom	2.57	3	15	399
Work a journal of prevention Assessment & Rehabilitation	Netherlands	1.803	3	22	392

The research diversified into new directions, such as organisational perspective, best practice and decision making. The latest keywords are artificial intelligence, expert system, and designer assistance, indicating that research will utilise more advanced technology and take full advantage of the experts' knowledge. It is interesting that BIM is a continuous focus of SiD research in the whole advancement process of SiD.

4 Discussion

4.1 Discussion according to the scientometric analysis

Through the *co-author analysis,* findings show that John A. Gambatese (Oregon State Univ. USA), Michael Behm (East Carolina University, US), and Patrick Manu (University of Wolverhampton, UK) are the most prolific researchers. The trajectory and focus from influential researchers the in the area worth focusing to better understand SiD.

Through the countries and institutions analysis, we found that researchers in the USA contribute most to the research domain, even Weinstein et al. (2005) commented on the USA's safe design implementation. However the review found that the research on SiD has not been fully explored and the reasons for constraints of SiD research are unclear. The theory has been promoted through empirical studies, but the grounds and methods aimed at implementing SiD are yet to be solved. A future research direction potentially exists in exploring the path to global cooperation for advancing SiD implementation.

Through the sources analysis, we found that Safety Science, the Journal of construction engineering and management, and Automation in construction are high-ranked journals on SiD

research. Significantly, these three journals were among the top sources where articles on SiD are cited.

Table 4. The top-cited articles in SiD research

Times Cited	Title	Authors and time	Journal
337	Building Information Modelling (BIM) and Safety: Automatic Safety Checking of Construction Models and Schedules	Zhang et al. (2013)	Automation in Construction
165	Overview and analysis of safety management studies in the construction industry safety	Zhou et al. (2015)	Safety science
146	Design's role in construction accident causality and prevention: Perspectives from an expert panel	Gambatese et al. (2008)	Safety Science
138	BIM-based fall hazard identification and prevention in construction safety	Zhang, Sulankivi, et al. (2015)	Safety Science
121	Ontology-based semantic modelling of construction safety knowledge: Towards automated safety planning for job hazard analysis (JHA)	Zhang, Boukamp, et al. (2015)	Automation in Construction

The most popular research topics are automatic safety checking using BIM, exploring the knowledge, attitude, and practice in SiD, measuring designers' hazards recognising skills. These topics are the mainstreams enlightening future research and practice. SiD-related assessment elements have been added to LEED credits (Lee et al., 2020). An evaluation system that automates BIM-based risk rating estimation has been developed (Lee et al., 2020). Another representative research was to leverage VR in the design-for-safety-process (Hadikusumo, 2000).

4.2 Research themes, gaps and trends

The reviewed articles focused on a wide range of questions from design effectiveness, design linkage to morbidity and mortality, design metrics, information diffusion, and economic and business issues. In this review, we have used the categories of research, practice, education, and policy for SiD (Schulte et al., 2008) to analyse these studies. The research gaps and future research potentials were generated in the framework shown in Figure7. With the evidence from the scientometric record, a "survey" method is significantly used in previous studies. According to the science mapping, tacit knowledge on construction is essential for successful implementation of SiD (Hadikusumo & Rowlinson, 2004). The future direction recommends usage of objective data (Tixier et al., 2017) and empirical evidence (Tymvios et al., 2020) instead of personal experience. Hence evidence-based knowledge is essential for advancing SiD research. The sharing of technical knowledge advocated by Behm (2008) is still a gap to be addressed. There is a need for more efficient methods for assisting designers in understanding the SiD process.

There exist gaps in education and policy, requiring research in these areas. Gaps still exist in the approaches to better involve decision-makers, H&S professionals, project managers and clients in SiD. The project demands indicated the popularity of implementing SiD. Future research needs to be undertaken to look at the role the project owner/client and developers could play, design decision making, preliminary design stage, maintenance safety considerations, professional certification, and health & safety professional involvement.

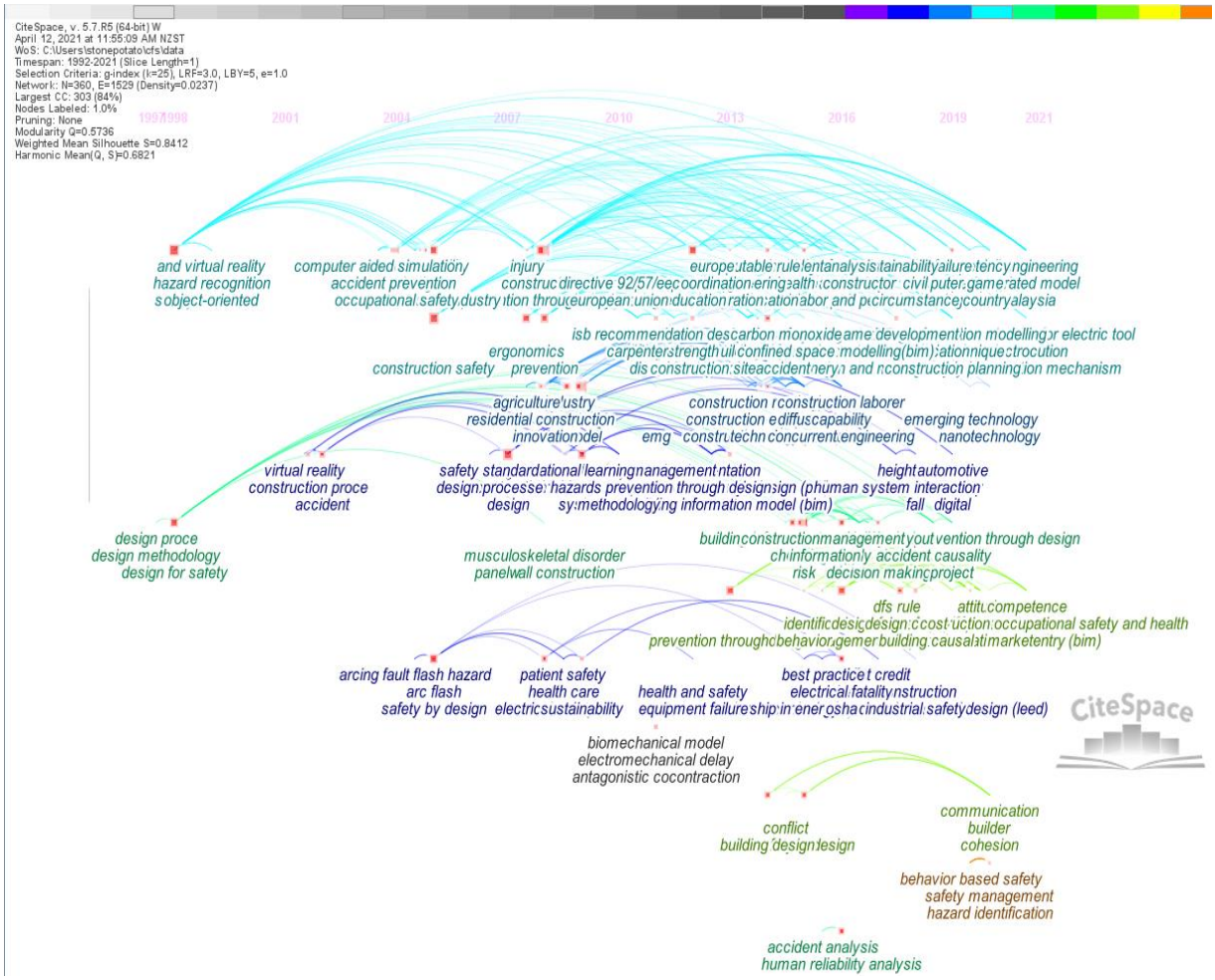

Figure 6. Keywords according to the timeline

Education, especially through experimental studies, is essential to enable the enhancement of awareness of SiD. Educating future designers and professionals using advanced technology is needed. However, for educational purposes, collecting and transferring experts' knowledge (such as experience and skills) still presents a challenge.

5. Conclusions and future directions

In the research area, four directions can be summarised from the scientometric review: (1) new techniques like prefabrication and industrialisation; (2) more cooperation between countries or institutions; (3) knowledge exploration and promotion; (4) business value. Four gaps can be identified as research directions: (1) the current market demand for safe construction; (2） the contractor's contribution; (3) safe design in the conceptual design stage; (4) methods for assisting designers to facilitate SiD. Meanwhile, as in a practice preference field, collecting design features are of great importance. Furthermore, the methods bringing the emerging technologies into the SiD knowledge transfer are in need, thereby finally promising safety knowledge sharing.

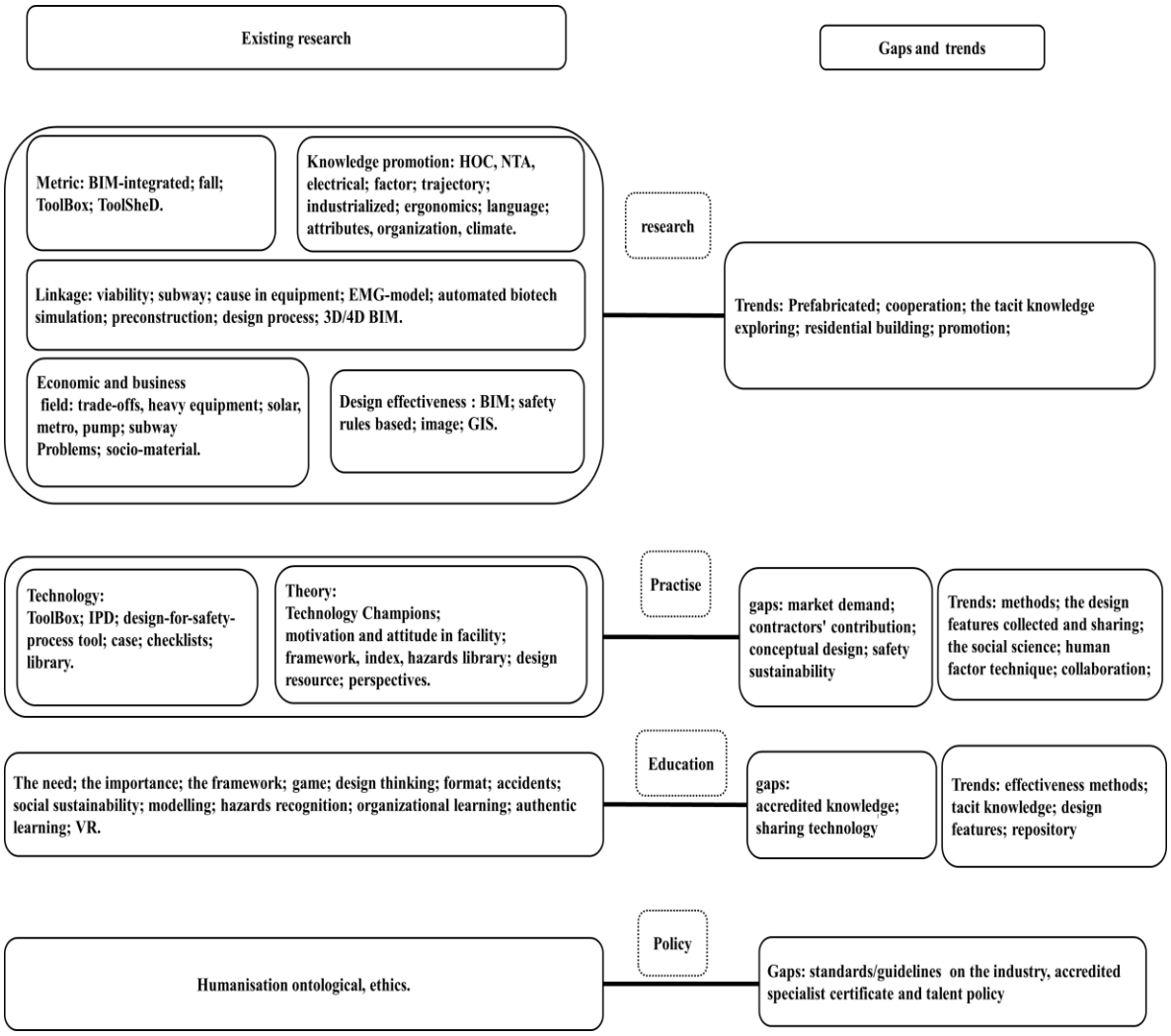

Figure 7. The framework of gaps and trends

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