Resource management at modern construction sites

Bridging the gap between scientific knowledge and industry practice and needs

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Published in:
Journal of Environmental Management

DOI (link to publication from Publisher):
10.1016/j.jenvman.2024.121835

Publication date:
2024

Document Version
Publisher's PDF, also known as Version of record

Journal of Environmental Management 366 (2024) 121835

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Review

Resource management at modern construction sites: Bridging the gap between scientific knowledge and industry practice and needs

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ARTICLE INFO

Handling editor: Dr. Lixiao Zhang

Keywords:
Construction process
Resource consumption
Decision-making
Sustainable solutions
Life Cycle Assessment
Upfront emissions

ABSTRACT

The urgent need to address the construction sector's significant contribution to global greenhouse gas (GHG) emissions underscores the importance of developing more sustainable construction practices. This paper presents a comprehensive review that offers valuable insights into evolving research and guides future strategies for sustainable resource management in construction processes. A systematic literature review (SLR) examined on-site activity data to identify emission reduction measures, and ten in-depth interviews with industry practitioners validated the theoretical concepts against field experiences and practices. The research identified seventy-three (73) measures with emissions mitigation potential within six resource categories: transport, fuel, heating, electricity, water, and waste. The study highlights a gap between theoretical knowledge and on-site practices, with many identified measures not being used in practice. Only 26% of reviewed articles measured on-site resource consumption, indicating a need for on-site monitoring and real-time evaluation of emissions. The interviews revealed 31 challenges hindering the practical implementation of these measures and identified nine enablers to overcome these obstacles. The findings emphasise the opportunities presented by regulatory initiatives, technological advancements, and standardised methods for conducting life cycle assessments (LCAs) and data collection. The paper underscores that collaboration among stakeholders and policymakers is not just beneficial but crucial for driving meaningful progress in reducing the construction sector's environmental footprint. Ultimately, this integrated approach, validated, and contextualised by the interviews, provides practical insights that enrich our understanding of sustainable construction practices.

1. Introduction

1.1. Background

The rise of global climate change, propelled by greenhouse gas (GHG) emissions, presents a pressing challenge to modern civilisation (IPCC, 2022). A leading contributor to GHG emissions, the building and construction sector accounts for approximately 39% of the world's energy production and energy-related GHG emissions (IEA, 2019), making it a focal point for reduction strategies. Studies show that building construction alone, in addition to the direct and indirect emissions, contributes to an annual emission of 2.5 $GtCO_2$ (IEA, 2023), where a significant portion considering its concentrated occurrence during the initial phases of a building's life cycle (Fufaa et al., 2019). The construction process accounts for more than 10% of buildings' total climate impact (Kanafani et al., 2023), emphasising the significant environmental footprint associated with construction activities. Mitigating these emissions emitted prior to the commencement of building operations, commonly referred to as upfront carbon emissions, yields instant benefits. In urban centres, construction-related GHG emissions constitute a notable percentage of total city emissions, highlighting the sector's environmental impact (European Environment Agency, 2015). Construction activities also generate various pollutants, including particulate matter, noise, and waterborne pollution; this study focuses on GHG emissions.

1.2. Life cycle assessment and construction process

The European Standard, EN 15978, delineates the system boundaries for the construction phase of buildings, outlining the assessment of environmental performance in the construction works (European Committee for Standardization, 2011). This standard divides the life cycle of a building into distinct stages, commencing from the product stage, progressing through the construction process, and extending to the

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https://doi.org/10.1016/j.jenvman.2024.121835
Received 23 April 2024; Received in revised form 8 July 2024; Accepted 10 July 2024
Available online 14 July 2024

utilisation of the building until it reaches its end-of-life stage. Fig. 1 illustrates the subdivision of these stages into modules for clearer understanding and analysis. The inventory data is crucial for accurate assessments, requiring comprehensive data on the consumption of electricity, heat, fuel, water, transport, and waste throughout the construction process. However, while adhering to standardised boundaries aids in regulating environmental monitoring and control systems, the absence of standardised methods for conducting LCAs for the construction process means significant variability in how environmental impacts are measured and reported. This inconsistency complicates the accurate assessment and comparison of the effectiveness of different resource reduction measures. Our study aims to bridge the gap between theoretical reduction measures and their practical implementation on construction sites.

Due to emerging regulatory initiatives, attention to cutting emissions from construction processes and on-site activities has recently risen. The current revision proposal of the Energy Performance of Buildings Directive (EPBD) suggests a whole life cycle to EU-wide building carbon regulation. Mandatory carbon declaration and limit values, including the construction process, are already in force in some countries like Denmark (SBST, n.d.), Sweden (Boverket, 2024) and France (MTE, 2024), while Norway has demonstrated the potential of emission-free construction sites (Wiik et al., 2022). While ongoing initiatives attempt to gain a better and harmonised understanding of making construction process GHG assessments and mitigating emissions (Balouktsi et al., 2024), there is still a lack of fundamental knowledge on how to expedite emissions reduction efforts.

As the demand for reducing emissions continues to grow, decision-makers in the construction sector are facing the challenge of identifying effective sustainability measures (Fořt and Černý, 2022). Although research on carbon mitigation is gaining momentum (Satola et al., 2021), there is a lack of practical decision-support tools during the early stages of a project's lifecycle (Hannouf and Assefa, 2018). Existing frameworks lack contextual guidance for non-technical users and may not align with industry workflows, which hinders their adoption (Turner et al., 2020). By addressing the need for standardised LCA methodologies tailored to the construction phase, our research underscores the importance of developing consistent and reliable environmental impact assessments to enhance resource management and emissions reduction strategies in the construction industry.

1.3. Research approach

The main focus of this study is to collect data and measurements to establish a standard method for real-time data collection. Accessible consumption data can help construction professionals measure and reduce resource consumption on-site, identify necessary technological support, compare data, and propose initiatives to minimise resource consumption. This research combines information from a systematic literature review and interviews with industry experts to guide future research for making informed decisions about decarbonisation. This study aims to answer the research question: How can resource monitoring and reduction strategies be effectively implemented and aligned with industry practice to mitigate greenhouse gas emissions in building construction processes? To do this, the study aims to 1) systematically review existing literature on mitigating on-site emissions, 2) examine the challenges industry actors face in adopting the mitigation measures, and 3) provide directions to facilitate decision-making on emission mitigation strategies during the construction process.

This research effort is structured to review the current academic and industry perspectives on on-site construction emissions. A critical review of the literature was conducted to assess and synthesise literature on the literature on mitigating on-site emissions to provide a comprehensive overview of existing knowledge and research gaps. To ensure thorough and transparent reporting of results, this qualitative analysis was performed in three iterative steps: 1) SLR as the primary approach, 2) semi-structured interviews, and 3) contextualisation of findings, as illustrated in Fig. 2. Step 1 involved the collection of journal articles for analysis. By combining a systematic review with the synthesis of primary qualitative data, a body of evidence can be created that inductively develops new theories or informs practice. Therefore, in step two, findings from the systematic literature review were supplemented with empirical evidence from in-depth interviews with industry practitioners to determine industry challenges in adopting monitoring of resources and reduction measures. The results gathered from the systematic literature review helped to explain and interpret the findings from the empirical research, providing a rich tapestry of research approaches that may only have been possible if the research had been undertaken purely using the systematic literature review approach. In stage three, the research findings were contextualised to real-world settings by providing a nuanced understanding of the issues faced by industry practitioners in implementing theoretical concepts into practice and providing directions for future research. The proceeding section details these steps in depth.

2. Material and methods

2.1. Literature collection

A systematic literature review has been conducted. The literature

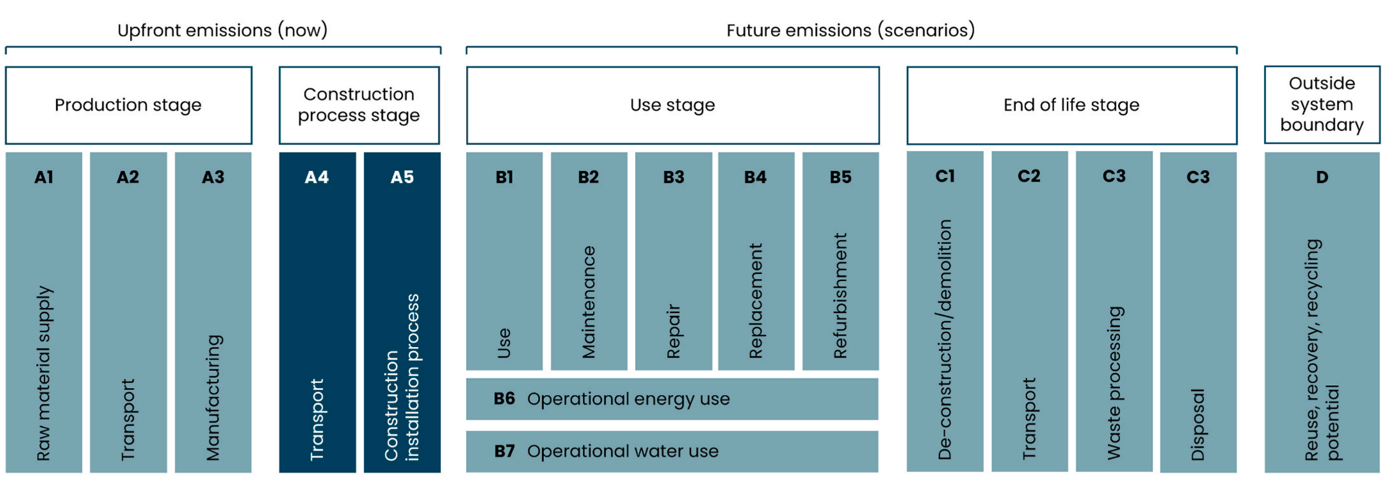

Fig. 1. Life cycle stages and modules after EN 15978 (European Committee for Standardization, 2011). The modules concerned in this study are highlighted with darker colours. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

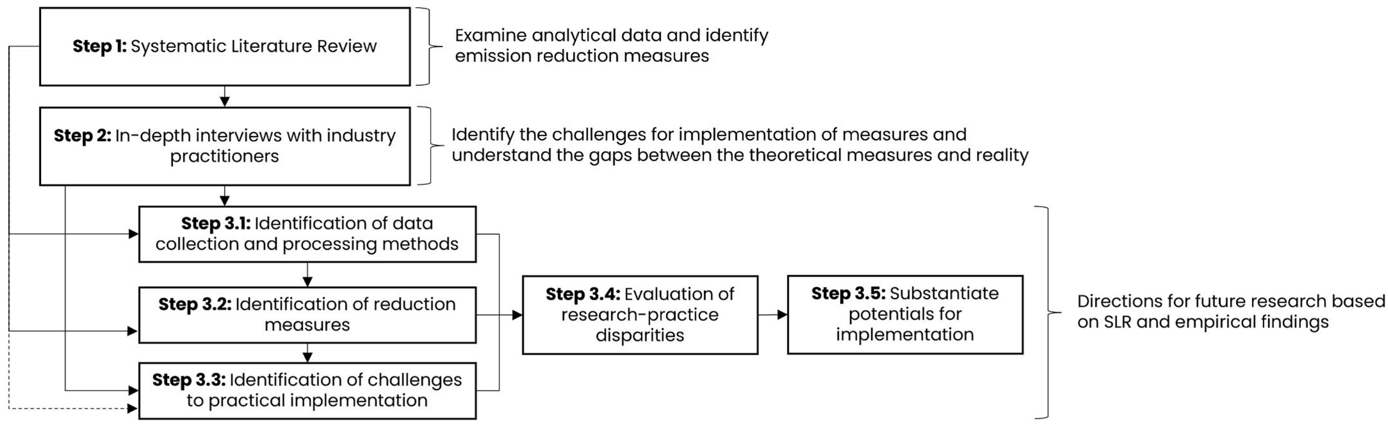

Fig. 2. Overview of the research design.

review takes outset in the guideline proposed by Randolph (2019), where the literature review has been split up into two primary phases, where the first is a database search, and the second is a backward snowballing of identified key articles.

A systematic literature review is an appropriate method only when the expected number of relevant articles is low. The search has therefore been carried out using the Scopus database with a secondary search for cross-checking in Web of Science but with limitations to reduce the sample size and only to include the best and newest articles. Three preliminary search criteria were defined where a) only peer-reviewed journal articles were included, b) only articles published after 2010 were included, and c) only articles in English were included.

The database search in Scopus involved a keyword search using a developed search string. The literature review focuses on resource consumption and emissions in on-site construction. The developed search string is based on keywords representing the focus of each of the five identified resource streams: electricity, fuel, heating, waste, transportation, and water, as well as overall energy. Thus, the literature search was conducted using a very specific set of keywords related to the construction process, reduction measures and their synonyms: (reduc* OR optimi* OR mitigat*) AND (emission OR carbon) AND ("construction site*" OR "construction process*" OR "construction activit*") AND (electricity OR fuel OR diesel OR machinery OR equipment OR transport OR heat OR water OR waste OR energy).

Search techniques like including different inflexions of keywords were applied together with 'and' or 'or' statements. Moreover, some keywords are included with an or statement where there only must be a hit in one of a list of keywords like reduction, optimisation, and mitigation. Other keywords are included with an and statement where both keywords need to be present, for instance, construction and site. The general keywords include reduction, optimisation, mitigation, emissions, construction, and site, while specific keywords include keywords referring to consumption like waste, heat, water, electricity, etc. The search string was searched applying four criteria.

(1) Publications must contain resource consumption data from the construction site(s), i.e., papers focusing on a national or urban scale are excluded.
(2) Publications must contain at least one reduction measure for on-site resources during the construction process.
(3) The measure for reduction must focus solely on the construction processes i.e., strategies related to the production of materials, building operation as well as demolition are excluded.
(4) The strategy/strategies must focus on optimising the building's resource consumption, waste generation and/or embodied environmental impacts (quantities) i.e., articles only focusing on reduction of time and cost are excluded.

The search string initially resulted in a hit of 385 articles in Scopus, with an additional 129 from Web of Science. The articles were moved to and organised in a Microsoft Excel document to keep track of the articles that were in or excluded in the following filtering process. At the outset of that sample, first titles and later abstracts were reviewed, and only articles were considered relevant to the study; thus, focusing on resource consumption was included in the next phase. Only 85 articles passed these two filtering steps. Further examination involved a comprehensive reading of the entire text of the articles, which led to the identification of 32 publications for inclusion. Additionally, backward snowballing, as proposed by Wohlin (2014), was conducted among these papers, leading to the inclusion of 3 additional relevant papers.

In total, 35 publications were reviewed and analysed for synthesis. The high exclusion rate highlights the broad scope of the search query, necessary to ensure comprehensive coverage of the literature. Despite the high number of exclusions, the rigorous selection process was essential to capture the diverse approaches and measures in the construction process. This approach ensured that the final articles were highly relevant, providing a strong foundation for the analysis. Future refinements in the search query could increase specificity and reduce the number of irrelevant articles, but the broad terms used were justified to avoid missing any potentially relevant studies. The outline of the study method is shown in Fig. 3.

The studied resources were extracted from the 35 publications and systematically added to a spreadsheet as the search progressed. In instances where a study provided data for multiple resources, each resource was registered individually. Each identified resource was annotated with the research stage associated with the processed data in the article. Specifically, the first stage focused on predicting or simulating consumption data to facilitate the advancement of actual construction activities, the second stage centred on real-time consumption data during the construction phase, and the third stage involved quantitative analysis of consumption data post-construction activities. Furthermore, it was documented whether the resource consumption reported in the article was based on actual measurements or estimated from given parameters. Additionally, the processes falling within the boundaries delineated by modules A4 and A5 in EN 15978 (European Committee for Standardization, 2011) were identified based on the data collection. Lastly, all reduction measures pertaining to the observed resource consumption were recorded. Based on the overall objective of the study, the following information was registered for each resource.

(a) Number of occurrences
(b) Relation to LCA modules: A4 transport (Material transport, Transport of equipment, Losses due to the transportation) and A5 construction installation processes (Groundworks and landscaping, Storage of products, On-site Transport, Temporary works, On-site production and transformation, Heating, cooling,

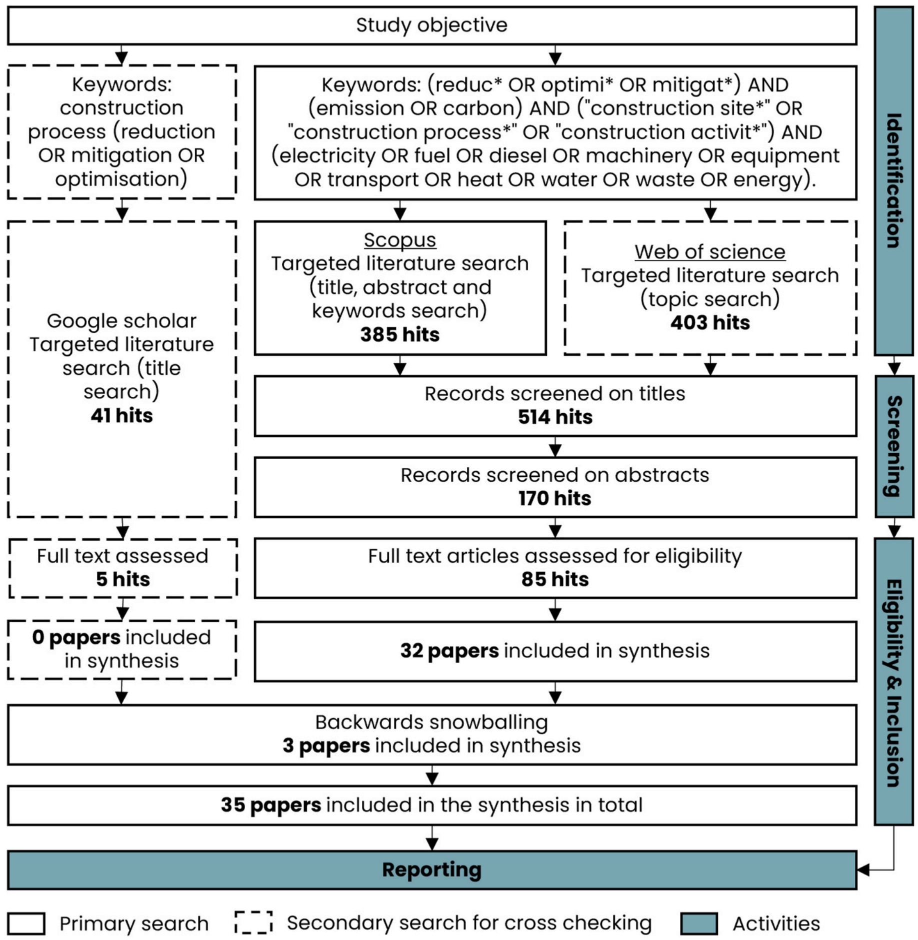

Fig. 3. Flowchart for the systematic review methodology.

ventilation, humidity control etc, Installation of products, Water use, Waste generation, Waste transport)

(c) Data collection method and/or technology
(d) Research stage (1. Prediction/simulation of consumption before the construction stage, 2. Real-time consumption data during the construction stage, 3. Quantitative analysis of consumption data after construction activities)
(e) Reduction strategies/measures related to resource consumption.

The systematic extraction and categorisation of resources from the 35 publications facilitated a comprehensive understanding of resource consumption dynamics within the construction industry. This detailed analysis serves to advance the knowledge and inform strategic interventions aimed at mitigating resource consumption and promoting sustainability in construction practices.

2.2. Qualitative data collection

To ensure that the study did not end with a large gap between scientific published knowledge and practice application, semi-structured interviews were conducted to provide real-life qualitative data. The semi-structured interviews followed the method outlined by Brinkmann and Tanggaard (2015), employing conversation as the primary means of gathering empirical data. Consistent with the approach advocated by Brinkmann and Tanggaard (2015), the interviews encouraged active engagement from both the interviewer and the respondent. The interviewer's function remained that of a facilitator in the dissemination of pertinent information rather than a co-producer thereof (Gubrium and Holstein, 2012).

The semi-structured interview methodology was chosen to collect qualitative data in this study due to its capacity to incorporate both predetermined inquiries and spontaneous questions arising from the ongoing conversation. This approach enabled the respondents to articulate narratives, thereby not only delineating the chronological aspects of events but also offering reflective insights into the underlying rationales. Consequently, the utilisation of semi-structured interviews facilitated the provision of comprehensive descriptions encompassing contextual nuances and anticipated outcomes within the discussed scenarios. The primary objective of employing this method was to gain insights into the company's perspective on monitoring and collecting data regarding resource consumption at construction sites during the installation process. This involved understanding their current practices, motivations behind them, and demands for improving workflow efficiency.

In all, ten respondents participated in interviews concerning their experiences with the collection of data on resource consumption during the construction process. The interviews were carried out in November and December 2023. All participants were drawn from the Danish building sector across diverse regions of Denmark, predominantly representing contractor companies. This selection was made to centre the analysis on the individuals directly engaged in on-site activities. Respondents were purposefully selected to encompass a spectrum of roles within the construction value chain, including directors, on-site managers, data specialists, public clients, and suppliers. This diverse representation aimed to foster a comprehensive, industry-wide understanding of resource management practices at construction sites. For further details, see Table 1.

The semi-structured interview focused on the following questions.

Table 1
Overview of the informant profiles in the conducted semi-structured interviews.

Respondent	Profile	Company Type	Revenue[a]
A	Technical Consultant	Municipality	Publicly funded
B	Development Manager	Waste Management	1000–1999
C	Digital director	Machine and Equipment Supplier	800–899
D	Site Manager	Contractor	4000–4999
E	Head of Sustainability	Contractor	4000–4999
F	Environmental and Sustainability Manager	Contractor	2000–2999
G	Construction Manager and Sustainability Coordinator	Contractor	3000–3999
H	Process Supporter	Contractor	3000–3999
I	Head of Sustainability	Contractor	1800 - 1899
J	Head of Sustainability	Contractor	1700 - 1799

[a] Latest publicly available revenue in million DKK.

- How have you worked with the collection of data on your project(s), and which solutions have you used? (methods, technology, management and practice application)
- What results have you achieved, and are they at the documentation level or proven resource savings?
- What could have been done differently on your project(s)?
- Where do you see the greatest reduction potential, and what are your expectations for the future workflow within the subject?
- What challenges do you see in relation to data collection of the resource flows on site and the associated work with resource savings?

The interviews underwent analysis and categorisation employing a blended approach of deductive and inductive coding techniques. Deductive coding draws from established theoretical frameworks, whereas inductive coding emerges from the discourse of the interviewees (Hsieh and Shannon, 2005). This methodological blend serves the purpose of elucidating practitioners' workflow dynamics within the context of extant literature on resource consumption and emissions in on-site construction. Additionally, it incorporates themes derived from discussions with informants, including the challenges encountered in documenting consumption data.

As mentioned earlier, the informants encompass a diverse array of professional backgrounds and represent companies ranging from large to medium-sized enterprises, excluding small-scale or sole proprietorships. While these companies collectively constitute a substantial portion of the Danish construction industry, it is important to acknowledge the presence of numerous smaller entities within the sector. For the purposes of this study, smaller firms were deemed to possess insufficient experience in on-site resource consumption monitoring, thus precluding their inclusion as valuable contributors.

The respondent companies were specifically selected for their expertise and hands-on familiarity with various on-site resource consumption processes during construction. They are participants in a pioneering initiative (ConTech Lab, 2024) aimed at testing on-site technology within the framework of a collaborative effort to develop a unified data platform, incentivising minimised resource consumption at construction sites. Given their advanced knowledge relative to many smaller firms, their insights offer detailed perspectives on practical workflows, challenges, and requirements.

3. Results and discussion

3.1. Descriptive findings

As evident from the search process outlined in section 2.1, numerous articles touch upon the subject of reducing emissions in construction to varying degrees. While the large number of articles offers benefits in terms of diversity and richness of information, it also presents challenges related to information overload. However, when considering studies that specifically address actual resource consumption data and emissions from the construction process, the pool of relevant literature diminishes significantly in accordance with the inclusion and exclusion criteria defined in this study. Furthermore, an analysis of the publication dates depicts a clear increasing trend in the number of scientific journal articles published from 2011 to 2023. In this period, the number of published articles has steadily risen, indicating a growing interest and research activity within the field (see Fig. 4).

The increasing number of published articles provides a rich source of information for literature review purposes, encompassing a diverse array of studies, methodologies, and findings concerning emissions from construction processes. This proliferation of literature provides a broader spectrum of perspectives and approaches, thus enriching understanding of the subject matter. The upward trajectory in scientific publications may indicate emerging trends and patterns within the field, reflecting a heightened awareness of environmental sustainability and climate change concerns over time. Moreover, the implementation of stricter environmental standards by regulatory bodies and policymakers has prompted researchers and industry professionals to explore innovative solutions for reducing resource consumption and emissions in construction processes. Additionally, advancements in technology and methodologies have facilitated the monitoring, measurement, and mitigation of environmental impacts throughout the construction lifecycle. These developments collectively underscore the increasing emphasis on sustainability within the construction research landscape.

Among the 35 publications analysed, 11 originate from Europe, while Asia, North America, and Australia collectively account for 24 publications. This distribution, as illustrated in Fig. 3(b), underscores the global perspective on resource management in construction practices.

Across the publications, a total of 78 resource consumption datasets from the six distinct resources are synthesised (Fig. 4(c)). The distribution of the resources shows a preponderance of targets for energy resources, such as electricity, fuel, and transport. Many of the articles included in the synthesis that were found by the search term energy as a resource focus on the energy consumption of equipment in construction activities, primarily concerning fuel consumption, reflecting a key area of concern within the literature. All articles in the synthesis contain at least one reduction measure, aligning with the search criteria, although not every resource within each article necessarily includes such measures. This observation is evident in Fig. 4(c), where the cumulative count of resources under focus across all studies totals 78, with reduction measures documented for 59 of these resources. It should be noted that individual articles may encompass multiple reduction measures pertaining to a single resource within the same study.

The Sankey diagram (Fig. 5) provides a visual representation of the relationships among key variables, including EN 15978 compliance, resource types, whether the data is estimated or measured during construction, and the research stage of the article. Due to the possibility of multiple classifications and associated resources within each paper, the total numbers specified for each observation do not precisely align with the total number of articles reviewed.

A notable observation is the limited inclusion of certain aspects such as equipment transport, losses during transport, storage practices, temporary work, on-site production and transformation, and water consumption in the literature. The absence of certain aspects in the literature may be attributed to several factors. These aspects could be included in the data but not explicitly mentioned in the articles, or they might have been absent at the observed construction sites. Nevertheless, this highlights an inconsistency in the scope of consumption data across the literature, making direct comparisons of resource consumption challenging.

Approximately 74% of consumption data across the reviewed articles are based on estimation, with no instances of waste generation being actually measured, indicating a gap in on-site monitoring and direct

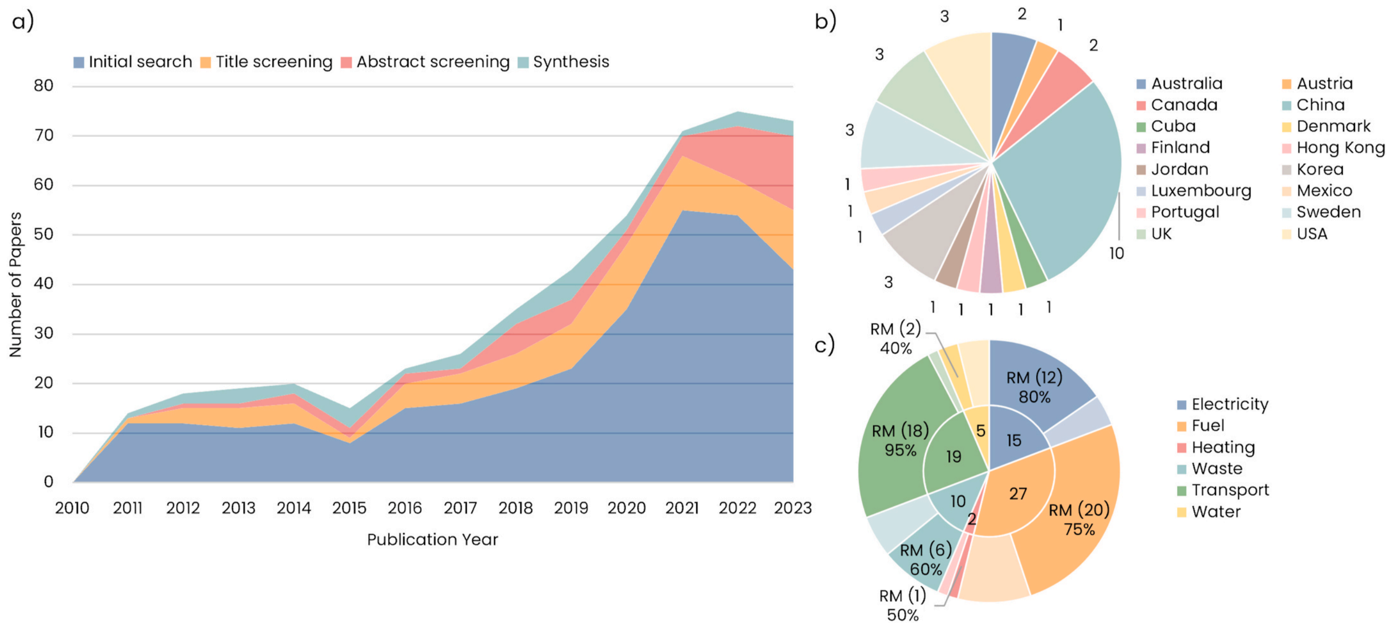

Fig. 4. (a) Distribution of publication years from the systematic literature search, (b) Spatial analysis representation, and (c) Frequency of different resources in the synthesised literature, including the percentage of reduction measures (RM) within each resource. The figure shows the number of records registered.

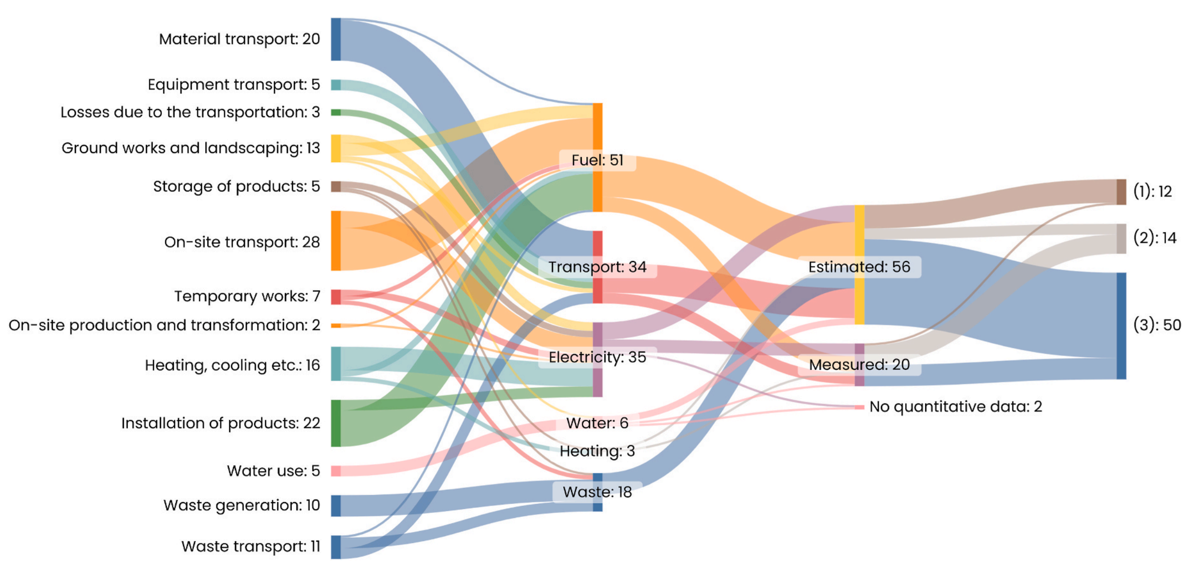

Fig. 5. The distribution of data processing pathways in the literature culminates in the research stages of the processed data, where (1) represents prediction or simulation of consumption before the construction stage, (2) signifies real-time consumption data during the construction stage, and (3) denotes quantitative analysis of consumption data after construction activities.

emissions evaluation. Electricity and heating consumption tend to be measured more during construction processes, ~43% and 50%, respectively. This is likely owing to the availability of meters and the direct cost implications associated with these resources. It's important to acknowledge the limited observations regarding heating consumption, which may signify a gap in the literature rather than an accurate portrayal of its prevalence in construction contexts. Additionally, the scarcity of data on heating consumption could be influenced by the geographic origin of the studies; regions with warmer climates may have less demand for heating during construction periods, resulting in fewer building cases connected to heat supplies during the construction process. Consequently, it's anticipated that a limited number of articles would specifically address heating consumption in such contexts.

3.2. Data collection and processing methods

The interviews conducted shed light on the practical application of resource monitoring at construction sites. While there is a recognition of the importance of data collection and analysis, the findings reveal that the respondents primarily utilise the gathered data for documentation purposes rather than actively employing it to reduce consumption during construction processes. The interviewed contractors emphasised the significance of resource monitoring for fulfilling the requirements of a sustainability certification system and EU taxonomy standards. They highlighted the necessity of robust data collection systems to meet these documentation obligations effectively. Similarly, the respondents acknowledged the role of resource monitoring in Environmental, Social, and Governance (ESG) reporting. They emphasised the need for accurate data to demonstrate compliance with sustainability metrics and enhance reporting practices' transparency.

However, despite the acknowledgement of the importance of resource monitoring, eight out of ten respondents expressed that the utilisation of collected data for consumption reduction purposes at construction sites remains limited. Respondents F, G, H, I, and J noted that while data collection is integral to their operations, the primary focus is meeting regulatory requirements and fulfilling reporting obligations rather than actively implementing measures to reduce resource consumption. The findings suggest a gap between data collection and practical application, where data are primarily leveraged for compliance and documentation purposes rather than driving substantive changes in resource management practices at construction sites. This underscores the need for a paradigm shift towards utilising data-driven insights to inform decision-making processes to minimise resource consumption and promote sustainable construction practices. Efforts to bridge this gap involve fostering a culture of resource efficiency within the construction industry, incentivising the adoption of innovative technologies for real-time monitoring and analysis, and integrating sustainability considerations into project planning and execution strategies. Additionally, initiatives aimed at raising awareness about the potential benefits of data-driven resource management practices could play a crucial role in fostering a more sustainable construction ecosystem.

The method or technology used for the measurement of resource consumption data varies among respondents, with some leveraging advanced technologies for data collection and analysis. In contrast, others rely highly on manual data entry processes. The respondents utilise IoT sensors, smart meters, GPS tracking systems, mobile applications, and cloud-based platforms for real-time monitoring of energy, water, equipment usage, and logistics. However, the majority of the on-site measurements for all contractors were, to a large extent, done manually, after which the consumption data was collected in a spreadsheet for documentation. This observation is further substantiated by existing literature, which predominantly centres on emission prediction during the advancement of construction activities or on quantitative analysis post-building construction (see Fig. 5). Only 8 of the 35 articles focus on real-time consumption data during the construction stage. The lack of real-time emission monitoring systems means that irregular emissions cannot be promptly identified and controlled, thereby posing potential risks associated with emissions.

The literature focusing on real-time consumption offers additional technologies for monitoring. Guerlain et al. (2019) focus solely on material transportation, employing manual data collection on a daily basis, including delivery distance, -time and -schedule, as well as unloading time and -process. The material transportation was simulated using a stochastic optimisation approach for generating freight trips, incorporating average speed, routing, and traffic parameters. Assumptions were derived from the Google distance matrix API. This simulation was used to plan transportation and compare it with the actual transportation data. Moreover, Ren et al. (2012) and Seo et al. (2016) acquire transportation data through utility bills and loading factors, conducting additional inquiries into actual fuel usage logs, vehicle instrument panel readings (oil gauge), and interviews with drivers to ensure accuracy. Variations in fuel economy are considered by factors like load capacity, driving speed, road conditions, and latency. Hajibabai et al. (2011) use GPS for real-time location tracking and propose GIS and CAD-based approaches for visualising emissions from fuel consumption from on-site transportation. Hong and Lü (2022) utilise discrete-event simulation to analyse fuel consumption and equipment scheduling. Tao et al. (2018) utilise an IoT-based monitoring system to monitor real-time emissions during prefabricated components' manufacturing. Radio Frequency Identification (RFID) sensors are employed to identify component IDs, extracting material usage data from a pre-established database within the monitoring system. Laser sensors installed along the production line measure equipment running times for real-time energy usage calculations. Additionally, a data service platform facilitates wireless data transmission from the production line to a computing platform, where monitoring results are visually displayed.

These diverse approaches to resource consumption data measurement highlight the industry's evolving landscape. A combination of traditional methods and advanced technologies is employed to gather, analyse, and manage data effectively. The integration of digital platforms and real-time monitoring systems offers opportunities to enhance transparency, optimise resource utilisation, and drive sustainable practices within the construction sector.

3.3. *On-site resource reduction measures*

From the systematic literature review, 67 reduction measures were identified. Since the practitioners from the interview almost solely have been using the consumption data for documentation purposes, only six additional reduction measures were found from the interviews. During the interviews with practitioners, a recurring theme emerged regarding the perception of "common sense" in implementing reduction measures, noted by three out of the seven interviewed contractors. The respondents referenced practices akin to turning off lights when leaving a room or sorting waste, akin to actions taken at home. However, despite this sense of resource reduction strategies being intuitive, substantive action has yet to be taken or documented on the construction sites as a result. Furthermore, practitioners underscored the challenge of documenting consumption, which complicates the ability to substantiate reductions or identify potential areas for reduction.

The association between various reduction measures was documented, acknowledging the interconnectedness observed in the literature. For instance, one reduction measure might amplify or facilitate the implementation of another measure. For example, the adoption of engine-stop technology not only contributes to energy conservation but also mitigates equipment idling. Similarly, establishing an early connection to the electrical grid enhances the feasibility of utilising electric equipment or machinery, thereby promoting the reduction of fuel consumption. Table 2 lists the reduction measures found. The measures are categorised according to the resources associated with the construction process.

3.3.1. *Transportation*

The construction process stage transportation carbon emission has garnered attention in the reviewed literature, with discussions detailed by Fang et al. (2018). However, it primarily focuses on material transport and, to some extent, overlooks the transportation of equipment and wasted materials. Material transport encompasses carbon emissions during transportation from manufacturers to dedicated areas on construction sites or contractors' preferred storage points. Notably, studies like Seo et al. (2016) underscored the significant contribution of material transportation to total emissions during construction projects. Prioritising the use of electric vehicles as suggested by Respondent C and Ren et al. (2012), and improving the logistics of transportation can mitigate carbon emissions, as evidenced by Sezer and Fredriksson (2021). Improving logistics can reduce unnecessary freight movements and can be managed by, for example, using construction logistics setups such as a terminal or checkpoint. These systems provide planning systems and can act as a system coordinator (Sezer and Fredriksson, 2021). The study by Sandanayake et al. (2019) revealed that minimising transport distances significantly impacts emission reduction efforts, regardless of construction methods, with the prefabrication approach showing potential but limited by certain factors (Weigert et al., 2022). In regards to the choice of construction method, Sandanayake et al. (2019) mention the importance of the construction site location, as the use of off-site production plants can involve longer distances to the construction site when located in or near a city compared to concrete batching plants, making transportation a critical factor in choosing a construction method. Strategies such as on-site material reuse and recycling, including aggregates during earthworks, highlighted by Burciaga et al.

Table 2
Resource reduction measures for the construction process were synthesised from literature studies (references) and interview respondents (labelled A-J).

	Resource reduction measure	Source
	Transport to and from the site (Module A4)	
Transport	Procurement of materials from local suppliers	(Hong et al., 2014; Kanafani et al., 2023; Lee et al., 2018; Ren et al., 2012; Seo et al., 2016)
	Optimisation of loading and utilisation of the truck's capacity	(Guerlain et al., 2019; Kanafani et al., 2023)
	Reduce unnecessary freight movements through coordination and consolidation	(Guerlain et al., 2019; Sezer and Fredriksson, 2021), (C, J)
	Recycle and reuse building materials on-site	(Burciaga et al., 2019; Seo et al., 2016), (Respondent F and J)
	Use of high-efficiency heavy transportation equipment	(Han et al., 2020; Lee et al., 2018)
	Use of electric vehicles	(Ren et al., 2012), (Respondent C)
	Maximise the utilisation of dumping sites to minimise sediment transportation and reduce the distance required for backfilling operations	(Seo et al., 2016; Szamocki et al., 2019)
	Reuse aggregates on site	Burciaga et al. (2019)
	Minimise the lead time between sub-tasks	Han et al. (2020)
	Reallocate the transportation time to avoid road congestion	Han et al. (2020)
	Adopting a combination of an existing road system with rail for long-distance transportation	Han et al. (2020)
	Applying hauling distances to select equipment	Jassim et al. (2020)
	Find the optimum distance which provides environmental reduction in off-site construction	Sandanayake et al. (2019)
	Link the purchase process to an emission management plan	Seo et al. (2016)
	Development of green supply chains to ensure that low-carbon construction materials can be easily obtained locally	Zhang et al. (2023)
	Construction installation process (Module A5)	
Fuel	Reduce equipment idling	(Hajibabai et al., 2011; Ren et al., 2012; Sandanayake et al., 2019; Szamocki et al., 2019; Weigert et al., 2022; Wong et al., 2012; Wu, 2015), (Respondent C)
	Optimise equipment fleet scheduling for construction activities by carefully selecting and planning appropriate equipment combinations, types, and numbers	(Boddi Reddy et al., 2023; Hong and Lü, 2022; Hummer et al., 2017; Ren et al., 2012; Szamocki et al., 2019; Zhang, 2015)
	Optimise construction site logistics through better planning and scheduling	(Fang et al., 2018; Hajibabai et al., 2011; Sandanayake et al., 2019; Weigert et al., 2022; Wong et al., 2012)
	Use of biodiesel or electricity from fossil-free sources for equipment and lighting	(Boddi Reddy et al., 2023; Kanafani et al., 2023; Ren et al., 2012; Zhang et al., 2023), (Respondent A and C)
	Use of electrified construction equipment and machinery	(Weigert et al., 2022), (A, C)
	Use of non-fossil fuels, including wind and solar	(Boddi Reddy et al., 2023; Zhang et al., 2023)
	Improved maintenance of equipment	(Hong et al., 2014; Ren et al., 2012)
	Reduce the need for equipment through better organisation of the work and selection of suitable equipment	(Szamocki et al., 2019; Wong et al., 2012)
	Minimise the soil volume to be excavated	Cabello Eras et al. (2013)
	Early connection to the electrical grid	Davies et al. (2013)
	Use of engine stop technology	Szamocki et al. (2019)
	Appropriate composition of equipment and personnel with a uniform work pace	Szamocki et al. (2019)
	Use draw distance as a selection parameter for equipment	Jassim et al. (2020)
	Train machine operators in emissions-efficient driving	Ren et al. (2012)
	Use of low-emission equipment	Ren et al. (2012)
	Minimise distance to the dumping site	Szamocki et al. (2019)
	Adjusting the loading actions of a loader	Szamocki et al. (2019)
	Adjusting the swing angle of the excavator	Szamocki et al. (2019)
	Use of digital platforms for tracking and managing resource consumption data	(Respondent C)
Heating	Take seasons into account and optimise activities and work distribution according to expected climate (temperature)	Li et al. (2017)
Electricity	Properly scheduling construction activities and the use of machinery	(Li and Chen, 2017; Ren et al., 2012; Seo et al., 2016; Takano et al., 2014)
	Use on-site renewable energy sources, such as solar panels or wind turbines, to power construction activities and reduce reliance on fossil fuels	(Hong et al., 2014; Imam and Ayadi, 2022; Zhang et al., 2023), (Respondent A, C, I, and J)
	Time- and light control using timers for on-site offices and lighting	(Respondent A, D, E, G, and I)
	Providing improved information and understanding to facilitate energy-efficient behaviour	Davies et al. (2013)
	Capture additional project variables to improve the understanding of energy use on-site	Davies et al. (2013)
	Reuse of photovoltaic (PV) panels to provide site lighting	Durão et al. (2014)
	Reuse of temporary accommodation sites with reused installation (e.g. pipes, PV modules for power supply)	Durão et al. (2014)
	Implement "Just-in-Time" delivery to reduce the need for on-site storage and associated waste	Guerlain et al. (2019)
	Enhanced management of storage of materials	Li and Chen (2017)
	Use of electricity monitoring systems during the construction phase	Seo et al. (2016)
	Smart construction site office with IoT sensors	(Respondent C)
	Use of sensors for concrete drying	(Respondent J)
	Use of district heating for concrete drying	(Respondent A)
Water	Identify industries in the vicinity to provide used water (e.g. vegetable washing water from the food industry)	Durão et al. (2014)
	Use of treated wastewater from municipal treatment plants or from portable plants on-site	Durão et al. (2014)
	Use of grey water or treated wastewater in concrete production	Durão et al. (2014)

(*continued on next page*)

Table 2 (*continued*)

	Resource reduction measure	Source
	Reusing water flows from other companies or activities	Durão et al. (2014)
	Regular maintenance of machines	Yao et al. (2020)
	Recycling and better utilisation of water resources	Yao et al. (2020)
Waste	Undertake on-site segregation to provide clean secondary materials	(Durão et al., 2014), (Respondent G and J)
	Influence suppliers to offer take-back schemes	(Durão et al., 2014), (Respondent G and J)
	Minimise stored material to reduce the risk of excess materials, damaged materials and double-handling	(Burciaga et al., 2019; Fu et al., 2015)
	Enhance the reuse and recycling of material directly on the construction sites	(Burciaga et al., 2019; Durão et al., 2014)
	Implement procurement waste minimisation strategies	(Burciaga et al., 2019), (Respondent J)
	Conduct waste awareness and training activities	(Durão et al., 2014), (Respondent G)
	Disseminate good practices and demonstrate their feasibility through targeted dissemination activities	(Durão et al., 2014), (Respondent J)
	Develop a comprehensive waste management plan to minimise construction waste and maximise recycling and reuse of materials on-site	Burciaga et al. (2019)
	Prioritise waste prevention and reuse	Burciaga et al. (2019)
	Develop a systematic approach to identify and quantify construction and demolition waste, determining precise treatment requirements for effective waste management	Burciaga et al. (2019)
	Optimisation of waste containers available according to construction stage and expected waste categories	Burciaga et al. (2019)
	Optimise the size of waste containers in relation to emptying frequency	Burciaga et al. (2019)
	Separate and process waste to maximise the production of recycled aggregates	Burciaga et al. (2019)
	Reintegrate materials/components resulting from on-site activities	Durão et al. (2014)
	Effective reuse of temporary construction materials, such as formwork	Durão et al. (2014)
General	Adopting prefabricated construction methods	(Fu et al., 2015; Hong et al., 2014; Mao et al., 2013; Sandanayake et al., 2019; Takano et al., 2014; Teng and Pan, 2019; Weigert et al., 2022; Yao et al., 2020)
	Implement lean construction principles to reduce waste, optimise resource use, and streamline processes, reducing construction time and energy consumption	(Fu et al., 2015; Wu, 2015)
	Adapt carbon trading in the construction industry	Fang et al. (2018)
	Adding resource management strategies in construction programs and tenders	(Respondent A)

(2019), offer additional avenues for emission reduction. Reuse aggregates on-site refers to repurposing existing aggregate materials, such as crushed concrete, stone, or other construction debris, generated during construction activities within the same site. Instead of transporting these materials off-site for disposal, they are processed and reused in the current project. Environmental benefits of this practice include reducing virgin raw material demand, transportation costs and emissions, and waste sent to landfills.

Respondents also highlight the engagement with internal recycling centres to mitigate transportation distances. This involves bypassing the transportation step to the material recovery facility (MRF) and directly sending waste materials to the nearest utilisation facility (Respondent C). Alternatively, respondents discuss establishing agreements with stakeholders to facilitate voluntary arrangements for direct recycling. This may involve collaborations with organisations serving people experiencing homelessness or other vulnerable populations (Respondent J). Moreover, Kanafani et al. (2023) highlight the potential benefits of using local product manufacturing whenever available. As explained by Zhang et al. (2023) this can be achieved by developing green supply chains that help ensure the easy availability of low-carbon construction materials. Such findings underscore the necessity for the construction industry to address transportation carbon emissions to minimise its environmental footprint (Fang et al., 2018).

3.3.2. Fuel and equipment use

According to findings from a study conducted by Seo et al. (2016), three primary work types (civil engineering incl., pile- and earthwork, reinforced concrete, and ground heat construction) collectively accounted for approximately 90% of the total carbon emissions generated on-site during the construction of a building complex in Korea. The emissions were primarily attributed to the energy consumed by construction machinery and equipment employed in these tasks. This assertion aligns with Szamocki et al. (2019), who suggested that a significant amount of the emissions from the construction process stem from the fossil fuels utilised by machinery, such as excavators and dumpers. Implies a large potential for implementing reduction measures in construction activities, including strategic planning of construction equipment operations with a focus on appropriate equipment selection, aligning hauling equipment with loading equipment, optimising loading procedures of loaders, selecting closer dumping sites, adjusting the swing angle of excavators as part of task planning, and minimising engine idling. The problem with construction machines is the amount of idling during working hours, resulting in large emissions, which is frequently mentioned in the literature. Respondent C utilises GPS tracking systems to meet this problem, meaning that the construction project can use a mobile application on-site and then track each machine so unnecessary waiting time, idling, and unnecessary work can be significantly reduced by planning the optimal way to organise the work. Moreover, they use algorithms that can recognise effective routing for equipment transport to reduce unnecessary freight movements. However, these algorithms for effective routing have yet to be implemented for on-site transportation, and none of the contractors mentioned the use of telematics in machinery to optimise the fleet schedule or site logistics on-site. Training drivers in fuel-efficient driving, as proposed by Ren et al. (2012), can further aid in emission reduction efforts. Studies, including Boddi Reddy et al. (2023), emphasise the importance of adopting strategies such as alternative fuels or optimising equipment fleet scheduling in construction operations to mitigate fossil fuel consumption and associated emissions. Specifically, it is suggested that the use of forklifts be minimised due to their relatively high emission rates. Instead, considering the presence of a mobile crane on the project site capable of fulfilling similar heavy-material movement tasks as a forklift, a balance between forklift and mobile crane usage can be established based on feasibility and site conditions to reduce emissions effectively.

Similarly to the use of alternative fuels such as biofuels, transitioning from diesel machinery to electric equipment, especially if powered by renewable sources like wind or solar, can minimise fossil fuel usage and emissions, as mentioned by many of the practitioners from the interviews. Li and Chen (2017) investigated the comparison between emissions from electrical machinery and fuel-based machinery. Their findings suggest that despite the higher emission factors associated with fossil fuels compared to electricity usage, machinery powered by electricity emits more carbon than machinery powered by fossil fuels. Consequently, there is an emphasis on managing electric machinery to mitigate emissions in the construction process. However, it is essential to acknowledge that this study was conducted in China, which possesses a markedly different electricity mix compared to Denmark, where the interviewees conducted their projects. Therefore, a similar study conducted in Denmark may yield substantially different results. The significant emphasis placed by practitioners on utilising electric equipment underscores the importance of early connection to the electrical grid for minimising fuel consumption (Davies et al., 2013). Respondent D highlighted the necessity of establishing a temporary transformer due to the absence of an accessible transformer station in the construction site area. Prompt access to the electrical grid is crucial for enabling the feasibility of employing diesel-free equipment during the initial construction phases. However, in the absence of immediate access to the grid, the interim use of batteries can be considered. Nevertheless, the utilisation of batteries introduces logistical considerations regarding battery charging, which necessitates additional transportation of the batteries.

3.3.3. *Heating, electricity and water*

Reducing heating consumption during construction is a frequently overlooked aspect in practical implementation and research. However, Li et al. (2017) underscore the significance of employing labour allocation to optimise the trade-off between crew size and on-site heating requirements during winter periods in construction projects. Moreover, concrete curing is frequently mentioned as an energy-intensive process, as the process is time-consuming, and there is often a need for forced curing. Forced curing requires energy for heating, ventilation, dehumidification, etc., primarily in the form of electricity. To meet this problem, sensors are used to keep an eye on drying out (Respondent J) or the use of district heating instead of electricity, as mentioned by Respondent A.

Effective lighting is essential during construction projects, but its source and management play a crucial role in minimising electricity wastage and associated emissions. Obtaining electricity from renewable sources like solar and wind, whether on-site or from the grid, can significantly reduce emissions during construction (Imam and Ayadi, 2022). Respondent A emphasised the adoption of energy-efficient equipment and renewable energy sources, such as solar panels and LED lighting systems. Respondent J has decided only to use electricity produced from renewable sources, and if the client is responsible for supplying the electricity, they buy certificates to compensate for this. These measures aim to minimise energy consumption and reduce emissions during construction activities. On-site offices are commonplace, and their energy usage contributes to construction-stage emissions. As Respondent C suggested, retrofitting existing site cabins for energy efficiency and deploying energy-efficient new ones can substantially reduce emissions. Measures such as occupant sensors, lighting delay switches, heating timers, and equipment shutdown when not in use contribute to reducing emissions for on-site offices and lighting, as mentioned by almost all practitioners from the interviews.

Water consumption is not found to be a focus point either in research or for the practitioners, which may be due to water's smaller climate footprint compared to the other resource consumption on-site (Kanafani et al., 2023). However, efficient water management in construction is explained by Durão et al. (2014) to involve sourcing used water from nearby industries, utilising treated wastewater, and recycling grey water. Regular machine maintenance reduces water wastage while recycling efforts optimise water resource usage. These strategies enhance sustainability by minimising water consumption and environmental impact in construction operations.

3.3.4. *Waste generation*

Reduced waste generation leads to a corresponding decrease in emissions associated with waste transportation from construction sites, the embodied carbon of discarded materials and waste treatment such as incineration or utilisation. All interviewed respondents emphasise that efficient waste management in construction requires comprehensive planning involving stakeholders such as contractors, waste management organisations, and suppliers. Prioritising waste prevention, reuse, and recycling is paramount, necessitating the implementation of construction and demolition waste management plans to set minimum requirements and quantify waste amounts for effective treatment (Burciaga et al., 2019). Material reuse, including bricks, tiles, and concrete, reduces on-site waste generation, supported by improved logistics and innovative storage practices (Fu et al., 2015). Waste segregation, processing, and reintegration through mobile and stationary plants maximise the production of high-quality recycled aggregates, including the direct recovery or transformation of ceramic waste into recycled aggregates (Burciaga et al., 2019). On-site segregation ensures the cleanliness of secondary materials while integrating reused and recycled materials into buildings or supporting infrastructures enhance sustainability efforts. Collaborating with suppliers for take-back schemes and conducting staff awareness programs further promote sustainable construction practices (Durão et al., 2014). Additionally, reusing formwork wood contributes to waste reduction and sustainable resource utilisation, leading to a corresponding decrease in emissions associated with waste transportation from construction sites and the embodied carbon of discarded materials and waste treatment processes like incineration or utilisation (Durão et al., 2014). Implementing separate bins for reusable, recyclable, and combustible waste further aids in carbon reduction by ensuring the segregation of inert materials, such as concrete and soil, from non-inert ones, like packaging and wood (Burciaga et al., 2019). This practice mitigates waste transportation emissions and encourages on-site material reuse, thus contributing to embodied carbon reduction. Effective construction waste management seems critical for achieving emission reduction goals in the construction sector.

3.4. *Challenges and barriers for resource reduction*

Understanding barriers to necessary advancements and mitigating greenhouse gas emissions from construction sites is crucial. During interviews, respondents were asked about challenges encountered when measuring resource consumption during construction to reduce both consumption and associated emissions. These challenges, categorised into eight themes, are listed in Table 3.

The interviews shed light on several significant challenges facing the construction industry in implementing sustainable practices. For instance, the need for more emphasis on waste management and sustainability practices reflects a pervasive issue among e.g. concrete subcontractors, who are often responsible for a large share of the waste generation due to the high weight and extensive use of the material in construction. These subcontractors often neglect waste sorting and recycling, resulting in low rates of material reuse and diversion from landfills. This challenge is exacerbated by the absence of waste management clauses in contracts, limiting enforceability.

Another recurring challenge is the reluctance among contractors to engage in on-site waste management services (Respondent A). This reluctance stems from entrenched attitudes among workers accustomed to traditional waste disposal methods. Respondent D also highlighted the difficulty of educating older workers about new waste management protocols, indicating a need for targeted training initiatives. Furthermore, issues related to data accuracy, reliability, and interpretation pose significant hurdles in resource optimisation efforts. All the respondents emphasised the lack of management or standardisation of data models, leading to challenges in analysing resource consumption effectively. Technological constraints, such as limitations in existing infrastructure and interoperability issues among monitoring systems, further impede the integration of advanced technologies for real-time data collection and monitoring.

Resistance from subcontractors and smaller firms to invest in sustainability measures due to perceived cost implications and uncertain return on investment further impedes progress towards broader sustainability objectives in the construction sector (Respondent A and F).

Table 3
Challenges of reducing on-site resource consumption mentioned by the respondents (labelled A-J).

Category	Comments
Documentation or Reporting	• Data collection is mainly for documentation of sustainability standards (D, E, F, G, H, I, J) • Recycling percentages are pursued without focus on genuine recycling practices (B) • Reliable site reporting is necessary without reducing construction sites to accounting exercises while addressing administrative burdens and quality work diversion among small companies (J)
Technological	• Manual data retrieval and analysis due to lack of automation in resource monitoring processes (e.g., electricity, water, diesel) is time-consuming (A, G, J) • Special relays used for tower cranes cannot be used for measuring (D) • Signal issues from meter placement can result in manual data entry processes (G)
Cost	• Switching to electric trucks is expensive, making it hard for customers to invest without incentives (C) • Installing metering systems on construction sites is costly, especially after-hours, leading to manual readings (D) • There's a price difference between monitoring devices and electrical submeters (D) • A take-back system for materials was discontinued due to high cost (G) • Managing deliveries on construction sites is expensive without widespread technological solutions (H) • Smaller firms resist investing in sustainability due to cost implications and uncertainties (A, F)
Data Management	• Without established industry baselines, verifying performance is challenging, leading to debates over effectiveness (A, F) • Relying on certain suppliers may result in incomplete and misleading data (F) • Data transfer from waste management systems is hindered by a gap between data holders and users, hindering informed decision-making (H)
Regulatory Compliance	• Procurement regulations in the public sector complicate the selection and specification of metering equipment (A) • Absence of standardised industry practices and reporting frameworks exacerbate challenges in monitoring and benchmarking resource consumption (B, F) • A diverse array of systems used by different stakeholders requires standardisation of reporting formats to avoid manual data entry (B) • Navigating the ambiguity surrounding resource utilisation metrics inhibits the advancement of true circular economy practices and challenges achieving recycling rate targets by obscuring genuine recycling from other waste management methods (B, J) • Meeting future regulatory compliance standards for green transport remains a challenge (C)
Behaviour	• Resistance to change among construction professionals (A, D) • Lack of comprehensive understanding and engagement regarding sustainability objectives (A, F) • Limited demand for sustainability practices and insufficient platform development for data sharing (C) • Inadequate support and resources (F, I) • Focus on cost over sustainability (F) • Complex bureaucratic processes and data accessibility issues (H) • Misconceptions about sustainability and its measurement (J)
Logistics	• Installing meters and coordinating with contractors on construction sites pose logistical challenges (A) • Waste disposal and material handling are challenging due to limited space, requiring strategic planning for temporary offices and waste fraction allocation (J)
Supply Chain	• Ownership of resources like electricity hinders reducing consumption (A, B, C) • Limited user-friendly tools and platforms for data collection and reporting inhibit collaboration in the construction supply chain (F, H, I) • There's a need for reliable data transfer and documentation standards across the value chain (B, F)

Financial considerations also play a crucial role in hindering sustainability efforts. The high initial investment required for deploying comprehensive monitoring systems and implementing resource reduction measures can pose financial challenges for construction projects (Respondent D). Space constraints and neighbourly pressures often necessitate after-hours installation to minimise disruption. This can lead to the need for additional expenses, such as overtime pay and specialised equipment, which further inflate the overall cost of implementation. The dynamic nature of construction site layouts also requires frequent adjustments, such as relocating panels or connecting new utilities, which can incur additional costs associated with manual tracking and potential inaccuracies in consumption data. Manual readings remain the preferred method of tracking energy consumption for some of the respondents due to their perceived cost-effectiveness compared to comprehensive monitoring devices. The respondents mentioned disparities in cost estimates for monitoring systems, highlighting the complexity of decision-making processes. Moreover, respondent C mentioned that transitioning to a more environmentally friendly transport fleet can be financially difficult. This is because the upfront costs of electric trucks are significantly higher than those of traditional diesel trucks. Customers may hesitate to invest in electric alternatives without clear incentives to offset the initial financial outlay. Furthermore, the discontinuation of a costly take-back system for materials highlights the financial obstacles to sustainable practices (Respondent G). Maintaining personnel dedicated to recording and managing incoming deliveries on construction sites also presents financial challenges (Respondent G), as it requires constant supervision and lacks technological solutions among subcontractors.

Regulatory compliance adds another layer of complexity, with diverse regulatory frameworks and environmental guidelines imposing administrative burdens on construction projects. Compliance with industry standards and certification criteria further complicates resource reduction initiatives. As an example, multiple respondents mention problems regarding the EU taxonomy rule that at least 70% of the waste, measured in weight, must be prepared for reuse, recycling, or other material recovery since by directly reusing something, it never becomes waste and is therefore not included in the accounts for reporting. This creates an incentive to put the materials in the waste containers and send them for recovery rather than directly reusing the materials or generating more waste to achieve the percentages.

Supply chain challenges, including coordination issues among suppliers, subcontractors, and project teams, contribute to inefficiencies and suboptimal resource utilisation throughout the construction process. For example, the contractors express a problem with the ownership of e.g. heating expenses, particularly in residential buildings where district heating or natural gas suppliers often only bill for consumption after the handover. Typically, heating and electricity costs are the responsibility of the owner, who is often not the contractor, leading to potential oversights in the contractor's data delivery. Addressing these challenges requires collaborative efforts from construction stakeholders, policymakers, and industry experts to develop innovative solutions, promote knowledge sharing, and foster a culture of sustainability within the industry.

3.5. Gaps between research and practice

Several gaps existed between research and practice regarding the

Table 4
Enablers, specific issues, and opportunities guiding the direction of sustainable construction practices.

Enablers	Specific Issues	Potentials
Monitoring systems	Data collected for documentation	Real-time monitoring for timely intervention
Regulatory Frameworks and Benchmarks	Complex industrial processes require standardised methods	Standardised methodologies for conducting LCAs of the construction process to evaluate on-site emissions.
	Lack of basis for comparison	Regulatory frameworks and benchmarking for comparing LCA results
Cooperative Ownership Models	Complex bureaucratic processes	Simplifying bureaucratic processes and fostering collective responsibility for resource usage.
Digital Platforms and Tools	Manual data retrieval and analysis	Investing in technologies that automate data collection and analysis processes for streamlining operations and reduce manual efforts
	Limited user-friendly tools and platforms	Digital platforms and tools for streamlining data-sharing processes and facilitating collaborative decision-making.
Financial Incentives	High costs associated with sustainable actions	Economic incentives for adopting on-site resource reduction measures
Education Programs	Reluctance, misconceptions and ownership issues	Implementation of targeted training programs
Collaborative Platforms and Tools	Limited demand for sustainability practices and insufficient data-sharing platform	Development of collaborative data-sharing platforms
Strategic Planning	Managing logistics for waste disposal, material handling, and meter installation	Strategic logistics planning and optimising space utilisation
Data Accessibility and Partnerships.	Reliance on certain suppliers may result in incomplete and misleading data.	Diversifying data sources and partnering with multiple suppliers

climate impact of on-site resource consumption during building construction. These gaps reflect the challenges and opportunities in addressing the environmental impact of construction. Addressing these gaps requires a collaborative effort among researchers, industry practitioners, policymakers, and other stakeholders. Bridging the divide between research and practice is crucial for advancing sustainable construction and reducing the climate impact of on-site resource consumption.

Research often highlights the potential benefits of sustainable practices or innovative technologies and materials to reduce climate impact, such as using monitoring sensors, low-impact equipment, or energy-efficient construction techniques. However, sustainable practices and innovations may not be widely adopted in the construction industry due to various barriers, including technological constraints, cost considerations, ownership complications, lack of awareness, and resistance to change or concerns about reliability, scalability, and industry norms. Human behaviour and cultural factors within the construction industry can present challenges in adopting sustainable practices. Resistance to change, lack of training, and cultural norms can hinder the implementation of research findings. Construction projects involve multiple stakeholders in a fragmented supply chain, and research may not always consider the interdependencies and complexities within this chain, making it difficult to align research findings with on-site practices.

The construction industry often operates with a short-term perspective, emphasising project completion and cost control. Research findings may not always align with this short-term focus, making it challenging to implement long-term sustainability measures. The upfront costs of sustainable construction practices can be higher, even if they lead to long-term cost savings. The construction industry may prioritise immediate cost considerations over long-term environmental benefits.

Assessing the climate impact of on-site resource consumption is a complex task that involves multiple variables, such as material choices, construction methods, transportation, and energy use. Research often simplifies these variables and often relies on estimation models and assumptions, which may not accurately represent real-world scenarios. This makes it challenging to provide a comprehensive understanding of real-world construction projects, which hinders the ability to use the data to make informed decisions. The reason for estimating the resource flows is due to the need for adequate and consistent data on on-site consumption during construction practices. While there are standard methodologies for conducting LCAs in construction, there can be variations in how LCAs are carried out. Moreover, the modules for the construction process, A4 and A5, are often overlooked, and there needs to be a standardisation of how to conduct the assessment of these modules. Out of the included articles, nine conduct an LCA to some extent. However, none of these articles uses the same method for data collection, system boundary, background processes or assumptions. This lack of standardisation can lead to inconsistency in reporting and comparing results, hindering practice implementation. Moreover, it makes it difficult to set up benchmark values that practitioners request in order to start initiatives for reduction.

Research often identifies the need for stronger regulations and policies to promote sustainable construction practices. Nonetheless, there appears to be a disconnect between research findings and the information flow to construction professionals. This limited dissemination of knowledge hampers the effective transmission of research outcomes to practitioners. Consequently, policies may need to be established or enforced adequately, leading to a disparity between research recommendations and their practical implementation in the field.

3.6. Potentials for monitoring and on-site reduction

While the interviews with practitioners yielded limited information regarding currently integrated reduction measures, they highlighted the potential for on-site resource consumption monitoring and real-time reduction strategies within the construction industry, echoing findings from research articles. The challenges highlighted in the interviews also pointed to key enablers and opportunities in Table 4.

Real-time monitoring systems offer an unparalleled level of visibility into resource usage patterns and operational inefficiencies on construction sites. This enables accurate measurement of the environmental impact of construction operations and practical analysis of resource consumption patterns. By collecting data in real-time, monitoring systems provide a foundation for immediate analysis and identification of opportunities for strategic reduction efforts. Transparency across resource utilisation processes is significantly enhanced through the utilisation of data analytics and advanced technologies such as Building Information Modelling (BIM) and Internet of Things (IoT) sensors. Predictive analytics, enabled by real-time data insights, allow for proactive resource management by anticipating demands and identifying optimisation opportunities. By forecasting requirements and detecting anomalies in consumption patterns, construction projects can mitigate risks associated with resource scarcity and operational disruptions.

Integration of real-time monitoring systems streamlines operational efficiency throughout the construction lifecycle. Digital technologies play a pivotal role in minimising resource wastage by identifying bottlenecks, optimising workflows, and synchronising resource allocation, resulting in notable improvements in productivity and cost-effectiveness. Timely intervention and risk mitigation strategies are facilitated by real-time monitoring, as emphasised by practitioners who underscore proactive risk management practices, including early detection of equipment malfunctions or safety hazards.

According to the respondents, setting clear project goals and utilising predictive analytics to anticipate resource usage is paramount. Integrating predictive models based on historical data enables realistic target setting and optimised resource allocation throughout the construction process. Robust data reporting and analysis are essential for implementing effective resource management strategies, with active measures involving data-driven solutions being critical to monitor usage patterns continually and identify areas for improvement. Diversifying data sources and partnering with multiple suppliers provide comprehensive and reliable resource utilisation data. This approach minimises the risk of incomplete or misleading data and promotes collaboration, transparency, and better decision-making.

On-site resource monitoring cultivates a culture of continuous improvement and innovation within the construction industry. Data-driven decision-making processes and performance benchmarking initiatives are emphasised, which drive innovation, optimise resource utilisation, and achieve long-term sustainability goals. Standardised reporting frameworks and collaboration among stakeholders are highlighted as necessary for uniform data collection for ESG reporting. Streamlining data collection processes through sensor-based technologies reduces the burden on on-site personnel, ensuring accurate and timely reporting and facilitating continuous improvement efforts. Investing in technologies that automate data collection and analysis processes, construction companies can streamline their operations, reduce manual efforts, and improve the accuracy and efficiency of resource monitoring. Digital platforms and tools can improve collaboration and communication in the construction supply chain by streamlining data-sharing processes and facilitating collaborative decision-making.

The financial benefits associated with resource optimisation are recognised, including reduced costs and potential long-term gains, driving the adoption of efficient resource monitoring and reduction strategies within construction projects. Financial incentives can offset the initial costs associated with emission reduction measures like metering systems, making them feasible for construction firms to adopt them. Streamlined decision-making and cost estimates can address the challenges and benefits of deploying monitoring systems. Prioritising material circularity and waste reduction efforts, coupled with implementing incentive structures for responsible resource management practices, is underscored as pivotal for fostering sustainable behaviours among stakeholders.

4. Conclusions

This study aims to connect academic research with real-world practices in the construction industry, shedding light on significant discrepancies in reducing resource usage. Conducting in-depth interviews with industry practitioners and a systematic literature review has identified a range of reduction measures, with 15 concerning transport and 58 for on-site processes. However, this adequate list highlights the gap between theoretical knowledge and on-site practices, as many identified reduction measures from the SLR are not used in practice. Only 26% of the reviewed articles actually measured on-site resource consumption, while the remaining used estimated data for analysis. This indicates a general need for on-site monitoring and real-time evaluation of emissions.

The interviews with the practitioners revealed that they are not taking strategic reduction initiatives, although data on construction sites is being collected for reporting and documentation purposes. Despite numerous reduction measures identified in the literature, the practitioner interviews revealed 31 challenges hindering their practical implementation. These challenges were divided into eight categories: Documentation or Reporting, Technological, Cost, Data Management, Regulatory Compliance, Behaviour, Logistics, and Supply Chain. To address some of these specific issues, nine enablers were identified as having the potential to implement reduction measures. These findings echo those from the SLR, highlighting several crucial factors that must be considered for the practical adoption of reduction measures during the construction process.

i. Targeted training initiatives to address entrenched attitudes and resistance to new waste management protocols to facilitate the adoption of sustainable practices.
ii. Real-time metering should be implemented to provide quantified evidence of the climate impact of construction activities, enabling practical analysis of resource consumption patterns.
iii. Standardised methodological approaches for conducting LCAs of the construction process to evaluate on-site emissions.
iv. Addressing financial challenges and benefits associated with deploying monitoring systems and implementing reduction measures by providing cost estimates and streamlining decision-making processes.
v. Establishment of standardised regulatory frameworks and benchmarking so that building practitioners can compare their LCA results with the standards.

It is crucial to evaluate the environmental impact of construction activities and determine practical ways to implement solutions. Regulatory bodies must set requirements to address this issue, but the lack of standardised methods and benchmark values makes it challenging. Although the perspective presented in the study is from Danish practice, the challenges identified, such as high costs, resistance to change, and the need for better regulatory frameworks, are likely global. To make meaningful progress towards sustainable resource management in construction, regulatory bodies need to establish clear requirements, standardise methods, and promote collaboration among stakeholders. It is important to note that many specific measures highlighted in this study can already be put into practice. Industry practitioners, policymakers, and researchers are encouraged to adopt and customise these measures to their specific contexts, thereby ensuring that the insights from this study contribute to promoting sustainable construction practices globally and advancing efforts to reduce the environmental impact of the construction sector.

4.1. Limitations and future research

The keywords used during the search process determined the literature study's scope, influencing the quantity of relevant literature obtained, which should be considered when interpreting the findings. While grey literature could provide additional insights into the gap between scientific knowledge and practical application, our focus was solely on published peer-reviewed journal articles to ensure methodological consistency and academic rigour. The interviews offered valuable insights into resource monitoring practices and challenges at construction sites, though limitations exist, particularly in representing smaller-scale construction operations. Future research could benefit from incorporating grey literature and insights from diverse construction stakeholders to provide comprehensive guidance on resource management practices applicable across the industry spectrum. Future research directions that can be extended from the current study include.

i. Develop and validate standardised LCA methodologies explicitly tailored to the construction phase to improve the reliability of environmental impact assessments.
ii. Test the environmental mitigation potential of emerging technologies, such as sensors and IoT applications, for automating and streamlining resource monitoring and data collection and sharing on construction sites.
iii. Perform case studies implementing relevant resource management and emission reduction strategies. The approach should include a whole-life perspective for identifying potential trade-

offs between life cycle stages. Site locations should include a variety of global locations.

There is scope to explore the potential use of the reviewed reduction measured in decision-making during the construction process to enhance their practical applicability. By addressing these areas, future research can build on the foundation laid by this study and contribute to the advancement of sustainable practices in the construction industry, including the often-overlooked construction phase.

CRediT authorship contribution statement

Lea Hasselsteen: Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Søren Munch Lindhard:** Writing – review & editing, Methodology. **Kai Kanafani:** Writing – review & editing, Supervision.

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

During the preparation of this work the author(s) used the Whisper Transcription application in order to transcribe the interviews in this study. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

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.

Data availability

Data will be made available on request.

Acknowledgements

This work was financially supported by the Innovation Fund (grant no. 2050-00026A).

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