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Review

# Towards BIM-Based Sustainable Structural Design Optimization: A Systematic Review and Industry Perspective

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**Abstract:** Structural design optimization (SDO) plays a pivotal role in enhancing various aspects of construction projects, including design quality, cost-efficiency, safety, and structural reliability. Recent endeavors in academia and industry have sought to harness the potential of Building Information Modeling (BIM) and optimization algorithms to optimize SDO and improve design outcomes. This review paper aims to synthesize these efforts, shedding light on how SDO contributes to project coordination. Furthermore, the integration of sustainability considerations and the application of innovative technologies and optimization algorithms in SDO necessitate more interactive early-stage collaboration among project stakeholders. This study offers a comprehensive exploration of contemporary research in integrated SDO employing BIM and optimization algorithms. It commences with an exploratory investigation, employing both qualitative and quantitative analysis techniques following the PRISMA systematic review methodology. Subsequently, an open-ended opinion survey was conducted among construction industry professionals in Europe. This survey yields valuable insights into the coordination challenges and potential solutions arising from technological shifts and interoperability concerns associated with widespread SDO implementation. These preliminary steps of systematic review and industry survey furnish a robust knowledge foundation, enabling the proposal of an intelligent framework for automating early-stage sustainable structural design optimization (ESSDO) within the construction sector. The framework ESSDO addresses the challenges of fragmented collaboration between architects and structural engineers. This proposed framework seamlessly integrates with the BIM platform, i.e., Autodesk Revit for architects. It extracts crucial architectural data and transfers it to the structural design and analysis platform, i.e., Autodesk Robot Structural Analysis (RSA), for structural engineers via the visual programming tool Dynamo. Once the optimization occurs, optimal outcomes are visualized within BIM environments. This visualization elevates interactive collaborations between architects and engineers, facilitating automation throughout the workflow and smoother information exchange.

**Keywords:** automated structural design; Building Information Modeling (BIM); design automation; generative design; interoperability; Structural Design Optimization (SDO); systematic framework

## 1. Introduction

Structural design represents a critical aspect of architecture, engineering, and construction (AEC) projects, entailing the creation of robust, secure, and enduring structures capable of withstanding diverse loads and environmental conditions. The global market for structural engineering reached a value of \$10.4 billion in 2019 and was forecasted to attain \$14.4 billion by 2027, displaying a Compound Annual Growth Rate (CAGR) of 4.1% from 2020 to 2027 (Report, 2023). Due

to this enormous investment and the paramount significance of structural integrity within this realm, recent advancements in computational design and theoretical frameworks have advanced structural design practices (Bianconi, Filippucci, & Buffi, 2019). This evolution has ushered in novel perspectives for the construction industry, ushering in automation and innovative design methodologies. The convergence of computer technology, modern structural engineering, and advances in construction materials has led to the structural design optimization (SDO) (Afzal, 2019), and structural design automation (Bourahla, Larfi, Souaci, Bourahla, & Tafraout, 2023), both enhancing the efficiency of AEC practices. Moreover, the utilization of these computational tools and methodologies in structural design has prompted AEC stakeholders to increasingly consider crucial environmental sustainability factors during the initial phases of building structure design (Afzal, Liu, Cheng, & Gan, 2020).

Recent advancements in SDO aim to optimize the configuration and dimensions of structures to optimize augmenting strength (Gan, Cheng, & Lo, 2019; Tae, Baek, & Shin, 2011), minimize material usage (M. Li et al., 2021; Mangal & Cheng, 2018), reduce costs (Chutani & Singh, 2018), enhance energy efficiency (Stathis Eleftheriadis, Mumovic, & Greening, 2017; Tumminia et al., 2018), improve sustainability (Bragança, Vieira, & Andrade, 2014; S. Eleftheriadis, Duffour, & Mumovic, 2018; Yoon, Kim, Lee, & Yeo, 2018; X. Zhang & Zhang, 2021), and optimize several other performance criteria (Stathis Eleftheriadis et al., 2017; Yousuf, Alamgir, Afzal, Maqsood, & Arif, 2017). Concurrently, structural design automation endeavors to streamline the design process, mitigate human errors, and enhance productivity through computer-based tools and optimization algorithms. Prominent practices and technologies in this domain include parametric design (Gan et al., 2019; Wong, Wu, Gan, Chan, & Cheng, 2023), generative design (Khoshamadi et al., 2023; Liao, Lu, Huang, Zheng, & Lin, 2021), Building Information Modelling (BIM) technology (Caires, 2013; Hamidavi, Abrishami, & Hosseini, 2020; Kim, Hadadi, Kim, & Kim, 2018; S. Zhang, Teizer, Lee, Eastman, & Venugopal, 2013), machine learning (ML), and artificial intelligence (AI) (Castro Pena, Carballal, Rodríguez-Fernández, Santos, & Romero, 2021; Liao et al., 2021; J. Liu et al., 2021), as well as integrating finite element analysis (FEA) with simulation tools (Lin, Xu, Lu, Guan, & Li, 2020a, 2020b). Parametric modeling techniques empower structural designers to define parameters governing a structure's geometry and dimensions, facilitating rapid exploration of diverse design variations and their performance analysis. Similarly, generative design employs algorithms to automatically generate designs based on predefined constraints and objectives. BIM, a transformative technology in AEC, facilitates the 3D model creation and management, data sharing among stakeholders, and automates structural design (Bourahla et al., 2023). AI algorithms and automated design and simulation tools enrich structural practitioners with intelligent platforms to analyze extensive data, predict structural behavior, and expedite design alternatives, ensuring alignment with envisaged structural performance.

These recent computational strides heighten the technological adoption during early design phases, and they have offered new prospects for the AEC industry (Hamidavi, Abrishami, Ponterosso, Begg, & Nanos, 2020). According to a McKinsey & Company study, firms integrating digital technologies in engineering and construction could shorten project delivery times by 20% and achieve cost savings of up to 15% (Jan Koeleman 2019). Beyond design automation, intricate structural designs necessitate digitally driven decision support tools that are stable, cost-effective, and aligned with project objectives. The synergy between design automation and optimization algorithms proves especially advantageous in the initial phases of the structural design (Hamidavi, Abrishami, Ponterosso, et al., 2020). This synergy accelerates the design workflow while delivering optimal design solutions, recognizing the pivotal influence architects and structural designers wield in shaping a built asset's performance throughout its lifecycle. Consequently, there is a growing emphasis on early-stage optimization to create optimal design solutions. Various studies have endeavored to automate structural design optimization during early-stage conceptualization, enhancing dependability, structural integrity, economic efficiency, and environmental sustainability of built environments. For instance, Mangal and Cheng (Mangal & Cheng, 2018) employed a hybrid genetic algorithm coupled with BIM technologies to automate detailed RC structure design. Eleftheriadis et al. (S. Eleftheriadis et al., 2018) utilized BIM and Finite Element Method (FEM) to optimize flat slabs, reduce building material usage, mainly steel reinforcement. Another study by

(Afzal, 2019) integrated BIM and metaheuristic algorithms for RC structural design optimization, lowering steel reinforcement in high-rise structures and decreasing overall construction costs. Numerous studies other studies (Gan et al., 2018; Hamidavi, Abrishami, & Hosseini, 2020; Marzouk, Abdelkader, & Al-Gahtani, 2017; Marzouk, Azab, & Metawie, 2018; Porwal & Hewage Kasun, 2012; Wong et al., 2023) integrated various optimization strategies with BIM, presenting promising computational avenues for complex early-stage structural engineering challenges.

### 1.1. Research Significance

Optimized structural designs reduce costs and enhance efficiency, material conservation, and sustainability enhancements, as well as enable designers and practitioners to explore a multitude of design variations quickly, resulting in high-quality and practical outcomes. Even though, digitally driven SDO practices benefit stakeholders, especially architects and structural engineers, across the entire lifecycle of a built asset by enabling them to harness automation and optimization to explore creative design possibilities while engineers ensure structural integrity and efficiency. However, the often-neglected aspect is a seamless collaboration between architects and structural engineers, as these advanced SDO practices can complicate coordination between architects and structural engineers (Smith & Tardif, 2009). Additionally, although optimization, automation, and sustainability inclusion in SDO processes offer substantial advantages, they can complicate coordination between architects and structural engineers. Challenges include interoperability issues arising from the integration of various tools and platforms, complex decision-making that involves trade-offs between structural performance and sustainability goals, a learning curve as stakeholders adapt to new technologies, data sharing difficulties, and the need to align often diverse objectives related to aesthetics, structural integrity, and sustainability. The existing studies lack a comprehensive and proactive approach to coordination and collaboration between these stakeholders that can address these complexities. Previous studies have not addressed the means to enhance collaboration between stakeholders in SDO processes. Though some studies have examined related concerns (Beghini, Beghini, Katz, Baker, & Paulino, 2014; Bourahla et al., 2023; Byrne et al., 2011; Reisinger et al., 2022; Sibenik & Kovacic, 2020), they focused on integrating structural engineering considerations into architectural processes or vice versa or addressed collaboration during digital construction stages.

A notable research gap thus remains within BIM-based structural design optimization and automation during early construction phases, particularly concerning interactive collaboration between architects and structural engineers. In this context, Hamidavi et al. (Hamidavi, Abrishami, & Hosseini, 2020) highlighted the challenge of interoperability between these disciplines during automation and optimization. The current focus on automation and optimization should not overshadow the critical need for real-time and interactive collaboration. While automation and optimization are vital, facilitating real-time collaborative interaction is equally crucial. Automating design changes without enabling architects and engineers to iteratively modify parameters and observe instant structural changes could impede holistic, collaborative automation. Addressing this gap mandates refining interoperability by automating platforms, fostering continuous communication, enabling joint exploration and decision-making, and maximizing BIM-based design optimization and automation potential.

To bridge these research gaps, this study employs a systematic approach to comprehensively review the current state-of-the-art, offering quantitative and qualitative analyses. A thorough evaluation of existing research concentrates on early-stage structural design optimization using emerging technologies. The quantitative analysis provides a statistical overview of pertinent research documents retrieved from scientific databases using specific keywords in search queries. Simultaneously, qualitative analysis categorizes research documents into distinct objectives of structural design optimization tailored to different project phases and process levels across the building lifecycle. These categories encompass the *conceptualization and configuration stage*, *automated code compliance stage*, *fabrication and prefabrication details*, *construction execution stage*, and *structural monitoring phase*. An exploratory study supplements the analysis through an online survey among

accredited structural engineers, primarily from Italy as well as from the whole of Europe, gathering insights on collaboration challenges from an industry perspective. Integrating quantitative and qualitative analyses and survey results, the study proposes an intelligent framework for BIM-based early-stage sustainable structural design optimization (ESSDO). The ESSDO framework seamlessly integrates BIM platforms for architecture and structural design (for instance, Autodesk Revit, which is extensively used for architectural design, and Autodesk Robot Structural Analysis-RSA extensively used for structural design and analysis) using the visual programming tool Dynamo. The framework facilitates design, analysis, and optimization by generating optimal design configurations and fostering interactive collaboration between architects and engineers. The framework finds application across various structures, from tall buildings to residential units and bridges, addressing challenges in early design stages.

### 1.2. Research Questions and Objectives

This holistic literature review study mainly targets to answer the following research questions (RQs):

- (RQ<sub>1</sub>) What are the current research trends in automated structural design optimization (SDO) efforts?
- (RQ<sub>2</sub>) How do automation, optimization, and sustainability inclusion aspects during SDO affect the interactive coordination among architects and structural engineers for decision-making?

To comprehensively answer these research questions, the following are the research objectives/tasks (RTs) to be executed in this research study.

- (RT<sub>1</sub>) Systematic analysis of the present state of research on the automation of structural design optimization (SDO).
- (RT<sub>2</sub>) Provision of quantitative and qualitative analyses of the current state-of-the-art in automating structural design optimization.
- (RT<sub>3</sub>) Exploration of challenges for collaboration and interoperability between architects and structural engineers for structural design optimization through online opinion survey.
- (RT<sub>4</sub>) Proposal of a systematic BIM-based framework for early-stage sustainable structural design optimization (ESSDO) to streamline interactive coordination between architects and structural engineers.

### 1.3. Paper Organization

The overall structure of this study is organized as follows. Following this introduction, Section 2 consists of the *“methodology and literature retrieval”* (RT<sub>1</sub>) from the scientific databases. Research findings and discussions on the overview of the *“quantitative analysis of the current status”* (RT<sub>2</sub>) are then provided in Section 3. This section also consists of the *“qualitative analysis of the research and categorization of the available research”* (RT<sub>2</sub>) based on the project phases and process levels. *“Opinion survey results from professionally acclaimed structural engineers”* (RT<sub>3</sub>) are also provided in Section 3. The *“ESSDO framework proposal”* (RT<sub>4</sub>) is presented in Section 4, followed by the *“conclusions”* highlighted in Section 5.

## 2. Materials and Methods

This study embarks on an exhaustive retrieval and examination of research content concerning the automation of structural design optimization employing digital tools from 2010 to 2023. The initial objectives of this study, i.e., RT<sub>1</sub> and RT<sub>2</sub>, are directed toward furnishing quantitative and qualitative analyses of the current state-of-the-art. These analyses form the foundation for subsequent objectives, including an opinion survey and the development of the ESSDO framework. In light of this, a systematic literature review (SLR) is employed, as it adheres to a meticulous and specified procedure for identifying, assessing, and synthesizing the existing body of knowledge on a specific subject (Fink, 2019). This approach serves to establish the present current state-of-the-art in the field of discussion, i.e., the automation of structural design optimization through digital tools and

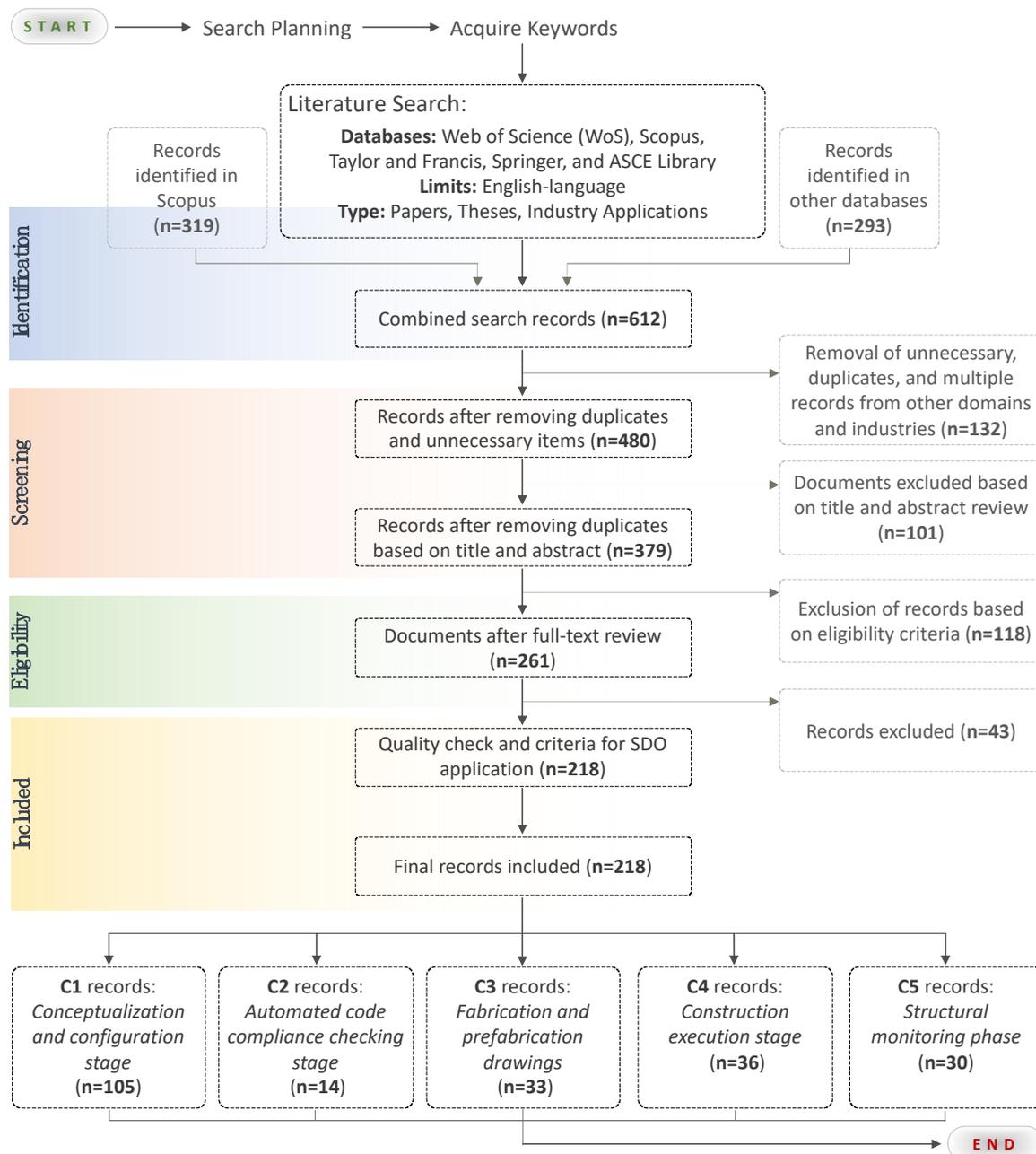
optimization approaches. A detailed examination of the SLR process unveils a three-phase framework comprising planning, implementation, and reporting. The initial planning phase involves crafting pertinent research queries and setting specific criteria to facilitate the identification of relevant research articles and search strategies. The subsequent implementation stage encompasses gathering and selecting pertinent literature for incorporation into the study. Lastly, the reporting phase entails synthesizing and thoroughly analyzing the gathered literature. Therefore, in this research undertaking, the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) method is adopted to collect data for the systematic review. PRISMA's wide acceptance in systematic review studies is attributed to its lucid delineation of the rationale and methodologies employed to locate, screen, exclude, and include pertinent literature (Moher, Liberati, Tetzlaff, & Altman, 2009; Shamseer et al., 2015), bolstering the precision and accuracy of the systematic review process.

### 2.1. Categorization and Scope Criteria

The principal categorization criteria for this study's literature stem from pertinent research focusing on the automation of structural design optimization. Digital tools encompassing BIM platforms and collaborative digital processes augment structural design optimization by facilitating the creation and management of 3D models of buildings or infrastructure units. This enables engineers and other stakeholders to benefit from information-rich representations of structural models. Consequently, the existing research documents are categorized based on structural design optimization and automation efforts targeting diverse project phases and process levels, including the *conceptualization and configuration stage*, *automated code compliance stage*, *fabrication and prefabrication details*, *construction execution stage*, and *structural monitoring phase*. While there exist multiple stages in AEC projects where SDO efforts could streamline work processes, this study focuses on systems and processes typically influenced by early-stage SDO practices. Furthermore, SDO applications extend to various structural systems like steel structures, composite structures, and pre-stressed forms, but this study confines itself to reinforced concrete (RC) structures, the most prevalent structural form that may exhibit specific configurations during the design stage.

### 2.2. PRISMA Workflow

Similar to David, A., et al. (David et al., 2023), this study follows a step-by-step PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) workflow to retrieve literature pertaining to the subject matter, utilizing specific keywords to filter research documents in line with inclusion and exclusion criteria, depicted in **Figure 1**. The following steps outline the process of implementing the PRISMA methodology in this study.



**Figure 1.** Description of procedural steps involved in the research PRISMA approach for literature retrieval, filtering, inclusion and exclusion criteria, and categorization of research records. (Figure source: authors).

**Step 1) Literature Search Process:** The methodology for literature search has a profound impact on the outcomes of systematic reviews (Kugley et al., 2017), particularly in emerging research fields such as the automation of design processes in the AEC sector. This study adopts a rigorous approach to retrieve literature from reputable scientific research databases, including Scopus, Web of Science (WoS), Springer, Taylor and Francis, and ASCE Library. All these databases are chosen to cover a maximum amount of relevant research records and offer a comprehensive overview of state-of-the-art research in automating structural design optimization. Notably, Google Scholar is excluded from the review due to its unsuitability for systematic reviews (Gusenbauer & Haddaway, 2020). The search queries used during this step were as follows: (“BIM-based” OR “automated” OR “BIM-assisted” OR “advanced” OR “intelligent” OR “integrated”) AND (“reinforced concrete structural design” OR “RC design” OR “structural systems” OR “structural patterns” OR “multi-objective”) AND (“optimization” OR “optimisation” OR “optimum” OR “optimal”) AND (“framework” OR “approach” OR “technique” OR

“algorithms” OR “methods” OR “procedures”). These queries aim to identify articles published between 2010 and July 2023, encompassing a significant volume of literature in this research domain. The initial emphasis is on the Scopus database, yielding a total of 319 records, followed by other databases, yielding an additional 293 articles.

**Step 2) Literature Inclusion and Exclusion Criteria:** This stage involves a comprehensive review of each article, from the abstract to the conclusion sections. 612 documents are collected from all the databases mentioned above. The screening process is carried out in three phases, commencing with the elimination of duplicate findings and studies from other industries, resulting in 379 articles. Subsequent screenings evaluate the titles and abstracts of publications, leading to the exclusion of papers centered on structural systems beyond the study’s scope. Additional records not meeting the eligibility criteria outlined in the study’s scope and not aligning with the service or functional area for which the SDO study is intended are excluded in the final phase. Ultimately, 218 records remain for a full evaluation.

**Step 3) Literature Categorization:** The final step involves categorizing the documents for a comprehensive full-text review. The available research records are categorized based on their primary contributions to structural design optimization and automation, targeting distinct project phases and process levels. These categories encompass the *conceptualization and configuration stage*, *automated code compliance stage*, *fabrication and prefabrication details*, *construction execution stage*, and *structural monitoring phase* (further elaborated upon in the qualitative content analysis section). **Table 1** succinctly summarizes the steps, including search strings, filtering, inclusion and exclusion, and categorization, involved in the SLR review of available research on SDO.

**Table 1.** Literature search parameters and conditions involved in the SLR review process.

<b>Source Databases</b>	Scopus, Web of Science (WoS), Springer, Taylor and Francis, and ASCE Library
<b>Search String</b>	(TITLE (bim-based) OR TITLE (automated) OR TITLE (bim-assisted) OR TITLE (advanced) OR TITLE (intelligent) OR TITLE (integrated) AND TITLE ("reinforced concrete structural design") OR TITLE ("RC structural design") OR TITLE ("RC design") OR TITLE ("structural systems") OR TITLE ("structural patterns") OR TITLE (multi-objective) AND TITLE (optimization) OR TITLE (optimisation) OR TITLE (optimum) OR TITLE (optimal) AND TITLE (framework) OR TITLE (approach) OR TITLE (technique) OR TITLE (algorithms) OR TITLE (methods) OR TITLE (procedures))
<b>Time-period Restriction</b>	2010-2023
<b>Article Types</b>	Journal, Conference Paper, Book Chapter, Review
<b>Language Restriction</b>	English
<b>Included Subject Areas</b>	Engineering, Computer Science, Energy, Mathematics, Environmental Science, Decision Sciences, Business, Management and Accounting, Materials Science, Economics, Econometrics and Finance, Multidisciplinary
<b>Excluded Subject Areas</b>	Physics and Astronomy, Social Sciences, Earth and Planetary Sciences, Chemical Engineering, Chemistry, Agricultural and Biological Sciences, Neuroscience, Medicine, Biochemistry, Genetics and Molecular Biology
<b>Work Area/Industry</b>	AEC, Construction, Structural Engineering, Civil Engineering

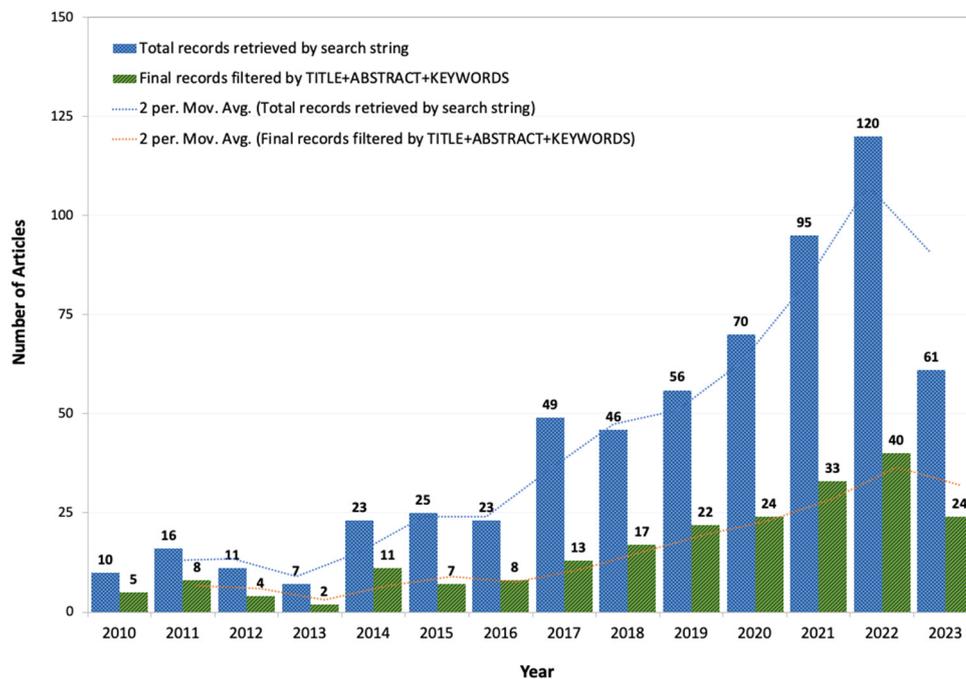
### 3. Results and Discussions

This section of the study unveils the outcomes derived from the retrieved literature through both quantitative and qualitative analyses. Furthermore, it presents the results of an online opinion survey targeting professionally accredited structural engineers in Italy and globally. These insights provide a practical foundation for comprehending the hurdles encountered while coordinating architects and structural engineers for SDO processes. The culmination of these analyses and survey inquiries has

catalyzed the authors' inclination towards devising a structured framework to automate and enhance early-stage structural design optimization processes, fostering improved collaboration between architects and structural engineers within the AEC sector.

### 3.1. Quantitative Analysis of Current State-of-the-Art

From 2010 to 2023, quantitative analysis exposes a substantial growth in the volume of publications pertaining to automating SDO using digital tools to enhance collaboration. **Figure 2** illustrates the escalating trend of this research field, particularly in recent years, signifying its mounting popularity among global researchers. This surge in digitized SDO endeavors could be attributed to a convergence of factors, including technological advancements and evolving demands within the modern AEC industry. Notably, the proliferation of advanced AI and ML algorithms has reshaped how designers and engineers analyze intricate structural data, leading to more efficient and precise optimization techniques (Castro Pena et al., 2021).

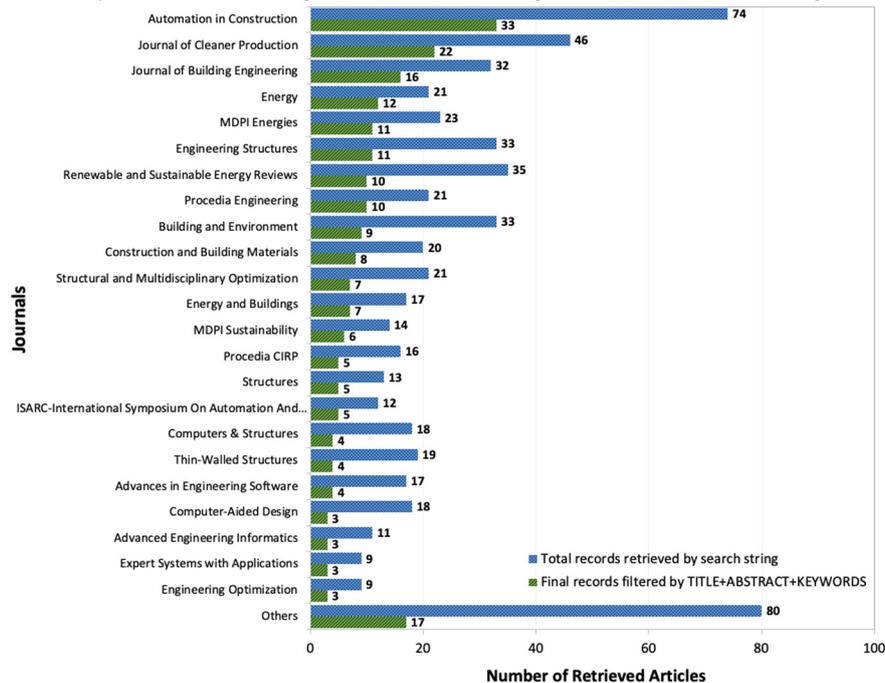


**Figure 2.** Number of articles on structural design optimization and automation per year between 2010-2023. (Figure source: authors).

The AEC sector's landscape is also witnessing a surge in innovative architectural projects demanding cutting-edge optimization and automation to address complex geometries and load-bearing prerequisites. Traditional manual design methods struggle to match the precision and speed mandated by these visionary ventures. Furthermore, structural optimization and automation play a pivotal role in crafting environmentally sustainable structures with reduced carbon footprints, addressing the construction industry's growing sustainability concerns (Chen, Tsay, & Ni, 2022). This push drives architects and engineers to explore sustainable materials, lightweight structures, and energy-efficient designs, aligning with the global thrust towards eco-friendly construction practices. Additionally, heightened competition within the AEC sector fuels the impetus to optimize and automate key phases of projects, including structural designs. Construction firms embrace state-of-the-art technologies to deliver superior projects faster at lower costs than their competitors (Bianconi et al., 2019). The surge in advanced SDO research in recent years finds its roots in technological progress, visionary projects, sustainability imperatives, and the pursuit of a competitive edge.

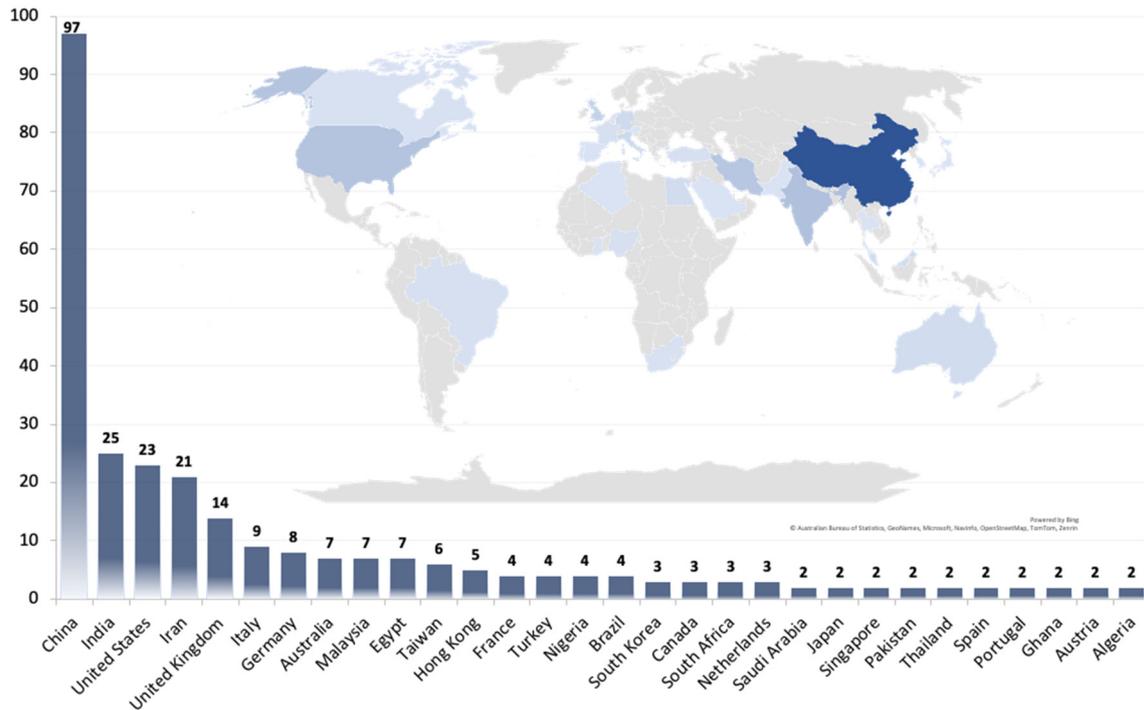
According to the search and selection criteria outlined in **Table 1**, several prominent journals have been identified as primary publishers of SDO research. The *Automation in Construction* journal

published the most automating structural design optimization research (33 articles). This journal assumes a pivotal role in driving innovation across AEC practices and fostering the adoption of Construction 4.0 technologies by disseminating cutting-edge research spanning automation, robotics, AI, IoT, and other technological solutions. The *Journal of Cleaner Production*, renowned for pioneering research in cleaner production methods, circular economy, renewable energy, and eco-friendly technologies across sectors, including construction, propels transformative change, houses 22 articles. Other notable contributors to SDO research include the *Journal of Building Engineering*, *Structural and Multidisciplinary Optimization*, and the *ISARC – International Symposium on Automation and Robotics in Construction*. **Figure 3** encapsulates the major journals along with the corresponding number of articles, delineated by the search string and refined through selection and filtering criteria.



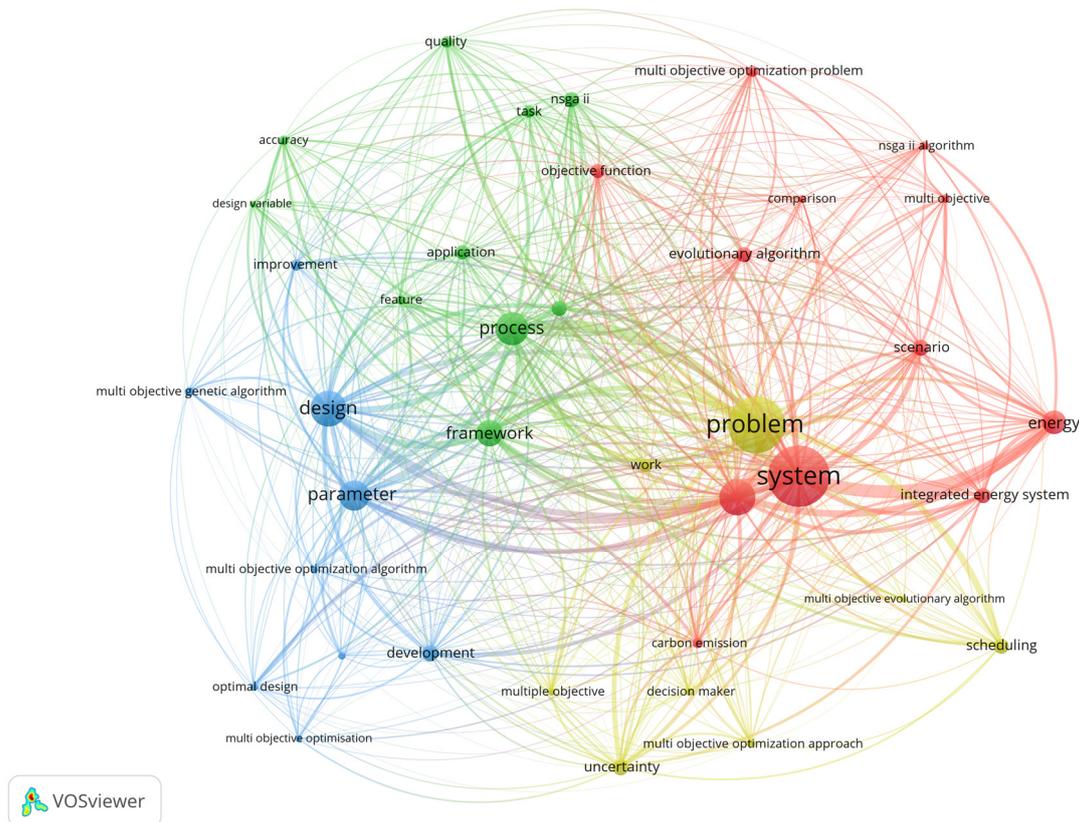
**Figure 3.** Number of collected and filtered records in major journals publishing relevant research. (Figure source: authors).

This study extends its rigorous analysis to the countries with the highest number of articles retrieved from 2010 to 2023. According to this analysis, *China* leads with 97 publication records, encompassing nearly 45% of the final documents. *India* takes second place, contributing 25 documents, a substantial portion of the total records (**Figure 4**). *China*, *India*, *the United States (US)*, *Iran*, and *the United Kingdom (UK)* collectively account for approximately 83% of the retrieved documents. Other countries, including *Italy*, *Germany*, *Australia*, and *Malaysia*, follow the list. The dominance of *China*, *India*, *the US*, *Iran*, and *the UK* is noteworthy, indicating their prominent roles in investigating the SDO topic. Chinese researchers' prevalence in the SDO domain can be attributed to various interlinked factors stemming from historical and contemporary contexts. Chinese researchers have committed to embracing technology across construction disciplines, recognizing technological advancement and innovation as key drivers of economic growth. For instance, a study by (Wong et al., 2023) harnessed BIM technology to design complex high-rise building envelope geometries, predicting structural behaviors and energy performances at the early design stage. Another Chinese study (Liao et al., 2021) proposed an AI-based intelligent methodology leveraging existing structural design datasets for shear walls, enabling automatic design of optimal shear walls with enhanced quality and performance in residential buildings. Notably, major funding sources for SDO research projects in China include *the National Natural Science Foundation of China*, *the National Key Research and Development Program of China*, *the National Office for Philosophy and Social Sciences*, *the Natural Science Foundation of Shandong Province*, and *the China Scholarship Council*.



**Figure 4.** Top countries published structural design optimization research. (Figure source: authors).

The quantitative analysis extends to keyword occurrences, with VOSviewer employed to consolidate keywords with more than 10 instances. In this context, 39 terms meet the criteria and are clustered into 4 groups in VOSviewer, as depicted in **Figure 5**. The clusters contain the following number of keyword items: *Cluster 1* (12 items): carbon emission, comparison, cost, energy, evolutionary algorithm, integrated energy system, multi-objective, multi-objective optimization, NSGA II algorithm, objective function, scenario, and system; *Cluster 2* (10 items): accuracy, application, decision, design variable, feature, framework, NSGA II, process, quality, task; *Cluster 3* (9 items): design, development, improvement, integrated approach, multi-objective genetic algorithm, multi-objective optimization, optimal design, parameter; *Cluster 4* (8 items): decision maker, multi-objective evolutionary algorithm, multi-objective optimization approach, multiple objectives, problem, scheduling, uncertainty, and work. The keyword analysis underscores that system, problem, process, and design are recurrently used terms, indicating the central focus of automating SDO efforts across diverse stages and levels of AEC projects.



**Figure 5.** Keyword clustering analysis on the final articles.

Furthermore, within the context of this research, which emphasizes SDO endeavors at project phases and systems, operations, and process levels, it is pivotal to dissect the motivations driving these efforts. During the era of Construction 4.0, architects and structural engineers are keen to adopt emerging digital tools and technologies that enhance systems, operations, and processes. This transformation redefines approaches to structural design optimization and automation (Caires, 2013). For instance, practitioners recognize the potential of comprehensively analyzing building systems using digital tools and advanced algorithms, leading to more efficient and cost-effective designs for buildings and infrastructure (Granadeiro, Duarte, Correia, & Leal, 2013). Automating early-stage structural design aspects unlocks the capability for process-level automation, replacing labor-intensive tasks with intelligent machines, mitigating human errors, and accelerating project delivery. An illustrative instance of process-level automation is outlined in a study by Liu Y. et al., (Y. Liu, Afzal, Cheng, & Gan, 2020), which utilizes BIM semantic information delivery to automate rebar fabrication processes, reducing waste and manual rebar bending time. Consequently, the enhancement of AEC projects at systems, operations, and process levels through the automation of early-stage SDO engenders significant enhancements in collaboration between architects and structural engineers, which addresses the integration challenges. Moreover, the keyword clustering during the analysis accentuates the preeminence of systems in the selected documents. Although keyword analysis offers a mapping of the reviewed literature, more nuanced exploration is required for emerging themes such as automation, computational design, and generative design. Hence, in line with the articles' focus areas and contributions, a qualitative content analysis is undertaken to identify themes and patterns within the examined articles.

### 3.2. Qualitative Content Analysis

This qualitative analysis segment focuses on the early-stage SDO efforts that facilitate the other lifecycle phases of the built asset across diverse systems, operations, and process levels. The gathered

literature is segmented into the following categories, aligned with the principal emphasis of the SDO approach, targeting specific aspects of AEC projects:

**C1) Conceptualization and Configuration Stage:** This category encompasses SDO efforts undertaken in the preliminary design and conceptualization phase. It involves evaluating various design parameters and investigating the influence of design variables and constraints.

**C2) Automated Code Compliance Stage:** In this category, SDO efforts center on automating code compliance checks during the design process. This involves verifying adherence to codes related to safety, structural integrity, building regulations, and other AEC domain rules.

**C3) Fabrication and Prefabrication Details:** This category pertains to SDO studies focusing on providing comprehensive fabrication and prefabrication layout information. These efforts facilitate the smooth execution of construction processes.

**C4) Construction Execution Stage:** In this category, SDO initiatives are directed towards automating construction execution processes for structural systems in building assets or infrastructure facilities.

**C5) Structural Monitoring/Operations Phase:** This category encompasses SDO endeavors that propose frameworks and approaches for monitoring the health and performance of structural facilities. This facilitates predictive maintenance strategies.

These thematic categories stem from the primary contributions of SDO efforts towards specific structural systems, operations, and process levels while aligning with the scope criteria defined within this study. For a more in-depth qualitative analysis and to propose a future effort of creating a BIM-based early-stage sustainable structural design optimization (ESSDO) framework, **Table 2** presents further insights into the categorization, accompanied by select literature studies.

**Table 2.** SDO automation articles categorized per AEC project's systems, operations, and processes.

Category	Thematic Description	Research Contribution	Sub-categories	Relevant Literature
C1	SDO efforts at the very early design and conceptualization stage, where the configuration of various design parameters is evaluated while inspecting the impact of design variables and constraints.	Research puts forth intelligent frameworks based on BIM to explore design detailing and configurations, and aims to optimize materials, cost, and time in structural design projects.	Construction Materials' Optimization Construction Cost Optimization Energy (carbon emissions) Optimization Planning and Scheduling Optimization	(Afzal, 2019; Afzal et al., 2020; Agustí-Juan, Müller, Hack, Wangler, & Habert, 2017; Bogomolny & Amir, 2012; Dunant, Drewniok, Orr, & Allwood, 2021; García de Soto et al., 2018; García-Segura, Penadés-Plà, & Yepes, 2018; Hamidavi, Abrishami, & Hosseini, 2020; Kaveh, Izadifard, & Mottaghi, 2020; M. Li, Liu, Wong, Gan, & Cheng, 2023; Mangal & Cheng, 2018; Mangal, Li, Gan, & Cheng, 2021; Mergos, 2022; Sacks, Eastman, Lee, & Teicholz, 2018; Victoria &

				Perera, 2018; Yoon et al., 2018; X. Zhang & Zhang, 2021)
C2	SDO for streamlining the review of complicated rules and regulations.	Research studies BIM-centered automated code compliance checking methodologies, replacing traditional manual trial-and-error methods. These approaches enhance efficiency in verifying compliance with complex rules and regulations.	Automated Code Compliance Checking Structural Design Authoring Automated Design Review and Evaluation Rule-Based Generative Design Optimization	(Graser et al., 2023; Häußler, Esser, & Borrmann, 2021; Y.-C. Lee, Eastman, Solihin, & See, 2016; Malsane, Matthews, Lockley, Love, & Greenwood, 2015; Peng & Liu, 2023; J. Wu, Dubey, Abualdenien, & Borrmann, 2023; W. Wu & Hyatt, 2016; S. Zhang et al., 2013)
C3	SDO studies that provides information on fabrication and prefabrication layout information for executing the construction processes.	Research uses Computer-Aided Design (CAD) methods to offer information about fabrication and prefabrication layouts. These methods enhance the precision of manufacturing and prefabrication processes for structural components.	Fabrication and Prefabrication Building Façade and Structural Components Structural Design Layout Digital Manufacturing	(Agustí-Juan et al., 2017; Delgado Camacho et al., 2018; Deng, Gan, Tan, Joneja, & Cheng, 2019; Graser et al., 2023; Hager, Golonka, & Putanowicz, 2016; Hinkle, Wang, & Brown, 2022; J. Liu et al., 2021; J. Liu, Xu, Wu, & Chen, 2020; Y. Liu et al., 2020; Y. Liu et al., 2021; Manrique, Al-Hussein, Bouferguene, & Nasseri, 2015)
C4	SDO automates the construction processes	Studies automates construction through BIM and advanced digital	Automated and Robotic Construction	(Davtalab, Kazemian, & Khoshnevis, 2018; Eastman, Eastman, Teicholz, Sacks, & Liston,

	technologies, reducing time and minimizing waste.	DfMA (Design for Manufacturing and Assembly)	2011; Jiang et al., 2022; M. Li et al., 2021; J. Liu, P. Liu, et al., 2020; Marzouk et al., 2017; Pacheco-Torres, Jadraque, Roldán-Fontana, & Ordóñez, 2014; Popov, Juocevicius, Migilinskas, Ustinovichius, & Mikalauskas, 2010; Pourreza Movahed, Kabiri, Ranjbar, & Joda, 2020; Sandanayake, Zhang, & Setunge, 2016; Yuan, Sun, & Wang, 2018; X. Zhang & Zhang, 2020; Zheng, Yi, & Lu, 2019)
		Waste Management and Scheduling	
		Construction Modelling (4D, 5D)	
C5	SDO for monitoring the building and infrastructure health and energy performance	Scholar works integrated BIM automation and other technologies for monitoring health and performance monitoring of the structural facilities. These might involve predictive maintenance, contributing to the longevity and operational efficiency of the structural assets.	Structural Health Monitoring Retrofitting Optimization Energy Performance Renovation Optimization Smart Infrastructure and Predictive Maintenance (Afzal, 2021; Afzal, Sousa, Valente, & Roux, 2021; Bourahla et al., 2023; S. Eleftheriadis et al., 2018; Stathis Eleftheriadis et al., 2017; Jaillon & Poon, 2014; Kim et al., 2018; Panah & Kioumars, 2021; Schlueter & Geyer, 2018; Sebaibi & Boutouil, 2020; Seghier et al., 2022; Tumminia et al., 2018; Vitiello et al., 2019; Wang & Mahin, 2018; Zhou et al., 2021)

Most articles (105) fall under the C1 category, which involves optimizing structural design configurations during the design stage, accounting for almost half of the articles. This underscores the industry's recognition of the importance of strategically addressing challenges and design configurations in the early stages, offering manifold benefits throughout a building's lifecycle (Bragança et al., 2014). Consequently, enriching early-stage design decision-making through SDO approaches contributes to safer structures, reduced maintenance costs, and adaptability to evolving needs, thereby ensuring sustained value for stakeholders.

In contrast, the C2 category, related to automated code compliance checking, comprises only 14 documents, constituting less than 1% of the final documents. This observation serves as a call to action

for structural designers and engineers to explore this domain and propose solutions for automatic code compliance. The integration of digitalization in SDO efforts, driven by complex modeling and design, introduces new challenges in the design collaboration and review (P.-C. Lee, Lo, Tian, & Long, 2019). Manual reviews of intricate norms and regulations have become error-prone and time-consuming, motivating the need for innovative solutions that automate code compliance. C3 (33), C4 (36), and C5 (30) follow in the number of articles retrieved pertaining to fabrication and prefabrication details, construction execution stages, and structural monitoring/operations phases, respectively.

The retrieved literature covers diverse areas of early-stage decision-making, including optimization of construction materials, structural behavior, economic aspects, energy prediction and consumption, fabrication and prefabrication of structural units, façade generation, and smart infrastructures through digital BIM and optimization methodologies. This research enhances the structural design assessment performance of building assets and infrastructure facilities, explores the design, and reduces the computational time for optimization, consequently, minimizing costly revisions. These SDO initiatives highlight that outputs during early design stages significantly impact the entire lifecycle of building assets or infrastructure facilities. Such outcomes result in cost savings, enhanced efficiency, prolonged lifespan, and improved safety, all of which reverberate positively in the operational and maintenance phases of structural facilities. For instance, studies like (M. Li et al., 2023; M. Li et al., 2021; J. Liu, P. Liu, et al., 2020; Mangal & Cheng, 2018; Mangal et al., 2021) propose BIM-based approaches to optimize steel reinforcement quantities in RC building structures while preserving allowable structural performance. These methodologies not only curtail material consumption but also automate SDO processes, significantly influencing the lifecycle of building structures. The literature search has resulted in retrieving almost half of the filtered studies targeting early-stage decision-making about structural design configurations. This might be because the optimized solutions at the earliest design stages of the design significantly impact the later stages up to the operations and maintenance stages of a building asset or infrastructure facility. Besides, Liu et al. (M. Li et al., 2023; Y. Liu et al., 2021) developed a BIM-based collaborative approach to facilitate the fabrication workflow and data interoperability toward automatic prefabrication of optimized steel reinforcement. Similarly, the BIM-based parametric modeling (Asl, Bergin, Menter, & Yan, 2014; Khoshmadi et al., 2023; Victoria & Perera, 2018; Wong et al., 2023) plays a substantial role in enhancing RC building designs during the early stages. Recognizing that measuring and managing embodied carbon from the outset of structural design projects unlocks emission reduction opportunities otherwise unattainable later.

Automation in the design stage using BIM and knowledge graphs transforms the construction industry, allowing automated code compliance checking (Peng & Liu, 2023), a pivotal driver of BIM-based automatic design review. In the structural engineering realm, reliance on 2D building plans for manual compliance checks with building regulations is a time-consuming and error-prone (Ismail, Ali, Iahad, Kasseem, & Al-Ashwal, 2023). While BIM models have been adopted for a design review in recent years, the complexity of models and diverse regional and international codes hinder comprehensive research in this domain. The significance of SDO practices (Davtalab et al., 2018; Delgado Camacho et al., 2018; García de Soto et al., 2018; Jiang et al., 2022; Pacheco-Torres et al., 2014; Popov et al., 2010; W. Wu & Hyatt, 2016) in automating construction processes for complex structural systems, through 3D printing, prefabrication, additive manufacturing, and robotic construction, is acknowledged. However, the transition from research advancement to practical implementation is hampered by complexity and information collaboration challenges.

Based on the literature review conducted above, it is evident that, despite notable progress in integrating various digital tools and methodologies within the domain of SDO, persistent challenges hinder the effective collaboration between architects and engineers during architectural modeling and structural design and analysis processes. This gap results in inefficient information exchange among stakeholders, leading to interoperability issues on both organizational and technical fronts. For instance, any alteration made to the architectural model necessitates a comprehensive rework, reanalysis, and rescheduling of the entire structural model when handed over to structural engineers. This underscores the urgent need for streamlined information transfer processes. While systematic

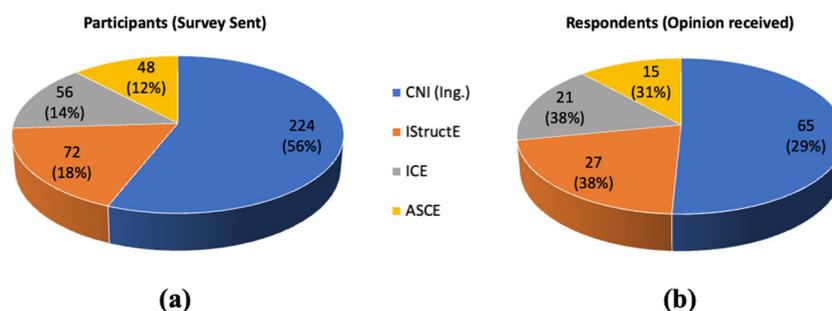
reviews have offered valuable insights into the existing challenges associated with the coordination between architects and structural engineers in SDO-based construction projects, they often fall short of delving into the real-world difficulties faced by these stakeholders. To bridge this gap between theoretical and practical perspectives within this research, it becomes imperative to conduct opinion surveys among industry experts and practitioners. Consequently, this study embarks on an opinion survey conducted among professional structural engineers and many other experts in the BIM and architecture disciplines in the European region to gain practical insights into the collaboration challenges encountered when employing digital tools like BIM in structural design and analysis projects.

### 3.3. AEC Professionals Opinion Survey Results

After conducting PRISMA research, this study then conducts surveys with AEC professionals, especially in Italy and Europe. Surveys were commonly used to gauge industry opinion on various issues, such as the AI (David et al., 2023), housing (Meng, Li, Taylor, & Scrafton, 2021), and construction safety (R. Y. M. Li, 2018). The objective is to explore their viewpoints on the challenges faced during the coordination between architects and structural engineers for structural design and analysis processes. The survey identifies challenges faced by these professionals in joint projects and gathers insights for solving these challenges. Online opinion surveys are a commonly used method to gather expert opinions, complementing the semi-structured expert interview approach (Döringer, 2021). The survey questionnaire focused on challenges in structural design and analysis collaboration between architects and structural engineers, with an emphasis on interoperability issues and other impediments to their seamless teamwork. To broaden the participant pool, Italian engineers registered with local bodies such as Consiglio Nazionale degli Ingegneri (CNI), Collegio degli Ingegneri (CdI), and Ordine degli Ingegneri (OdI) were initially invited. Additionally, structural engineers affiliated with renowned international organizations like the Institution of Structural Engineers (IStructE) in the UK, the Institution of Civil Engineers (ICE) in the UK, and the American Society of Civil Engineers (ASCE) in the USA were contacted to contribute to the survey. Most of the participants registered with these global engineering governing bodies from Europe were invited not to limit the participants pool only to Italy.

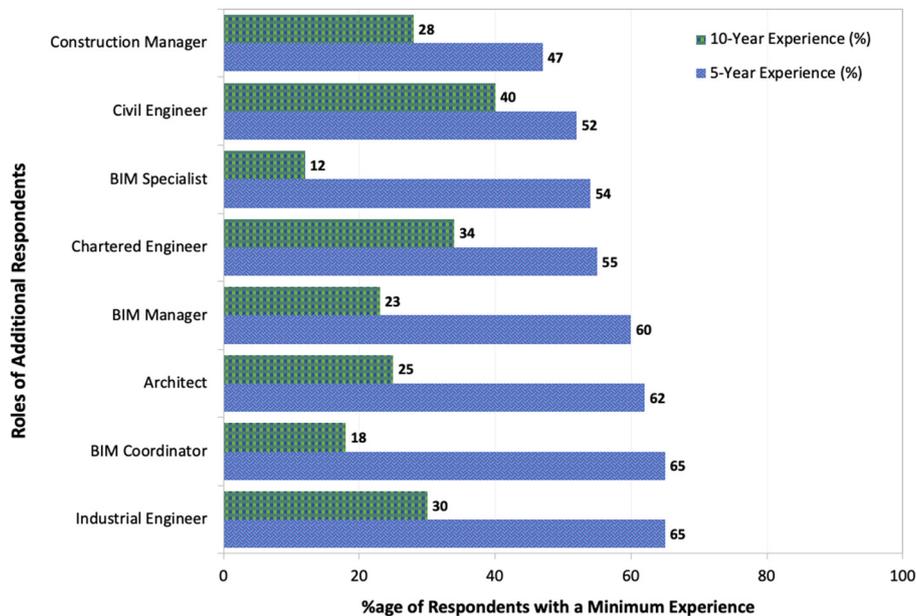
#### 3.3.1. Participants Profiles

Various methods were employed to collect participants' contact details. Professional profiles and emails were gathered primarily through the LinkedIn search database. Additional information was sourced from publication records, regional chapters of engineering bodies, and networking connections. A total of 400 opinion surveys were distributed online, reaching engineers via email, LinkedIn connections, and personal connections. The distribution of contacted structural engineers and the response proportions are depicted in **Figure 6**. The participants' breakdown from the 400 surveys sent online is as follows (**Figure 6(a)**): 56% CNI-accredited engineers (Ing.), 18% IStructE professionals, 14% ICE engineers, and 12% ASCE-affiliated members. Of these, 128 responses were received, with the following distribution (**Figure 6(b)**): 29% CNI-accredited engineers (Ing.), 38% IStructE professionals, 38% ICE engineers, and 31% ASCE-affiliated members.



**Figure 6.** Proportion distribution of (a) Participants, and (b) respondents in the opinion survey. (Figure source: authors).

This study focused on spreading over Europe to increase participants and have more global perspectives for meaningful research investigations involving regional engineering groups and companies across the continent. These entities possessed BIM expertise and hands-on experience in structural engineering tools such as Revit for Architecture and Structures, Autodesk RSA, and other relevant competencies. Snowball sampling was employed to gather additional data beyond the target group in Italy, extending to chartered engineers, construction managers, architects, civil engineers, and BIM roles (BIM Manager, Coordinator, and Specialist). Participants received an introductory statement outlining the survey's goals, followed by a request for information about their roles and experience. Consent for data processing was also obtained for the study's purposes. **Figure 7** offers an overview of additional participant profiles approached through snowball sampling for data collection, including the percentage representation of respondents with different levels of experience in various sectors of structural engineering (e.g., residential, commercial, high-rise buildings, industrial structures, and bridges).



**Figure 7.** Additional participant profiles with corresponding years of professional experience. (Figure source: authors).

### 3.3.2. Data Collection

To ensure the survey's reliability and relevance to the research objectives, a pilot study was conducted. Ph.D. students and academic instructors specializing in BIM and structural engineering from Politecnico di Milano (Italy), and the University of Bologna (Italy) participated in the pilot opinion survey. Their feedback refined the survey questions, with a significant number of participants providing insights. The survey was administered in both English and Italian to accommodate native Italian respondents and English-proficient researchers from Europe. The survey questions served three purposes: (a) understanding collaboration challenges faced by architects and structural engineers during design and analysis; (b) exploring solutions for seamless integration between these professionals; and (c) gauging practitioners' perspectives on automated structural design and optimization using emerging methods.

### 3.3.3. Data Analysis and Results

A thematic analysis following the guidelines of Braun et al., (Braun, Clarke, Hayfield, & Terry, 2019) was employed to analyze participant responses. The process involved familiarizing with the data, identifying patterns, and extracting thematic observations related to the research questions. Key themes such as inconvenient communication, data interoperability, design coordination, interdisciplinary communication, conventional collaboration, model complexity, problems in the integration of sustainability, resource constraints, etc., emerged from coherent response patterns.

An illuminating insight into the multifaceted panorama of challenges and prospective solutions within the collaborative realm of structural design and analysis. Qualitative responses unearthed a spectrum of challenges and corresponding solutions within the realm of structural design, analysis, optimization, and interdisciplinary collaboration. These insights were organized into three distinct streams: generic, automated, and sustainable structural design and analysis. For a detailed depiction of the thematic analysis findings, refer to **Table 3**, which meticulously categorizes the delineated issues and solutions, illuminating the generic, automated, and sustainable facets of structural design and analysis. These thematic categories impeccably aligned with the study's core objective: to scrutinize challenges hindering collaboration and productivity within the AEC sector. Notably, prevalent challenges such as deficient communication, design coordination hurdles, and reliance on outdated structural engineering methods were acknowledged as commonplace issues. Their resolution necessitated the integration of advanced structural engineering design approaches and design optimization techniques.

**Table 3.** Thematic analysis of responses from the respondents about the issues faced during the integration between architects and structural engineers for structural design and analysis for different disciplines across a typical construction project.

Issues Theme	Reported Issues	Solutions Theme	Suggested Solutions	Potentials of ESSDO Framework in solving existing issues
Issues and Solutions in Integration between Architects and Structural Engineers for <i>Generic Structural Design and Analysis</i>				The framework developed within this study, titled "BIM-based Early-Stage Sustainable Structural Design Optimization" (ESSDO), represents a robust methodology that capitalizes on BIM and optimization algorithms. The primary objective of this approach is
Inconvenient Communication	Language and terminology differences	Interdisciplinary Communication	Standardized nomenclature	
	Lack of clear communication channels		Properly centralized communication	
Design Coordination and Conflict Resolution	Difficulty in sharing complex design configurations	Conceptual Design Coordination	Strategic organization of design details	
	Excessive design changes and revisions		Involvement of SE in early-design processes	
	Time-consuming coordination		Alignment of architectural and	

			structural elements	to furnish optimal design configurations for building structures and infrastructure facilities, with a keen focus on construction materials, overall cost, construction time, and sustainability factors. In a distinct departure from extant frameworks documented in the literature, ESSDO uniquely amalgamates sustainability considerations, thereby ensuring ecologically conscious design choices. The ESSDO framework seamlessly integrates architectural design BIM platforms (such as Revit) with structural design and analysis BIM platforms (like RSA) through a specialized visual programming tool based on
	Risk of design discrepancies		Reducing design errors early with efficient tools	
Overdesign	Old methods of SE design and analysis	Optimization	Adoption of advanced methods of SE design	
	Manual calculation discrepancies		Utilization of design optimization	
Complex Regional Regulatory	Complex building codes	Regulatory Compliance	Normalization through standard translation of complex regulatory	
	Challenges of frequent code changes		A generic code translation system to accommodate changes	
Issues and Solutions in Integration between Architects and Structural Engineers for <i>Automated Structural Design and Analysis</i>				
Data Interoperability	Different software platforms	Compatible Interoperability	Acquiring software packages from same provider company	
	Incompatible file formats and data structures		Standardization of data schemas and formats	
	Loss of information during data transfer		Schemas with specialist in the SE	
Legacy Systems/Tools and Data Migration	Legacy design systems/tools and outdated data formats Data migration issues across software versions	Emerging Technologies	Customization of applications for given problems  Smooth data migration to	

	Conversion issues for historical project data		modern platforms	Dynamo. This tool orchestrates the transfer of pertinent input data from the architectural Revit model to RSA, thus facilitating precise structural design and analysis. Subsequent to the
Frequent Software Updates	Difficulty in tracking design iterations Errors while working with outdated information tools	Digital Design Iterations	Solve interoperability  Validate and verify design versions  Work with updated information tools	structural analysis, optimization procedures are employed to refine structural design configurations, while accounting for sustainability penalties to discourage excessive designs. The integration of sustainability parameters is notably advantageous, as it leads to enhanced sustainability through judicious material usage and resource consumption throughout the design phase. Furthermore, the analysis of
Monotonous Design and Analysis	Lack of design variations and options  Possible conflicts on design options	Iterative Design and Analysis	Use of parametric and generative modelling to explore multiple design options  Reduce conflicts through automated design iterations	
Conventional Collaboration	Paper-based design data handling  Time-consuming asynchronous collaboration  Local data handling issues	Cloud-based Collaboration	Use of cloud platforms to store, access, and share project data securely  Facilitate real-time collaboration across project players  Eliminate the need for local data storage and minimize compatibility issues	
2D and Uncollaborative 3D Visualization	2D or non-interactive visualization platforms	Advanced Visualization (Digital Twins)	Use advanced visualization tools to present design concepts	

	Tedious modelling for built asset		Leverage rapid prototyping and model creation	material properties following optimization
	Poor collaboration on digital models		Enhance project players' engagement through tangible representations	further aids in evaluating sustainability outcomes. In summary, the ESSDO framework culminates in the generation of structural models that embody resilience, sustainability, and cost-effectiveness. This comprehensive approach epitomizes a significant stride towards cultivating environmentally responsible and economically viable structural designs.
	Slow and inaccurate design and analysis results		Create digital replicas for real-time monitoring and analysis	
Legacy SE Design and Analysis	Potential risks involved in design and analysis results	AI and Optimization for Design and Analysis	Apply AI algorithms for faster and more accurate structural analysis	
	Imperfect manual safety and cost estimations		Predictive modeling to identify potential design flaws early	
			Optimize structural design for better safety and cost-effectiveness	
Generic BIM Implementations	Same BIM environment for architectural and structural designs	Rigorous BIM Capabilities	Employ specialized BIM software specifically tailored for structural design, analysis, and optimization	
	BIM for modelling purpose only		Implement optimization	

	Blind reliance on BIM design and analysis outcomes		algorithms within the BIM environment Move towards performance-based design approaches within BIM platforms
	BIM for SE design and analysis stages only		BIM for whole lifecycle of building structure
<hr/>			
Issues and Solutions in Integration between Architects and Structural Engineers for <i>Sustainable Structural Design and Analysis</i>			
Limited Awareness and Expertise in Sustainable SE Design and Analysis	Lack of awareness regarding sustainable design principles and practices  Insufficient expertise on sustainable building techniques  Difficulty in integrating sustainability into traditional design workflows	Raise Awareness and Sustainability Concerns	Provide specialized awareness on sustainable design for architects and structural engineers  Encourage professional development in green building practices  Foster collaboration with sustainability consultants
Problems in Solo Integration of Sustainability in SE	Conflicting priorities between sustainable design and other concerns (cost, time, safety, etc.)  Challenges in convincing clients to invest in sustainable features	Balancing Sustainability with Other Concerns	Conduct life-cycle cost analysis that includes sustainable design  Showcase successful case studies of cost-effective

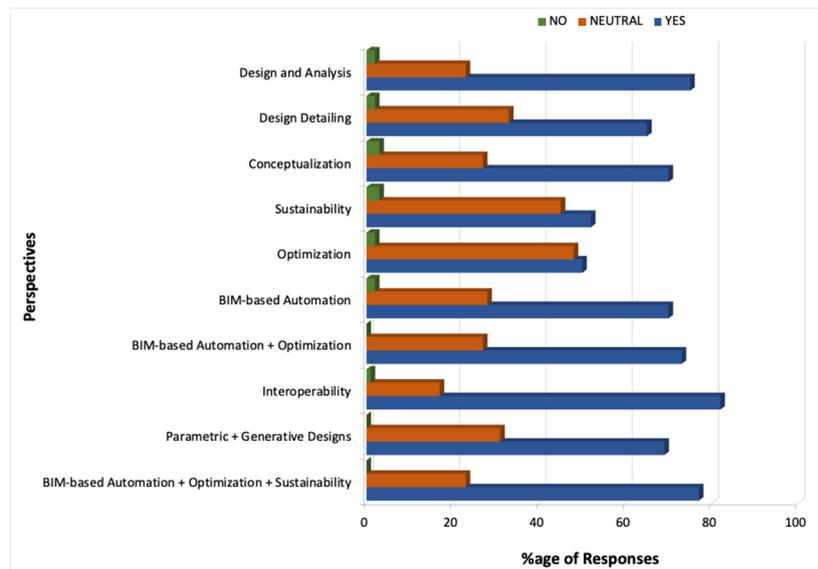
			sustainable projects
	Identifying sustainable options within budgetary limitations		Advocate for financial incentives to encourage sustainable SE designs
	Lack of incorporating energy sources in building SE design		Use parametric design tools to optimize orientation of building structures
Conventional Sustainable Design Strategies	Infeasible structural elements with renewable energy systems	Integration of Renewable Energy Solutions	Integrate efficient renewable energy systems
	Technical challenges of such integrations		Merge renewable energy with building structural components
	Lack of recommendation of sustainable materials with low environmental impact		Utilize databases and tools to assess environmental impacts of construction materials
Use of Excessive Steel and Concrete	Lack of implementation of advanced principles	Material Selection and Lifecycle Analysis	Implement circular economy principles, promoting recycling and reusing materials
	Incompatibility of sustainable materials with structural requirements		Explore innovative and compatible sustainable materials

	Complex and evolving sustainability regulations		Advocate for streamlined green building regulation
	Ignorance of design for safety and environment protection		Ensure design meet safety and environmental standards
Regulatory and Policy Constraints	Addressing inconsistencies in green building regulations	Sustainability Regulatory Compliance	Establish partnerships with sustainability-focused organizations
	Compliance challenges with varying local, national, and international standards		Engage with policymakers and industry associations to influence sustainable policies
Vulnerability of Structural Systems	Structural designs unable withstand climate change-related challenges	Resilience and Climate Change Adaptation	Employ climate modeling and risk analysis
	Lack of long-term structural durability and adaptability		Adopt resilient design and construction techniques

In the specific context of automated structural design and analysis, an apparent concern emerged – the seamless transfer of data between architects and structural engineers. Addressing this challenge necessitated the creation of tailored applications and the establishment of a smooth mechanism for data migration. Solutions proposed by participants encompassed diverse dimensions. To foster sustainable structural design, recommendations included the incorporation of life-cycle cost analysis, the presentation of successful case studies, and the introduction of financial incentives. In the domain of material selection, leveraging databases and tools for assessing environmental impacts, coupled with embracing circular economy principles, emerged as effective strategies for suggesting environmentally conscious materials in the early stages of design. Moreover, the integration of renewable energy solutions and sustainable materials aligned with structural prerequisites was deemed crucial in propelling the adoption of eco-friendly designs.

Quantitative analysis results, vividly depicted in **Figure 8**, underscored the strong inclination to complement structural design and analysis with advanced methodologies encompassing sustainability, automation, and interoperability. Remarkably, the survey participants unanimously favored steering clear of neglecting the amalgamation of these elements in the initial design phases. It's worth noting that the survey design didn't encompass the in-depth investigation of obstacles and intricacies linked to implementing these advanced synergies. Interoperability has received a significant concern from the opinion perspectives as it is already the concern of the AEC sector when

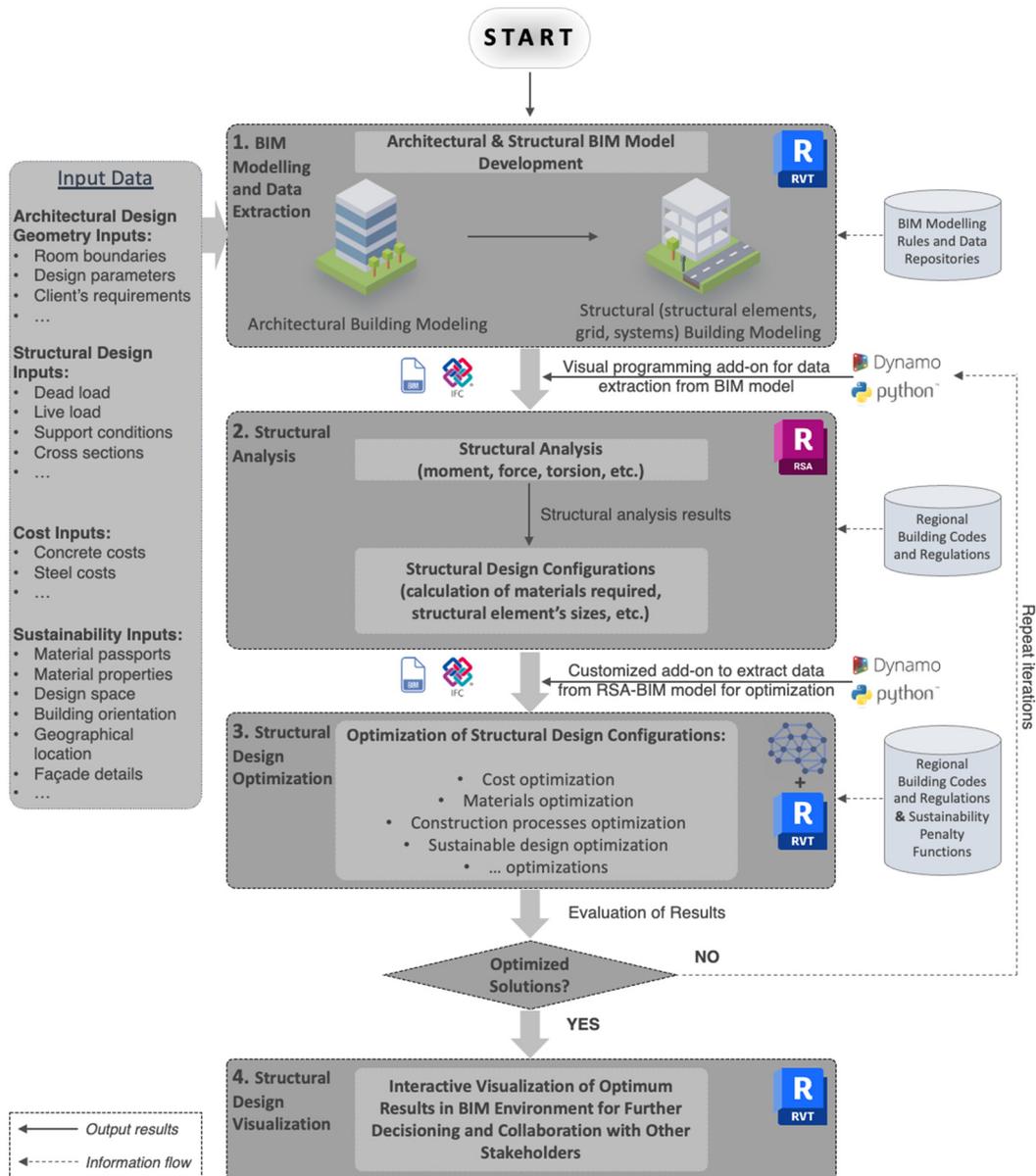
sharing digital information between project players, and many problems are usually discovered, such as misinterpretation, data loss, and inaccuracy. For instance, BIM-based structural design automation complemented by sustainability integration in early design stages has also received a significant perspective of inclusion in the early-stage design stages for SDO.



**Figure 8.** Participants' perspectives on different advancements in the SDO at early stages. (Figure source: authors).

#### 4. Framework Proposal for BIM-based Early-stage Sustainable Structural Design Optimization (ESSDO)

The main purpose of proposing a BIM-based framework for early-stage sustainable structural design optimization (ESSDO) is to offer seamless integration between architecture and structural engineering works through automation to enhance design and analysis processes. ESSDO also provides the flexibility of integrating sustainability concerns at the early-stage structural design and analysis processes to obtain optimum solutions for design configurations that exhibit minimized environmental impacts by reducing construction materials quantities while maintaining structural safety by following regional building codes. Although ESSDO could be slightly comprehensive to adopt, having a clear understanding, it offers customization of processes according to the subject matter, which is an important aspect of the framework. In **Figure 9**, the ESSDO framework is shown that was developed and proposed to illustrate the viability of automating and streamlining the coordination between project players by connecting the structural and architectural models, allowing engineers to create structural designs based on input data from the architectural model, such as geometry, design specifications, material properties, material costs, and structural elements. Then, ESSDO analyzes and optimizes generated models within architectural and structural BIM environments to deliver the results to structural designers/engineers for additional optimization and detailed designs.



**Figure 9.** Development and proposal of an intelligent framework for BIM-based early-stage sustainable structural design optimization (ESSDO) to streamline the interactive collaboration between architects and structural engineers. (Figure source: authors).

The ESSDO framework comprises four pivotal components:

**BIM Modelling and Data Extraction:** Commencing with modeling architectural and structural designs for the targeted building structure or infrastructure facility, this phase generally falls within the domain of architecture works' project players. Architects, including structural engineers, typically resort to Autodesk Revit for Architecture and Structures, a widely employed BIM tool for architectural and structural designing applications. The architectural design environment is aptly facilitated by Revit. During BIM modeling, meticulous attention is given to imbuing the model with vital information encompassing architectural attributes, spatial organization, material costs, structural attributes, and material selection. Dynamo is harnessed to extract essential data from Revit into Dynamo, addressing the interoperability challenge via application programming interface (API) capabilities.

**Structural Analysis:** Parametric data extracted in the previous stage are channeled through BIM-supported file formats such as Industry Foundation Classes (IFC) or Information Delivery Manual (IDM) to execute structural analysis and ascertain structural attributes within the RSA. RSA software

equips structural engineers to undertake sophisticated BIM modeling and analysis for diverse building structures and infrastructure facilities. RSA fosters a more collaborative workflow and interoperability by interlinking bidirectionally with Autodesk tools like Revit and Dynamo in three dimensions (3D). This step employs Dynamo's structural analysis package within RSA software, undertaking structural analysis and generating calculations for structural attributes. These calculations serve as a foundation for calculating requisite material quantities and sizes to withstand analyzed outcomes. Employing Python scripts within the Dynamo API, the computed results are conveyed back to Dynamo to fuel optimization across various objective functions, encompassing the maximization of building asset sustainability.

**Structural Design Optimization:** This phase hinges on insights garnered from structural analysis results. It entails determining requisite construction material quantities in alignment with regional building codes and standards. An array of options pertaining to material quantities and associated properties, structural geometries and performance, façade designs, structural element orientations, and structural systems are presented for selection within the design realm. Driven by the overarching design objective and defined objective function, the structural design optimization takes flight, propelled by a suite of mathematical and optimization algorithms (SDO algorithms are extensively studied in (Afzal et al., 2020)). Of notable significance, the integration of sustainability aspirations incorporates a pioneering penalty function designed to forestall overdesign and undue stress on structural elements. This pivotal step aspires to yield models that embody stability, safety, resilience, and cost-effectiveness, thus echoing the essence of sustainable design practices. The optimization process unfurls iteratively until preset criteria are met, at which point the optimization ceases.

**Structural Design Visualization:** Upon the culmination of the optimization processes, the concluding phase of the framework involves updating structural design configurations within the BIM environment. This final visualization proves instrumental in facilitating interactive collaboration amongst stakeholders. It assumes a critical role in enriching decision-making processes, thereby augmenting coordination between architects and structural engineers during the design and construction journey.

In summation, the ESSDO framework emerges as an innovative methodology for structural design that accords paramount importance to factors like cost, time, and material efficiency. The integration of sustainability considerations across the early-stage design process is emblematic of the framework's comprehensive scope. By harnessing the prowess of BIM technology and optimization strategies while earnestly addressing environmental impacts, ESSDO envisions a modern era characterized by sustainable and ecologically mindful building and infrastructure design. With the innate parametric attributes of architectural and structural models during the preliminary stages of ESSDO and an automated workflow that persists across the framework's various stages, any modifications to the Revit architectural model are automatically synchronized with Dynamo. This, in turn, generates novel optimized structural designs within RSA. This synthesis of BIM modeling and visualization platforms fortifies collaboration, streamlines workflows, and bolsters coordination between architects and structural engineers, culminating in improved design outcomes and enhanced efficiency throughout construction.

Hence, the ESSDO framework introduces a groundbreaking approach for early-stage conceptualization, assessment, and optimization of RC structural designs. Integrating architecture and structural engineering through automation enhances design and analysis processes while incorporating sustainability. This empowers engineers and designers to explore diverse design alternatives and select optimal solutions, leveraging automation's potential. The integration of automation and parametric modeling ensures real-time updates, dynamically generating optimized structural designs in response to changes. Focused on RC structures, this study provides a proof-of-concept, informed by a thorough literature review and practitioner input. The ESSDO enriches prevailing SDO practices by seamlessly integrating sustainability from the outset, fostering efficient, safe, and sustainable structures in alignment with global environmental goals. This BIM-based automation and optimization synthesis elevates collaboration, streamlines workflows, and enhances

design outcomes and construction efficiency. Thus, ESSDO stands as a potent methodology and framework to address modern construction challenges while forging sustainable and impactful structures.

## 5. Conclusions

This paper presents an advanced study focused on optimizing early-stage structural design and analysis within BIM-based practices in the construction sector. An extensive literature review examines relevant research efforts and initiatives to establish context. Employing both quantitative and qualitative methods, this analysis forms a knowledge base for comprehending SDO practices and challenges during the early design phases. The study brings attention to research gaps, particularly in the overlooked domain of automated code compliance, prompting the need for further investigation. Addressing challenges architects and engineers encounter in automated SDO collaboration, an online survey is conducted among accredited structural engineers and BIM practitioners. Survey outcomes underscore interoperability as a crucial concern, echoing challenges witnessed in the AEC sector concerning digital information exchange. This paper presents both quantitative and qualitative findings while also elucidating how the ESSDO framework tackles the challenges pinpointed in the survey. The proposed early-stage sustainable structural design optimization (ESSDO) framework responds to the absence of automated and interactive collaboration in BIM-integrated SDO processes. The framework automates structural design, analysis, and optimization tasks by incorporating visual programming within a widely used BIM platform. It effectively addresses the interactive collaboration obstacles between architects and engineers. Additionally, integrating sustainability principles augments SDO by seamlessly embedding these principles from the outset, fostering the development of efficient, secure, and sustainable structures. The ESSDO framework synchronizes parametric data between architectural and structural models, facilitating dynamic collaboration between architects and engineers. Any changes made to the architectural model are promptly reflected in the corresponding structural models. The core objective of this framework is to streamline and automate the structural design optimization process. It is designed to be user-friendly, catering to individuals regardless of their programming expertise. The framework's scope is currently delimited to reinforced concrete (RC) structures. Nonetheless, ongoing efforts are dedicated to expanding its applicability for validation in real-world building structures or infrastructure facilities.

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