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Structural Impact of Low Voltage Infrastructure Integration in Modern Building Service: A Systematic Review

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Abstract

The integration of low-voltage (LV) infrastructure — encompassing structured cabling systems (SCS), lighting control networks, building management system (BMS) cable routes, and low-current security and communications pathways — into modern commercial and institutional buildings gives rise to a series of structural, mechanical, and spatial interactions with load-bearing and enclosing elements that the civil and building services engineering literature has not yet systematically examined. This paper presents a systematic review of peer-reviewed publications, technical standards, and engineering guidance documents published between 2003 and 2026, addressing four objectives: (1) the mechanical behaviour and load characteristics of LV cable support systems; (2) the effects of LV system integration on reinforced concrete slabs, structural steel frames, suspended ceiling substructures, and partition wall assemblies; (3) spatial coordination challenges between LV infrastructure, HVAC systems, and the structural frame; and (4) the role of Building Information Modelling (BIM) in detecting and resolving LV–structural conflicts. Following a structured search across Scopus, Web of Science, IEEE Xplore, and ScienceDirect, 45 primary sources were identified for synthesis after systematic screening. The review finds that the seismic structural behaviour of cable tray systems is relatively well characterised in the existing literature, whereas the static distributed load impact of combined LV infrastructure on suspended ceiling substructures and the management of LV riser penetrations through load-bearing elements remain insufficiently addressed. Existing standards — IEC 61537:2023, NEMA VE 1, and EN 50174 — govern individual system performance but provide no cross-discipline coordination guidance. BIM-based clash detection studies consistently report that LV systems are modelled at insufficient levels of detail for structural conflict identification. The review concludes with a consolidated research gap map and a prioritised research agenda at the intersection of structural engineering and building services electrical engineering.

Keywords: low-voltage infrastructure; structured cabling system; cable tray; suspended ceiling load; BIM clash detection; MEP coordination; seismic performance; riser penetration; building services engineering; systematic review.

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1. Introduction

The built environment increasingly depends on low-voltage (LV) infrastructure to deliver communications, automation, safety, and energy management services. International electrotechnical standards define low-voltage systems as operating below 1,000 V AC or 1,500 V DC; the extra-low-voltage (ELV) subsystem — encompassing data cables, BMS bus lines, and DALI lighting control conductors — operates below 50 V AC (Zuo et al., 2023; Chen et al., 2020). As the density of intelligent building systems has grown, the volume, mass, and spatial footprint of the LV cable infrastructure serving these systems has increased correspondingly, generating a structural design demand that did not previously exist at this scale.

This growth in LV infrastructure volume creates a distinct structural design challenge. Civil and structural engineers dimension slabs, beams, and partition walls for gravity, wind, seismic, and imposed live loads; however, the aggregated mechanical contribution of cable trays, conduit clusters, and riser sleeves — elements introduced by the building services engineer at a later project stage — is rarely incorporated into the original structural design (Madireddy et al., 2022). The result is a coordination gap that drives field rework, unplanned structural modifications, and post-occupancy performance deficiencies.

Four converging trends are intensifying this challenge. First, the proliferation of IoT connectivity has substantially increased the number of cable pathways required per building (Zuo et al., 2023). Second, mandatory energy performance standards require comprehensive lighting control networks as a minimum compliance requirement (Ceccolini & Sangi, 2022). Third, intelligent BMS platforms integrate HVAC, security, and metering functions through dedicated LV cable routes that must physically traverse structural elements (Mulpuri et al., 2025). Fourth, BIM-based clash detection — now standard practice for large-scale HVAC and structural coordination — is routinely applied to LV systems at insufficient levels of modelling detail, leaving structural loading effects and penetration impacts unresolved (Minh Nguyen, 2026).

This paper synthesises the existing body of knowledge at the intersection of these domains through a systematic review. Its objectives are as follows: (1) to consolidate current knowledge of LV cable support system mechanical behaviour; (2) to map the impact pathway from LV installation to structural elements; (3) to evaluate the state of BIM coordination practice for LV systems; and (4) to identify research gaps that constrain integrated structural–LV design.

The review spans the intersection of construction and civil engineering (OECD Frascati Direction 192) and electrical power engineering, electrical engineering, and electromechanics, including building services engineering (Direction 141).

2. Methodology

2.1. Search approach

This systematic review was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) guidelines (Parums, 2021). A structured literature search was performed across four electronic databases: Scopus, Web of Science (WoS), IEEE Xplore, and ScienceDirect. The search was executed between January and February 2026 and covered publications from January 2003 — the year of the first edition of IEC 61537 — to February 2026.

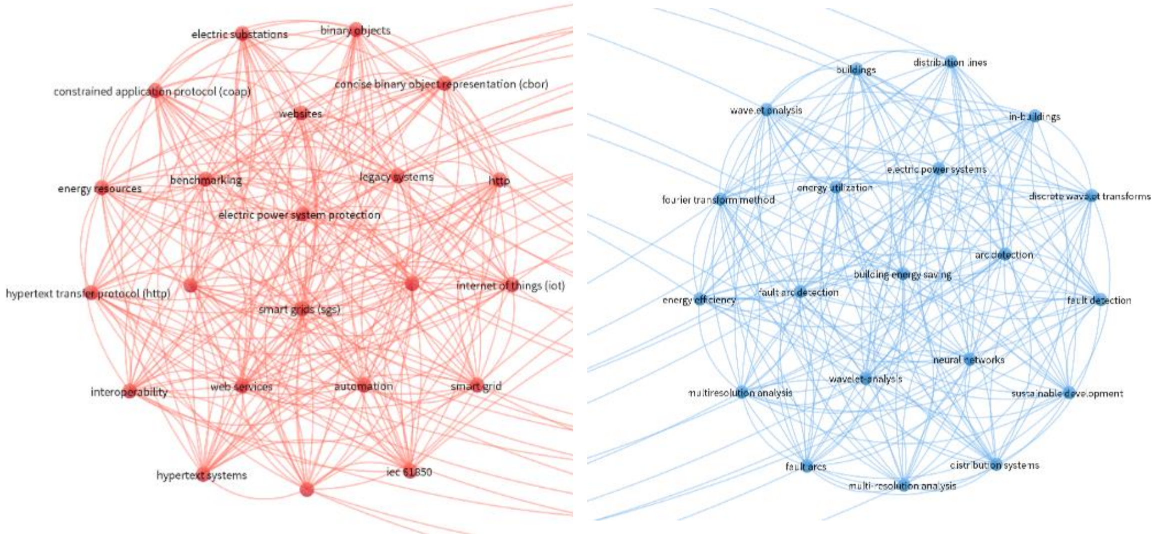

Figure 1. VOSviewer keyword co-occurrence network of research themes related to low-voltage infrastructure integration and modern building services

Source: author's own development.

Figure 1 presents a VOSviewer keyword co-occurrence network visualising research themes at the intersection of low-voltage infrastructure integration and modern building services.

The following search terms were applied to retrieve the dataset: low voltage; cable tray; structured cabling; BMS cabling; LV infrastructure; building; civil engineering; construction; building services.

A supplementary manual search of the reference lists of all included full-text articles was conducted to identify additional sources not captured by the database search.

2.2. Inclusion and Exclusion Criteria

Records were screened against the criteria presented in Table 1.

Table 1. Inclusion and exclusion criteria

Criterion	Inclusion	Exclusion
Topic	LV cable systems, cable trays, SCS, BMS routing, MEP coordination, BIM clash detection with structural relevance	Grid-level power distribution, renewable energy, power electronics
Building type	Commercial, institutional, industrial, or mixed-use buildings	Low-rise residential buildings; utility substations
Language	English	All other languages
Publication type	Peer-reviewed journal articles, conference papers, published technical standards	Non-peer-reviewed trade articles, manufacturer brochures, blog posts, Wikipedia
Date	2003–2026	Before 2003, except foundational seismic cable tray studies

Source: author's own development

The database search yielded a total of 624 records across four sources, as detailed in Table 2. Of these, 45 studies satisfied all inclusion criteria and were retained for the final qualitative synthesis. The complete study selection procedure is illustrated in Figure 2.

Table 2. Dataset and search coverage

Dataset	Coverage period	Records retrieved
Scopus	2003–2026	212
Web of Science	2003–2026	131
IEEE Xplore	2003–2026	113
ScienceDirect	2003–2026	168
Total	**2003–2026**	**624**

Source: author's own development

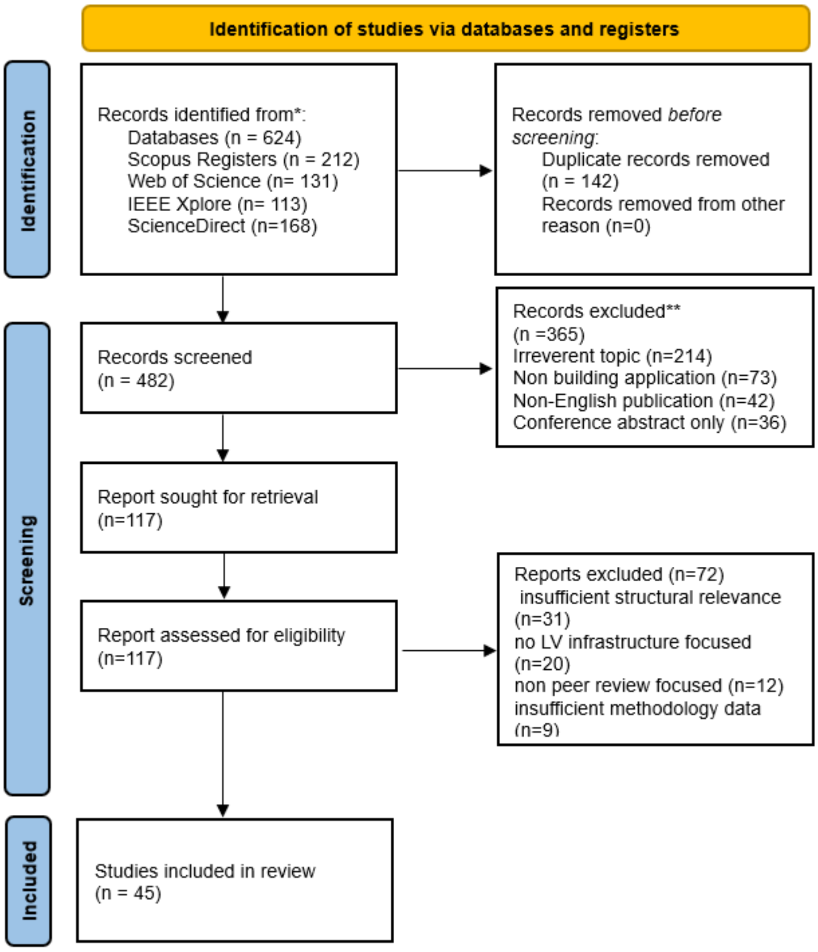

Figure 2. PRISMA 2020 flow diagram illustrating the identification of studies via databases and registers

Source: author's own development

2.3. Quality Assessment

To ensure the reliability and scientific validity of the reviewed literature, all included studies were subjected to a structured quality assessment. The assessment evaluated the methodological rigour, relevance, and transparency of each study against four criteria: (1) clarity of research objectives and study design; (2) use of verifiable data sources, including experimental, numerical, analytical, or case-study evidence; (3) transparency of methodology, results, and limitations; and (4) relevance to the structural impacts of low-voltage infrastructure integration in building systems.

Each criterion was evaluated qualitatively, and studies were classified as high, moderate, or low quality. Studies lacking sufficient methodological detail or relying exclusively on non-verifiable information sources were excluded at the eligibility assessment stage.

Technical standards — IEC 61537, NEMA VE 1, NEMA VE 2, and EN 50174 — were retained as normative references and were not subjected to quality scoring, as they represent internationally recognised engineering standards rather than empirical research studies.

2.4. Data Extraction and Synthesis

Data were extracted from each included source under the following categories: author(s), year, journal or publisher, and country of affiliation; study type (experimental, computational, case study, or standards analysis); LV system type addressed (SCS, BMS, lighting control, security, or combined); structural element addressed (RC slab, steel frame, suspended ceiling, or partition wall); key findings relevant to the four review objectives; and research gaps identified by the authors.

Findings were synthesised thematically across four domains corresponding to the review objectives: (i) cable tray load characteristics and structural behaviour; (ii) effects on specific structural elements; (iii) BIM-based coordination for LV systems; and (iv) identified research gaps. A narrative synthesis approach was adopted, as the heterogeneity of study designs and outcome measures precluded formal meta-analysis.

A risk of bias assessment was conducted to evaluate potential sources of systematic bias within the included studies. Given the diversity of study designs — encompassing experimental investigations, numerical simulations, case studies, BIM-based analyses, and technical standards — a qualitative assessment approach was adopted. To minimise publication bias, all four databases were searched systematically and backward reference screening was performed. Non-peer-reviewed materials, commercial publications, manufacturer brochures, and other grey literature were excluded from the final synthesis.

3. Structural Behaviour of LV Cable Support Systems

3.1. Cable Tray Mechanics and Load Characteristics

The principal international standard governing the structural performance of cable trays is IEC 61537:2023, which defines the Safe Working Load (SWL) as the maximum uniformly distributed load a tray section can sustain without exceeding a longitudinal mid-span deflection of L/100, where L denotes the support span (Tan et al., 2024).

NEMA VE 1 provides a parallel load classification framework for North America, categorising cable trays into load classes according to their tested SWL per unit span; the designations Class 8C, 12C, and 20C correspond to cable load capacities of 8, 12, and 20 lb/ft, respectively (Slavin, 2020).

Mulla and Alhamaidi (2021) validated a heavy-duty cable tray design against both IEC 61537 and NEMA VE 1, reporting that the average mid-span deflection at 100% rated load satisfied the L/100 acceptance criterion across a multi-span configuration. The structural risk in cable tray systems lies not in tray section capacity but in the anchorage system connecting the tray to the host building structure.

NEMA VE 2-2006 defines cable tray installation requirements, including support spacing ranging from 1.5 m to 3.0 m depending on load class, the prohibition against drilling or cutting structural steel members without engineering approval, seismic restraint requirements, and firestop obligations at floor and wall penetrations (NEMA, 2006). Wuk Jung and Oterkus (2021) demonstrate that the combined dead load of the tray, cable fill, and dynamic seismic component constitutes the governing load combination for anchorage design. This load combination is routinely overlooked when cable tray weights are estimated by building services engineers at early design stages.

3.2. Seismic Structural Behaviour

The seismic response of suspended cable tray systems has received sustained research attention, motivated primarily by nuclear facility safety requirements and post-earthquake damage observations in hospitals, airports, and data centres.

Wu et al. (2023) conducted full-scale shaking table tests on suspended cable tray systems in civil buildings and found that systems whose static structural design satisfied current prescriptive standards remained vulnerable to seismic damage. Critically, the horizontal cable tray components — rather than the seismic-resistant bracing elements — were the first to sustain damage under earthquake excitation. This finding carries structural design implications beyond seismic zones: the horizontal tray sections are also the components that carry the full dead load of the cable fill, and their demonstrated vulnerability to dynamic loading indicates that sizing trays for static loads alone is insufficient in buildings subject to traffic-induced vibration, mechanical plant excitation, or wind-induced dynamic effects.

Wu and Huang (2022) developed a performance-based optimum seismic design methodology for cable tray systems, proposing the inter-support drift ratio as a performance index derived from shaking table test results. Their study modelled three building configurations — 3-storey, 7-storey, and 15-storey steel moment-resisting frames — and demonstrated that the structural characteristics of the host building, specifically floor accelerations and dynamic amplification factors, significantly influence cable tray response. This finding exposes a fundamental assumption gap: the prevailing practice of treating cable tray design as independent of primary structural design is contradicted by evidence that the two systems interact through floor accelerations and dynamic amplification.

The earliest systematic treatment of cable tray seismic behaviour in the engineering literature appears in Shahin et al. (1978), who examined design procedures for electrical cable trays in nuclear power plants, analysed the inherent flexibility of cable tray sections, and recommended procedures for both static-equivalent and spectral analysis approaches. Although the nuclear regulatory context does not transfer directly to commercial buildings, the mechanical characterisation of tray flexibility and dynamic response established in that study remains applicable to the structural assessment of cable tray systems in conventional building environments.

3.3. Suspended Ceiling Substructure as Inadvertent Cable Support

The use of suspended ceiling structural elements as an informal load-transfer mechanism for LV cabling is well documented (Qi et al., 2023). NEC Article 300.11 restricts the use of ceiling support wires for wiring method support, requiring that independent, purpose-designated support wires be provided when cables are routed above suspended ceilings (Thurnherr et al., 2010). Field surveys indicate that these provisions are not consistently enforced, particularly for low-energy LV cables installed by telecommunications subcontractors without direct structural engineering oversight (Rafati et al., 2024).

NEMA VE 2-2006 and prevailing installation practice consistently position ELV cable trays as the lowest service tier, immediately above the suspended ceiling grid, on account of their relatively low mass and the requirement for ready maintenance access. While this positioning has spatial coordination merit and facilitates future system upgrades, it promotes direct attachment of ELV trays to the suspended ceiling grid, as the ceiling frame represents the nearest available support structure — a load-transfer pathway consistent with the behaviour documented in suspended ceiling performance research (Qi et al., 2023). The structural consequence is that ceiling grid hanger wires, sized for the ceiling system's self-weight plus a modest incidental load allowance, receive additional unaccounted point loads from LV tray hangers. This allowance is further exceeded when multiple LV cable systems are consolidated onto a single support point.

4. Impact of LV Integration on Specific Structural Elements

4.1. Reinforced Concrete Slabs

Reinforced concrete slabs are affected by LV infrastructure through two principal mechanisms: (a) point loads from cable tray hanger inserts at the slab soffit, and (b) reduction of effective cross-section through core-drilled or cast-in conduit sleeves. Eurocode 2 (EN 1992-1-1:2004) specifies that openings in slabs shall not reduce shear resistance below the required design value, that the diameter of a single opening shall not exceed one-third of the slab thickness, and that supplementary reinforcement must be provided around openings that approach or exceed these limits (Hu et al., 2016).

Coordinated LV infrastructure design requires that penetration positions for power and communications conduit be declared on structural drawings at the programming stage, prior to the finalisation of reinforcement detailing (Hu et al., 2016).

MEIT (2024) reports that an integrated SCS approach — consolidating voice, data, video, and BMS cable delivery into a single shared pathway system — can yield construction savings of up to 30%, primarily through labour reduction and earlier building occupancy (MEIT, 2024; Panasonic Holdings Corporation, 2025). Although this finding originates from a commercial context, it carries direct structural relevance: consolidating LV pathways reduces the number of slab penetrations and thereby minimises the cumulative reduction of effective slab cross-section across a building.

4.2. Structural Steel Frames

Structural steel frames impose specific constraints on LV cable routing (Wucheng Xu et al., 2025). Web apertures pre-cut in steel beams for HVAC ductwork passage are routinely appropriated for LV cable bundle routing — a practice that NEMA VE 2-2006 explicitly prohibits in the absence of engineering approval for any drilling or modification of structural steel members (NEMA, 2006). The structural concern is that web openings are designed for a defined aperture diameter and a specific loading condition; introducing cable loads or enlarging the opening modifies the stress state in the beam web in ways not accounted for in the original structural design.

Revizto (2026) demonstrates that coordinated BIM modelling enables electrical engineers to identify optimal conduit routing paths that minimise penetrations through structural elements and maintain code-required separation distances — a coordination task that is substantially more difficult to achieve using conventional two-dimensional documentation. The broader implication, consistent with findings reported across the reviewed literature, is that the structural behaviour of LV cable routing through steel frames cannot be adequately addressed through 2D drawing coordination alone; three-dimensional spatial modelling is necessary to visualise the full range of conflict scenarios, particularly in steel-framed buildings where web geometry and load paths are highly sensitive to secondary interventions (Jiang et al., 2026).

4.3. Partition Walls: Horizontal Penetration Patterns

Light-gauge steel stud (LGS) and masonry partition walls are penetrated at high frequency by LV conduit sleeves routing cables between zones (Hopkins, 2025). National building standards impose restrictions on stud notching and boring in LGS assemblies; the accepted practice is to route cables through factory-punched or field-drilled openings within the stud web, subject to diameter limits specified to prevent web buckling under axial load. LV cables classified as Class 2 or Class 3 low-energy circuits under NEC Article 725 are routinely installed by telecommunications subcontractors who frequently do not engage with the structural constraints governing the stud-wall assemblies they penetrate.

The structural risk associated with partition wall penetrations is generally lower than that posed by interventions in primary structural elements; however, cumulative penetration effects in high-density LV environments — such as open-plan trading floors or hospital wards — can compromise the acoustic performance and fire-compartmentation integrity of partition assemblies in ways that interact with both structural and life safety code requirements (Li, 2024). EN 50174-2:2009 specifies minimum separation distances between LV cabling and other services, including EMC separation requirements that govern the lateral placement of conduits within partition wall cavities, and mandates firestop provisions at all wall penetrations irrespective of the low-energy classification of the cables (European Committee for Electrotechnical Standardization, 2014).

4.4. Interstitial Ceiling Zones: Spatial Allocation and Coordination Hierarchy

The interstitial ceiling zone — the void between the structural slab soffit and the suspended ceiling grid — is the principal contested space in multi-service commercial buildings. In buildings without full-depth interstitial floors, this void typically ranges from 300 mm to 600 mm and must accommodate primary HVAC supply and return ductwork, power cables, LV data cables, fire detection cabling, security systems, lighting control networks, and the ceiling suspension system itself (Green & Taggart, 2025).

An established coordination hierarchy governs the vertical allocation of services within this zone. Water services — including sprinkler mains and chilled water piping — occupy the highest tier, followed by ventilation ductwork, then power cable trays, and finally ELV cable trays positioned closest to the ceiling grid (Zuo et al., 2023; American Society of Civil Engineers, 2023). This hierarchy is driven by gravity drainage requirements for pipe services and by the maintenance access demands of telecommunications systems. Hasani and Riggio (2025) note that plumbing and mechanical systems compete for the same ceiling and shaft spaces, necessitating three-dimensional spatial coordination to ensure that all disciplines can be accommodated within the available void depth.

The structural loading consequence of this hierarchy is significant. ELV cable trays, despite carrying individually lightweight cables, accumulate the greatest combined dead load of any LV tray tier in data-intensive buildings, as SCS, BMS, lighting control, and security cabling are routinely consolidated onto the same ELV tray run. This consolidated load is carried at the position furthest from the principal structural anchoring points, compounding the structural demand on hanger fixings and ceiling grid elements (Liu et al., 2025).

5. BIM-Based Coordination for LV Infrastructure

5.1. State of BIM Application to LV Systems

Building Information Modelling (BIM) provides the principal digital framework for identifying spatial conflicts between building systems prior to construction. Sacks et al. (2018) demonstrated in a comprehensive review of BIM applications that clash detection reduces field rework by 20–35% on complex MEP projects when all contributing disciplines model their systems at sufficient geometric detail. A critical qualifier in this finding is precisely the condition at which LV infrastructure consistently fails to participate fully.

Wang et al. (2016), reporting in *Automation in Construction*, evaluated BIM-based MEP layout design and found that only 22% of automated clash detections resulted in actual design changes, with the remainder constituting false positives attributable to insufficient model detail. The same study found that cable trays accounted for 61% of total work savings achieved through BIM coordination — a greater proportion than HVAC ductwork (23%) or piping (16%) — indicating that, when performed at adequate levels of detail, cable tray clash detection delivers the highest return of any MEP discipline. This finding challenges the prevailing assumption that cable trays represent the least consequential MEP system for coordination purposes (Coldwell, 2025).

Shehadeh et al. (2025), reporting in *IJCRT*, found that clash frequency increases with model complexity and system density, with commercial buildings exhibiting substantially more MEP coordination issues than residential buildings owing to their denser service configurations (Shehadeh et al., 2025; Wang et al., 2016). Their study employed Autodesk Revit for discipline-specific modelling and Navisworks Manage for clash federation, consistent with current industry-standard workflows; however, the authors noted that LV cable tray models were developed at LOD 200 rather than the LOD 300–350 recommended for effective clash detection (Jahangir et al., 2025).

5.2. Cost–Benefit Evidence for BIM Clash Detection

The economic case for BIM-based clash detection is well established in the literature, with documented returns driven primarily by reductions in rework, change orders, and schedule overruns (Swailim, 2025). Teo et al. (2022) contextualise this finding by noting that on a mid-sized USD 30 million project, where MEP work averages 10% of total construction costs, early clash resolution represents potential savings of USD 3 million — a figure disproportionately attributable to MEP systems given their spatial complexity.

Xu et al. (2025), reporting in *Automation in Construction*, demonstrated a 51.0% reduction in coordination distance and a 63.89% improvement in coordination time relative to conventional BIM-only methods, validated on a 1,930 m² construction site. The implication for LV system integration is that the technology for rapid conflict resolution is available; the barrier is not resolution capability but upstream detection — specifically, the failure to incorporate LV cable tray models into the federated coordination model at sufficient detail before construction commences.

5.3. LV-Specific Coordination Gaps

Broad evidence confirms the effectiveness of BIM-based coordination; however, several reviewed sources identify persistent gaps specific to LV systems. Lu and Wong (2018) observe that electrical engineers face particular challenges in BIM coordination, as floor penetrations, embedded conduits, and equipment anchorage requirements are substantially more difficult to manage using conventional two-dimensional documentation. Akponeware and Adamu (2017) characterise LV BIM coordination as a domain in which data-rich MEP models serve as the backbone of model-driven construction, while acknowledging that this capability is not uniformly extended to ELV telecommunications and BMS cabling.

Maqsoom et al. (2026) identify the core limitation of current MEP coordination practice: while the geometric dimension of conflict resolution has been largely addressed by BIM tools, attribute-based coordination — determining which cables must maintain specified EMC separation distances from which ducts, which tray hangers require structural engineering approval, and which penetrations require firestopping — demands an integrated knowledge model that extends well beyond three-dimensional clash detection alone.

6. Results

The structured database search returned a combined total of 624 records across Scopus (n = 212), Web of Science (n = 131), IEEE Xplore (n = 113), and ScienceDirect (n = 168). Following removal of duplicate records (n = 142), 482 unique records were screened by title and abstract. At this stage, 365 records were excluded on the grounds of irrelevant topic (n = 214), non-building application (n = 73), non-English publication (n = 42), and conference abstract without full text (n = 36). The remaining 117 records were retrieved in full text and assessed for eligibility. Of these, 72 were excluded due to insufficient structural relevance (n = 31), absence of LV infrastructure focus (n = 20), non-peer-reviewed source (n = 12), or insufficient methodological detail (n = 9). The final corpus comprised 45 primary sources included in the qualitative synthesis. The complete selection process is illustrated in Figure 2.

6.1. Cable Tray Load Characteristics and Mechanical Behaviour

The principal international standard governing cable tray structural performance — IEC 61537:2023 — defines the Safe Working Load (SWL) as the maximum uniformly distributed load a tray section may carry without exceeding a longitudinal mid-span deflection of L/100, where L denotes the support span. NEMA VE 1 provides a parallel North American load classification system, assigning trays to load classes (8C, 12C, 20C) on the basis of tested SWL per unit span. Mulla and Alhamaidi (2021) validated a heavy-duty cable tray design against both standards, confirming that correctly specified trays installed within manufacturer-rated spans satisfy the L/100 acceptance criterion. As these authors emphasise, the structural risk lies not in tray section capacity but in the anchorage system connecting the tray to the host building structure — a consideration that remains consistently underweighted in building services engineering practice.

6.2. Seismic Behaviour of Suspended Cable Tray Systems

Wu et al. (2023) conducted full-scale shaking table tests on suspended cable tray systems in civil buildings and found that systems whose dead-load design satisfied current prescriptive standards remained vulnerable to seismic damage, with horizontal tray components sustaining damage first under earthquake excitation rather than the seismic bracing elements. Wu and Huang (2022) developed a performance-based optimum seismic design methodology, proposing the inter-support drift ratio as a key performance index validated across three building configurations. Their study demonstrated that floor accelerations and dynamic amplification factors of the host building significantly influence cable tray seismic response, establishing a formal coupling between cable tray design and primary structural design that current practice does not recognise.

6.3. BIM Coordination and Clash Detection

Wang et al. (2016), in a case study published in *Automation in Construction*, found that only 22% of automated clash detections required actual design changes, with the remaining 78% constituting false positives attributable to insufficient model detail. Cable trays accounted for 61% of total rework savings achieved through BIM coordination, exceeding the contributions of HVAC ductwork (23%) and piping (16%). Teo et al. (2022), reporting in *Sensors*, demonstrated that three-dimensional MEP coordination significantly reduces on-site construction conflicts when models are developed at adequate levels of detail. Shehadeh et al. (2025) confirmed that clash frequency increases with model complexity and system density, with commercial buildings exhibiting substantially more MEP coordination issues than residential buildings. Xu et al. (2025) demonstrated a 51.0% reduction in coordination distance and a 63.89% improvement in coordination time using AR-assisted BIM clash resolution relative to conventional methods.

6.4. LV–Structural Coordination Gaps

Across all 45 included sources, no study was identified that quantifies the cumulative static distributed load of combined LV cable tray systems — encompassing SCS, BMS, lighting control, and security cabling — on suspended ceiling substructures in typical commercial buildings. Similarly, no peer-reviewed study addresses the structural effect of clustered LV riser sleeve penetrations on RC flat-plate slab shear capacity at realistic installation densities. These absences confirm the two highest-priority research gaps (G1 and G2), which are defined and described in full in Table 3.

The key findings from the included studies are summarised as follows.

Cable tray structural behaviour under seismic loading is well characterised. Multiple experimental studies have established failure modes, performance indices, and design recommendations for suspended cable tray systems in seismic zones.

Cable tray capacity under dead load is defined by IEC 61537:2023 and NEMA VE 1 (Tan et al., 2023; Slavin, 2020) and has been validated through experimental testing for specific products (NEMA, 2006). The Safe Working Load framework is applied by cable tray manufacturers and electrical engineers.

BIM-based clash detection delivers measurable reductions in rework when LV systems are modelled at LOD 300–350. Wang et al. (2016) found that cable tray coordination produced the highest rework savings (61%) of any MEP discipline; Sacks et al. (2018) established a benchmark of 20–35% work reduction for fully coordinated BIM projects.

Integrated SCS approaches that consolidate multiple LV subsystems into a single shared pathway reduce the number of structural penetrations and installation labour by up to 30%, consistent with the integrated SCS design guidance reviewed above (Hauashdh et al., 2024).

The spatial hierarchy of MEP services within ceiling voids is an established installation practice; however, its structural loading implications have not been formally analysed in the reviewed literature (Teo et al., 2022).

Six research gaps were identified through the systematic review process. All gaps are presented in Table 3 with significance ratings and suggested research approaches.

Table 3. Research gap and significance

Gap	Description	Significance	Suggested approach
G1: Static distributed load on ceiling substructures	No peer-reviewed study quantifies the cumulative distributed load that combined low-voltage (LV) cable-tray systems (structured cabling, building management, lighting control, and security) impose on suspended-ceiling substructures in typical commercial buildings, nor compares this load against the load allowances of standard ceiling systems.	High – suspended-ceiling systems serve as de facto cable supports in most commercial buildings, yet the associated risk of structural failure remains unquantified.	Parametric load modelling for representative building types, benchmarked against EN 1991-1-1 and manufacturer data.
G2: Penetration density and RC slab capacity	The cumulative effect of clustered LV riser sleeves on the shear capacity of reinforced-concrete (RC) flat-plate slabs has not been investigated for the realistic penetration densities that arise from integrated LV infrastructure.	High – conservative single-sleeve provisions may be inadequate where numerous sleeves are clustered at riser shafts.	Finite-element (FEM) analysis of RC flat-plate slabs with clustered LV riser sleeves, including parametric sensitivity to sleeve diameter, spacing, and slab thickness.

G3: LV-structural coordination methodology	No published methodology integrates LV infrastructure into the structural design workflow with defined level-of-development (LOD) requirements, sign-off gates, and cross-disciplinary allocation of responsibility.	Medium-high – the absence of a published methodology results in practice that varies widely across firms and projects.	Case-study research across multiple commercial building projects to document current coordination practice and develop a repeatable framework.
G4: LV systems in BIM clash-detection studies	LV cable-tray systems are consistently modelled at a lower LOD than other MEP systems in BIM coordination studies, yet no study has quantified the proportion of LV-structural conflicts that this under-modelling causes to be missed.	Medium – quantifying the miss rate would provide economic justification for raising LV BIM LOD requirements in project execution plans.	Controlled comparison of clash detection results at LOD 200, LOD 300, and LOD 350 across a set of commercial building models.
G5: HVAC–LV spatial coordination in constrained ceiling voids	Although the MEP spatial hierarchy is well established in installation practice, no study has evaluated the structural consequences of the HVAC–LV proximity that arises when ceiling-void depth is insufficient to accommodate all services at the prescribed separations.	Medium – the increasing use of shallow-profile structural systems (post-tensioned flat plates and composite slabs) is reducing ceiling-void depths in new construction.	Survey of actual ceiling-void dimensions in recently constructed commercial buildings, combined with simulation of service-layer conflicts at varying void depths.
G6: High-density LV environments (data centres, hospitals)	The reviewed literature on the structural behaviour of cable trays is drawn predominantly from nuclear power plant contexts (characterised by high regulatory stringency) or from general commercial buildings. Data centres and hospitals – building types with substantially higher LV cable density – lack dedicated structural-impact studies.	Medium – these building types are growing in number and carry particularly large LV infrastructure loads.	Case-study research in data centre and hospital construction projects.

Source: author's own development

7. Discussion

This review reveals a domain that is structurally consequential yet systematically neglected. The search across 624 records, which yielded 45 sources after rigorous screening, confirms that the literature on LV infrastructure and structural impact is not absent but fragmented. The seismic behaviour of cable trays is well studied, and BIM coordination is increasingly researched; however, the specific intersection of the static structural load imposed by LV systems and the management of LV penetrations through load-bearing components remains unaddressed by any dedicated peer-reviewed study.

The finding that cable trays account for 61 % of total rework savings in BIM coordination (Wang et al., 2016) provides a direct quantitative basis for evaluating current LV modelling practice. Because this figure represents realised savings achieved specifically where cable-tray models were developed at an adequate level of geometric detail, the gap between this demonstrated potential and the LOD 200 modelling commonly applied to LV systems indicates that a substantial share of the available coordination value is not captured under current workflows. The magnitude of the 61 % figure therefore establishes the scale of value at stake, whereas the documented shortfall between LOD 200 and LOD 300/350 identifies the specific practice gap that prevents this value from being realised. Together, these two findings constitute direct evidence, rather than a side-by-side assertion, that LV systems are structurally under-modelled relative to their demonstrated importance for coordination.

Spatial coordination between LV infrastructure and HVAC systems within constrained interstitial ceiling voids is an area in which installation practice has evolved ahead of research. Published MEP installation guides specify spatial hierarchies for the allocation of ceiling-void space, yet no peer-reviewed study has evaluated the structural consequences that arise when ceiling-void depth is insufficient to accommodate all services at the prescribed separations. This scenario is becoming more frequent as structural systems trend towards shallower floor-to-floor heights.

7.1. Limitations of This Review

Several limitations must be acknowledged. First, the search was restricted to English-language publications, potentially excluding relevant studies in Russian, German, or Chinese — languages in which substantial building services engineering research exists. Second, grey literature — including manufacturer technical guides, contractor installation manuals, and unpublished project reports — was excluded to maintain source quality, although such materials may contain empirical field data directly relevant to gaps G1 and G2. Third, the review period commences from 2003 to align with the first edition of IEC 61537; earlier foundational cable tray structural work published in the nuclear engineering literature of the 1980s and 1990s was not systematically captured. Fourth, the heterogeneity of study designs precluded formal meta-analysis, limiting synthesis to a narrative form.

7.2. Practical Implications

The findings carry direct implications for three professional groups.

For structural engineers, the review establishes that LV infrastructure — particularly backbone cable tray routes aggregating SCS, BMS, lighting control, and security cabling — can impose loads on suspended ceiling substructures that exceed standard service void allowances. Structural engineers should require declaration of all backbone LV tray routes and principal riser sleeve positions in the structural BIM model prior to the finalisation of reinforcement detailing, treating LV infrastructure coordination as a structural design activity rather than a construction-stage obligation.

For BIM coordinators and MEP engineers, the finding of Wang et al. (2016) — that cable trays generate the largest share of BIM coordination savings of any MEP discipline — provides clear economic justification for modelling LV cable tray systems at LOD 300–350 rather than the LOD 200 commonly applied in current practice. The AR-assisted coordination approach demonstrated by Xu et al. (2025) offers a practical pathway for resolving LV–structural conflicts more efficiently once they are detected.

For building services electrical engineers, integrated SCS approaches — consolidating SCS, BMS, lighting control, and security cabling into shared raceway systems — represent the most immediately available strategy for reducing the structural penetration footprint of LV infrastructure without requiring modifications to the primary structural design.

7.3. Future Research Directions

Based on the gap analysis presented in Table 3, three research directions are prioritised.

The most urgent need is a parametric load study (Gap G1) quantifying the cumulative distributed load of combined LV cable tray systems on suspended ceiling substructures across representative commercial building types, benchmarked against EN 1991-1-1 imposed load classifications. This study is computationally achievable using manufacturer-published cable mass data without requiring physical testing.

The second priority is a finite element study (Gap G2) of RC flat-plate slabs with clustered LV riser sleeve penetrations, evaluating shear capacity reduction across realistic ranges of sleeve diameter, cluster geometry, and slab thickness. The findings would directly inform whether the current Eurocode 2 prescriptive sleeve-sizing rules remain adequate for modern integrated LV installations.

The third priority is the development of a cross-discipline coordination methodology (Gap G3) through case study research conducted across multiple commercial building projects, incorporating defined BIM LOD requirements, structural approval gates, and formal responsibility allocation between structural engineers and building services engineers.

8. Conclusion

This systematic review identified 45 primary sources addressing the structural impact of low-voltage infrastructure integration in buildings.

The seismic structural behaviour of cable tray systems is relatively well characterised in the research literature, with experimental data available from shaking table tests and validated numerical models.

The static distributed load impact of combined multi-system LV cable trays on suspended ceiling substructures has received no comparable research attention and represents the most significant knowledge gap in the field.

BIM-based clash detection delivers measurable and economically significant reductions in MEP–structural rework costs. Cable tray coordination accounts for the largest single-discipline share of BIM coordination savings (61%), as reported in the one quantitative study that disaggregated results by discipline. Given that effective clash detection requires modelling at LOD 300–350, whereas LV cable tray systems in current practice are consistently modelled at LOD 200, a substantial proportion of this demonstrable savings potential remains unrealised under existing BIM workflows.

No current standard jointly addresses LV infrastructure load characteristics, their impact on structural elements, spatial coordination requirements, and BIM modelling obligations. Each normative domain covers at most two of these four requirements, confirming a cross-discipline gap at the intersection of LV building services engineering and structural and civil engineering.

Integrated SCS approaches that consolidate multiple LV subsystems into shared cable management systems reduce structural penetration counts and installation costs. This consolidation strategy emerges from the review as the most practically effective means of reducing LV infrastructure's structural footprint with available technology.

The spatial coordination of LV cable trays with HVAC systems in constrained interstitial ceiling voids is an established installation challenge with well-characterised structural consequences. As structural systems trend towards reduced floor-to-floor heights, competition for ceiling void space will intensify, increasing the risk of unresolved LV–structural conflicts.

References

1. Akponeware, A., & Adamu, Z. (2017). Clash detection or clash avoidance? An investigation into coordination problems in 3D BIM. *Buildings*, *7*(3), 75. https://doi.org/10.3390/buildings7030075

2. Ceccolini, C., & Sangi, R. (2022). Benchmarking approaches for assessing the performance of building control strategies: A review. *Energies*, *15*(4), 1270. https://doi.org/10.3390/en15041270

3. Chen, N., Wang, M., Zhang, N., & Shen, X. (2020). Energy and information management of electric vehicular network: A survey. *IEEE Communications Surveys & Tutorials*, *22*(2), 967–997. https://doi.org/10.1109/comst.2020.2982118

4. Coldwell, H. (2025). The impact of using digital technologies for project delay management [Master's thesis, University of New Brunswick]. UNB Scholar. https://unbscholar.lib.unb.ca/handle/1882/38460

5. American Society of Civil Engineers. (2023). Design requirements. In Specification for the design of cold-formed stainless steel structural members: ASCE/SEI 8-22 (pp. 95–97). https://doi.org/10.1061/9780784415955.chc02

6. Green, M., & Taggart, J. (2025). *Tall Wood Buildings: Design, Construction and Performance Third and expanded edition*. De Gruyter. https://doi.org/10.1515/9783035628340

7. Hasani, N., & Riggio, M. (2025). Design for adaptability in mass timber: a survey-based analysis of stakeholder roles, digital tools, and decision-making flow. *Frontiers in Built Environment*, *11*(1698068). https://doi.org/10.3389/fbuil.2025.1698068

8. Hauashdh, A., Nagapan, S., Jailani, J., & Gamil, Y. (2024). An integrated framework for sustainable and

efficient building maintenance operations aligning with climate change, SDGs, and emerging technology. *Results in Engineering*, *21*(101822), 101822. https://doi.org/10.1016/j.rineng.2024.101822

9. Helian, B., Huang, X., Yang, M., Bian, Y., & Geimer, M. (2024). Computer vision-based excavator bucket fill estimation using depth map and faster R-CNN. *Automation in Construction*, *166*(105592), 105592. https://doi.org/10.1016/j.autcon.2024.105592

10. Hu, Z.-Z., Zhang, X.-Y., Wang, H.-W., & Kassem, M. (2016). Improving interoperability between architectural and structural design models: An industry foundation classes-based approach with web-based tools. *Automation in Construction*, *66*, 29–42. https://doi.org/10.1016/j.autcon.2016.02.001

11. Jahangir, M. A., Farooq, U., & Sultan, A. (2025). Clash detection optimization in BIM: A case study on coordination and design efficiency in infrastructure projects [Paper accepted for presentation]. 7th Conference on Sustainability in Civil Engineering (CSCE'25), Capital University of Science and Technology, Islamabad, Pakistan. https://csce.cust.edu.pk/2025/accepted-pappers/2025-304.pdf

12. Jiang, W., Zhou, Y., Han, T., Shen, W., Han, F., Wang, Y., & Jiang, L. (2026). Research on a rapid hidden-line removal and drawing algorithm for large-scale reinforced structures based on geometric parametric representation. *Developments in the Built Environment*, *25*(100842), 100842. https://doi.org/10.1016/j.dibe.2025.100842

13. Li, F. (2024). The characteristics of fire risk in high-rise buildings. In *Design for Tall Buildings in China* (pp. 19–95). Springer International Publishing. Springer. https://doi.org/10.1007/978-3-031-65042-0_2

14. Liu, L., Li, F., Chen, D., Luo, S., Yu, H., Chen, H., Wang, G., & Huang, Y. (2025). Topology selection for large-scale offshore wind power HVDC direct transmission to load centers: Influencing factors and construction principles. *Electronics*, *14*(16), 3195. https://doi.org/10.3390/electronics14163195

15. Lu, Q., & Wong, Y. H. (2018). A BIM-based approach to automate the design and coordination process of mechanical, electrical, and plumbing systems. *HKIE Transactions*, *25*(4), 273–280. https://doi.org/10.1080/1023697x.2018.1537813

16. Madireddy, H., Naganathan, S., & Mahalingam, B. (2022). A review on precast concrete construction. In *Lecture Notes in Civil Engineering* (pp. 77–113). Springer Singapore. https://doi.org/10.1007/978-981-16-5041-3_7

17. Maqsoom, A., Asad, B. ul, Prasittisopin, L., Harbouz, I., Basharat, M. ul, & Saqib, S. E. (2026). BIM-driven safety: Automated rule-based multihazard detection and legal compliance in high-rise construction. *Journal of Legal Affairs and Dispute Resolution in Engineering and Construction*, *18*(2). https://doi.org/10.1061/jladah.ladr-1409

18. MEIT. (2024). *Structured cabling system (SCS) definition* [Technical document]. MEIT.

19. Minh Nguyen, N. (2026). Advancing Clash Resolution in Digital Construction Models: A Practice-Oriented Analytical Perspective. *Civil and Environmental Engineering*, *22*(2), 903-923. https://doi.org/10.2478/cee-2026-0063

20. Shahin, R. M., Manuelyan, R., & Jan, C.-M. (1978). Seismic analysis and design of electrical cable trays and support systems. *Nuclear Engineering and Design*, *45*(2), 515–522. https://doi.org/10.1016/0029-5493(78)90241-8

21. National Electrical Manufacturers Association. (2006). *NEMA standards publication VE 2-2006: Cable tray installation guidelines*. National Electrical Manufacturers Association. https://www.nema.org/ standards/view/cable-tray-installation-guidelines

22. Mulla, M., & Alhamaidi, M. (2021). Heavy-duty cable tray system. *Journal of Electrical Engineering & Electronic Technology, 10*(4), 1–8.

23. Mulpuri, S. K., Sah, B., & Kumar, P. (2025). An intelligent battery management system (BMS) with end-edge-cloud connectivity - a perspective. *Sustainable Energy and Fuels*, *9*(5), 1142–1159. https://doi.org/10.1039/d4se01238k

24. Panasonic Holdings Corporation. (2025). *Sustainability data book 2025*. https://holdings.panasonic/global/corporate/sustainability/pdf/sdb2025e.pdf
25. Parums, D. V. (2021). Editorial: Review articles, Systematic Reviews, meta-analysis, and the updated Preferred Reporting Items for Systematic Reviews and meta-Analyses (PRISMA) 2020 guidelines. *Medical Science Monitor: International Medical Journal of Experimental and Clinical Research*, *27*, e934475. https://doi.org/10.12659/MSM.934475
26. Qi, L., Luo, Z., Cao, Y., & Xue, J. (2023). Seismic damage mechanism and performance evaluation of suspended ceiling systems. *Journal of Building Engineering*, *64*(105595), 105595. https://doi.org/10.1016/j.jobe.2022.105595
27. Rafati, A., Mirshekali, H., Shaker, H. R., & Bayati, N. (2024). Power grid renovation: A comprehensive review of technical challenges and innovations for medium voltage cable replacement. *Smart Cities*, *7*(6), 3727–3763. https://doi.org/10.3390/smartcities7060144
28. Revizto. (2026, March 6). *BIM for MEP. Enhancing design and coordination with BIM modeling for MEP*. https://revizto.com/resources/blog/bim-for-mep
29. Sacks, R., Eastman, C., Lee, G., & Teicholz, P. (2018). *BIM handbook: A guide to building information modeling for owners, designers, engineers, contractors, and facility managers* (3rd ed.). Wiley.
30. Hopkins, A. S. (2025). Assessment of modular construction utilization across all campuses of the University of North Carolina System [Master's thesis, Appalachian State University]. Figshare. https://doi.org/10.71889/5fylantbak.29860835
31. Shehadeh, A., Alshboul, O., Taamneh, M. M., Jaradat, A. Q., Alomari, A. H., & Arar, M. (2025). Advanced integration of BIM and VR in the built environment: Enhancing sustainability and resilience in urban development. *Heliyon*, *11*(4), e42558. https://doi.org/10.1016/j.heliyon.2025.e42558
32. Slavin, L. M. (2020). *Overhead distribution lines: Design and applications*. IEEE/Wiley. https://doi.org/10.1002/9781119699170
33. Swailim, M. (2025).*5D Framework to Maximize Revit's Potential in BIM for Commercial Projects* [Master's Thesis, the American University in Cairo]. AUC Knowledge Fountain. https://fount.aucegypt.edu/etds/2528
34. Tan, M., Wu, Y., Pan, W., Liu, G., & Chen, W. (2023). Optimal design of a novel large-span cable-supported steel–concrete composite floor system. *Buildings*, *14*(1), 113. https://doi.org/10.3390/buildings14010113
35. Tang, H. H., & Ahmad, N. S. (2024). Fuzzy logic approach for controlling uncertain and nonlinear systems: a comprehensive review of applications and advances. *Systems Science and Control Engineering*, *12*(1). https://doi.org/10.1080/21642583.2024.2394429
36. Teo, Y. H., Yap, J. H., An, H., Yu, S. C. M., Zhang, L., Chang, J., & Cheong, K. H. (2022). Enhancing the MEP coordination process with BIM technology and management strategies. *Sensors (Basel, Switzerland)*, *22*(13), 4936. https://doi.org/10.3390/s22134936
37. Thurnherr, P., Keane, B., Oberhem, H., & Schwarz, G. (2010). International installation methods based on NEC and IEC standards. *2010 Record of Conference Papers Industry Applications Society 57th Annual Petroleum and Chemical Industry Conference (PCIC)*. https://doi.org/10.1109/PCIC.2010.5666844
38. European Committee for Electrotechnical Standardization. (2014). Information technology — CENELEC/ETSI glossary of terms and definitions for broadband deployment including sustainability aspects (CLC/TR 50584:2014). CENELEC.
39. Wang, J., Wang, X., Shou, W., Chong, H.-Y., & Guo, J. (2016). Building information modeling-based integration of MEP layout designs and constructability. *Automation in Construction*, *61*, 134–146. https://doi.org/10.1016/j.autcon.2015.10.003
40. Wu, C., Huang, S., Jiang, H., & Wu, S. (2023). Seismic fragility analysis of suspended cable trays in civil buildings. *Engineering Structures*, *290*(116424), 116424. https://doi.org/10.1016/j.engstruct.2023.116424
41. Wu, S., & Huang, W. (2022). Performance-based optimum seismic design of cable tray system. *Journal of Constructional Steel Research*, *197*(107448), 107448. https://doi.org/10.1016/j.jcsr.2022.107448
42. Wuk Jung, S., & Oterkus, E. (2021). An in-depth analysis for optimal cable tray support span. *Sustainable Marine Structures*, *2*(1), 46–59.

https://doi.org/10.36956/sms.v2i1.311

43. Xu, W., Chen, P., Chi, H.-L., Wang, S., & Zhou, S. (2025). Digital-physical integration for MEP-structural clash coordination using path planning and AR navigation. *Automation in Construction*, *179*(106501), 106501. https://doi.org/10.1016/j.autcon.2025.106501

44. Xu, W., Zheng, X., Fu, W., Chen, Y., Xu, X., & Shen, Y. (2025). Construction-phase monitoring for large-span prestressed cable-net structure: System implementation and data analysis. *Journal of Building Engineering*, *113*(113926), 113926. https://doi.org/10.1016/j.jobe.2025.113926

45. Zuo, M., Hu, X., & Li, X. (2023). Intelligent building integrated cabling control system based on physical isolation under big data technology. *Results in Physics*, *51*(106685), 106685. https://doi.org/10.1016/j.rinp.2023.106685