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Integrating MEP Frameworks with Architectural Design: A BIM-Driven Material Take-Off and Lifecycle Assessment for Contemporary Multi-Level Residential Villas

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Abstract **Original Research Article**

Contemporary residential villa designs require intense multi-disciplinary synergy between structural parameters, spatial architecture, and Mechanical, Electrical, and Plumbing (MEP) layouts. This paper evaluates an integrated, data-driven Building Information Modeling (BIM) framework using the practical case study of a contemporary multi-level single-family villa designed at the Poznan University of Technology. Fragmentation between distinct spatial design layouts and engineering frameworks traditionally breeds unexpected material surpluses and geometric conflict during installation. To mitigate these systematic inefficiencies, an integrated, parametric workflow using Autodesk Revit and Navisworks was implemented to perform automated cross-disciplinary clash detection, optimize material take-offs (MTO), and map an explicit Life Cycle Assessment (LCA) focused on high-density copper-based hydraulic plumbing networks. The empirical database accounts for multi-level spatial tracking ranging from ground floor partition zones up to specific copper piping schedules spanning 10 mm to 90 mm nominal diameters. The findings indicate that unified BIM coordination and structural optimization resolve physical geometric interferences prior to onsite construction, substantially dropping material scrap rates and establishing a reproducible pipeline for early-stage carbon mitigation within Central European residential architectures.

Keywords: Building Information Modeling (BIM); MEP Frameworks; Material Take-Off (MTO); Life Cycle Assessment (LCA); Spatial Coordination; Sustainable Construction.

1. INTRODUCTION

The global architecture, engineering, and construction (AEC) sector faces escalating regulatory and societal pressure to reduce its environmental footprint while satisfying growing regional demands for urban housing [1]. Historically, sustainability optimization was placed primarily on reducing building operational energy consumption via highly insulated building envelopes [2]. However, as operational loads drop due to strict energy efficiency guidelines, the share of embodied carbon within primary building construction materials and technical building networks has assumed dominant structural importance [3].

In residential engineering, a recurring challenge is the disconnected design workflow between spatial architects and MEP engineers [4]. Complex hydraulic routing such as supply loops, distribution manifolds, and soil pipes are frequently superimposed onto structural framing grids late in the project timeline [5]. This fragmentation prompts geometric anomalies, necessitating uncoordinated onsite adaptations that yield substantial material waste, elongated schedules, and structural integrity risks [6].

Building Information Modeling (BIM) offers a parametric methodology to mitigate these systematic inefficiencies by hosting explicit geometric dimensions and physical material traits within an interactive, unified common data repository [7]. Parametric modeling allows engineering teams to execute automated clash checks and synchronize material take-offs (MTO) directly with Life Cycle Assessment databases during early design iterations [8][11].

While LCA has become a recognized methodology for evaluating environmental impacts throughout a building's lifespan, its implementation remains data-intensive and time-consuming due to the complexity of manual material inventory compilation

[12][14]. This research addresses this gap by investigating how an integrated, BIM-based architectural and MEP framework can enhance MTO accuracy and lifecycle environmental tracking within a representative contemporary residential villa case study [15][18].

2. MATERIALS AND METHODS

2.1. Case Study and Spatial Modeling Parameters

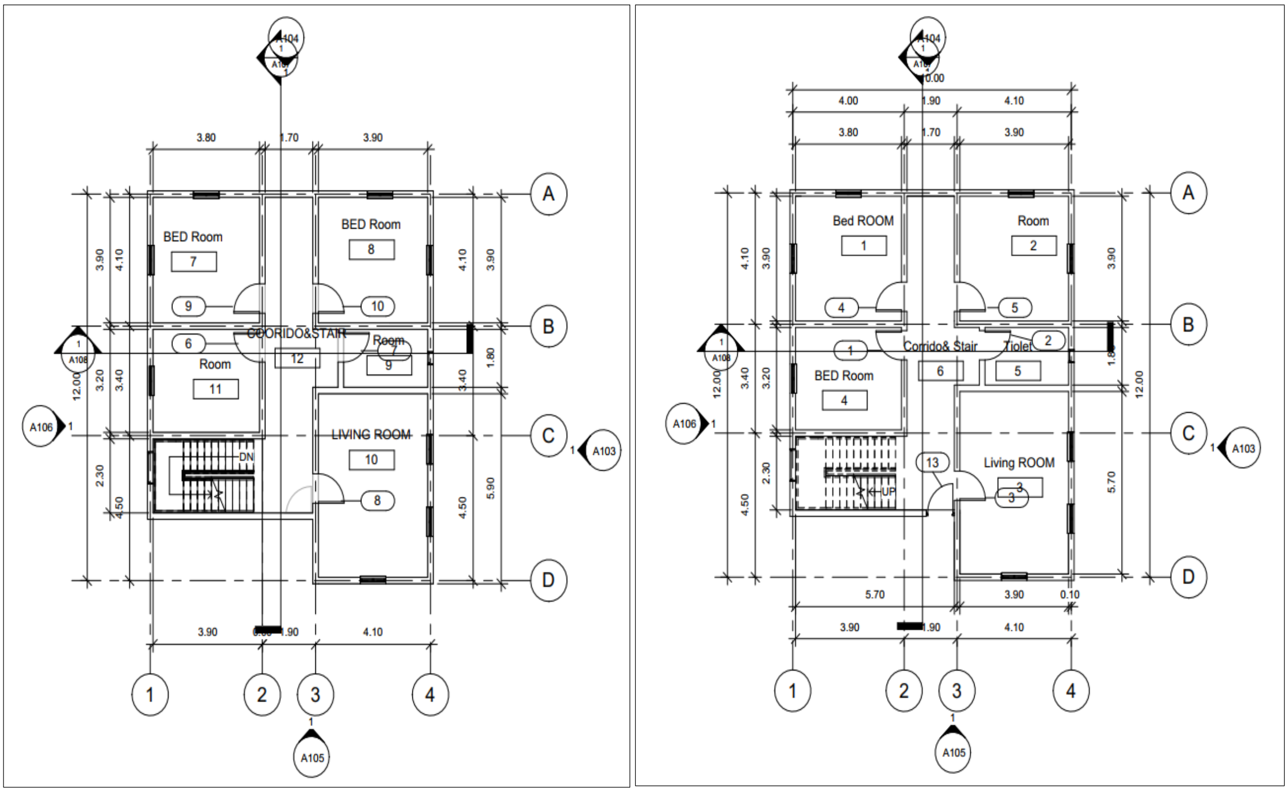

Figure 1: Floor plans of the case study building: (a) Ground floor plan; (b) 1st floor plan

The study evaluates a modern, multi-level residential single-family structure (shown in **Figure-1**) designed within the European geographic context at the Poznan University of Technology. The spatial architecture features distinct room zoning on the Ground Floor including primary bedroom quarters, localized toilet zones (Toilet 2), a central corridor/stair layout, and a primary living room spanning 5.70 m × 3.90 m. The First Floor maintains architectural continuation, introducing supplementary bedrooms, master corridor access, and localized wet spaces that demand highly dense MEP infrastructure.

The federated model was engineered parametrically in Autodesk Revit at a baseline scale of 1:100. Detailed window and door parameters such as Double Swept-Head windows and Single-Flush doors were modeled with strict dimensional criteria to establish valid building envelope parameters and wall boundary conditions crucial for geometric routing constraints.

2.2. MEP Framework and Piping Schedules

The hydraulic component of the BIM model establishes comprehensive water supply and drainage networks distributed across Level 1 and Level 2. The 3D visualization of the case study building is illustrated in Figure 2, highlighting its overall architectural design layout (Figure 2a) and the localized MEP plumbing infrastructure (Figure 2b). Unlike standardized, low-fidelity models that approximate MEP systems via simplified area allowances, this model incorporates explicit physical routings for copper piping. The structural layout captures detailed engineering components categorized by specific diameters:

- Distribution Loops and Feeder Lines: Controlled using high-ductility 10 mm, 15 mm, and 20 mm copper runs.
- Main Hydraulic Riser and Waste Stacks: Managed through heavier 50 mm and 90 mm copper conduits engineered to handle multi-level gravity drainage and pressure distribution.

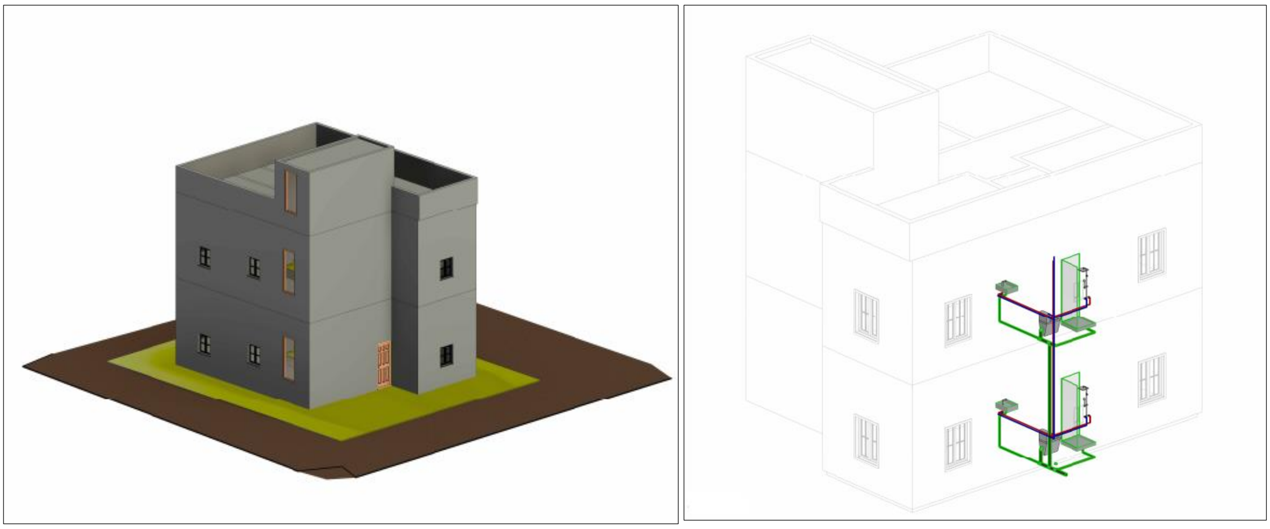

Figure-1: 3D models of the case study building: (a) Architectural design overview; (b) MEP infrastructure and plumbing layout

2.3. Spatial Interference Detection Setup

To eliminate real-world construction material waste, the integrated architectural structural boundaries and the itemized MEP routing layers were subjected to automated clash detection within Autodesk Navisworks. The spatial logic isolates two categories of conflicts:

- Hard Clashes: Instances where the volume of a 50 mm or 90 mm copper drainage stack directly intersects structural concrete slabs or weight-bearing partition boundaries.
- Soft Clashes: Spatial overlaps where a hydraulic run violates maintenance clearance radii or compromises accessibility requirements around the central stairwell and corridor cavities.

2.4. Lifecycle Assessment (LCA) Procedure

The material take-offs automatically compiled by the parametric model form the foundation for the Life Cycle Inventory (LCI) dataset. The LCA follows ISO 14040 [9] and ISO 14044 [10] guidelines. The system boundaries were defined as a cradle-to-gate framework, evaluating the primary extraction and manufacturing impacts associated with the specified metallic networks. Environmental profiles and impact categories primarily focusing on Global Warming Potential (GWP) and embodied carbon values were obtained from integrated Environmental Product Declarations (EPDs).

3. RESULTS AND DISCUSSION

3.1. Parametric Material Take-Off (MTO) Analysis

The integration of the MEP framework allowed the automated extraction of high-fidelity material schedules directly from the building model's database. Rather than relying on traditional estimation factors, the precise calculation of individual plumbing runs across multiple levels ensures error-free quantification. An excerpt of the raw material tracking data for the multi-level copper infrastructure is categorized in **Table 1**, demonstrating the high data granularity achieved on Level 2.

Table 1: Material Take-Off Excerpt for Level 2 Copper Infrastructure.

Component Material	Nominal Diameter (mm)	Segment Length (mm)	Spatial Level Assignment
Copper	10	162	Level 2
Copper	10	193	Level 2
Copper	15	306	Level 2
Copper	20	214	Level 2
Copper	50	513	Level 2
Copper	50	1783	Level 2
Copper	90	3883	Level 2
Copper	90	301	Level 2

3.2. Clash Optimization and Waste Mitigation

Running spatial clash checks revealed multiple points of interference where the main 90 mm drainage line compromised structural floor layers near the central staircase. In conventional uncoordinated construction workflows, these conflicts are solved onsite by cutting through existing components or diverting pipelines using emergency fittings. Such manual corrections cause localized pressure drop issues and add unbudgeted material scraps.

By resolving these geometric issues within the virtual BIM environment before construction, the layout was adjusted to route through dedicated utility shafts. This proactive clash resolution reduces expected onsite plumbing adjustments, cutting down material waste during installation and protecting structural load-bearing paths.

3.3. Environmental Lifecycle Environmental Performance

Evaluating the lifecycle profile using the exact inventory data clarifies key environmental trade-offs. Copper maintains a relatively high initial embodied carbon value during raw extraction and manufacturing stages compared to synthetic alternatives like PEX or PPR. However, its exceptional durability and high end-of-life recycling potential provide notable long-term sustainability benefits over a standard 50-year residential building lifespan.

Integrating precise material schedules within the early design platform enables architects and engineers to test alternative material strategies dynamically [13] [16]. This digital workflow makes it practical to optimize carbon outcomes without sacrificing structural performance or building code compliance [17].

4. CONCLUSIONS

This study presented a BIM-driven framework integrating architectural and MEP systems for material take-off and lifecycle assessment of contemporary multi-level residential villas. The findings demonstrate that:

i. BIM significantly improves interdisciplinary coordination by resolving physical interferences between structural components and hydraulic networks during the design phase, avoiding costly fieldwork.
ii. Automated material take-off enhances quantity accuracy, providing reliable material inventories suitable for advanced environmental lifecycle tracking.
iii. BIM-generated inventories facilitate reliable lifecycle assessment, supporting an optimized approach toward lower-carbon residential development.

Future research will expand this digital workflow by incorporating real-time cost estimation (5D BIM) and operational energy simulations to establish a holistic multi-criteria decision framework for sustainable residential projects.

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