Bill of Material Characterization for Commercial Building Prototypes

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ABSTRACT

The U.S. Department of Energy's Commercial Prototype Buildings are developed by the Pacific Northwest National Laboratory (PNNL). Originally developed for characterizing operational energy performance, researchers have recently explored their utility for expanded analyses beyond this original use case. When defined with more detailed material and system information, beyond strictly energy related systems, prototype buildings can offer a consistent baseline to support a wider range of technical research at component and whole building scales such as cost analyses and lifecycle analyses.

PNNL has developed a detailed Bill of Materials (BOM) for the Medium Office and Midrise Apartment prototypes, with more specifically defined building systems including structural, shell, interiors, mechanical, electrical, and plumbing systems. Our methodology started with an investigation of how the prototype buildings are being further defined for research beyond energy performance. From this investigation, we prioritized characterizing building components which are most often needed for broader building analyses. A structured approach for incorporating this information into the prototype models was developed based on:

1. cataloging materials and systems from existing prototype documentation,
2. cross-referencing with data requirements from previous studies,
3. prioritizing components for additional definition based on project needs, and
4. developing consistent data formats for seamless integration into future datasets and analysis tools.

By applying this approach, the prototypes can serve as an adaptable, higher resolution dataset capable of supporting a broader spectrum of building analyses and modeling needs.

Introduction

PNNL maintains the commercial building prototypes used for national model energy codes analysis (DOE, 2026). Because the commercial building prototype models were developed to provide a robust framework for modeling operational energy use, the representation of building materials and assemblies is limited to those needed for the operational energy use analysis only. Leveraging the commercial building prototype models for expanded whole-building technical analyses, such as early-stage design option comparisons and related first-cost impacts, life cycle cost analysis, and supply chain assessments require additional enhancements such as prototype bills of materials (BOMs).

Building-level analyses which consider a full BOM for a new construction building are gaining importance to clearly understand impacts and interactions of design options on the analyzed metrics. A comprehensive BOM provides a full understanding of all building components, systems, assemblies and materials which can offer clarity in evaluating energy, costs, and material quantities. However, whole building life cycle analyses are less common due to their perceived complexity, as well as lack of consistent methodologies, material units, and consistent baselines.

To support broader analytical applications, it is essential to expand the characterization of the commercial building prototypes. This effort focuses on creating a BOM methodology that provides detailed information on building components, including structural elements, envelope assemblies, interior finishes, and building systems. By systematically documenting these features, the prototypes can serve as baseline models for comprehensive whole-building analyses—such as evaluating total energy and resource use across the building life cycle, common construction practices and related costs, material and related sourcing impacts, and long-term performance trade-offs.

Background

DOE is directed by statute to review the technical and economic basis of model energy codes, participate in the industry process for review and modification of model energy codes, and evaluate technical and economic feasibility of energy efficiency measures.[1] DOE's Building Energy Codes Program (BECP) has developed representative energy models for 16 commercial building prototypes to evaluate the technical and economic impact of proposed updates as well as fully updated model energy codes. Building characteristics for these prototypes are limited to specific details needed for associated energy modeling, such as heat transmittance, or U-factors, for building envelope assemblies, but exclude reference to types of materials used to achieve this performance.

While model energy codes have traditionally focused on energy and energy costs during the operation of a building as primary metrics of performance and impact, individual states and jurisdictions are asking for additional analyses and metrics across the full life cycle of a building that require a more comprehensive understanding of building materials and systems. The current datasets provided for the commercial building prototypes do not address elements needed for technical analysis of whole-building life cycle research. Figure 1 describes the currently defined BOM specific to operational energy analysis in contrast to the missing expanded building BOM needed to fully evaluate whole-building impacts.

These whole-building analyses are dependent on the building materials and system details provided in a BOM and how they are mapped to modeling tools and data resources. Like an energy model, a higher level of detail provided in a BOM will result in a more refined research outcome. Common building systems and components defined for a comprehensive BOM include the structural system, from the sub-structure to the super-structure, the building envelope systems, interior equipment and finishes, and active building systems, including HVAC, service hot water, lighting, elevators, etc. (Charette 1999).

[1] Section 307 of the Energy Conservation and Production Act (ECPA) (Pub. L. No. 94-385), as amended by the Energy Policy Act of 1992 (EPACT 1992) (Pub. L. No. 102-486), the Energy Policy Act of 2005 (EPACT 2005) (Pub. L. No. 109-58) and the Energy Independence and Security Act of 2007 (EISA 2007) (Pub. L. No. 110-140), (42 U.S.C. 6836(b)) https://www.govinfo.gov/content/pkg/USCODE-2011-title42/pdf/USCODE-2011-title42-chap81-subchapII.pdf

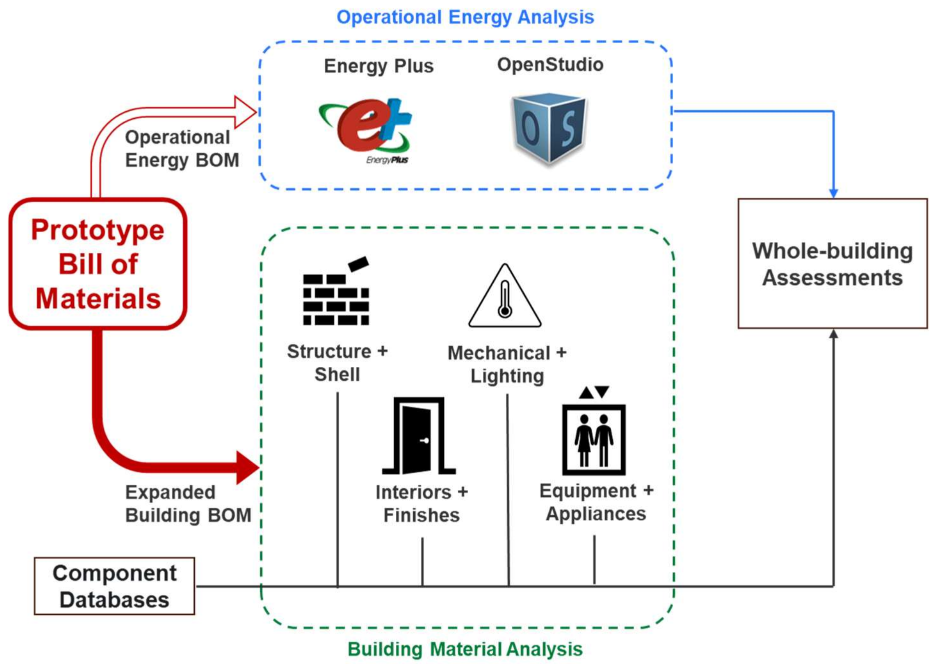

Figure 1: Expanded Prototype BOM Methodology Summary

Through a literature review of existing research, the structural and building envelope systems and components have been shown to hold the highest percentage of cost and resources in the construction of a new building (Hunziker 2021). Within the current prototype building datasets, structural systems are not defined. Details of the building envelope are limited to insulation thermal performance with some inferences of assembly system type. An initial focus in the development of the prototype building BOMs has been to refine the details of the structure and building envelope systems representing typical industry construction practices.

In addition to structural and building envelope system details, other details for building components and systems are missing from the prototype buildings datasets. The extent and quantities for interior walls and finishes, for example, are not defined. Lighting system types are also not defined. In addition, mechanical, electrical, and plumbing systems can have a significant impact on total materials in a building as well as energy use, resource use, and total costs (McCord 2025).

As a starting point, research studies were reviewed which used the commercial building prototypes for whole-building analyses. Each study identified data gaps in the prototypes used. Equally, each study identified different strategies to fill those gaps to successfully complete the intended analysis. Many studies developed an organized and expanded prototype BOM through extraction from a building information model (BIM) or building energy model (BEM) tool. This approach, which is broadly accessible and translatable both for researchers and building industry, is important for the foundation of the prototype expanded BOM framework.

Table 1 highlights the additional BOM detail that was defined in four whole-building analysis research projects using the commercial building prototypes (citations provided in table). Across the four reports, additional detail was defined for the exterior vertical and horizontal enclosures, however, these definitions were not consistent. Further, none of the projects developed a comprehensive BOM. This may impact the overall research goal and limits the ability to compare research outcomes.

Table 1. Prototype Buildings and Additional Defined Systems in Existing Research Studies

Prototype Buildings Researched (citation)	Substructure			Shell			Interiors				Building Systems	
	Foundation	Subgrade Enclosure	Slab-On Grade	Super-structure	Ext. Vert. Encl.	Ext. Horiz. Encl.	Interior Partitions	Wall Finishes	Floor Finishes	Ceiling Finishes	HVAC	Lighting
Medium Office and Highrise Apartment (Srubar III, et al. 2021)	✗	✗	✓	✗	✓	✓	✗	✓	✗	✓	✗	✗
Small Office, Medium Office, Sit-down Restaurant, Stand-alone Retail, and Primary School (Zhang 2022)	✗	✗	✓	✗	✓	✓	✗	✓	✓	✓	✓	✓
Medium Office (Shindo 2023)	✓	✓	✗	✓	✓	✓	✓	✓	✓	✓	✓	✗
Single-family (Jungclaus, et al. 2024)	✓	✓	✓	✓	✓	✓	✓	✗	✗	✗	✗	✗

Methodology

The prototype BOM methodology developed establishes a systematic process to expand prototype building definitions which, when combined with additional cost or material data, can result in expanded whole-building analyses. The process emphasizes consistency, transparency, and adaptability so that the resulting framework can be applied across multiple prototypes and for various analyses. The methodology was developed with the following key steps:

1. Review and define the scope boundaries for the BOM,
2. Establish a structured BOM framework,
3. Determine system and material data gaps,
4. Prioritize building components for further characterization,
5. Identify strategies to fill those gaps in selected prototypes, and
6. Validate data gaps and building data strategies with industry experts.

This methodology was applied to two commercial prototype buildings - the Medium Office and the Midrise Apartment - as case studies to demonstrate the application of this methodology.

Scope Boundaries

Buildings interact with site-related features which could be defined in a BOM, such as parking lots, sidewalks, and other location-specific components. However, these components can vary significantly depending on project context which is beyond the fixed boundary of prototype buildings used for building analysis. While the authors recognize these site features can impact building loads or WBLCAs, they generally do not align with the intent of consistent prototype characterization and have been excluded from the prototype boundary.

The scope of the BOM was therefore limited to components that are consistent across prototype definitions, which is generally at the limit of the exterior envelope. The only exception to this boundary is the exterior lighting system. Exterior lighting is retained as part of the scope because it can both be defined given commercial energy code requirements and is already included in building energy code evaluations as part of whole-building performance. While exterior lighting may be related to parking, sidewalks, or landscaped areas, the materials for these external areas are excluded, and only lighting defined per code maximum allowances. All other site-specific systems were omitted to ensure a clear and consistent boundary across prototypes.

BOM Framework

A framework was then established to translate prototype building definitions into a structured inventory of assemblies and materials. The proposed BOM is organized according to the Uniformat II inventory framework to maintain consistency with industry conventions and to facilitate alignment with existing material databases and whole-building analysis tools (Charette 1999). This framework is commonly used in cost estimation and construction management. The Uniformat structure was integrated into a uniform spreadsheet which organizes assemblies and materials into a consistent set of data fields, including:

- Uniformat Elements: Level 3 category for individual elements
- Element Category: Classification of the element in traditional construction terms.
- Uniformat Building Sub-Element: Level 4 description of the assembly.
- Component / Material(s): Specific materials in the assembly or component.
- Material Units: Defined in accordance with industry references.
- Quantity: Numerical value representing the material or assembly.
- Additional Notes: Further characterization, clarification, or notes related to material or assembly definitions.

The format ensures transparency and comparability across prototypes, while remaining adaptable for future refinement. It can integrate into existing workflows using BIM or BEM and integrates with construction cost estimating tools such as RSMeans.

Gap Analysis Summary

The prototype building models serve as consistent representations of common building types in the U.S. construction market, defined for various ASHRAE 90.1 versions and climate zones. These models, developed by PNNL, consist primarily of geometric, thermal, and operational parameters necessary for energy simulation in EnergyPlus as shown in Figure 2.

Medium Office Prototype Building   Midrise Apartment Prototype Building

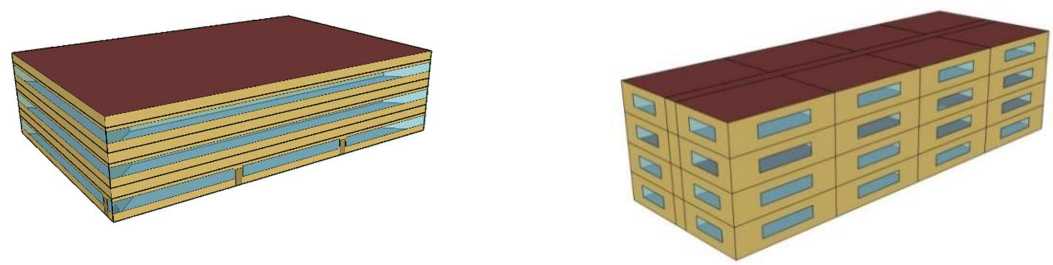

Figure 2. Case Study Prototype Buildings in EnergyPlus

The Medium Office Prototype Building includes the following defined building components with energy modeling related detail available within the prototype models across all climate zones:

- Three-story steel frame structure
- Steel-frame exterior walls
- 33% Window-wall ratio
- Built-up roof
- ASHRAE 90.1 defined minimum insulation performance (by CZ)
- Lighting schedule aligned with ASHRAE 90.1 maximum lighting allowance
- Packaged VAV with central gas heating and electric reheat
- Central electric storage water heater
- Two elevators

The Midrise Apartment Prototype Building includes similar relevant defined building components with energy modeling related detail available within the prototype models across all climate zones:

- Four-story light gauge metal framing
- Steel-frame exterior walls
- 20% Window-wall ratio
- Built-up roof
- ASHRAE 90.1 defined minimum insulation performance (by CZ)
- Lighting schedule aligned with ASHRAE 90.1 maximum lighting allowance
- Packaged Single Zone per dwelling unit, gas furnace with DX-coil
- Individual gas storage water heaters
- One elevator

The initial review of the existing building system and material data provided with the prototype buildings revealed several gaps that limit their applicability beyond energy analysis. While the prototypes provide sufficient detail for energy modeling, such as envelope performance values and HVAC system types, they generally lack the material-level and assembly-level information needed for broader analysis such as supply chain and cost analyses. Table 2 outlines a summary of BOM building system and component data gaps which exist in the current prototype definitions.

Table 2. Building System and Component Data Gaps in Current Prototype Models

Building Component Category	BOM Information Gaps
Substructure and Superstructure	Limited definition of foundations, reinforcement, and structural framing details.
Envelope Assemblies	Exterior wall and roof systems are often described only in terms of thermal performance requirements (e.g., U-factors, R-values), without corresponding material layers.
Interior Systems	Partitions, finishes, and other interior assemblies are either absent or insufficiently characterized.
Building Services and Equipment	Mechanical and electrical systems are included at a high level but lack detail needed for life cycle or material intensity assessments.
Furnishings and Site Elements	Typically excluded from the prototype definitions, even though they can significantly affect whole-building assessments.

Prioritizing Component Definitions

A unified prioritization scheme was developed to identify priority systems and materials to be defined relative to impact on type of analysis and level of detail available for the system type. Each component was assessed and grouped into High, Medium, or Low priority categories within life cycle analysis and energy analysis, taking into consideration details available to provide within a comprehensive BOM. The intention is to ensure that components with the greatest combined impact are addressed first in both whole building analyses and energy modeling efforts.

High priority components have significant impact on expanded analysis such as cost and large material use and/or can have a major influence on energy performance. Example components which were designated as high priority were structural elements whose primary materials are concrete, steel, or wood. This category also includes building envelope materials used in exterior walls, fenestration, and roofing systems. These assemblies dominate material quantities and strongly affect building loads, heating/cooling demand, and energy simulation outcomes.

Medium priority components contribute materially to expanded analyses and are moderately relevant to energy modeling. Expanded descriptions of the HVAC system, for example, include quantification of ductwork and related insulation, as well as zoning and related thermostat and other controls. Similarly, the lighting system is further defined, to include wiring, conduits, and distribution panels, and quantified material information related to fixtures and controls. This category also includes material quantification for interior partitions and interior finishes. These components are particularly important in refining assumptions and additional analyses for the prototypes.

Lower priority systems and components typically have less impact per building area and limited effect on energy use but should be considered for completeness or future expansion of the BOM. This category includes expanded definition of plumbing systems, fire protection system, elevators, and utility hookups. These systems and components may be included where data is available or if specific project goals (e.g., water use or expanded site preparation impacts) require their inclusion.

When evaluating priority, it became clear that priority levels may change depending on the type of analysis. For example, for energy analysis, the structure of a building is less important, but for a whole-building life cycle analysis—which includes construction costs, material quantity, maintenance and replacement considerations—the type of structure can have a significant impact. Table 3 demonstrates the varying priorities depending on the analysis and priority level assigned to each building component category. Components that have a "high" life cycle impact are those which represent a significant percentage of construction costs, a larger percentage of total building material, and have minimum replacement opportunities during the life of a building. Components that have a "medium" life cycle impact are those that may represent a large percentage of construction costs, but a smaller percentage of total building materials, and are likely to be replaced during the life of a building. Lower impact components have lower construction costs, less percentage of total building materials, and are replaced more often during the life of a building. This assessment was applied to the Uniformat Level 3 Building Elements categories to focus work on designated high and medium priority components and systems.

Table 3 Component Category Prioritization Analysis

Component Category	Life Cycle Impact	Energy Analysis Relevance	Final Priority
Structural Frame	High	Medium	High
Exterior Walls	High	High	High
Windows/Glazing	Medium	High	High
HVAC Equipment	Medium	High	Medium
Interior Finishes	Medium	Low	Medium
Plumbing Fixtures	Low	Low	Low

Identifying Expanded BOM Components

Starting with the high priority building systems and components, each building component category was assessed for missing system, component, and material BOM information. For example, structural systems are generally not defined in the existing prototype dataset. Both the foundation system and superstructure system were defined for the case study prototypes as shown in the BOM excerpt in Table 4.

Common industry practices and reference material were reviewed to validate designated systems, materials, and quantities. For example, details about welded wire fabric for concrete reinforcement were validated with reference to material published by the Wire Reinforcement Institute (Wire Reinforcement Institute, 2021) and structural steel column spacing was initially outlined using resources from the American Institute of Steel Construction (Ioannides 2000).

Table 4. Expanded BOM Sample Excerpt

Element Category	Uniformat Level 4 Building Sub-element	Units	Quantity	Component / Material	Notes**
Concrete Slab	A103001 Standard Slab on Grade	Surface Area (ft^2)	17,878	Base Layer - compacted gravel	6 inch depth
				Vapor Barrier	6 mil
				Concrete	6 inch Concrete mix TBD
				Light reinforcement	Steel rebar
				Insulation - perimeter edge*	Per CZ requirements
Interior Concrete Slab	B101003 Floor Decks And Slabs	Surface Area (ft^2)	35,756	100mm Normal weight Concrete	
				Structural deck reinforcement	Steel rebar
	B102001 Structural Frame	Surface Area (ft^2)	35,756	Columns*	Steel with fire retardant
				Beams*	Steel with fire retardant
Built-up Roofing	B102003 Roof Decks and Slabs	Surface Area (ft^2)	17,878	Structure – Steel Beams & Columns	Steel with fire retardant
				Decking - Steel	Steel with fire retardant
				Concrete roof*	4 inches at max depth
				Reinforcement*	Steel rebar
				Insulation*	Polyisocyanurate, average depth by CZ

* Example of a building component with a variety of material or system choices depending on regional preferences and climate zones.

** Additional quantification of materials may be needed depending on level of analysis

Validating Expanded BOM Components with Industry Expertise

The prototype models have been used as a consistent baseline and resource for external stakeholders. Industry experts were identified and interviewed to validate building components for the expanded BOM. During this process, industry experts offered additional insights to inform common construction elements. Industry experts represented a broad cross-section of expertise including leaders of international architecture and engineering firms, regional design firms, engineering experts, and building consultants.

The industry experts also offered additional resources to identify or quantify building systems and components in remaining gaps of the expanded BOMs. In addition, general consensus was achieved in defining building system types and components that were previously not defined for both case study prototypes including structural systems. Industry experts also requested multiple building system options defined within the expanded BOM structure for comparison purposes; discussed examples included different insulation materials or mechanical systems. Overall, industry experts confirmed an expanded BOM for all prototypes would benefit the construction industry to normalize assumptions and be able to compare building system and material options with a consistent reference framework.

Application and Further Development

Applying the above methodology resulted in an initial expanded BOM for each prototype in climate zone 4A. While developing each BOM, it became clear that variations of the BOM would be necessary to capture distinctions of energy code requirements across climate zones so all can be represented. For example, insulation requirements in Florida, or Climate Zone 1, are significantly different than insulation requirements in Minnesota, or Climate Zone 7. These factors will also impact heating and cooling system sizes. Further, different building system choices, whether structural, mechanical, or interior fit out, can greatly impact a whole-building analysis. The utility of the BOMs would be improved with multiple system choices to account for variations in climate zones, as well as regional building practices or specific building needs. Offering alternatives within each building system family can improve analysis and research across multiple technical domains.

Expanding the prototypes to support broader whole-building assessments and analyses requires careful consideration of alternatives. Providing alternatives allows the prototypes to represent a broader range of design practices, construction methods, and material choices, thereby improving their flexibility and relevance for different technical applications. Two complementary approaches to defining alternatives are being considered:

1. Material-Level Alternatives – Providing substitutions at the material layer within a given assembly. Examples include varying insulation type (e.g., mineral wool, fiberglass, or extruded polystyrene), modifying insulation thickness, or adjusting finish layers (e.g., gypsum board types). This approach allows analysts to adjust material properties while retaining the overall assembly structure.
    a. Pros:
        i. Provides flexibility to test incremental changes in performance and costs.
        ii. Allows analysts to isolate impact of individual material substitutions but compare against the whole performance of the building.
        iii. Easier to integrate into existing assemblies without redefining the entire system.
    b. Cons:
        i. May not capture the full range of construction practices, as many real-world decisions occur at the assembly level.
        ii. Can increase complexity if too many individual material variations are introduced.
        iii. Risk of inconsistency if assembly context (e.g., structural support or finish requirements) is not well defined.

2. Assembly-Level Alternatives – Defining entire assemblies with different material breakdowns. For example, offering alternatives to exterior walls such as steel-frame with batt insulation, insulated concrete form walls, or mass timber panels. This approach enables the substitution of whole building systems, allowing for a broader evaluation of construction typologies.
    a. Pros:
        i. Captures realistic construction practices, since many design choices are made at the system or assembly level.
        ii. Allows exploration of fundamentally different building systems (e.g., steel-frame vs. concrete vs. mass timber).
        iii. Reduces the need for users to reconstruct assemblies when testing alternative design options.
    b. Cons:
        i. Less granular—difficult to isolate the impact of a single material within the assembly.
        ii. Requires more effort to define and document full assemblies, especially for multiple climate zones or building types.
        iii. May reduce flexibility if alternatives are too narrowly defined.

Examples of alternatives within building system categories that could be included in the expanded prototypes include:

- Foundation Alternatives – Variations in foundation design are needed to account for differences in soil bearing strength, regional construction practices, and structural requirements.
- Insulation Levels – Insulation requirements vary significantly across climate zones; providing flexible alternatives ensures applicability across regions.
- Structural Systems – Mass timber and other emerging materials are increasingly adopted and should be reflected as alternatives to conventional steel and concrete systems.
- Mechanical Systems – System choice and distribution design can greatly impact long term maintenance, replacement costs, and overall energy use over time.

By incorporating both material- and assembly-level alternatives, the expanded prototype BOMs can better capture the wide-range of real-world construction practices and provide a flexible foundation for whole-building analysis. This enhanced level of detail allows researchers and practitioners to evaluate not only energy and energy-cost impacts, but also a broader set of performance metrics, including economic, material and supply chain, long-term maintenance considerations, and system-level trade-offs. These metrics heavily influence first costs as well as affordability and long-term resilience. By structuring these alternatives within a consistent and transparent BOM framework, the prototypes become adaptable for this wider range of technical applications – from early-state decision-making to comparative scenario analysis- while still supporting the industry's need for reproducible and comparable results. Feedback from industry experts further reinforces the value of providing multiple system pathways, noting that this flexibility enables stakeholders to explore design strategies relevant to their research, align building system selections with regional practices, and better account for uncertainties and emerging technologies. Collectively, these enhancements position the expanded prototype BOMs as a robust resource for informing whole-building evaluations and supporting consistent, rigorous, and relevant future building research.

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