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ERASMUS MUNDUS JOINT MASTER DEGREE

MASTER DEGREE IN SUSTAINABLE DESIGN, CONSTRUCTION AND MANAGEMENT OF THE BUILT ENVIRONMENT

MBUILD

BIM-Based 4D–6D Performance Analysis of Construction Techniques for Single Housing in Thailand: Cost, Time, and Embodied Carbon

PIRAWIT SUKHANESKUL

Supervision: Abduaziz Juraboev, Co-supervision: Kerstin Lenz

Gießen, July 2026

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From 2600 B.C. until the 18th century A.D., there was no distinction between an architect and a civil engineer. There was only the architéktōn, the master builder who simultaneously designed, drafted, and managed construction. As an architect, my focus has always extended beyond function and aesthetics to encompass how a project is actually built. My goal throughout the six months of developing this paper was to analyse every factor contributing to a project's completion: finance, labor, machinery, and environmental trade-offs. This proved highly challenging, as my selected case study is based in Thailand, where data is not always digitalized or readily accessible, highlighting a construction sector that still lags behind the EU in various aspects.

I would like to express my deepest gratitude to Prof. Abduaziz Juraboev and my co-supervisor Kerstin Lenz, whose continuous feedback helped me strengthen my ideas; transitioning from a design background to academic research was a significant challenge, and their guidance was invaluable. Thank you to FEUP, THM, and UC for hosting me and providing a robust logical foundation in construction management, sustainability, and the latest industry trends. I am also immensely grateful to Prof. Jorge Moreira da Costa, Prof. Dr.-Ing. Christian Baier, and Prof. Elena Blanco for pioneering the MBUILD coursework and designing such an innovative combination of construction disciplines.

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ABSTRACT

In Thailand, the decision of how to build a house still comes down to cost and speed. Embodied carbon rarely enters the conversation, even as it becomes a defining measure of construction performance. Prefabrication is sold as the faster and greener alternative to traditional building, yet little local evidence tests that claim by weighing the two on time, cost, and carbon at a comparable scope. To address this gap, we built a model of a single-family home, synthesized by blending architectural planning typology from five existing projects, similarly sized local dwellings, and room layouts. We integrated a BIM to get the precise quantity based on LOIN (Level of Information Need) for analysing 4D scheduling, 5D costing, and 6D life-cycle assessment (EN 15978, modules A1–A5). The work breakdown structure code is directly linked to a single-family type of element by shared parameter in Revit, which is represented in different BIM model cases as 1. traditional cast-in-place (TC), 2. precast frame (PF), 3. precast panel (PP), and 4. a renovation scenario (RS). They run on a single traceable data set in which each work breakdown structure code maps to one family type, so the same model quantities drive the 4D BIM, 5D BIM, and 6D BIM under EN 15978. Cost and emission inputs are calibrated to Thai sources. There is no absolute solution that is the best solution for cost, time, and embodied carbon; every construction typology has a trade-off. Regarding relying on construction logic, PP is the quickest at 94 days, ahead of PF at 125 and TC at 197; RS finishes in 40, though its scope is far narrower. In terms of cost, TC is the cheapest new build at roughly 8,300 THB/m^2, while PP and PF land about 40% higher, at 11,600 THB/m^2. For the embodied carbon from construction activity, TC is the lowest among the new builds at 141,439 kg CO_2e, with PF at 161,436, PP at 163,130, and RS at 50,893 under its partial scope. The result that matters most runs against intuition. Choosing precast does not, on its own, secure a lower carbon footprint for a single house, because the A1 to A5 total depends on several factors working together. The contribution is not a ruling on the best technique. It is a transparent and repeatable way to make the trade-off between time, cost, and carbon visible, just as Thailand prepares to put a price on carbon.

Keywords:

Building Information Modelling (BIM), Life Cycle Assessment (LCA), Construction Cost Estimation, Prefabricated Construction, Traditional In Situ Construction, Construction Scheduling (4D/5D/6D), Sustainable Housing, Thailand

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SYMBOLS, ACRONYMS, AND ABBREVIATIONS

BIM – Building Information Modelling

QTO – Quantity Take Off

CAD – Computer Aided Design

CI – Construction Industry

AEC – Architecture, Engineering, and Construction

PC – Prefabricated Construction

TC – Traditional (In Situ) Construction

PF – Precast Structural Frame Construction

PP – Precast Structural Panel Construction

RS – Renovation Scenario

RC – Reinforced Concrete

LCA – Life Cycle Assessment

UC – Use Case (UC1–UC4)

WBS – Work Breakdown Structure

LOD – Level of Development

LOIN – Level of Information Need

IFC – Industry Foundation Classes

MEP – Mechanical, Electrical, and Plumbing

EPD – Environmental Product Declaration

CFP – Carbon Footprint for Products

GHG – Greenhouse Gas

NDC – Nationally Determined Contribution

EIA – Environmental Impact Assessment

TREES – Thai's Rating of Energy and Environmental Sustainability

TREES-H – TREES for Homes

TGBI – Thai Green Building Institute

LEED – Leadership in Energy and Environmental Design

BREEAM – Building Research Establishment Environmental Assessment Method

USGBC – U.S. Green Building Council

FSC – Forest Stewardship Council

TGO – Thailand Greenhouse Gas Management Organization

REIC – Real Estate Information Center

BMR – Bangkok Metropolitan Region

AAC – Autoclaved Aerated Concrete

THB – Thai Baht

VAT – Value Added Tax

KPI – Key Performance Indicator

SPT – Sustainability Performance Target

SCB – Siam Commercial Bank

1

INTRODUCTION

1.1 SCOPE OF STUDY

Due to climate change and the global economic crisis, the construction industry has been significantly affected worldwide[1], [2]. Housing, as the smallest unit of construction, continues to be developed in response to market demand and supply[3]. However, increasing environmental regulations, rising labour costs, and higher construction material prices place additional pressure on designers and contractors, who require reliable guidelines and information to support effective decision-making[4], [5].

At the master's dissertation level, this study focuses on a comparison of different construction scenarios applied to the same building model, based on a single residential housing project. The comparison emphasizes construction productivity, cost performance, and environmental impact through BIM-based analysis.

The case study is selected from an existing housing project in Bangkok, Thailand, developed by a private real estate company. Thailand, as a developing country, has many ongoing housing projects across urban areas to support increasing capital demand[6]. In response, designers and contractors have begun to explore alternative construction techniques, such as precast panel systems and structural precast construction[7]. Within the Thai context, these alternatives must be carefully evaluated in terms of construction duration, cost, and environmental performance.

The scope of analysis is based on information obtained from market data and government sources. BIM is used to combine construction sequencing, quantity take off, cost estimation, and life cycle assessment. The study aims to provide reference data through comparative analysis, pinpoint critical factors shaping productivity, cost, and embodied carbon, and support practical decision-making under project budget and time constraints.

1.2 RESEARCH QUESTIONS

This research is guided by one overarching question, divided into four sub-questions that follow the structure of the use cases.

Global research question

For a two-storey single-family house in Thailand, how do traditional cast-in-place (TC), precast frame (PF), precast panel (PP), and renovation (RS) compare in construction time, direct cost, and embodied carbon (A1 to A5), and how far can a BIM-based 4D to 6D framework help in choosing between them on the evidence available?

Sub-questions

- SQ1 (UC1, 4D): How long does each technique take to build, by total and by phase, and what drives the differences in time?
- SQ2 (UC2, 5D): What does each technique cost in direct terms, overall, and per m2, and which components are most sensitive?
- SQ3 (UC3, 6D): What is the embodied carbon of each technique across A1 to A5, and where are the hotspots?
- SQ4 (UC4): Once time, cost, and carbon are placed on a common scale, which technique suits which decision priority?

1.3 RESEARCH METHODOLOGY

This study employs a BIM-integrated, multidimensional framework to evaluate four construction techniques for single-family housing in Thailand. A 150m^2 case study house in Bangkok is modelled using Revit 2025 as the baseline for comparison. The analysis is structured across four use cases (UC1–UC4): 4D scheduling (UC1), 5D cost estimation (UC2), 6D carbon assessment (UC3), and a comparative synthesis (UC4). AI-assisted tools support data extraction and analysis throughout the process. Detailed methodology for each use case is presented in **Chapter 3.**

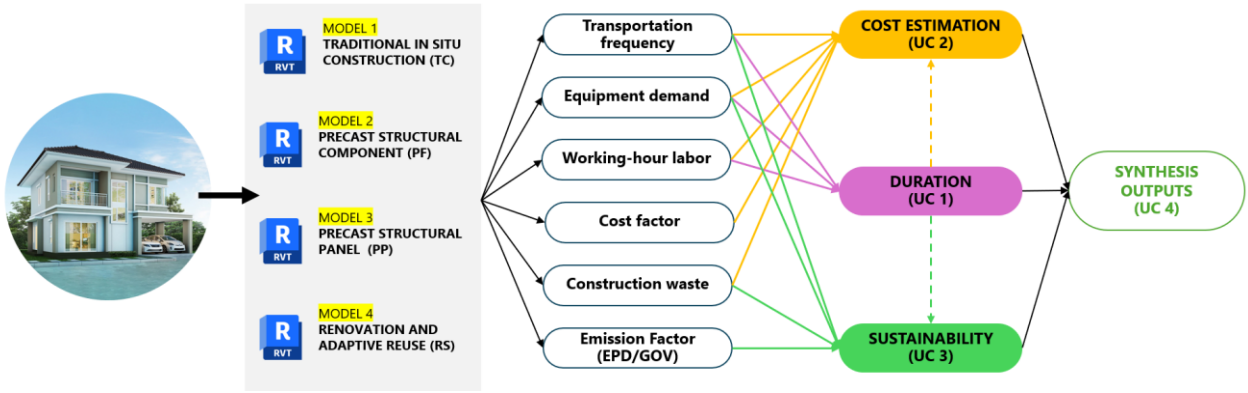


Figure 1.1 - Research methodology diagram

Source: Thesis author

1.4 EXPECTED RESULTS

This research is expected to contribute to sustainable construction decision-making by producing a comparable performance dataset for four construction techniques in the Thai single-family housing context.

1.4.1 BIM PRODUCTIVITY AND TIME OUTPUTS (UC1)

- A 4D schedule for TC, PF, PP, and RS, including total duration in working days and phase-based distribution.
- Identification of critical activities and key drivers of time differences between scenarios.

1.4.2 BIM COST OUTPUTS (UC2)

- A direct cost breakdown per scenario (THB) structured by material, labour, equipment, and transportation, where applicable.
- Identification of cost-sensitive components and the main factors that increase or reduce cost relative to the baseline.

1.4.3 BIM AND LCA OUTPUTS (UC3)

- Embodied carbon results (kgCO2e) across A1–A5 per scenario with module-based distribution.
- Hotspot identification flagging elements and materials that contribute most to total emissions.

1.4.4 INTEGRATED SYNTHESIS OUTPUTS AND DECISION SUPPORT (UC4)

- A normalised performance matrix (indexed to TC = 100) comparing time, cost, and carbon across scenarios, reported with both absolute values and percentage differences.
- A multi-axis visual comparison (radar chart) combining quantitative dimensions with defined qualitative indicators (waste intensity, on-site labour dependency, implementation risk).
- A trade-off summary and recommendation framework showing which technique is preferable under time-critical, budget-constrained, or low-carbon decision priorities.

1.5 ORGANISATION OF DISSERTATION

This dissertation is divided into six chapters as follows;

Chapter 1: Introduction

Chapter 1 introduces the context of the Thai construction industry and outlines the background and motivation of the study. It defines the scope of the research and presents the objectives to be achieved.

Chapter 2: Background and literature review

Chapter 2 reviews relevant literature and supporting documents related to the research topic. It covers sustainable construction in the Thai context, construction materials in residential buildings, construction techniques and system typologies, and the challenges associated with different construction approaches.

Chapter 3: Methodology

Chapter 3 presents the research methodology and analytical framework adopted in the study. It defines the use cases, key input parameters, and assumptions, and explains the selection of tools and data sources. The chapter also describes the role of the BIM model as a central data platform and outlines the methodological approach for construction scheduling (4D), cost estimation (5D), and embodied carbon assessment (6D).

Chapter 4: Case study and application

Chapter 4 presents the selected case study and its application of the methodology defined in Chapter 3. It describes the project characteristics and BIM model development, followed by the implementation of the defined use cases, including scheduling analysis, cost estimation, embodied carbon assessment, and a comparative evaluation between renovation and new construction scenarios.

Chapter 5: Results and Discussion

Chapter 5 presents the results of the analysis and discusses the numerical outcomes to identify the critical factors influencing the results. It compares construction techniques in terms of time, cost, and environmental performance and interprets the findings in relation to the research objectives.

Chapter 6: Conclusion and Future Development

Chapter 6 summarises the key findings of the study and evaluates the extent to which the research objectives have been achieved. It also discusses the limitations of the research and provides recommendations for future development and further research.

Appendices

The appendices include supplementary information that supports the dissertation, including:

1. Construction material, machinery, and labour cost data
2. Labour productivity data
3. Carbon emission factors relevant to the study context

2

BACKGROUND AND LITERATURE REVIEW

2.1 SUSTAINABLE CONSTRUCTION

2.1.1 OVERVIEW OF SUSTAINABILITY IN THE CONSTRUCTION SECTOR

Although sustainability is often treated as a modern idea, its roots reach back several centuries. The German forester Hans Carl von Carlowitz coined the term Nachhaltigkeit in the 18th century to describe a simple principle: natural resources should only be used at a rate their natural regeneration can sustain [8]. The issue gained urgency much later, during the 1973 oil crisis, which exposed how dependent economies had become on energy and singled out buildings as one of the heaviest consumers. In response, the construction industry turned its attention to cutting operational energy through improved insulation, passive solar design, and more efficient building envelopes [9]. Sustainability at this stage meant the operational phase almost exclusively; material life cycle impacts and embodied energy went largely unexamined.

As buildings were increasingly recognized as major contributors to environmental impacts and empirical measurement methods were largely absent at the time, the United Kingdom developed systematic approaches to assess and improve building performance, particularly in response to its extensive stock of aging buildings[10], [11]. Consequently, the first green building rating system, BREEAM, was established in 1990, evaluating building performance based on national regulations and third-party assessment. In 1998, LEED was introduced in the United States to provide a more internationally applicable assessment framework[12]. Influenced by the energy crises of the 1970s and 1980s, both systems initially emphasized energy efficiency and operational carbon, focusing primarily on the operational phase of buildings, particularly energy consumption during occupancy (B6), while giving limited consideration to construction materials and upstream life cycle processes[13].

Life cycle assessment (LCA), the preferred technique for assessing environmental impacts over a building's entire life span, became more and more integrated into the building industry after 2000. While building-specific standards like EN 15978 offered a structured framework to apply LCA within the construction context, quantifying both embodied and operational impacts across the entire life cycle of buildings, international standards like ISO 14040 and ISO 14044 established the fundamental methodology for conducting LCA [14], [15]. With this shift, assessment finally extended beyond operational energy to the embodied carbon locked into building materials and processes.

Table 2.1 - Key sustainability focuses in construction from the 1970s to the 2000s

Period	Sustainability focuses on construction
1970s	Operational energy efficiency (building envelope focus)
1990s	Green building rating systems (operation-focused)
2000s	Life cycle assessment (embodied and operational carbon)

Source: Compiled by the author based on Finkbeiner et al. 2006

[16] From figure 2.2, In the 2019 IPCC report, GHG emissions from the building sector are 12 $GtCO_2$-eq, which equal to roughly 21% of global emissions. Most of these emissions did not come directly from buildings themselves, but from the electricity and heat they used. About 57% came from off-site electricity and heat generation, 24% came from direct on-site fuel use, and 18% came from producing construction materials such as cement and steel.

When focusing only on CO_2 emissions, the building sector's share is even higher, at around 31% of global CO_2 emissions. Of this, residential buildings accounted for 50% of energy-related emissions, non-residential buildings for 32%, and the remaining 18% came from embodied emissions associated with materials and construction.

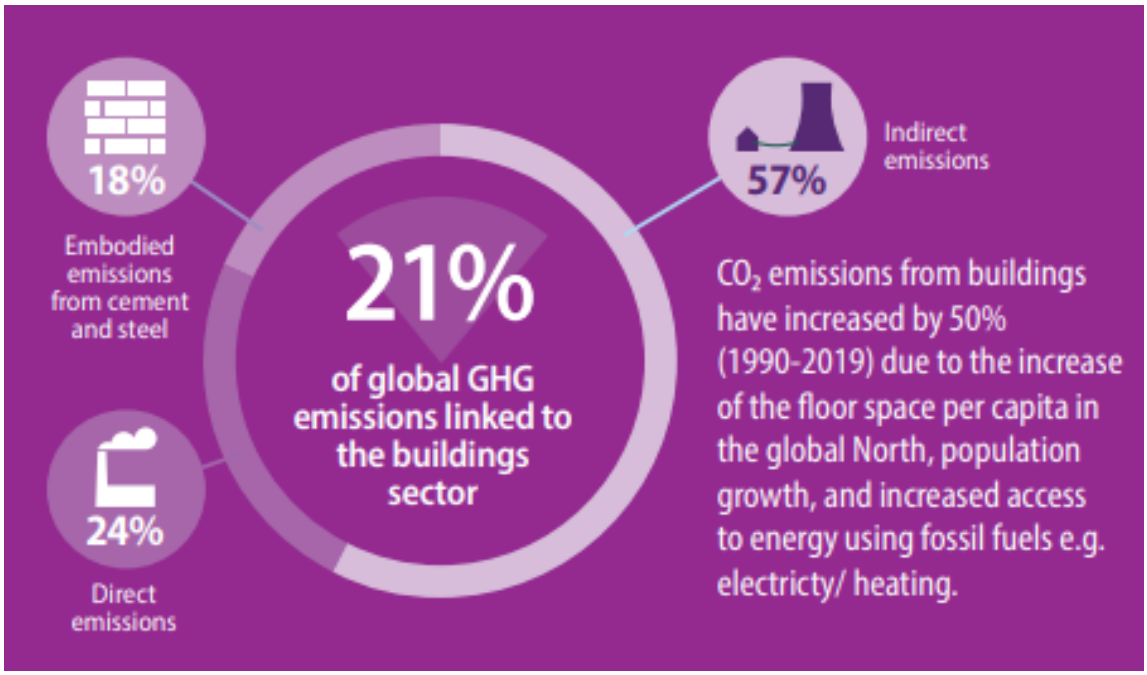


Figure 2.2 - Contribution of the building sector to global GHG emissions
Source: Adapted from Intergovernmental Panel on Climate Change (IPCC, 2022)

2.1.2 CLIMATE ACTION AND CONSTRUCTION IN THAILAND

In Thailand, building policy and research have predominantly focused on reducing operational energy consumption, particularly cooling loads driven by the country's tropical climate averaging 35–40°C[17], [18]. Design strategies such as improved thermal insulation and solar shading have received significant attention, while embodied carbon from structural material production, factory manufacturing, and transportation remains comparatively understudied in the Thai context [19], [20], [21].

However, embodied carbon emissions from the production of prefabricated construction materials and energy used in material transportation are not widely discussed in the Thai context[22]. Simultaneously, both large and small-scale construction companies are shifting towards off-site construction to reduce construction time, minimize on-site errors, and increase profitability, despite declining housing demand and increased competition[23], [24].

As the industry continues to shift from in-situ to off-site construction to improve productivity and reduce on-site waste, the environmental trade-offs of this transition warrant closer examination[25], [26]. Although prefabrication reduces construction waste and improves quality control, it may increase energy consumption during manufacturing and transportation, contributing to the overall embodied carbon of the building[27]. This gap directly motivates the comparative embodied carbon assessment conducted in this research.

2.1.3 THAILAND REAL ESTATE AND HOUSING MARKET

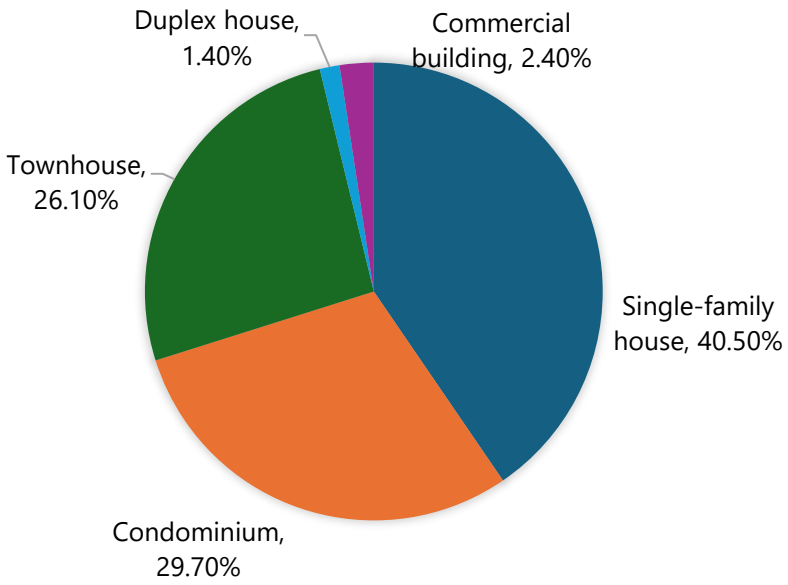


Figure 2.3 - Housing Demand Proportion by Type (Q3 2025)
Source: Real Estate Information Center (REIC), 2025, "Housing Market Situation, Q3 2025 and Outlook", adapted by the thesis author.

[3]Single-family housing represents the largest segment of the Bangkok Metropolitan Region (BMR) residential market, accounting for 40.5% of housing demand in Q3 2025 as you can see on Figure 2.3. However, as shown in Table2.2, new housing permits fell by over 51% year-on-year, reflecting weakening affordability driven by stagnant income growth, post-COVID economic slowdown averaging 2–3% GDP growth annually, and persistent construction cost escalation[28], [29] Labour costs have risen further following the government's minimum wage increase to 400 THB per day in mid-2025, compounding pressure on the highly labour-intensive low-rise residential sector *[30]*.

Table 2.2 - Change in Housing Development Permits in Bangkok Metropolitan Region

Housing Type	Q3 2024 (Units)	Q3 2025 (Units)	YoY Change (%)
Townhouse	5,105	2,404	−52.9%
Single-family house	4,503	2,196	−51.2%
Duplex house	1,842	808	−56.1%
Commercial building	58	134	131.00%
Land subdivision	113	18	−84.1%
Total	**11,621**	**5,560**	**−52.2%**

Source: Real Estate Information Center (REIC), 2025, adapted by the thesis author.

Table 2.3 - Units Transferred in the Bangkok Metropolitan Region by Price Range, 9M 2025

Price Range (Million THB)	Price Range (EUR, approx.)	Low-rise Units	Share (%)
≤ 1.00	≤ 27,000	6,932	12.6
1.01 – 1.50	27,000 – 40,500	6,499	11.9
1.51 – 2.00	40,500 – 54,000	7,203	13.1
2.01 – 3.00	54,000 – 81,000	**11,610**	**21.2**
3.01 – 5.00	81,000 – 135,000	**11,273**	**20.6**
5.01 – 7.50	135,000 – 203,000	5,581	10.2
7.51 – 10.00	203,000 – 270,000	2,086	3.8
> 10.00	> 270,000	3,611	6.6
Total		54,795	100

Source: Real Estate Information Center (REIC), 2025, adapted by the thesis author.

Table 2.3 illustrates the most active price segment is 2–5 million THB (around 54,000–135,000 EUR), which corresponds to house of 150-200 m^2[31]. This forms the basis for the case study selected in this research. Within this segment, developers such as Pruksa from the Table 2.4 have already adopted prefabricated wall systems, reflecting industry-level recognition that construction efficiency is becoming a competitive necessity.[32]

Table 2.4 - Examples of Single-Family Housing Projects in the 2–5 Million THB Price Range

		
Developer: Pruksa **Floor area:** 160 sq.m. **Location:** Bangkok **Price:** 3.00 million THB **Source:** https://www.pruksa.com/the-plant/kanchana-bangyai	**Developer:** Sansiri **Floor area:** 153 sq.m. **Location:** Nonthaburi **Price:** 4.29 million THB **Source:** https://www.sansiri.com/single-house/anasiri-chaiyapruek-wongwaen2/th/#home	**Developer:** Sena **Floor area:** 201 sq.m. **Location:** Nonthaburi **Price:** 4.99 million THB **Source:** https://www.sena.co.th/en/project/sena-ville-wongwaen-bangbuatong

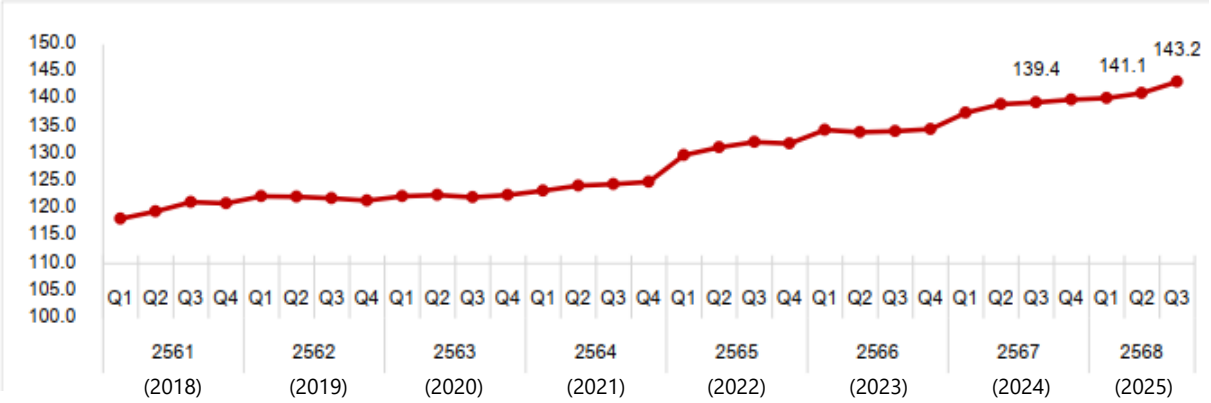


Figure 2.4 - Housing Construction Cost Index in Bangkok (Base Year 2010 = 100)
Source: Real Estate Information Center (REIC), Government Housing Bank of Thailand.

As shown in Table 2.5, the BMR recorded an overall vacancy rate of 13.3% across all housing types in 2020, with condominiums reaching 24.8% [33]. This oversupply, combined with continued escalation in housing construction costs from Figure 2.4 (driven by rising material prices across concrete, tiles, and building systems) creates a growing tension between new development and existing stock utilisation[34]Together, these conditions suggest that renovation and adaptive reuse may offer a more resource-efficient and cost-competitive alternative to new construction, a consideration that directly motivates the inclusion of the Renovation Scenario (RS) as one of the four construction systems compared in this study [35].

Table 2.5 - Summary of Total Unoccupied Units in the Bangkok Metropolitan Region (2020)

Housing Type	Total Housing Units	Unoccupied Units	Vacancy Rate (%)
Single-family house	858,483	69,149	**8.10%**
Duplex house	259,079	20,961	**8.10%**
Townhouse	1,817,562	147,235	**8.10%**
Shophouse	277,133	23,225	**8.40%**
Condominium	1,442,113	357,353	**24.80%**
Total	4,654,370	617,923	**13.30%**

Source: Thai Real Estate Information and Valuation Center, and Metropolitan Electricity Authority (2020).
Note: Unoccupied housing units use no more than 15 kWh per month.

2.1.4 REGULATORY AND GREEN BUILDING FRAMEWORK

New construction projects in Thailand are normally obliged to complete an Environmental Impact Assessment (EIA) to examine potential negative consequences from their development activities and during building operations[36]. The EIA requirement is legally controlled by the Enhancement and Conservation of National Environmental Quality Act B.E. 2535 (A.D. 1992), which comprises (1) physical resources, (2) biological resources, (3) waste generation and pollution, and (4) community and quality-of-life impacts. These categories collectively address land use, site conditions, ecosystem integrity, and human well-being. [37]This rule precisely describes the types and sizes of projects that would damage the environment on a wide scale, such as condos or commercial buildings. Therefore, single-family houses are generally exempt from EIA requirements under the Thai environmental law.

However, driven by increasing demand for green marketing, many projects voluntarily adopt green construction practices even though EIA is not mandatory[38]. Integrating sustainable practice into a project often receives greater market attention and indirect benefits[39]. For example, some financial institutions in Thailand may offer reduced loan interest rates or special incentives to developers or homeowners who can demonstrate the use of green construction practices with lower carbon emissions than conventional methods [40]. [41]For instance, SCB offers sustainability-linked loans with preferential interest rates tied to sustainability performance targets (SPTs), which are defined through client-specific key performance indicators (KPIs). These KPIs may include external sustainability ratings, improvements in energy efficiency, reductions in greenhouse gas emissions, and water conservation measures.

Thai's Rating of Energy and Environmental Sustainability (TREES)

From Figure 2.5, TREE was developed by the Thai Green Building Institute (TGBI) to promote sustainable construction practices in the Thai context, which is influenced by international standards such as LEED, as some criteria do not align with the country's market or supply chain[42]. TREES for Homes (TREES-H) is a subcategory that is specifically designed for residential buildings, including single-family houses. It simplifies criteria and assessment procedures, making it more accessible for small-scale residential projects, for example, by adapting prefabricated construction for disassembly. The system evaluates building performance across multiple categories[43].

- Urban and landscape (SL)
- energy efficiency (EA)
- water efficiency (WW)
- material selection and construction management (MR)
- indoor environmental quality (IE)

TREES HOME Energy-Efficient and Environmentally Friendly Home Certification Criteria

โครงการ ประเภทอาคาร ☐ C ME FAMILY ☐ ITE

Y	?	N	Code	Criteria	Max
0	0	0	SL	**Sustainable Location and Site**	12
Y			SL P1	Appropriate site selection and avoidance of unsuitable construction areas	Required
			SL 1	Development on previously developed land	5
			SL 2	Development within serviced urban areas	2
			SL 3	Residential density: minimum 1 unit per 50 sq.m. of open space (excluding setbacks)	1–2
			SL 4	Use of appropriate building orientation	2
			SL 5	Access to public transportation	1–2
0	0	0	WW	**Water, Waste, and Pollution**	16
Y			WW	Use of water-efficient fixtures for faucets, showers, and sanitary fittings, certified by Thai	Required
Y			WW	Installation of grease traps for kitchen wastewater	Required
Y			WW	Provision of designated areas for waste separation, including wet and dry waste	Required
			WW 1	Waste separation and construction waste management	6
			WW 2	Provision of waste separation areas at the project level	2
			WW 3	Use of water-saving devices such as sensor taps, automatic shut-off faucets, low-flow showerheads, dual-flush toilets, and irrigation systems, achieving at least a 10%	3
			WW 4	Household waste separation with designated areas for at least two categories or up to	3
			WW 5	Design and construction practices that reduce waste generation, including construction	2
0	0	0	MR	**Materials and Resources**	16
Y			MR P1	Use of environmentally friendly construction materials	Required
			MR 1	Use of local or low-impact materials	16
0	0	0	EA	**Energy Efficiency (30 points)**	30
Y			EA P1	Basic building energy performance assessment	Required
Y			EA P2	Use of energy-efficient building envelope	Required
Y			EA P3	Energy-efficient electrical systems	Required
Y			EA P4	Use of energy-efficient appliances	Required
			EA 1	Renewable energy systems	3
			EA 2	Overall thermal transfer value (OTTV)	8
			EA 3	Roof thermal transfer value (RTTV)	4

Y	?	N	Code	Criteria	Max
Y			P5	Use of natural daylight in living rooms, working areas, bedrooms, and window areas in accordance with requirements, with an average **Daylight Factor (DF) ≥ 1.5%**	Required
Y			EA P6	Maximum lighting power density (LPD) not exceeding **8 W/sq.m.**	Required
Y			EA P7	Use of energy-efficient lighting with lamps certified at **Energy Label No. 5**	Required
			EA 4	Use of environmentally friendly lighting systems, including appropriate lighting control	2
			EA 5	Maximum lighting power density (LPD) not exceeding **6.5 W/sq.m.**	5
			EA 6	Use of lighting control systems (lighting sensors) achieving at least **30% reduction in**	3–1
Y			EA P8	Reduction of energy consumption for water pumping, including provision of gravity-fed	Required
			EA 7	Use of renewable energy systems with hot water production from solar energy, including	3
			EA 8	Use of renewable energy, with preparation for installation of renewable electricity	2
			EA 9	Provision of parking spaces for electric vehicles and apartments, with at least **80% of units**	2
0	0	0	IE	**Indoor Environmental Quality**	Max Points
Y			IE P1	Ventilation rate compliance	Required
Y			IE P2	Indoor air quality management	Required
			IE 1	Daylighting and visual comfort	5–4
			IE 2	Use of low-emission materials	4
			IE 3	Acoustic performance and noise control	5–4
			IE 4	Thermal comfort performance	2–4
0	0	0	IN	**Innovation in Design**	6
0	0	0	IN	**Innovation in Construction**	4

Y	?	N	
0	0	0	Accumulate

Figure 2.5 - Assessment Framework and Criteria of TREES for Homes (TREES-H)
Source: Thai Green Building Institute (TGBI), TREES for Homes (TREES-H) Version 1.0

[44]GUTÉ Sukhumvit 76, created by Frasers Property Thailand, is an excellent representation of a sustainable housing project. It reaches the gold level of TREE-H and is the first LEED HOMES in Southeast Asia to incorporate energy-efficient design solutions, greater natural ventilation, and ecologically responsible material selection in compliance with TREE-H requirements. This case highlights how green construction concepts may be realistically implemented in low-rise residential buildings without the requirement for large-scale or complex certification processes.

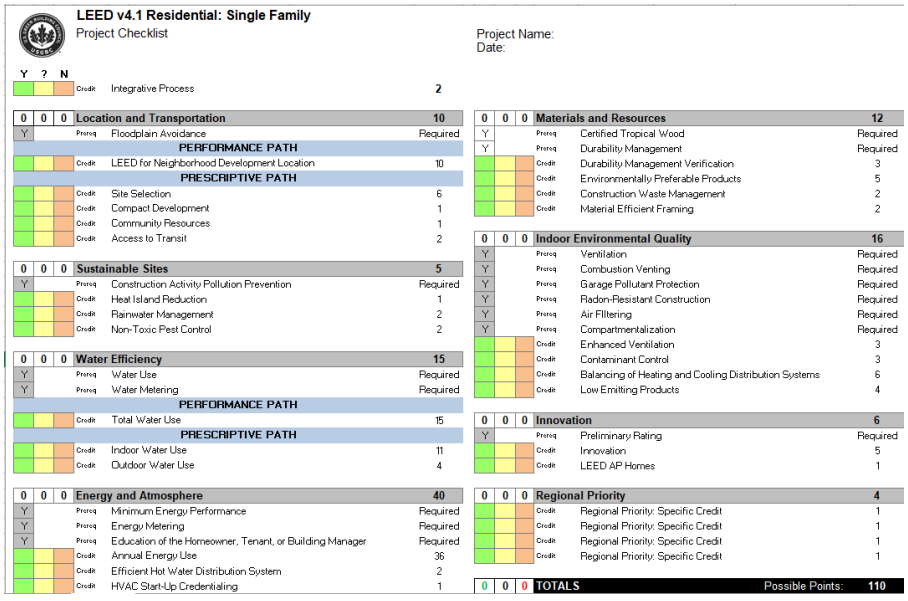


Figure 2.6 - GUTÉ Sukhumvit 76: TREES for Homes Certified Residential Project
Source: Frasers Property (Thailand) Public Company Limited (2026)

Leadership in Energy and Environmental Design (LEED)

As shown in Figure 2.7 (LEED) is one of the first green building certification systems, developed to apply environmental practices from the design process to the operation of buildings[45]. LEED intends to enhance resource efficiency, occupant health, and long-term operational performance[46]. With the scoring system, different criteria have different weight points based on their essential hierarchy. The more project achievements meet the criteria, the more they will be sustainable, which means the certificate can be used for marketing based on the level they achieve[47], [48]. The scoring stat from bronze, silver, gold, and platinum LEED evaluates building performance across a wide range of sustainability criteria, including:

- Location and Transportation (LT)
- Energy efficiency (EA)
- Water efficiency (WE)
- Sustainable site planning (SS)
- Material selection (MR)
- Indoor environmental quality (IEQ)



LEED v4.1 Residential: Single Family
Project Checklist

Project Name:
Date:

Y	?	N			
			Credit	Integrative Process	2

0	0	0	**Location and Transportation**		10
Y			Prereq	Floodplain Avoidance	Required
			PERFORMANCE PATH		
			Credit	LEED for Neighborhood Development Location	10
			PRESCRIPTIVE PATH		
			Credit	Site Selection	6
			Credit	Compact Development	1
			Credit	Community Resources	1
			Credit	Access to Transit	2
0	0	0	**Sustainable Sites**		5
Y			Prereq	Construction Activity Pollution Prevention	Required
			Credit	Heat Island Reduction	1
			Credit	Rainwater Management	2
			Credit	Non-Toxic Pest Control	2
0	0	0	**Water Efficiency**		15
Y			Prereq	Water Use	Required
Y			Prereq	Water Metering	Required
			PERFORMANCE PATH		
			Credit	Total Water Use	15
			PRESCRIPTIVE PATH		
			Credit	Indoor Water Use	11
			Credit	Outdoor Water Use	4
0	0	0	**Energy and Atmosphere**		40
Y			Prereq	Minimum Energy Performance	Required
Y			Prereq	Energy Metering	Required
Y			Prereq	Education of the Homeowner, Tenant, or Building Manager	Required
			Credit	Annual Energy Use	36
			Credit	Efficient Hot Water Distribution System	2
			Credit	HVAC Start-Up Credentialing	1

0	0	0	**Materials and Resources**		12
Y			Prereq	Certified Tropical Wood	Required
Y			Prereq	Durability Management	Required
			Credit	Durability Management Verification	3
			Credit	Environmentally Preferable Products	5
			Credit	Construction Waste Management	2
			Credit	Material Efficient Framing	2
0	0	0	**Indoor Environmental Quality**		16
Y			Prereq	Ventilation	Required
Y			Prereq	Combustion Venting	Required
Y			Prereq	Garage Pollutant Protection	Required
Y			Prereq	Radon-Resistant Construction	Required
Y			Prereq	Air Filtering	Required
Y			Prereq	Compartmentalization	Required
			Credit	Enhanced Ventilation	3
			Credit	Contaminant Control	3
			Credit	Balancing of Heating and Cooling Distribution Systems	6
			Credit	Low Emitting Products	4
0	0	0	**Innovation**		6
Y			Prereq	Preliminary Rating	Required
			Credit	Innovation	5
			Credit	LEED AP Homes	1
0	0	0	**Regional Priority**		4
			Credit	Regional Priority: Specific Credit	1
			Credit	Regional Priority: Specific Credit	1
			Credit	Regional Priority: Specific Credit	1
			Credit	Regional Priority: Specific Credit	1
0	0	0	**TOTALS**	Possible Points:	110

Figure 2.7 - LEED v4.1 Residential: Single-Family Scorecard and Reference Guide
Source: USGBC

2.2 GREEN BUILDING CRITERIA TO RESIDENTIAL CONSTRUCTION

This section examines the relevance of selected green building criteria to residential construction systems, with a specific focus on construction-related aspects. The analysis is based on building-type-specific assessment schemes rather than the overall green building rating frameworks. In particular, the study refers to LEED v4.1 Residential Design and Construction: Single Family Homes (LEED Home) and TREES Home, which function as sub-categories within their respective rating systems

A comparative review in Table 2.6 shows the different evaluation logics in addressing construction-stage sustainability. LEED Home focused on performance-based and quantitative standards, using measurable thresholds, baseline references, and material efficiency indicators[49]. In contrast, TREES Home puts more weight on design intent and building methods like modular construction, prefabrication, and construction procedures that cut down on waste[50]. These methods are based on how things are built and the legal framework in Thailand. Based on this distinction, five main construction themes were identified to structure the comparison, as summarized in Table 2.8.

Table 2.6 - Comparison of Construction-Related Criteria between LEED and TREES for Single-Family Resident

Main construction theme	LEED	TREES
Environmentally friendly / low-impact materials	Y	Y
Local material sourcing	Y	Y
Construction waste management	Y	Y
Design and construction approaches that reduce waste generation	N	Y
BIM application as innovation	N	Y

Source: Adapted from Leadership in Energy and Environmental Design (LEED) v4.1 Residential Design and Construction: Single Family Homes, U.S. Green Building Council (2018), and Thai's Rating of Energy and Environmental Sustainability (TREES) Home, Thai Green Building Institute (2022).

2.2.1 ENVIRONMENTALLY FRIENDLY CONSTRUCTION MATERIALS

To reduce environmental impacts associated with construction materials by **encouraging the use of products with lower life-cycle impacts**, such as recycled, reclaimed, or environmentally certified materials. This credit aims to shift material selection toward options that reduce embodied emissions and resource depletion during construction[49], [50]. TREES Home places greater emphasis on climate-responsive material performance and nationally certified environmental labeling systems, reflecting local construction practices and regulatory context[50].

How to get points

LEED

- Use environmental product (recycled, FSC wood, low-impact concrete, etc.)
- Up to 5 points under MR: Environmentally Preferable Products

TREES

- Up to 4 points are awarded for the use of high-performance thermal envelope materials, such as insulated walls, roofs, and floors (e.g., fiberglass, rock wool, cellulose fiber), with insulation usually thicker than 1 inch, which then helps lower heat transfer.
- Up to 3 points are granted for advanced material performance and systems, including materials with thermal insulation properties, lightweight concrete, rammed earth, precast concrete systems, hempcrete, and composite material applications.
- Up to 1 point is awarded for the use of construction materials or components certified with Thai environmental labeling schemes, such as the Thailand Environmental Label or product carbon footprint certification.
- Additional points (up to the category maximum of 16 points) may be accumulated through the combined application of multiple strategies, emphasizing both material environmental impact reduction and thermal

Figure 2.8 - Examples of FSC Certification and Thai Environmental Label Schemes



Source: Forest Stewardship Council (FSC); Thailand Environment Institute (TEI).

2.2.2 LOCAL MATERIAL SOURCING

To reduce environmental impacts from material transportation and support local supply chains by promoting the use of materials extracted, processed, and manufactured near the project site[49]. TREES Home places strategic emphasis on the use of nationally certified sustainable materials in Thailand to support regional production over imported products. This approach recognizes that imported materials, even when certified as environmentally friendly, may still generate significant transportation-related carbon emissions, thereby offsetting part of their environmental benefits[50].

How to get points

LEED

- Use locally produced materials within the specified distance and minimum percentage
- Up to 3 points (part of MR: Environmentally Preferable Products)

TREES

- Use Thai low-impact materials listed in the TREES material categories for at least 5 products
- Included in MR P1 (prerequisite)



Figure 2.9 - Illustration of Local Material Sourcing within a Defined Radius from the Project Site

Source: Adapted from Leadership in Energy and Environmental Design (LEED) Building Design and Construction Guidelines, U.S. Green Building Council, available at https://www.usgbc.org/guide/bdc.

2.2.3 CONSTRUCTION WASTE MANAGEMENT

[49], [50], [51]. Both certification systems adopt similar strategies for reducing on-site construction waste. However, implementation of TREES Home requires a minimum waste diversion start from 30%, which convince contractor in waste segregation, and the identification of feasible reuse or recycling pathways. Typical measures include separating recyclable materials and directing waste streams, such as steel scrap, to authorized recycling facilities[50]

How to get points

LEED

- Divert construction waste from landfill by meeting percentage thresholds
- Up to 2 points (50–75% diversion depending on option)

TREES

- Divert construction waste based on the percentage reused or recycled
- Up to 5 points (30–70% diversion thresholds)

Calculator

Material Description	Material Type	Material Stream	Total Waste (cubic yards)	Commingled Waste: Average Percentage of ADC Produced by the Sorting Facility (%)	Diverted Waste (cubic yards)	Percent Diverted (%)	Waste to Landfill (cubic yards)
	Wood	Donated				0.00%	0.00
	Carpet and pad	Reused				0.00%	0.00
	Gypsum board	Recycled - source separated				0.00%	0.00
						0.00%	0.00
						0.00%	0.00
						0.00%	0.00
						0.00%	0.00
						0.00%	0.00
						0.00%	0.00
Total construction waste (cubic yards)							0.00
Total diverted construction waste (cubic yards)							0.00
For D+C projects	Total number of material streams						3
For ND projects	Total diverted asphalt, brick, and concrete (ABC) waste (cubic yards)						0.00

Figure 2.10 - Example of Construction Waste Tracking and Diversion Calculation Tool

Source: Construction Waste Calculator developed under Leadership in Energy and Environmental Design (LEED) by U.S. Green Building Council.

2.2.4 DESIGN AND CONSTRUCTION APPROACHES THAT REDUCE WASTE GENERATION (MODULAR, PREFAB, DFD)

This criterion aims to **reduce construction waste by promoting prefabrication design** and design-for-disassembly (DfD) approaches that minimize material loss. TREES Home strongly encourages Thailand's building sector to use more industrialized construction processes as a tactic to reduce on-site waste output. This approach supports improved material efficiency, adaptability, and long-term environmental performance[50].

How to get points

LEED

- No mention

TREES

- Provide evidence that the chosen design and construction approach helps reduce construction waste, backed by drawings, construction methods, or material specifications, in order to earn up to 2 points under WW 5.
- Apply modular construction systems that cut material use and construction waste by standardizing components (e.g., 300 mm grid modules) and reducing on-site cutting and rework.
- Use prefabricated structural or architectural elements, moving construction activities into controlled factory settings to improve material efficiency and cut on-site waste generation.
- Apply Design for Disassembly (DfD) principles by designing building components and connections that allow later dismantling, replacement, or reuse without excessive material damage.
- Demonstrate waste-reducing construction methods that support later adaptation, renovation, or extension of the building, thereby cutting demolition waste across the building's life cycle.



Figure 2.11 - Example of Prefabricated Construction

Source: Author's compilation based on Thai construction market references

2.2.5 BIM APPLICATION AS INNOVATION

This criterion aims to **encourage the use of Building Information Modeling (BIM)** as an innovation tool to support modular construction, prefabrication, and design for disassembly through improved design coordination, material optimization, and construction planning. Within the TREES Home framework, BIM is promoted as a means to enhance construction efficiency and reduce waste through digital integration across the project lifecycle[50].

How to get points

LEED

- No mention

TREES

- Earn 3/6 innovation points by applying BIM within the architectural design process, showing integrated digital coordination and model-based workflows under the Innovation in design (IN).
- Provide evidence of BIM use, such as coordinated models, quantity take-off, clash detection, or construction planning outputs that improve project efficiency.
- Show that BIM supports innovation outcomes, for example, through fewer design conflicts, better information management, or support for sustainable and modular construction practices.

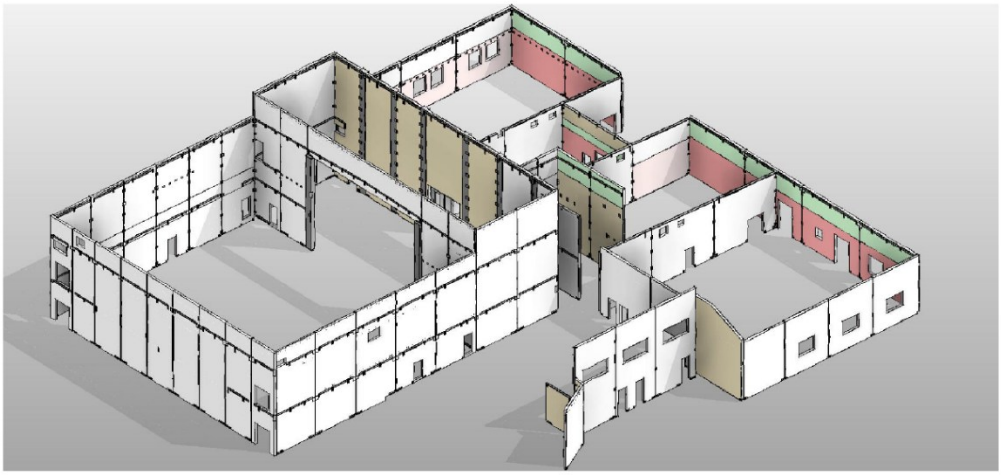


Figure 2.12 - Example of Prefabricated Construction Approach Using Integrated BIM Workflows

Source: Autodesk University article, Integrated BIM Workflows for Modular and Prefabricated Construction, Autodesk.

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2.3 STRUCTURAL SYSTEMS FOR THAI RESIDENTIAL CONSTRUCTION

2.3.1 STRUCTURAL COMPONENTS IN TRADITIONAL CONSTRUCTION

FOUNDATION AND FOOTINGS

- **Precast driven piles** are commonly produced with square cross sections of 0.22–0.35 m and lengths of 6–18 m. They provide reliable load capacity and consistent quality, but require piling equipment and generate vibration.



Figure 2.13 - Precast driven piles

Source: Author's compilation based on Thai construction market references.

- **Bored piles** are constructed in situ with typical diameters of 0.35–0.60 m depending on load and soil conditions. They allow flexible pile length adjustment but require heavy machinery and generate excavation spoil.



Figure 2.14 - Bored piles

Source: Author's compilation based on Thai construction market references.

- **Isolated footings** are cast in situ with typical plan dimensions of 1.2–2.0 m, depending on column loads. Formwork for footings is usually removed after 2 days, following standard practice for side form stripping. Although formwork can be removed early, concrete curing requires approximately 7 days before column construction proceeds.



Figure 2.15 - Isolated footings

Source: Author's compilation based on Thai construction market references.

- **Strip footings** are continuous foundations with typical widths of 0.6–1.0 m. Side formwork is generally removed after 2 days, while structural curing continues for several days. Wall construction is typically allowed after 7 days, depending on load conditions.



Figure 2.16 - Strip footings

Source: Author's compilation based on Thai construction market references.

BEAM COLUMN STRUCTURE

- **Cast-in-situ reinforced concrete columns** (RC columns) typically have cross sections of 200 × 200 mm to 300 × 300 mm. Side formwork is commonly stripped after 2 days, allowing subsequent construction activities to proceed. However, sufficient concrete strength for beam installation is typically achieved after 7 days of curing.



Figure 2.17 - Cast-in-situ reinforced concrete columns (RC columns)

Source: Author's compilation based on Thai construction market references.

- **Cast-in-situ reinforced concrete beams** (RC beams) commonly have widths of 200–300 mm and depths of 400–600 mm, requiring full soffit and side formwork. Side formwork may be removed earlier, but soffit formwork supporting the beam is typically retained for up to 21 days, following standard concrete practice. This extended support period affects construction sequencing and labour productivity.



Figure 2.18 - Cast-in-situ reinforced concrete beams (RC beams)

Source: Author's compilation based on Thai construction market references.

FLOOR STRUCTURES

- **Cast-in-situ reinforced concrete floor slabs** (RC slabs) are typically constructed with thicknesses of 100–150 mm. According to common practice, slab soffit formwork is generally retained for approximately 14 days before removal. The monolithic slab provides good water resistance, making it suitable for bathrooms, ground floors, and exterior floor areas requiring waterproofing.



Figure 2.19 - Cast-in-situ reinforced concrete floor slabs (RC slabs)

Source: Author's compilation based on Thai construction market references.

- **Prestressed Concrete Slabs** are factory-produced precast floor elements, commonly 50 mm thick, 350 mm wide, and up to 4.5 m long, designed for use as structural floor decking in houses and low-rise buildings. They are prestressed during manufacturing, providing high strength and dimensional accuracy, and their flat finished underside reduces on-site finishing time and labour. Used in combination with topping concrete.



Figure 2.20 - Prestressed Concrete Slabs

Source: Author's compilation based on Thai construction market references.

ROOF STRUCTURES

- **Steel roof structures** are commonly assembled from C-channel, H-beam, or box-section members sized 75–150 mm. They offer a high strength-to-weight ratio and allow rapid installation. Corrosion protection, such as galvanization or epoxy coating, is required in humid environments. Typical spans range from 4–12 m, depending on section size and roof load.

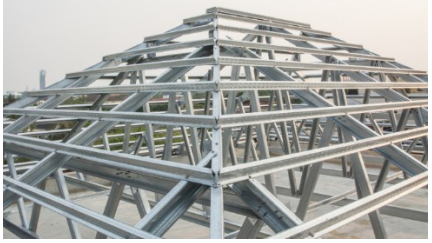


Figure 2.21 - Steel roof structures

Source: Author's compilation based on Thai construction market references.

2.3.2 STRUCTURAL COMPONENT IN PREFABRICATED CONSTRUCTION

STRUCTURAL FRAME PRECAST SYSTEM

The **precast structural frame** is the primary load-bearing system, typically manufactured off-site and assembled on-site[52]. To meet local engineering standards and ensure comprehensive strength, the contractor does not typically produce this on its own, as it requires laboratory test reports for safety purposes. Compared to cast-in-situ construction, this system reduces formwork usage and on-site material waste, although limited waste may still occur during grouting and minor on-site adjustments[53].

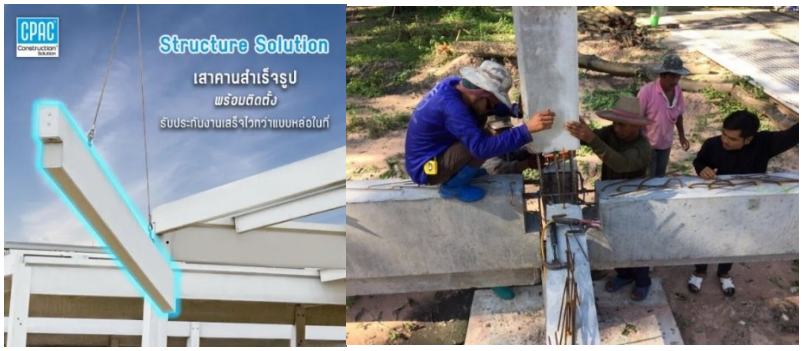


Figure 2.22 - Precast structural beam and column
Source: CPAC and Roiet Prestressed Concrete Co., Ltd.

As illustrated in Figure 2.23, there are two main joint details; the first is a wet joint connection where reinforcing bars are overlapped and welded to ensure structural continuity. The second type is a semi-dry connection that uses embedded steel parts to help with alignment and load transfer during installation before the final joint is finished. Both must ensure the transfer of axial, bending, and shear forces, providing structural continuity comparable to that of conventional reinforced concrete structures[54].



Figure 2.23 - Column to beam joint details
Source: Author's compilation based on Thai construction market references.

In terms of consideration, the precast structural frame system requires high precision during installation, particularly at connection points. Therefore, close coordination between structural prefabrication and architectural components is necessary to prevent misalignment. Moreover, due to the weight of individual elements, crane lifting operations and adequate site space are necessary, which may be limited under dense urban or small-site conditions[55].

PANELISED STRUCTURAL SYSTEM (LOAD-BEARING PANELS)

As seen in Figure 2.24, The **precast structural panel** is load bearing wall that functions as both a structural and enclosure element. Compared to a precast frame system, this approach enables faster construction by eliminating separate wall and rendering works, while allowing electrical conduits to be embedded within the panels during production. The panels must be manufactured in a controlled factory environment, which also helps reduce on-site waste and improve material efficiency[56], [57].



Figure 2.24 - Precast structural panel
Source: Author's compilation based on Thai construction market references.

Structural stability is achieved through connections using L-shaped steel angles or steel plates, which are welded to ensure rigidity between panels. As seen in Figure 2.25, at wall–floor and wall–wall interfaces, waterproofing is addressed through physical design measures combined with the application of non-shrink grout to seal the joints, while glue cement is applied as a surface sealing layer to limit water ingress at exposed joint interfaces. These details are essential to maintain both structural integrity and moisture resistance[54].

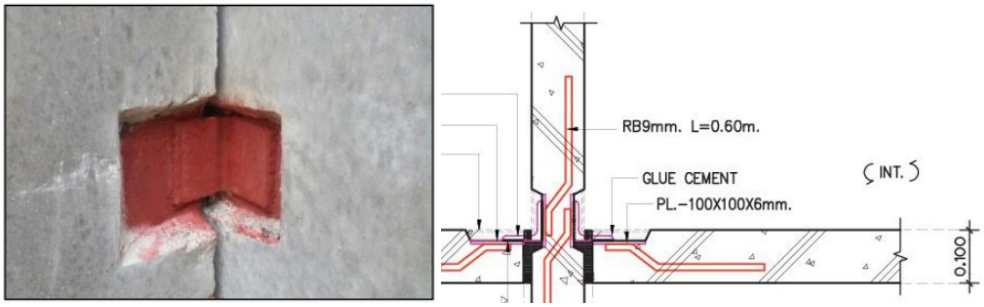


Figure 2.25 - Precast structural panel connection (Wall-Wall)
Source: Author's compilation based on Thai construction market references.

Key concerns of the panelized structural system include the performance of joint waterproofing and installation accuracy. Waterproofing membranes must be carefully applied along panel joints, with water ponding tests typically conducted for at least one day to verify the leakage. In addition, panel installation

requires crane operations and properly designed lifting and anchoring devices to ensure safe handling of heavy elements[57], [58].

2.4 CONSTRUCTION TECHNIQUES AND SYSTEM TYPOLOGIES

This section defines the construction system typologies for comparative analysis, shifting the focus from individual materials and components to overall construction logic and system configuration. The systems are classified by structural integration, production mode, and degree of prefabrication, which influence construction workflow and site dependency.

Table 2.7 - Construction system typologies and key characteristics

System	Production Mode	Structural Logic	Prefab Level	Workflow
Traditional in situ construction (TC)	On-site	Frame-based	Low	Sequential
Precast frame (PF)	Hybrid	Frame-based	Medium	Semi-parallel
Precast panel (PP)	Off-site dominant	Wall-based	High	Parallel
Renovation scenario (RS)	On-site	Existing structure retained	Low	Non-linear /selective

Source: Author's classification framework.

2.4.1 TRADITIONAL IN SITU CONSTRUCTION TECHNIQUES (TC)

Traditional in situ construction (TC) is characterized by an on-site production in which the majority of structural and architectural works are executed directly at the construction site[59]. The structural logic consists of a framing system that transfers loads using reinforced concrete (RC) columns, beams, and slabs.

From Figure 2.26, Structural concrete requires a minimum curing period under suitable conditions to meet compressive strength. Extreme heat or rain during casting may potentially contribute to strength loss[60]. Therefore, concrete for structural works is typically supplied by ready-mix concrete manufacturers rather than being mixed on-site to ensure quality control (e.g., 24 MPa for beams and columns)[61]. However, over-ordering is common due to uncertainty in volume estimation, which can result in construction waste, as ready-mix concrete is delivered in fixed truck capacities, typically around 5 cubic meters per truck.



Figure 2.26 - Ready-mix concrete truck

Source: Author's classification framework.

As Gantt Chart from Figure 2.27 show that all Architectural components, such as lightweight brick walls, are used as non-load-bearing elements which installed after the structural frame is completed. Most general construction materials, for example, bricks, nails, steel framing, and mortar, are usually sourced from local suppliers within the same city or province to minimize logistical time and to ensure material availability in case of shortage. Architectural works are carried out after the structural phase to ensure that materials can be safely supported by the completed structure and to avoid damage from vibration or movement during structural works.

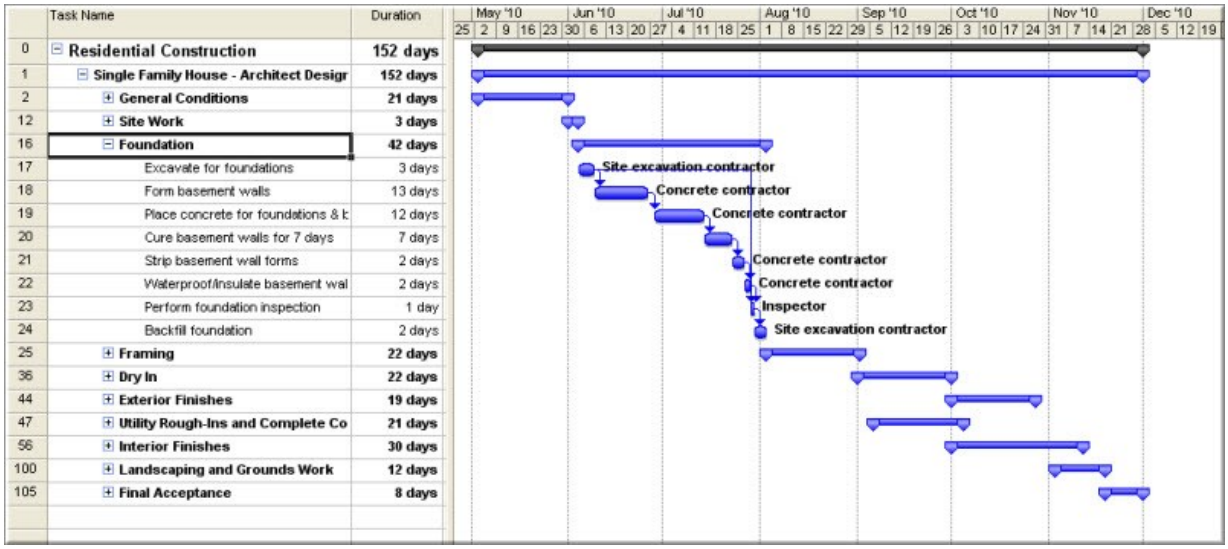


Figure 2.27 - Gantt chart showing the sequential workflow of structural and architectural works in traditional in situ construction (TC)

Source: Author's classification framework.

Due to its on-site dominant production mode, construction activities follow a largely sequential workflow. Architectural works and MEP installations frequently experience coordination conflicts, as electrical conduits and service routes often require cutting into finished masonry walls to embed conduits and outlets before final plastering and surface finishes are applied. Such MEP-related rework can result in additional labour, increased costs, and redundant activities. Consequently, opportunities for parallel construction are limited. While this strategy offers a certain degree of flexibility during construction, it leads to high site dependency, longer construction durations, and a larger reliance on trained personnel and good site management.



Figure 2.28 - Electrical conduit installation requiring wall cutting in masonry infill

Source: Author's classification framework.

2.4.2 PRECAST STRUCTURAL FRAME CONSTRUCTION (PF)

Precast structural frame construction (PF) is a hybrid system combined with manufactured structural frame components and on-site architectural assembly. The prefabricated columns, beams, and floor slabs are designed and cured in a controlled environment for on-site assembly.

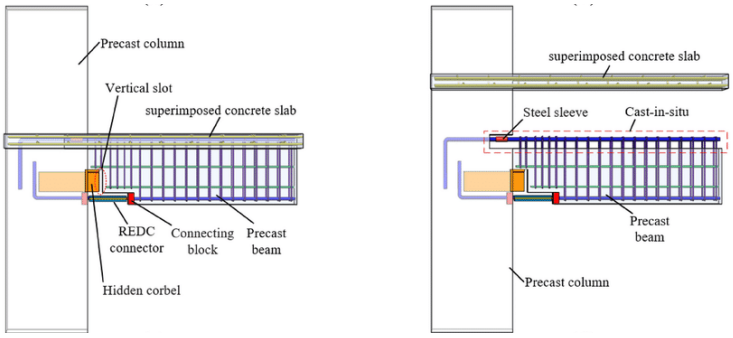


Figure 2.29 - Precast structural frame system diagram.

Source: Adapted from Tong, C., Wu, J., and Li, C. (2021). A novel precast concrete beam-to-column connection with replaceable energy-dissipation connector.

The structural logic remains frame-based, similar to traditional in situ construction (TC), with structural elements assembled through lifting and connection-based installation rather than on-site casting. Precast components are connected using welded steel plates and steel angles, which are integrated with the internal reinforcement of adjacent elements to ensure structural continuity and effective load transfer. Localized in situ concrete infill, including non-shrink grout and special cement or epoxy materials, is applied at connection zones to complete the joint and provide corrosion protection for embedded steel components[54]. (Based on typical INSEE precast details; variations may occur among manufacturers.)

This construction system enables a semi-parallel workflow which shown on Figure 2.29-2.30. While precast elements are fabricated off-site, foundation works and site preparation can proceed concurrently[62]. On-site activities focus mainly on erection, alignment, and jointing, reducing construction duration and dependence on curing conditions compared to fully in situ construction.



Figure 2.30 - Precast structural frame system illustrating on-site assembly.

Architectural components and MEP systems are typically installed after the completion of the structural frame, similar to traditional in situ construction (TC). Although higher dimensional accuracy and early coordination are required during design and fabrication, most architectural and service installations remain on-site activities. Overall, precast structural frame construction (PF) provides the benefit of time efficiency and the flexibility of future renovation.

2.4.3 PRECAST STRUCTURAL PANEL CONSTRUCTION (PP)

Figure 2.31 illustrates that precast structural panel construction (PP) is characterized by a panel-based load-bearing system in which vertical wall panels act as the primary structural elements. Structural loads are transferred directly through these panels, eliminating the need for a conventional reinforced concrete frame[63]. In this system, structural and enclosure functions are integrated, as wall panels simultaneously provide load resistance and a building envelope.

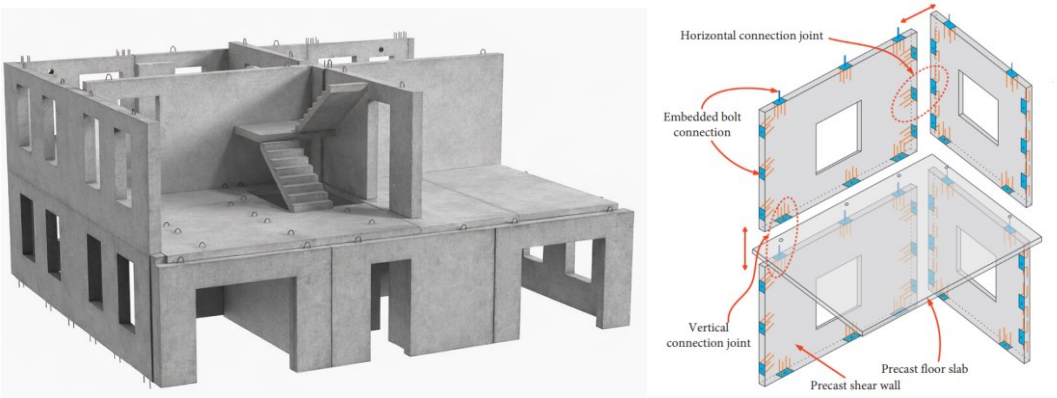


Figure 2.31 - Precast structural panel system illustrating load-bearing walls and floor integration.
Source: Guo et al., Experimental and Numerical Analysis of the Bolt Connections in a Low-Rise Precast Wall Panel Structure System, [Journal/Publisher], 2019.

The production mode of this system is predominantly off-site, with wall panels and floor elements manufactured in controlled factory environments. On-site activities, therefore, focus on erection-based construction rather than concrete casting[64]. Panels are transported to the site and installed using lifting equipment, while in situ concrete works are generally limited to localized joint infill and connection zones[65]. As a result, on-site wet works are significantly reduced compared to traditional in situ construction (TC).

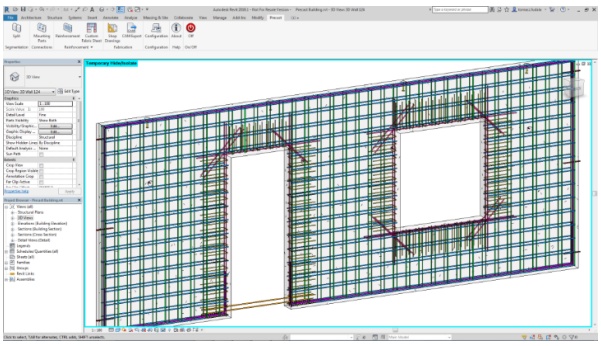


Figure 2.32 - Reinforcement layout and opening coordination of precast wall panels modeled
Source: *Announcing Autodesk Structural Precast Extension for Revit 2018*.

MEP systems are typically embedded within the panels which you can see in Figure 2.32 during the manufacturing stage, as the wall thickness is relatively thin (approximately 100 mm)[52]. Cutting and installing services on-site, similar to masonry walls, will reduce the structural capacity of the panels. Therefore, openings or service route details must be accurately designed, as opportunities for on-site modification are limited once panels are installed[66]. This requires a high level of coordination among structural, architectural, and MEP disciplines, with greater emphasis placed on early-stage design accuracy. BIM is commonly used as a supporting tool to facilitate this coordination[67].

Due to the high degree of prefabrication, construction activities can be carried out with a high level of parallelization. Panel fabrication, site preparation, and foundation works may proceed concurrently, resulting in reduced on-site construction duration[68]. Within the scope of this study, precast structural panel construction represents the highest level of prefabrication among the systems considered and serves as a reference for highly industrialized construction approaches.

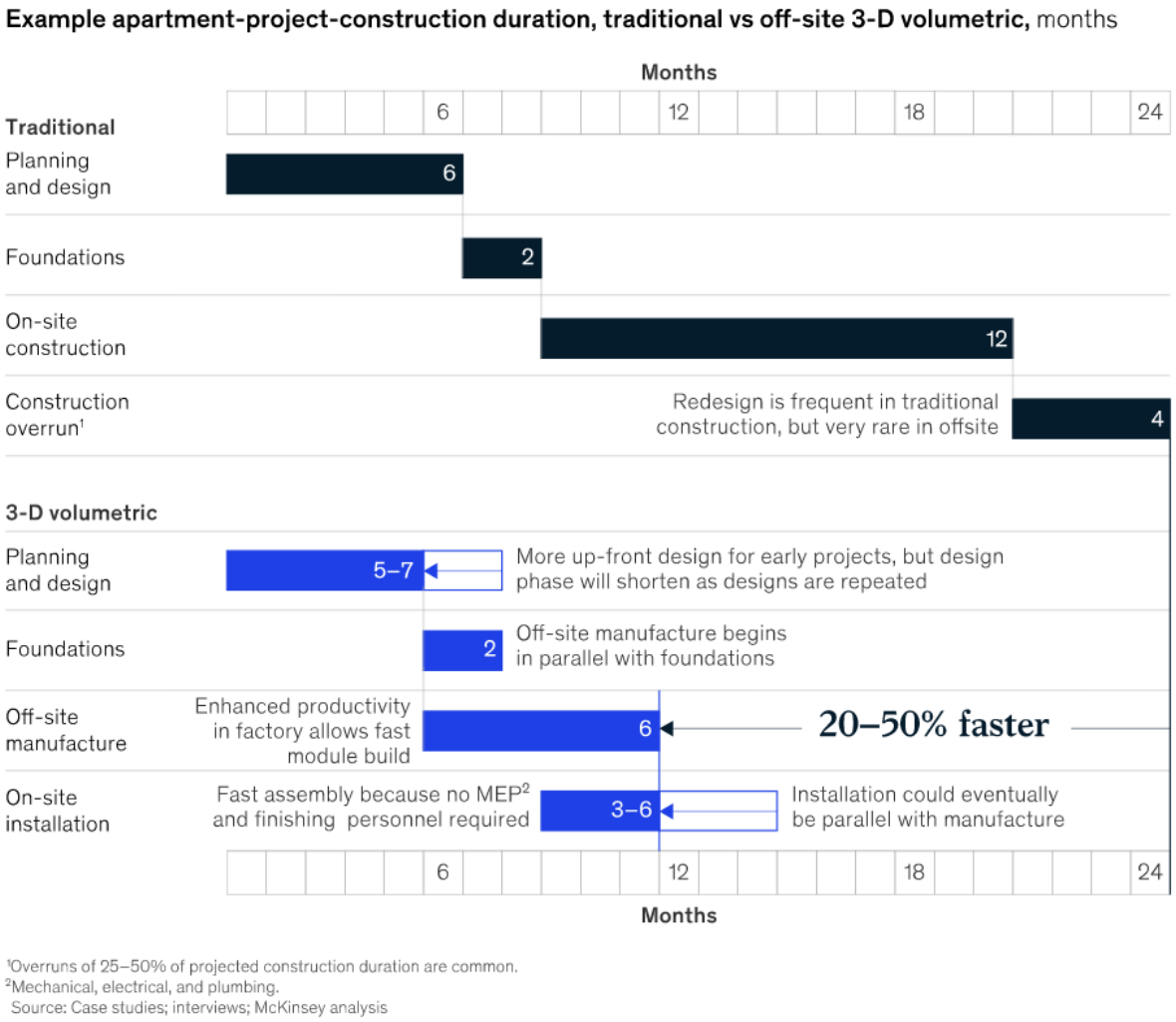


Figure 2.33 - Modular construction concept shifting from on-site projects to manufacturing.
Source: Bertram et al., Modular construction, McKinsey & Company Report (2019).

2.4.4 RENOVATION CONTEXT (RS)

Residential renovation cycles are often initiated by deterioration of interior finishes rather than by structural failure. In practice, roof coverings, façade coatings, floor finishes, and some MEP components tend to require major renewal after approximately 25 years of service, while reinforced concrete structures remain rigid during the life cycle for around 100 years[69], [70].

Table 2.8 - Life expectancy of different building layers, in years

Structure	Skin	Services	Space	Building type
100	25-50	25	10	House: timber frame, brick cladding, ceramic tile roof (Fay, Treloar and Iyer-Raniga 2000)
100	25	10-20	4-10	Non-residential Open building (Kendall 1999)

Source: Adapted from Crowther, P. (2015). Re-Valuing Construction Materials and Components through Design for Disassembly, Unmaking Waste 2015 Conference Proceedings, Adelaide, Australia.

Most renovation works focus primarily on architectural components rather than structural alteration. Typical tasks include replacing doors and windows, modifying internal layouts through localized wall cutting, renewing skim coatings, repainting interior and exterior surfaces, and replacing roof coverings or floor and wall tiles. Wall insulation in the external level is always attached to improved sound and heat insulation, and the roof as well. This adaptive reuse (AR) improves comfort, appearance, and environmental protection while maintaining the original building framework[69], [71].



Figure 2.34 - Interior renovation
Source: Author's compilation based on Thai construction market references.

In the Thai context, renovation projects are also influenced by legal thresholds that limit repair from structural improvement. Small-scale works that do not significantly influence the structural system can typically proceed as a repair with simplified procedures, whereas more complex adjustments require official building permits and expert certification by architects and engineers. As a result, many residential projects are intentionally designed to minimize structural intervention and keep additional loads within the original design capacity[71].

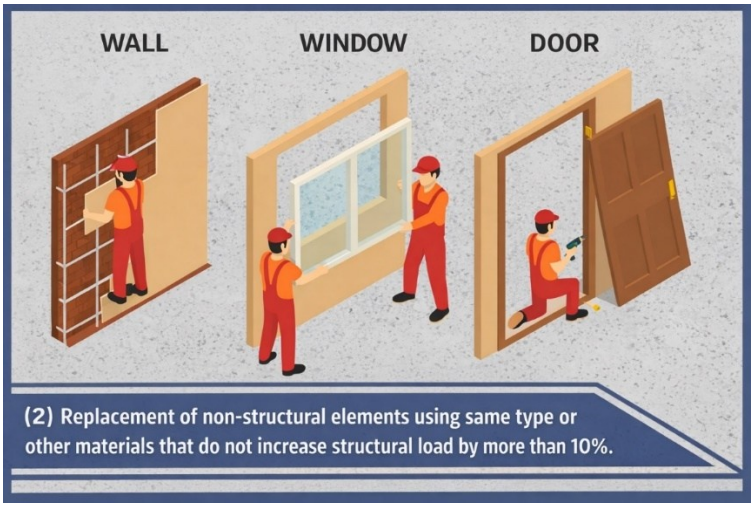


Figure 2.35 - Replacement of non-structural wall, window, and door elements

Source: Adapted from Seacon Co., Ltd., based on Ministerial Regulation No. 11 (B.E. 2528 / 1985) issued under the Building Control Act B.E. 2522 (1979) of Thailand.

In this study, the adaptive reuse (AR) system is defined as a localized renovation approach that preserves the existing structural frame while selectively renewing deteriorated building layers. By restoring the functional and envelope performance of the dwelling, these targeted interventions aim to extend service life and reduce operational carbon without the need for full reconstruction.

2.4.5 COMPARATIVE OVERVIEW OF CONSTRUCTION SYSTEM TYPOLOGIES

TC (traditional in situ RC) is the most flexible on-site: openings and service routes can be adjusted during construction, and masonry can be cut or modified with relatively low constraints. However, it is strongly sequential and work-driven, so curing and site conditions can create waiting time and variability. MEP changes often translate into chasing and rework.



Figure 2.36 - Wall demolition

Source: Author's compilation based on Thai construction market references.

PF (precast structural frame) is a hybrid approach: the fundamental framework is prefabricated, while most architectural and MEP work remains on site. Time savings depend greatly on lifting access, delivery schedule, and erection sequence. Flexibility is reduced once elements are fabricated, so late design changes can become costly. But this system normally integrates precast concrete slabs, which are not suitable for service penetration areas, such as toilets. As a result, precast concrete trays are often required to span over precast beams, limiting design adaptability[72].

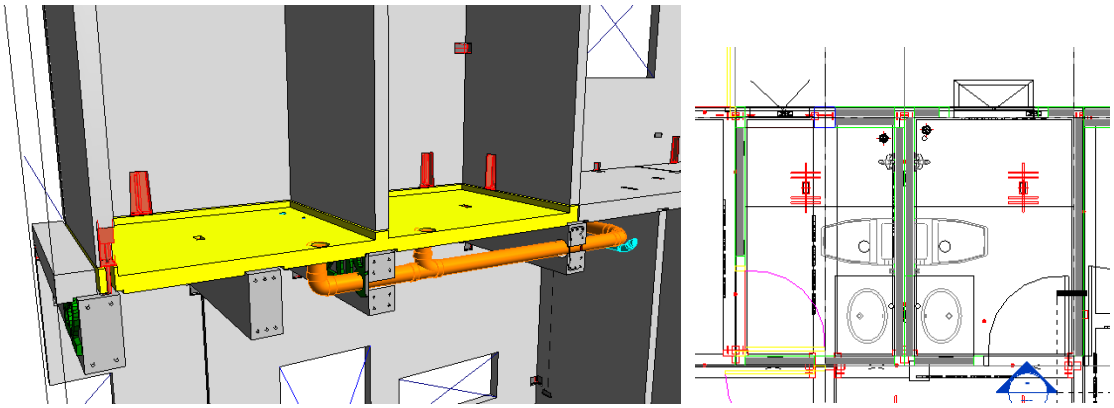


Figure 2.37 - Precast concrete trays

Source: Author's compilation based on the BIM reference project by Phatcharasaengmanat K.

PP (precast structural panel) is the most highly industrialised because panels serve as both structure and enclosure, enabling greater parallelism between factory fabrication and site preparation which you can notice on Figure 2.38. The trade-off is low tolerance for late change: openings and MEP provisions should be fixed early, and on-site cutting is constrained. Consequently, this system demands early design finalization and coordination[68]. Due to the size and weight of the panels, the use of lifting machinery is unavoidable during installation.



Figure 2.38 - Prefabricated panel manufacture
Source: Author's compilation based on Thai construction market references.

RS (renovation scenario) is a selective replacement workflow rather than a full reconstruction. Based on the WBS, it starts with survey and protection, then progresses through remove and install cycles focused on the roof (covering, insulation, structure if needed), floors (remove finishes, substrate preparation, new finishes), and openings, followed by finishing works such as ceiling replacement if required, painting, minor MEP adjustments, and handover. Compared with a new build, RS can reduce the total scope, but it typically has higher uncertainty due to hidden conditions and potential rework discovered after removal.

Table 2.9 presents a side-by-side typological assessment, establishing the system-level distinctions that underpin the multi-dimensional quantitative analysis developed through UC1–UC4 in Chapter 3.

Comparison aspect	TC	PF	PP	RS
Degree of industrialisation	Low	Medium	High	Low
On-site labour intensity	High	Medium	Low	High
Tolerance requirement	Low	Medium	High	Medium
Dependence on lifting equipment	Low	High	High	Low
Flexibility for design change	High	Low	Low	Medium
Quality control	Site dependent	Factory controlled	Factory controlled	Site dependent

Source: Thesis Author

2.5 BIM FOR INTEGRATED CONSTRUCTION ASSESSMENT

The concepts reviewed in this section provide the theoretical foundation for the methodology and use cases defined in the following chapter.

2.5.1 BIM FOR CONSTRUCTION PLANNING AND SCHEDULING (4D)

4D BIM integrates construction scheduling logic directly with model geometry by linking Work Breakdown Structure (WBS) activities to specific building elements. This enables productivity-based duration estimation, time-based comparison across construction systems, and early identification of sequencing constraints. The approach forms the analytical basis for **Use Case 1** in this research [73], [74], [75]

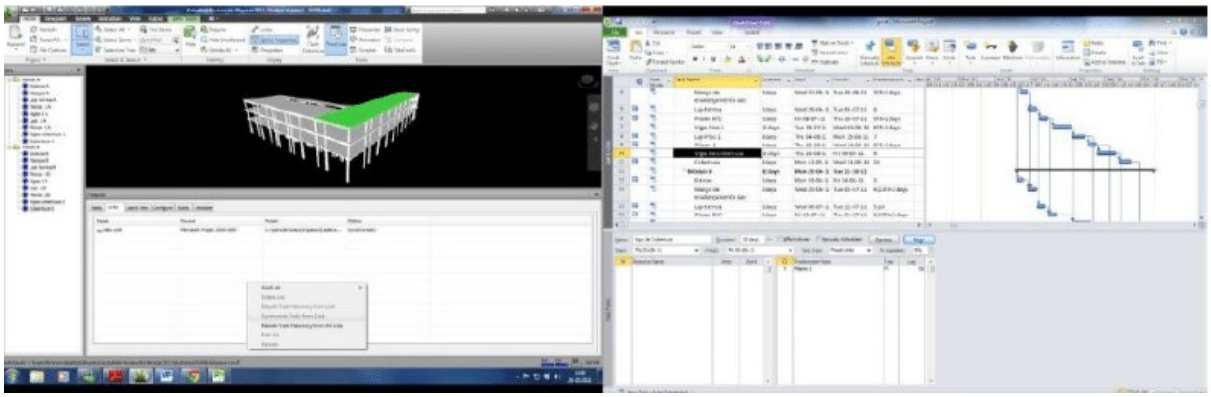


Figure 2.39 - IFC model and Gantt chart automatically generated in Navisworks
Source: Sampaio, A.Z., The Disclosure of the BIM Concept in Civil Engineering Training, Technical University of Lisbon.

2.5.2 BIM FOR COST ESTIMATION AND QUANTITY TAKE OFF (5D)

5D BIM builds on geometric modelling by attaching cost data to model elements, enabling automated quantity take-off and parameter-linked cost calculation. Unlike manual 2D-based estimation, this model-centred workflow maintains dynamic linkage between design quantities and unit rates, supporting rapid cost comparison across construction alternatives and accuracy which you can see on Figure 2.39. This capability forms the analytical basis for **Use Case 2** in this research[76], [77], [78]

Cost Estimate by traditional method (manual) and Estimate Cost by BIM (with Revit architectural) of each item				
S.No	Item	Cost Estimate by traditional method (manual)	Cost Estimate by BIM (with Revit architectural)	Percentage Reduced (%)
1	Column	768300	726012	8
2	Structural Framing	1342763	1237351.517	11
3	Stair	198400	192000	6
4	Wall	6822100	5818417	15
5	Floor	6476600	6152185	7
6	Door	1103455	1050815	6
7	Window	1077600	989653	10
8	Furniture	877000	877000	0

Figure 2.40 - Estimated cost comparison between the traditional method and BIM-based 5D estimation for selected building components.

Source: Khamees, S. A. A., Rashid, H. A., & Ahmed, R. H. (2020). *Improvement in estimating the project cost and design for a hospital project by using (3D&5D) simulation*.

2.5.3 BIM FOR ENVIRONMENTAL ASSESSMENT (6D)

The term 6D BIM broadly refers to the integration of sustainability-related analysis within the BIM environment, encompassing a wide range of applications such as daylight simulation, thermal performance, natural ventilation, and life cycle assessment (LCA) [79]. In this study, 6D BIM is specifically applied to embodied carbon assessment through LCA, focusing on the production and construction stages (A1–A5). Material quantities extracted from the BIM model are mapped to emission factors from Environmental Product Declarations (EPDs) and national databases, enabling systematic and comparable embodied carbon calculation across all construction scenarios. This approach forms the analytical basis for **Use Case 3** [80], [81]

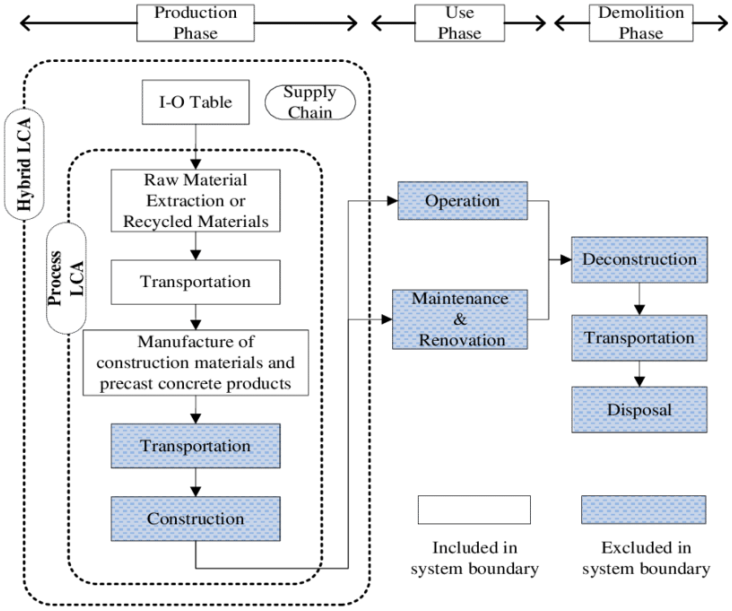


Figure 2.41 - System boundary for simplified LCA in building construction process
Source: Adapted by the thesis author based on Wan Omar, W. M. S. (2018).

2.6 EXTERNAL DATA SOURCES AND ASSUMPTIONS

This section defines the quantitative external inputs adopted across the 4D, 5D, and 6D analytical workflows. Since productivity rates, cost databases, transportation parameters, waste factors, and emission datasets are not intrinsic BIM attributes, they are explicitly documented to ensure methodological transparency, reproducibility, and comparability between construction scenarios.

2.6.1 LABOUR PRODUCTIVITY INPUT

Data Source

Labour productivity rates were primarily derived from the Builders' Guide on Measuring Productivity published by Singapore's Building and Construction Authority (BCA) and supplemented by Labour Costs which is represented on Table 2.10 and Labour Output Information for Building Construction 2006 (CIDB Malaysia). These sources provide benchmark outputs mainly reported per man-hour; values were converted to this study's working-day definition (1 day = 8 working hours). For activities not covered by BCA or CIDB, additional rates were adopted from peer-reviewed studies (a Singapore precast installation study), while a general guideline sheet was used only when no other references were available.[82], [83], [84], [85].

Table 2.10 - Example of general productivity rate

	Work item	*Units*	*Productivity indicators*
	Structural Work		
1.	Formwork (Table form for Slab / Beam)	m^2/man-hour	2.07 to 2.53 (Average – 2.30)
2.	Reinforcement placing and fixing (Slab)	kg/man-hour	68 to 83 (Average – 75)
3.	Concrete placement (with concrete pump) (Slab)	m^3/man-hour	1.677 to 2.04 (Average – 1.85)
	Architectural Work		
4.	Drywall (12mm thick board)	m^2/man-hour	2.03 to 2.48 (Average – 2.25)
5.	Painting (Emulsion – 3 coats) (using roller)	m^2/man-hour	4.95 to 6.05 (Average – 5.50)
6.	Timber door including door frame	Number/man-hour	0.31 to 0.37 (Average – 0.34)
7.	Ceramic wall tiling (using adhesive)	m^2/man-hour	1.52 to 1.86 (Average – 1.69)
8.	Ceramic floor tiling (using adhesive)	m^2/man-hour	1.83 to 2.23 (Average – 2.03)
9.	Suspended ceiling (exposed grid system)	m^2/man-hour	4.54 to 5.54 (Average – 5.04)
	Mechanical, Electrical and Plumbing Work		
10.	Air-conditioning duct (formed and insulated on site)	m^2/man-hour	2.60 to 3.19 (Average – 2.90)
11.	20mm diameter UPVC electrical conduit with wires fixed to ceiling	m/man-hour	2.44 to 2.98 (Average – 2.71)
12.	20mm diameter copper pipe for water (concealed in wall)	m/man-hour	1.50 to 1.84 (Average – 1.65)

Source: Building and Construction Authority (BCA), Singapore, 2014

Table 2.11 - Characteristics and installation productivity of precast concrete components.

Type	Mean (min.)	Productivity (Cycle/Hour)
Wall	27.69	1.81
Column	21.74	2.30
Beam	11.37	4.40
Slab	7.53	6.64

Type	Number of Cases	Length (range in m)	Width (range in m)	Height (range in m)	Weight (range in Kg)
Wall	19	3 – 4.4	0.15	3.575	3732 - 5428
Column	27	0.4 – 0.8	0.4 – 0.5	3.020 – 3.550	1233 – 3398
Beam	20	5.6 – 9.2	0.3 – 0.8	0.320 – 0.600	2064 – 5664
Slab	39	2.4 – 8.7	0.375 – 1.6	0.100 – 0.265	919 – 3088

Source: Adapted from Najafi, A., and Tiong, R. L. K. (2015). Productivity modeling of precast concrete installation using multiple regression analysis. ARPN Journal of Engineering and Applied Sciences, 10(6), April 2015.

Table 2.12 - Productivity rate of roof covering

Item	Description	Man-hour	Unit	Range Labour Output per Man-hour
	ROOF COVERINGS : LAYING ONLY			
	Laying of roof covering as described in Section 2 for Labour Unit Rates For Building Construction		**Note**	
1	**Concrete Roof Tile** Laid to pitch not exceeding 30 degrees	1	m2	1.59 - 1.81
2	**Metal Roofing Deck** Laid to pitch not exceeding 30 degrees	1	m2	1.93 - 2.50

Source: CIDB Malaysia (2007), Labour Costs and Labour Output Information for Building Construction 2006, Roof coverings: laying only.

Selection Rationale

Although these references were developed outside Thailand, they were selected because of comparable climatic conditions and construction practices across Southeast Asia. **To avoid overly optimistic scheduling outcomes, this study uses the minimum productivity value (MIN) for baseline duration calculation**, while AVG and MAX are retained to document variability and to support sensitivity checks. This approach minimizes the risk of underestimating construction duration and ensures that comparative results across construction scenarios (TC, PF, PP, RS) are unbiased.

From the Table 2.13, all rates were normalized to a per man-day basis by adopting 1 working day = 8 working hours. Where sources report crew-based installation productivity (for example, precast cycle rates), values were converted to per man-day using the stated crew size and expressed as a range (±25% around the mean) to reflect site variability.

Table 2.13 - Summary of productivity rate for all construction scenarios (TC, PF, PP, RS)

WBS_Code	Name of activity	Unit	MIN	AVG	MAX	inimum CRE	Construction metho	Ref
S01	Site clearing and setting out	m2	225	300	375	2	TC, PF, PP, RS	Guideline sheet
S02	Excavation (JCB excavation)	m3	480	560	640	1	TC, PF, PP	Guideline sheet
S03	Foundation piles (driven precast prestressed I-shape, 22×22cm, L=	piece	0.75	1	1.25	4	TC, PF, PP	BCA Singapore 2014; Thai industry
S04	Blinding concrete (lean concrete 50mm)	m2	40	43.6	47.2	4	TC, PF, PP	CIDB Malaysia 2006
S05	Footings (RC composite: FW+rebar+conc.)	m3	1	1.2	1.4	4	TC, PF, PP	CIDB Malaysia 2006 (composite)
S06	Column stumps (RC composite: FW+rebar+conc., 200×200mm)	m3	0.17	0.21	0.24	4	TC, PF, PP	CIDB Malaysia 2006 (composite)
S07	Ground beams (RC composite: FW+rebar+conc., cast in-situ)	m3	0.26	0.32	0.37	4	TC	CIDB Malaysia 2006 (composite)
S08	Slab-on-grade (RC composite: edge FW+mesh+conc., 150mm)	m3	1.34	1.61	1.88	4	TC, PF, PP	CIDB Malaysia 2006 (composite)
ST01	Columns 1F (RC composite: FW+rebar+conc., 200x200mm)	m3	0.17	0.21	0.24	4	TC	CIDB Malaysia 2006 (composite)
ST02	Beams 1F (RC composite: FW+rebar+conc., 200x400mm)	m3	0.26	0.32	0.37	4	TC	CIDB Malaysia 2006 (composite)
ST03	Suspended slab 1F (RC composite: FW+rebar+conc., 150mm, wet a	m3	0.47	0.56	0.66	4	TC	CIDB Malaysia 2006 (composite)
ST04	Columns 2F (RC composite: FW+rebar+conc., 200x200mm)	m3	0.17	0.21	0.24	4	TC	CIDB Malaysia 2006 (composite)
ST05	Beams 2F (RC composite: FW+rebar+conc., 200x400mm)	m3	0.26	0.32	0.37	4	TC	CIDB Malaysia 2006 (composite)
ST06	Upper slab 2F (RC composite: FW+rebar+conc., 150mm / precast p	m3	0.47	0.56	0.66	4	TC	CIDB Malaysia 2006 (composite)
ST07	Stair construction / stair finishes replacement	m2	4.56	4.96	5.36	3	TC, RS	CIDB Malaysia 2006
P01	Ground beams (precast install, incl. connections)	piece	8.8	11.73	14.66	3	PF	Singapore precast research
P02	Columns 1F (precast install)	piece	4.6	6.13	7.66	3	PF	Singapore precast research
P03	Beams 1F (precast install)	piece	8.8	11.73	14.66	3	PF	Singapore precast research
P04	Floor slab 1F (precast install)	piece	9.96	13.28	16.6	4	PF	Singapore precast research
P05	Columns 2F (precast install)	piece	4.6	6.13	7.66	3	PF	Singapore precast research
P06	Beams 2F (precast install)	piece	8.8	11.73	14.66	3	PF	Singapore precast research
P07	Floor slab 2F / roof ring beam (precast install)	piece	9.96	13.28	16.6	4	PF	Singapore precast research
P08	Stair installation (precast)	piece	8.8	11.73	14.66	3	PF	Singapore precast research
B01	Ground beams (precast install, incl. connections)	piece	8.8	11.73	14.66	3	PP	Singapore precast research
B02	Beams 1F (precast install, incl. connections)	piece	8.8	11.73	14.66	3	PP	Singapore precast research
B03	Beams 2F (precast install, incl. connections)	piece	8.8	11.73	14.66	3	PP	Singapore precast research
W01	External wall panels 1F install (incl. jointing)	piece	2.72	3.62	4.53	4	PP	Singapore precast research
W02	Internal wall panels 1F install (incl. jointing)	piece	2.72	3.62	4.53	4	PP	Singapore precast research
W03	External wall panels 2F install (incl. jointing)	piece	2.72	3.62	4.53	4	PP	Singapore precast research
W04	Internal wall panels 2F install (incl. jointing)	piece	2.72	3.62	4.53	4	PP	Singapore precast research
F01	Precast floor slab panels 1F install	piece	9.96	13.28	16.6	4	PP	Singapore precast research
F02	Precast floor slab panels 2F install	piece	9.96	13.28	16.6	4	PP	Singapore precast research
T01	Stair installation (precast)	piece	8.8	11.73	14.66	3	PP	Singapore precast research
R01	Roof primary structure (gable roof truss)	m2	7.5	10	12.5	3	TC, PF, PP, RS	Guideline sheet
R02	Roof covering and waterproofing (roof tile)	m2	12.72	13.6	14.48	3	TC, PF, PP, RS	CIDB Malaysia 2006
A01	Masonry walls — external + internal (AAC block)	m2	8	10	12	2	TC, PF	Industry practice estimate
A02	Plastering (internal + external walls, 12mm)	m2	8.72	9.8	10.72	2	TC, PF	CIDB Malaysia 2006
A03	Doors and windows installation	piece	2.48	2.72	2.96	2	TC, PF, PP, RS	BCA Singapore 2014
A04	Floor finishes (ceramic tiling, adhesive)	m2	14.64	16.24	17.84	2	TC, PF, PP, RS	BCA Singapore 2014
A05	Ceiling installation (suspended ceiling)	m2	36.32	40.32	44.32	2	TC, PF, PP, RS	BCA Singapore 2014
A06	Painting works (interior + exterior, emulsion 3 coats)	m2	39.6	44	48.4	2	TC, PF, PP, RS	BCA Singapore 2014
A07	Facade cladding installation (fiber cement board)	m2	14	16	18	2	TC, PF, PP, RS	BCA Singapore 2014 (drywall prox
RS01	Remove existing roof covering	m2	20	25	30	2	RS	Industry practice estimate
RS02	Dismantle existing roof structure	m2	12	15	18	3	RS	Industry practice estimate
RS03	Remove existing floor finishes (tile hacking)	m2	8	10	12	2	RS	Industry practice estimate
RS04	Substrate preparation / leveling (screed)	m2	13	15	17	2	RS	CIDB Malaysia 2006
RS05	Demolish existing AAC wall partition (Living Area)	m2	15	20	25	2	RS	Industry practice estimate
RS07	New AAC block partition construction (Living Area, per gridline)	m2	8	10	12	2	RS	Industry practice estimate

Source: Adapted by thesis author

Crew Size Definition

Minimum crew sizes in the table represent the smallest feasible operational team to execute each activity without fractional labour allocation. The 10-worker limit corresponds to a typical residential plot size (200–300 m^2) where concurrent workfaces are spatially constrained. A Thai government estimating guideline likewise discusses labour estimation using MAN-DAY and notes that, for public-sector "ราคากลาง" estimating, labour should follow an official labour account framework, reinforcing the use of standardized labour inputs in planning models.

Roles: Foreman (F), Skilled (S), General (G), Operator (O). Composition is shown as counts in the format F# / S# / G# / O# and sums to the Minimum Labour value.

Table 2.14 - Minimum crew size

WBS_Code	Name of Activity	Scenario	Labour Count (excl. Foreman)	Composition (S/G/O only)	Note
S01	Site clearing and setting out	TC, PF, PP, RS	2	S1 / G1	Manual clearing; no equipment operator needed
S02	Excavation (JCB excavation)	TC, PF, PP	1	O1	Operator only; foreman excluded
S03	Foundation piles (driven precast prestressed)	TC, PF, PP	4	S2 / G1 / O1	Pile rig operator + 2 skilled riggers + 1 general
S04	Blinding concrete (lean concrete 50mm)	TC, PF, PP	3	S1 / G2	Pour + screed; skilled + 2 general
S05	Footings (RC composite: FW + rebar + conc.)	TC, PF, PP	3	S1 / G2	Formwork, rebar, concrete; foreman excluded
S06	Ground beams (RC composite, cast in-situ)	TC	3	S1 / G2	Same composition as S05
S07	Slab-on-grade (RC composite, 150mm)	TC, PF, PP	3	S1 / G2	BRC mesh + edge FW + concrete
ST01	Columns 1F (RC cast in-situ, 200×200mm)	TC	3	S2 / G1	FW + rebar + pour; skilled-heavy
ST02	Beams 1F (RC cast in-situ, 200×400mm)	TC	3	S2 / G1	Same as ST01
ST03	Suspended slab 1F (RC cast in-situ, 150mm)	TC	3	S2 / G1	Soffit FW + BRC + pour
ST04	Columns 2F (RC cast in-situ, 200×200mm)	TC	3	S2 / G1	Same as ST01
ST05	Beams 2F (RC cast in-situ, 200×400mm)	TC	3	S2 / G1	Same as ST02
ST06	Upper slab 2F (precast plank + RC topping)	TC	3	S2 / G1	Plank lay + topping pour
ST07	Stair construction / stair finishes replacement	TC, RS	2	S1 / G1	TC = RC formwork; RS = tile replacement
P01	Ground beams (precast install)	PF	2	S1 / O1	Crane op + rigger; foreman excluded
P02	Columns 1F (precast install)	PF	2	S1 / O1	Same as P01
P03	Beams 1F (precast install)	PF	2	S1 / O1	Same as P01
P04	Floor slab 1F (precast install)	PF	3	S2 / O1	2 riggers + crane op for panel weight
P05	Columns 2F (precast install)	PF	2	S1 / O1	Same as P02
P06	Beams 2F (precast install)	PF	2	S1 / O1	Same as P03
P07	Floor slab 2F / roof ring beam (precast install)	PF	3	S2 / O1	Same as P04
P08	Stair installation (precast)	PF	2	S1 / O1	Same as P01
B01	Ground beams (precast install)	PP	2	S1 / O1	Same rate as P01
B02	Beams 1F (precast install)	PP	2	S1 / O1	Same as B01
B03	Beams 2F (precast install)	PP	2	S1 / O1	Same as B01
W01	External wall panels 1F install	PP	3	S2 / O1	2 riggers + crane op; panel 4.8×2.4m
W02	Internal wall panels 1F install	PP	3	S2 / O1	Same as W01
W03	External wall panels 2F install	PP	3	S2 / O1	Same as W01
W04	Internal wall panels 2F install	PP	3	S2 / O1	Same as W01
F01	Precast floor slab panels 1F install	PP	3	S2 / O1	Same as P04
F02	Precast floor slab panels 2F install	PP	3	S2 / O1	Same as P04
T01	Stair installation (precast)	PP	2	S1 / O1	Same as P08
R01	Roof primary structure (gable roof truss)	TC, PF, PP, RS	3	S1 / G2	Steel truss erection; 1 skilled + 2 general
R02	Roof covering and waterproofing (roof tile)	TC, PF, PP, RS	3	S1 / G2	Tile lay + waterproofing membrane
A01	Masonry walls — AAC block (ext. + int.)	TC, PF	2	S1 / G1	Blocklayer + general labourer
A02	Plastering (internal + external walls, 12mm)	TC, PF	2	S1 / G1	Plasterer + general
A03	Doors and windows installation	TC, PF, PP, RS	2	S1 / G1	Carpenter/fitter + general
A04	Floor finishes (ceramic tiling)	TC, PF, PP, RS	2	S1 / G1	Tiler + general
A05	Ceiling installation (suspended ceiling)	TC, PF, PP, RS	2	S1 / G1	Ceiling installer + general
A06	Painting works (interior + exterior)	TC, PF, PP, RS	2	S1 / G1	Painter + general
A07	Facade cladding installation	TC, PF, PP, RS	2	S1 / G1	Dryliner/cladder + general
RS01	Remove existing roof covering	RS	2	S1 / G1	Careful removal to reuse tiles where possible
RS02	Dismantle existing roof structure	RS	3	S1 / G2	Structural dismantle; extra general for debris
RS03	Remove existing floor finishes (tile hacking)	RS	2	S1 / G1	Electric chisel + general clearing
RS04	Substrate preparation / leveling (screed)	RS	2	S1 / G1	Screeder + general
RS05	Demolish existing AAC wall partition (Living Area)	RS	2	S1 / G1	Manual AAC demolition; lightweight, no heavy equipment
RS07	New AAC block partition (Living Area, per gridline)	RS	2	S1 / G1	Same as A01; internal partition only

Source: Adapted by thesis author

2.6.2 COST INPUT: MATERIAL, LABOUR, EQUIPMENT, AND TRANSPORTATION

Material Cost Input

Material costs are sourced from official government databases supplemented by private sector rates where government data is unavailable. The primary source is the Comptroller General's Department of Thailand (สำนักงาน บัญชีกลาง), which monthly publishes standardized construction material pricing. The database contains around 4,400 items grouped into ten categories.

- Ready-mixed concrete
- Concrete aggregates and cement
- Structural steel and reinforcement bars
- Timber and lumber products
- Bricks, tiles, and ceramic products
- Gypsum boards and lightweight wall materials
- Paint, adhesives, and finishing materials
- Electrical and plumbing fixtures
- Insulation and waterproofing materials
- Glass and glazing products

Table 2.15 – Material cost database

Price Period: October 2025 (B.E. 2568)

Office of Trade Policy and Strategy, Ministry of Commerce

Note: Users of this price data must continuously monitor updates and announcements, as previously published prices may be revised.

Construction material prices shown are **central market prices (cash price, excluding VAT and excluding transportation cost).**

File download date: 11 November 2025, 22:55:26

Category Code	Category Name	Item Code	Item Description	Unit	Price (THB)
03	ชิ้นส่วนโครงสร้างสำเร็จรูป	0307010100500000	พื้นคอนกรีตสำเร็จรูปอัดแรง ชนิดกลวง ลวด 4 เส้น กว้าง 1.20 เมตร หนา 15 ซม. ศก. 3/8" ตราชีแพค	ตร.ม.	431.48
03	ชิ้นส่วนโครงสร้างสำเร็จรูป	0307010100600000	พื้นคอนกรีตสำเร็จรูปอัดแรง ชนิดกลวง ลวด 5 เส้น กว้าง 1.20 เมตร หนา 15 ซม. ศก. 3/8" ตราชีแพค	ตร.ม.	443.35
03	ชิ้นส่วนโครงสร้างสำเร็จรูป	0307010100700000	พื้นคอนกรีตสำเร็จรูปอัดแรง ชนิดกลวง ลวด 4 เส้น กว้าง 1.20 เมตร หนา 20 ซม. ศก. 3/8" ตราชีแพค	ตร.ม.	490.85
03	ชิ้นส่วนโครงสร้างสำเร็จรูป	0307010100800000	พื้นคอนกรีตสำเร็จรูปอัดแรง ชนิดกลวง ลวด 5 เส้น กว้าง 1.20 เมตร หนา 20 ซม. ศก. 3/8" ตราชีแพค	ตร.ม.	498.77
03	ชิ้นส่วนโครงสร้างสำเร็จรูป	0307010100900000	พื้นคอนกรีตสำเร็จรูปอัดแรง ชนิดกลวง ลวด 4 เส้น กว้าง 1.20 เมตร หนา 25 ซม. ศก. 3/8" ตราชีแพค	ตร.ม.	573.98
03	ชิ้นส่วนโครงสร้างสำเร็จรูป	0307010101000000	พื้นคอนกรีตสำเร็จรูปอัดแรง ชนิดกลวง ลวด 5 เส้น กว้าง 1.20 เมตร หนา 25 ซม. ศก. 3/8" ตราชีแพค	ตร.ม.	581.90

Source: Comptroller General's Department of Thailand (สำนักงานนโยบายและยุทธศาสตร์การค้า กระทรวงพาณิชย์), October 2024.

All prices use Thai Baht per unit (THB/unit) on a cash basis, excluding Value Added Tax (VAT) and transportation costs. The dataset is maintained in an Excel spreadsheet where items are organized by material type with relevant specifications (for example, concrete strength grade, timber dimensions, and steel grade). Where government prices are unavailable or outdated, supplier quotations are collected and used as substitute values. The database is updated quarterly, or whenever new government price announcements are released, to reflect prevailing market conditions.

Labour Cost Input

Labour rates are sourced from the **Wage Committee Announcement on Skilled Labour Wages (No. 13)**, issued by the Ministry of Labour, Thailand (January 2023). This document specifies minimum daily wage rates (THB/day per worker) for certified skilled construction workers, categorized by trade type and skill level which you can see on Table 2.16.

Table 2.16 - Labour Trade Categories and Skill Levels

Trade Category	Skill Level 1	Skill Level 2	Skill Level 3
Structural and Architectural Trades			
Bricklayer (Masonry)	410	530	645
Plasterer	455	565	675
Carpenter (Construction)	445	595	685
Aluminium Installer	435	545	650
Terrazzo Worker	470	–	–
Lightweight Wall and Finishing Trades			
Gypsum Board Installer	485	595	–
Gypsum Plasterer	470	–	–
Lightweight Concrete Block Installer (AAC)	510	625	–
Wall and Floor Tiler	485	580	685
Building Painter	500	640	–
Roofing Works			
Concrete Roof Tile Installer	470	590	685
Building Systems			
Electrician (construction-related)	440	530	–
Plumbing / Pump and Valve Technician	515	–	–

Source: Wage Committee Announcement on Skilled Labour Wage Rates (No. 12), dated 10 January B.E. 2566 (2023).

Equipment Cost Input

Equipment costs represent rental or hire rates for construction machinery commonly used in building projects. Equipment costs are sourced from private sector rental companies and market-based quotations, as no official government-published equipment rental rates exist.

- **Boom Trucks** (If required working radius is < 10m)
    - 3 ton: 4,500 to 5,500 THB/day (steel and precast small elements)
    - 5 ton: 5,000 to 6,000 THB/day (precast column, or beam lifting and installation)
    - 8 ton: 6,000 to 7,000 THB/day (heavier components on low-rise sites)
    - 10 ton: 7,000 to 8,000 THB/day (wall panel installation)
- **Mobile Crane:** (If required working radius is > 10m)
    - 10 to 15 ton: 5,000 to 6,000 THB/day (wall panel installation when radius exceeds 10 m)
    - 25 to 30 ton: 8,000 to 10,000 THB/day (very constrained sites requiring long reach, frequent heavy lifts)
- **Excavator (Backhoe)**
    - PC-30: 3,500 to 4,000 THB/day (small trenching and utilities)
    - PC-60: 5,500 to 6,000 THB/day (general site excavation, footing and slab preparation)
- **Roller (Compactor)**
    - to 5 ton: 4,500 to 5,500 THB/day (soil compaction for small areas)
    - 8 ton: 7,500 to 8,500 THB/day (road base compaction)
- **Tractor / Bulldozer**
    - D2: 5,500 to 6,000 THB/day (light pushing and grading)
    - D4: 6,500 to 7,000 THB/day (medium earthmoving)
    - Grader: 8,000 to 12,000 THB/day (leveling and fine grading)
- **Concrete Pump (Ready-mix concrete with pumping service)**
    - 280 KSC: 3,016 THB/cu.m. (ready-mix concrete with Easy Pump service)
    - 320 KSC: 3,100 THB/cu.m. (ready-mix concrete with Easy Pump service)
    - 350 KSC: 3,150 THB/cu.m. (ready-mix concrete with Easy Pump service)

Note: Concrete unit prices with pumping service are based on CPAC Easy Pump price list. Rates may vary by location, supplier, and site conditions.

Transportation Cost Input

Transportation costs cover the hire of dump trucks and other material haulage vehicles used to transport construction materials to project sites. Rates are derived from private sector market quotes and adjusted for current fuel costs which you can see on Table 2.17.

Table 2.17 - Dump Truck Rental daily Rates for Earthwork

TRUCK TYPE	VOLUME CAPACITY (M^3)	LOAD CAPACITY (TONS)	RATE (THB/DAY)	TYPICAL USE
6-WHEEL SMALL	3 m^3	4.5 tons	2,500–3,000	Small site hauling
6-WHEEL MEDIUM	5 m^3	7.5 tons	3,000–4,000	Medium excavation works
6-WHEEL LARGE	7 m^3	10.5 tons	3,500–4,500	Heavy soil transport
10-WHEEL	10 m^3	15 tons	6,000–7,000	Bulk earthwork hauling

Source: Private sector market quotations and Comptroller General's Department standards (adjusted for 2025 fuel costs).

Table 2.18 - Truck Rental rate per trip

Truck Type	Min (THB/trip)	Rate (THB/km)	Cost Logic	Notes
4-Wheel Large Pickup (Jumbo)	300	16.5	Trips × MAX(300 , Dist×2×16.5)	Doors, MEP, light finish items
6-Wheel Truck (Dump/Flatbed)	500	24	Trips × MAX(500 , Dist×2×24)	AAC block, soil, tiles, roofing
10-Wheel Truck	1000	34	Trips × MAX(1000 , Dist×2×34)	Precast elements, rebar
6-Wheel Dump – Waste Disposal	700–900 flat	800	Trips × 800 (flat rate)	No per-km charge
Ready-Mix Concrete Mixer	In material price	0	0 THB	Billed by concrete supplier

Source: Private sector logistics service provider rate card, Move Home Thailand (retrieved from the company website: https://movehomethailand.com/rates/

From Table 2.18, The MAX() function ensures that the base fee functions as a minimal floor: if the distance-based cost is lower than the base charge, the base charge applies. This reflects industry practice in Thailand where haulage companies set a minimum trip price regardless of distance. The truck types and their applicable rates, updated for 2026, are summarized in the reference table below.

Data Integration and Implementation

All unit cost inputs (materials, labour, equipment, transportation) are consolidated into a structured Excel database linked to the BIM cost estimation module. This database enables:

- Dynamic cost calculations based on current unit rates
- Rapid cost updates when government or market rates change
- Traceability of cost sources for audit and compliance purposes
- Consistency across multiple project estimates
- Generation of cost reports with transparent rate documentation

The cost input framework supports UC2: 5D cost estimation (Section 3.2.2) by providing accurate, legally compliant, and market-responsive unit rates that reflect current Thai construction market conditions. Regular updates to this database are performed to maintain estimate accuracy and relevance.

2.6.3 TRANSPORTATION ASSUMPTIONS AND DISTANCE

Transportation cost is a component of the total construction cost that varies significantly depending on the type of material, order quantity, delivery arrangement, and distance from the supply source to the construction site. In this study, transportation costs are estimated for a 150 m² two-story single-family house located in Pathumthani Province, Thailand which you can see on Figure 2.42. All suppliers are assumed to be within the same province or the immediate metropolitan fringe.

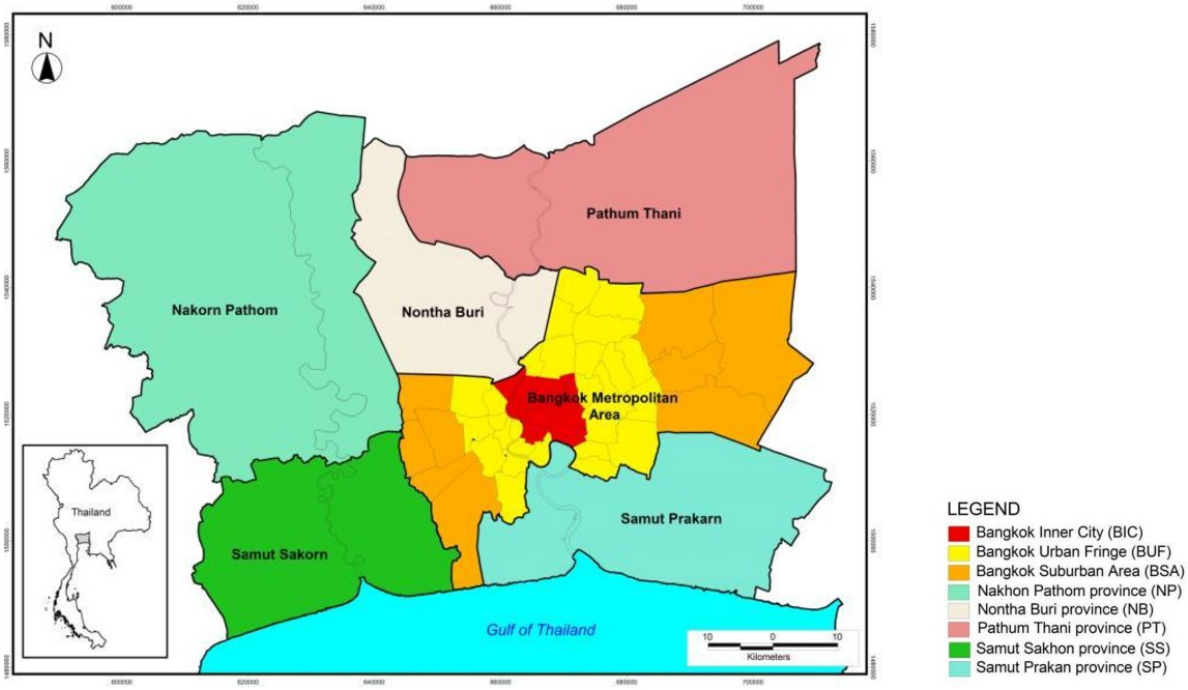


Figure 2.42 - Map of the Bangkok Metropolitan Region (BMR)

Source: D. Rinchumphu, 2021

Distance Assumptions.

Supply-to-site distances are assigned by material category based on the availability of suppliers within Pathumthani Province.

- Ready-mix concrete plants are assumed to be within 10 km of the site. This reflects the maximum practical batching radius to maintain workability.
- Precast concrete materials are produced from a provincial precast producer at an assumed one-way distance of 25 km. This relates to the reported location of precast suppliers in the Pathumthani area.
- General structural and finishing materials are similarly assumed to be available within 25 km from local distributors.
- Roofing materials, including the primary steel truss and roof tiles, are assigned a distance of 30 km to reflect sourcing from the Rangsit–Lak Hok industrial corridor.
- Waste and construction debris are assumed to be disposed of at a licensed dump site within 15 km of the project site.

Number of Trips.

The number of delivery trips required for each activity is calculated by the ratio of the estimated quantity to the truck capacity:

$$\boldsymbol{Number\ of\ Trips} = \lceil \boldsymbol{Estimated\ Quantity} \div \boldsymbol{Truck\ Capacity} \rceil$$

This ensures that partial loads are rounded up to a full trip. Truck capacities are defined per vehicle type: 4 m^3 per trip for 6-wheel dump trucks used in earthwork, 6 m^3 per trip for ready-mix concrete mixers, and weight- or area-based capacities for precast and finishing material deliveries.

Exempted Items.

- Finishing and MEP materials (including ceramic floor tiles, ceiling systems, gypsum board, paint, insulation, doors, glazing, electrical conduit, sanitary fixtures, and plumbing fittings) are assumed to be procured directly from manufacturers or authorised distributors in bulk quantities. Under this standard commercial arrangement, delivery to site is included in the supplier's unit price and is not charged separately. Accordingly, transport costs for these items are set to zero in the cost model. The calculated costs are retained in the schedule for reference purposes and are clearly flagged as exempted.
- Ready-mix concrete delivery is handled directly by the concrete batching plant and the haulage cost is incorporated within the concrete unit price quoted per cubic metre. No separate transport charge is therefore applied to concrete deliveries. The number of mixer truck trips is recorded in the schedule to support sequencing analysis under UC1 but contributes zero cost to the UC2 transportation total.

Waste Disposal

Construction waste disposal is handled by 6-wheel dump trucks at a flat rate of 800 THB per trip, representing the mid-point of the prevailing market range of 700–900 THB per trip for waste haulage in the Bangkok metropolitan region. Four disposal activities are identified across the construction programme: formwork and timber waste at the end of the structural stage, mid-project general waste, final project cleaning, and disposal of concrete offcuts and rejected precast elements.

Table 2.19 - Transportation schedule for UC2 and UC 3

TRANSPORTATION COST SCHEDULE — 150 m² Single-Family House, 2 Storeys | Pathumthani Province

Cost formula: Trips × MAX(Base Charge, One-Way Dist × 2 × Rate/km) | Source: Move Home Thailand rate card (movehomethailand.com/rates/) | Waste: flat 800 THB/trip | Ready-mix: 0 THB (included in concrete price) | Exempted: Finishing & MEP — delivery included in bulk purchase unit price

WBS Code	Activity Name	Description / Basis of Estimate	Est. Qty	Unit	Truck Cap.	Cap. Unit	Truck Type	Base Charge (THB)	Rate (THB/km)	One-Way Dist. (km)	No. of Trips	Calculated Cost (THB)	Exempted (Y/N)
EARTHWORK & EXCAVATION													
S01	Site clearing & setting out	Surface clearing, topsoil strip ~0.15m | 150 m² footprint	22.5	m³	4	m³/trip	6-Wheel Truck (Dump/Flatbed)	500	24	25	6	7,200	N
S02	Excavation soil disposal	Foundation trench + pad footing | net disposal ~18 m³ after backfill	18.0	m³	4	m³/trip	6-Wheel Truck (Dump/Flatbed)	500	24	25	5	6,000	N
S03	Backfill import (compacted fill)	Sub-base fill for ground-floor slab | ~10 m³	10.0	m³	4	m³/trip	6-Wheel Truck (Dump/Flatbed)	500	24	25	3	3,600	N
READY-MIX CONCRETE DELIVERY													
S03b	Blinding concrete (lean concrete 50mm)	Ready-mix 6 m³/load | 0.5 m³ → 1 trip | transport included in concrete price	0.5	m³	6	m³/trip	Ready-Mix Concrete Mixer	0	0	10	1	0	Y*
S04	Footing concrete (RC)	Strip + pad footings ~8 m³	8.0	m³	6	m³/trip	Ready-Mix Concrete Mixer	0	0	10	2	0	Y*
S05	Ground beam concrete (RC)	~5 m³	5.0	m³	6	m³/trip	Ready-Mix Concrete Mixer	0	0	10	1	0	Y*
S07	Slab-on-grade concrete (150mm)	~16 m³ incl. waste allowance	16.0	m³	6	m³/trip	Ready-Mix Concrete Mixer	0	0	10	3	0	Y*
ST01	RC columns 1F concrete	~2 m³	2.0	m³	6	m³/trip	Ready-Mix Concrete Mixer	0	0	10	1	0	Y*
ST02	RC beams 1F concrete	~4 m³	4.0	m³	6	m³/trip	Ready-Mix Concrete Mixer	0	0	10	1	0	Y*
ST03	RC suspended slab 1F (150mm)	~12 m³	12.0	m³	6	m³/trip	Ready-Mix Concrete Mixer	0	0	10	2	0	Y*
ST04	RC columns 2F concrete	~2 m³	2.0	m³	6	m³/trip	Ready-Mix Concrete Mixer	0	0	10	1	0	Y*
ST05	RC beams 2F concrete	~3 m³	3.0	m³	6	m³/trip	Ready-Mix Concrete Mixer	0	0	10	1	0	Y*
ST06	RC roof slab concrete (150mm)	~10 m³	10.0	m³	6	m³/trip	Ready-Mix Concrete Mixer	0	0	10	2	0	Y*
REINFORCEMENT STEEL													
RB01	Rebar delivery (all structural)	10–25mm dia. bars | total ~4,500 kg | 10-wheel flatbed	4,500.0	kg	10000	kg/trip	10-Wheel Truck	1,000	34	25	1	1,700	N
PRECAST ELEMENTS													
F01	Precast floor slab delivery	YELLO / local precast | hollow-core 0.35×0.05m | 2F floor ~75 m² | 66 m²/truck	75.0	m²	66	m²/trip	10-Wheel Truck	1,000	34	25	2	3,400	N
V01	Precast wall panel delivery	~80 m² external walls | 10-wheel flatbed | ~40 m²/trip	80.0	m²	40	m²/trip	10-Wheel Truck	1,000	34	25	2	3,400	N
P02	Precast column delivery	~10 pcs | 5 pcs/trip (weight constraint)	10.0	pcs	5	pcs/trip	10-Wheel Truck	1,000	34	25	2	3,400	N
P03	Precast beam delivery	~14 pcs | 4 pcs/trip	14.0	pcs	4	pcs/trip	10-Wheel Truck	1,000	34	25	4	6,800	N
MASONRY & WALL BLOCK													
A01	AAC block — 1F external walls	AAC 7.5cm thick | ~60 m² → 4.5 m³ | 6-wheel 3 m³/trip	4.5	m³	3	m³/trip	6-Wheel Truck (Dump/Flatbed)	500	24	25	2	2,400	N
A02	AAC block — 2F external walls	~55 m² → 4.1 m³	4.1	m³	3	m³/trip	6-Wheel Truck (Dump/Flatbed)	500	24	25	2	2,400	N
A03	AAC block — 1F internal partitions	~40 m² → 3.0 m³	3.0	m³	3	m³/trip	6-Wheel Truck (Dump/Flatbed)	500	24	25	1	1,200	N
A04	AAC block — 2F internal partitions	~35 m² → 2.6 m³	2.6	m³	3	m³/trip	6-Wheel Truck (Dump/Flatbed)	500	24	25	1	1,200	N
ROOFING MATERIALS													
R01	Steel box truss delivery	Primary roof structure | ~160 kg | 6-wheel flatbed	160.0	kg	3000	kg/trip	6-Wheel Truck (Dump/Flatbed)	500	24	30	1	1,440	N
R02	Roof tile delivery (ceramic/concrete)	~85 m² | boxed | 50 m²/trip	85.0	m²	50	m²/trip	6-Wheel Truck (Dump/Flatbed)	500	24	30	2	2,880	N
FINISHING MATERIALS													
A05	Timber door & frame delivery	Pre-hung sets | 6 pcs | jumbo 3 pcs/trip	6.0	pcs	3	pcs/trip	4-Wheel Large Pickup (Jumbo)	300	16.5	25	2	*1,650*	Y
A06	Ceramic floor tile delivery	~150 m² | boxed | 6-wheel 40 m²/trip	150.0	m²	40	m²/trip	6-Wheel Truck (Dump/Flatbed)	500	24	25	4	*4,800*	Y
A07	Ceiling board & grid delivery	Gypsum + exposed grid | ~140 m² | 50 m²/trip	140.0	m²	50	m²/trip	6-Wheel Truck (Dump/Flatbed)	500	24	25	3	*3,600*	Y
A08	Paint & primer delivery	Emulsion 3 coats | ~300 m² | 200L drums | jumbo 1 trip	300.0	m²	300	m²/trip	4-Wheel Large Pickup (Jumbo)	300	16.5	25	1	*825*	Y
GY01	Gypsum board & lightweight wall delivery	Internal wall lining | ~60 m² | 30 m²/trip	60.0	m²	30	m²/trip	6-Wheel Truck (Dump/Flatbed)	500	24	25	2	*2,400*	Y
IN01	Insulation & waterproofing delivery	Roof insulation + WP membrane | 1 pallet | jumbo	1.0	lot	1	lot/trip	4-Wheel Large Pickup (Jumbo)	300	16.5	25	1	*825*	Y
GL01	Glass & glazing delivery	Window units ~6 pcs | fragile | jumbo 1 trip	6.0	pcs	6	pcs/trip	4-Wheel Large Pickup (Jumbo)	300	16.5	25	1	*825*	Y
MEP MATERIALS													
M01	Electrical conduit & wiring delivery	UPVC 20mm conduit + cable | boxes/pallets | jumbo 1 trip	1.0	lot	1	lot/trip	4-Wheel Large Pickup (Jumbo)	300	16.5	25	1	*825*	Y
M02	MEP fixtures & final installation delivery	Sanitary ware, DB box, sockets, switches | jumbo 1 trip	1.0	lot	1	lot/trip	4-Wheel Large Pickup (Jumbo)	300	16.5	25	1	*825*	Y
PL01	Plumbing pipe & fitting delivery	PVC/PPR pipes + fittings | jumbo 1 trip	1.0	lot	1	lot/trip	4-Wheel Large Pickup (Jumbo)	300	16.5	25	1	*825*	Y
WASTE & CONSTRUCTION DEBRIS DISPOSAL													
WD01	Formwork & timber waste disposal	End-of-structure stage | ~3 m³	3.0	m³	4	m³/trip	6-Wheel Dump – Waste Disposal	800	0	15	1	800	N
WD02	General construction waste disposal	Mid-project | mortar bags, packaging | ~5 m³	5.0	m³	4	m³/trip	6-Wheel Dump – Waste Disposal	800	0	15	2	1,600	N
WD03	Final construction waste disposal	End-of-project cleaning | ~4 m³	4.0	m³	4	m³/trip	6-Wheel Dump – Waste Disposal	800	0	15	1	800	N
WD04	Concrete waste / broken block disposal	Offcuts + rejected precast | ~2 m³	2.0	m³	4	m³/trip	6-Wheel Dump – Waste Disposal	800	0	15	1	800	N

Source: Adapted by thesis author

2.6.4 CONSTRUCTION WASTE FACTOR

This study applies a construction waste factor to adjust model-based quantities before cost estimation (5D BIM) and, when relevant, material-related environmental calculations (6D BIM). The waste factor is material loss, which is primarily driven by cutting, breakage, handling, installation tolerances, and workmanship. Therefore, waste factors are assigned by material category (or element type, where appropriate) and applied directly to BIM-based quantities. The waste factors are applied from the Thai cost estimation manual. All of information was extracted into Table 2.20

Figure 2.43 - Cost Estimation Manual, Thailand



Source: Cost Estimation Manual issued by the Ministry of Interior (Thailand), Department of Public Works and Town and Country Planning[86].

Key rule used in this thesis: precast structural and precast panel elements are set to 0% waste, as they are factory-produced units delivered to the site as complete components. Any minor site losses for accessories (for example, joint grout and sealant) are either excluded or treated separately as an assumption, depending on data availability and modelling scope.

Table 2.20 - Construction Waste Factor

Work system (WBS)	Item (material category)	Min	Max	Allowance type
1. Substructure	Cast-in-situ concrete (blinding, footings, ground beams, ground slab)	**5%**	**10%**	Material waste (spillage, placement loss)
	Reinforcement steel SR D6	**5%**	**5%**	Rebar loss (laps, hooks, bending, cutting off-cuts)
	Reinforcement steel SR D9	**7%**	**7%**	Rebar loss
	Reinforcement steel SR D12	**9%**	**9%**	Rebar loss
	Reinforcement steel SR D15	**11%**	**11%**	Rebar loss
	Reinforcement steel SR D19	**13%**	**13%**	Rebar loss
	Reinforcement steel SD D10	**7%**	**7%**	Rebar loss
	Reinforcement steel SD D12	**9%**	**9%**	Rebar loss
	Reinforcement steel SD D16	**11%**	**11%**	Rebar loss
	Reinforcement steel SD D20	**13%**	**13%**	Rebar loss

2. Superstructure	Cast in-situ concrete (columns, beams, slabs, stairs)	**5%**	**10%**	Material waste
	Reinforcement steel (all bars by diameter as above)	**5%**	**15%**	Rebar loss (use exact % by diameter)
	Precast structural elements (PF/PP) (beams, slabs, stairs, columns)	**0%**	**0%**	Thesis rule (precast = 0)
	Precast wall panels (PP)	**0%**	**0%**	Thesis rule (precast = 0)
3. Roof structure	Roof steel members (standard lengths)	**3%**	**5%**	Cutting + stock-length rounding (roof-form dependent)
	Structural steel (general roof steelwork, if not using rule above)	**5%**	**10%**	Cutting and unusable off-cuts (practice)
	Roof tiles (concrete or fiber cement)	**3%**	**5%**	Breakage (roof-form dependent)
	Waterproofing/membrane (roll materials)	**5%**	**10%**	Overlaps + handling loss (practice)
4. Architectural works	Masonry units + mortar ingredients (brick/block + cement-sand mortar)	**3%**	**5%**	Cutting, breakage, site loss (assumption if manual not fixed)
	Plastering materials	**5%**	**10%**	Thickness variation + rework (practice)
	Floor finishes (tile/boards/screed-related finishes)	**5%**	**10%**	Cutting + breakage (practice)
	Ceiling boards/grid	**5%**	**10%**	Cutting + damage (practice)
	Painting materials	**5%**	**10%**	Loss in mixing, application, leftover (practice)
	Doors and windows (units)	**0%**	**2%**	Optional allowance (damage/adjustment)
5. MEP works	LV main conduit + main cable	**5%**	**10%**	Length allowance
	General conduits/pipes (water pipe, electrical conduit)	**10%**	**15%**	Cutting + joining + leftover segments
	Cable trays	**10%**	**15%**	Length allowance
	Power and signal cables	**15%**	**20%**	Length allowance

Source: Ministry of Interior (Thailand), Department of Public Works and Town and Country Planning, Cost Estimation Manual (Manual for Cost Estimation). Supplementary practice values are adopted where the manual does not specify a fixed allowance. Compiled by the thesis author.

2.6.5 EMISSION FACTORS

The emission factors applied in this Thailand-based study are derived from two primary databases as you can see on Figure 2.44. The selection is aligned with the life cycle stages considered within the system boundary, covering stages A1 through A5.

Figure 2.44 - Logos of the International EPD System and Thailand Greenhouse Gas Management Organization (TGO)

Source: EPD International AB, Brand assets (International EPD System logotype). ; Thailand Greenhouse Gas Management Organization (Public Organization), Logo (footer) on the T-VER platform website.

The EPD database represents the most comprehensive and internationally recognized source of product-level emission data, and notably includes Thai construction products such as Portland cement, Portland Bag Cement Type I (EPD-IES-0015828:002).



Figure 2.45 - International EPD® System library filtered for Thailand — showing example EPDs for Thai construction products such as SCG cement

Source: Portland cement Portland Bag Cement Type I (EPD-IES-0015828:002)

For materials not covered by the EPD database, **particularly precast concrete elements,** the second source is the Thailand Greenhouse Gas Management Organization (TGO) Carbon Footprint database (thaicarbonlabel.tgo.or.th). The TGO database encompasses both the Carbon Footprint of Products (CFP) and Carbon Footprint of Organization (CFO) certifications, covering more than 4,600 Thai construction products across the construction industry. This database is particularly valuable for products that lack an EPD, providing locally verified emission factors aligned with Thai manufacturing conditions and supply chains.

Figure 2.46 - Emission Factor of Precast Panel Concrete by Thai Manufacturer



Source: (TGO). (2023). Thai National Life Cycle Inventory (LCI). Retrieved from [https://thaicarbonlabel.tgo.or.th/index.php?lang=EN&mod=Y0hKdlpIVmpkSE5mWVhCd2NtOTJZV3c9&keyword=c%20panel]

The selection priority and allocation of emission factors to life cycle stages follow a structured hierarchy. For stages **A1–A3** (raw material extraction, transport to manufacturer, and manufacturing), EPD data is used as the primary source, supplemented by TGO CFP data where EPD coverage is unavailable. For stages **A4–A5** (transport to site and construction installation), TGO CFO data is applied, as this stage is predominantly governed by on-site construction energy consumption and equipment use that is better characterised by organisation-level carbon footprint assessments in the Thai context. This tiered approach ensures that emission factors are both locally representative and methodologically consistent with the declared unit and system boundary of each data source as an example in Table 2.21.

Table 2.21 - Emission factor for Transportation in Thailand

#	Name	Description	Unit	Emission Factor ($kgCO_2e$/unit)	Reference Source	Update Date
45.	Small 4-wheel cargo truck Normal driving, 75% Loading	Max load 1.5 tons; Diesel fuel; LCIA method IPCC 2013 GWP 100a V1.03	tkm	0.2706	Thai National LCI Database, TIIS-MTEC-NSTDA (with TGO electricity 2016-2018)	Update_Dec2019
46.	Small 4-wheel cargo truck Normal driving, 100% Loading	Max load 1.5 tons; Diesel fuel; LCIA method IPCC 2013 GWP 100a V1.03	tkm	0.2154	Thai National LCI Database, TIIS-MTEC-NSTDA (with TGO electricity 2016-2018)	Update_Dec2019
47.	Small 4-wheel cargo truck Mixed driving, 0% Loading	Max load 1.5 tons; Diesel fuel; LCIA method IPCC 2013 GWP 100a V1.03	km	0.3091	Thai National LCI Database, TIIS-MTEC-NSTDA (with TGO electricity 2016-2018)	Update_Dec2019
48.	Small 4-wheel cargo truck Mixed driving, 50% Loading	Max load 1.5 tons; Diesel fuel; LCIA method IPCC 2013 GWP 100a V1.03	tkm	0.4695	Thai National LCI Database, TIIS-MTEC-NSTDA (with TGO electricity 2016-2018)	Update_Dec2019

Source: (TGO). (2019). Thai National Life Cycle Inventory (LCI) . Retrieved from [https://thaicarbonlabel.tgo.or.th/index.php?lang=EN&mod=Y0hKdlpIVmpkSE5mWlcxcGMzTnBiMjQ9]

2.7 GAPS AND LIMITATIONS

From the detailed literature review, the identified gaps and limitations are:

- **Limited Integration between the construction scenario and LCA:** [87]Most model-based studies in Thailand predominantly focus on traditional in-situ construction methods. In addition, LCA studies on prefabricated construction in the Thai context often concentrate on the factory production stage, without fully accounting for the entire construction process[88], [89], [90]. Therefore, there are some factors insufficiently addressed for LCA in the construction process, such as transportation frequency, on-site assembly by machine activities, and construction waste.
- **Lack of integrated comparison between cost, time, and LCA performance:** [87]Although LCA studies for buildings in Thailand, particularly single-family housing, are increasingly available, they are often conducted independently from cost and construction time analyses. This incoordination analysis limits the clear benefit for investors, who require evidence to support sustainable decision-making. [91]Recent financial incentives and newly introduced Thai green building standards for residential structures highlight the necessity for evaluation frameworks
- **Material LCA Data Availability and Accuracy:** The availability of local material LCA databases remains limited because only a few manufacturers can invest in producing an environmental product declaration (EPD) for export products to the international market[92]. So, the existing databases vary in terms of data sources, system boundaries, and accuracy. Such variability can reflect in fluctuating embodied carbon outcomes, reducing the reliability of the decision-support tool. Addressing this limitation requires improved standardization and regional adaptation of material datasets[93].
- **Uncertainty in the cost structure of prefabricated construction:** Previous studies by McKinsey & Company on modular construction indicate that prefabrication can be either more or less cost-effective depending on project-specific factors and implementation strategies [68]. However, empirical studies on the critical cost-driving activities in prefabricated construction within the Thai context remain unclear and might overclaim as a cost-saving technique[58].
- **Software interoperability and BIM-based data integration:** While IFC provides a standardized format for openBIM data exchange and visualization, its application for downstream modification and advanced analyses, such as 4D scheduling, 5D cost estimation, and 6D environmental assessment, remains constrained [94]In 4D workflows, incomplete synchronization between models and scheduling platforms may reduce simulation reliability. In 5D environments, the lack of hidden cost integration constrains the cost updates. As a result, many BIM analyses still depend on semi-manual data validation on external software, increasing the risk of inconsistency and limiting reproducibility.

3

Methodology

3.1 OVERALL RESEARCH FRAMEWORK

This research conducts a comparative analysis of residential construction scenarios in Thailand, including traditional in situ reinforced concrete (TC), precast structural frame (PF), precast structural panel (PP), and renovation scenario (RS). Building Information Modelling (BIM) is adopted as the central analytical platform to ensure data consistency and transferability across analytical dimensions.

The model-based methodology is structured around three analytical layers: 4D BIM for construction duration, 5D BIM for construction cost estimation, and 6D BIM for environmental impact assessment. In this study, BIM functions as an integrated data environment in which geometric, material property, and parametric information are linked to scheduling, cost estimation, and life cycle assessment processes via software plugins, cloud-based platforms, or external analytical tools.

The research framework follows a sequential logic.

- Each BIM model is developed for a specific construction scenario to ensure compatibility. Model elements are developed at an appropriate Level of Development, with this research adopting LOD 350 to enable reliable quantity extraction across different material and construction activities.
- The geometric elements are mapped to the productivity rate of labour and machines, to the estimated duration, and to sequencing in a 4D environment.
- Quantity takeoff (QTO) is combined with construction activity and local material prices to estimate construction costs in a 5D workflow.
- Material quantities are mapped to environmental impact factors within defined system boundaries A1 to A5, enabling embodied carbon calculation through a 6D assessment approach for the production stage comparison.

To ensure reliable comparison, the same location, size, and layout of the building are similar across all construction system typologies. So, differences in the result of construction time, cost, or environmental impact are caused by differences in construction techniques, not by differences in architectural design. Key input parameters in this framework, including labour rates, productivity assumptions, transport distances, and environmental datasets, are standardized and transparently defined. This methodological approach establishes a structured basis for evaluating construction system performance within the Thai residential context.

3.2 USE CASES FRAMEWORK

Specifies each use case (UC1–UC3) by defining its analytical objective, required inputs, processing logic, and expected outputs in relation to construction time, cost, and embodied carbon.

3.2.1 UC1: SCHEDULING (4D)

UC1 develops a productivity-based construction schedule directly linked to the BIM model to compare different construction systems for a single-family house. The objective is not merely to visualize the construction sequence, but to derive activity durations from measurable production rates and extracted BIM quantities. The resulting schedule provides:

(1) total construction duration,

(2) phase-based duration distribution, and

(3) a consistent time reference for cost estimation (UC2) and environmental assessment (UC3).

Work Breakdown Structure (WBS)

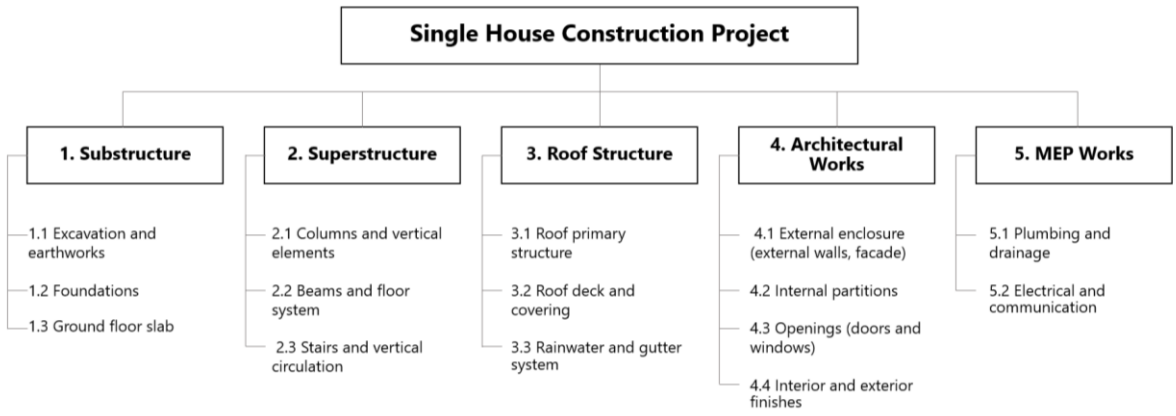


Figure 3.1 – Example of Work Breakdown Structure (WBS) of single-family housing
Source: Thesis author

The construction schedule is organised through a Work Breakdown Structure (WBS) that splits the single-family house into major work packages. Each package is further divided into detailed activities reflecting the actual construction method of the system under analysis. The same WBS logic is maintained across all construction alternatives. This ensures that time differences arise exclusively from variations in construction methods and productivity rates, rather than from structural changes in task definition.

BIM elements in the Revit model are grouped by level, zone, and system type and then mapped to the corresponding WBS activities. This mapping ensures that each scheduled activity is associated with a well-defined set of model elements and quantities.

Table 3.1 - Activities information

Act ID	WBS_Code	Name of Activity	WBS	Predecessors
1	S01	Site clearing and setting out	1.0 Substructure – Site works	-
2	S02	Excavation (bulk + trench)	1.1 Substructure – Earthworks	1FS
3	S03	Blinding concrete	1.2 Substructure – Blinding	2FS
4	S04	Footings (rebar + concrete)	1.3 Substructure – Foundations	3FS
5	S05	Ground beams (rebar + concrete)	1.4 Substructure – Ground beams	4FS
6	S06	Backfilling and compaction	1.5 Substructure – Backfill	5FS
7	S07	Slab on grade	1.6 Substructure – Ground floor slab	6FS
8	ST01	Columns 1F (RC / precast install)	2.1 Superstructure – Columns	7FS
9	ST02	Beams 1F (RC / precast install)	2.2 Superstructure – Beams	8FS
10	ST03	Upper slab 1F construction	2.3 Superstructure – Floor slab	9FS
11	ST04	Columns 2F (RC / precast install)	2.4 Superstructure – Columns 2F	10FS
12	ST05	Beams 2F (RC / precast install)	2.5 Superstructure – Beams 2F	11FS
13	ST06	Roof slab / ring beam	2.6 Superstructure – Roof slab	12FS
14	ST07	Stair construction	2.7 Superstructure – Stairs	10FS
15	R01	Roof primary structure	3.1 Roof – Structure	13FS
16	R02	Roof covering & waterproofing	3.2 Roof – Covering	15FS
17	R03	Rainwater & gutter system	3.3 Roof – Drainage	16FS
18	A01	External walls (masonry / precast)	4.1 Architectural – External walls	10SS
19	A02	Internal partitions	4.2 Architectural – Internal walls	10SS
20	M01	MEP rough-in (electrical & plumbing)	5.1 MEP – Rough-in	18SS
21	A03	Doors & windows installation	4.3 Architectural – Openings	18FS
22	A04	Floor finishes	4.4 Architectural – Floor finishes	20FS
23	A05	Ceiling installation	4.5 Architectural – Ceiling	20FS
24	A06	Painting works	4.6 Architectural – Painting	22FS
25	M02	MEP fixtures & final installation	5.2 MEP – Final installation	24FS

Source: Thesis author

The activity list in Table 3.1 represents a typical work breakdown structure and sequencing logic for traditional cast-in-situ construction (TC) of a single-family house[95]. It is used in this thesis as a reference schedule for traditional construction. In the subsequent analysis, this baseline WBS is adjusted to reflect Thai construction practice, local productivity rates, and the different construction scenarios considered in this study. The Predecessors column follows standard Critical Path Method (CPM) notation:

FS (Finish to Start): the successor can begin only after the predecessor has finished.

- Ex: 4FS for Activity 5 → Footing reinforcement (Act. 5) can start only when Blinding concrete (Act. 4) is finished.

SS (Start to Start): Both activities can start in parallel; the successor is linked to the start of the predecessor.

- Example: 15SS+1d → Stair reinforcement can start 1 day after Upper slab reinforcement starts, so they overlap instead of waiting until it finishes.

FF (Finish to Finish): the finish of the successor is linked to the finish of the predecessor, so they end at roughly the same time.

- Example: 17FF for Stair concrete → it must finish at the same time as Upper slab concrete (Act. 17), even if it starts later.

SF (Start to Finish): Used less frequently; the predecessor cannot finish until the successor has started.

- Example: 25SF-2d → Door and window frames must start 2 days before External wall construction is allowed to finish (to ensure openings are prepared in time).

Productivity-based Duration Estimation

The planned duration of each activity in the WBS is derived from BIM-based quantities and construction productivity rates representative of Thai single-house practice. The duration **D** is calculated using the simple logical productivity relationship:

$$D = \frac{Q}{P \times n}$$

Where:

Q = quantity of work (m^2, m^3, pcs)

P = productivity (e.g., m^2/crew/day)

N = number of parallel crews

D = duration (days)

This approach ensures traceability between geometric quantities and time estimation. The schedule is therefore derived analytically rather than assumed.

Productivity rates and crew compositions are taken from consolidated construction productivity data and applied consistently unless a system-specific difference is required. For example, prefabricated wall panels may exhibit significantly higher installation rates compared to masonry brickwork. Such differences directly influence calculated durations while maintaining identical WBS structures.

For instance, if an external wall area of 40 m^2 is modelled in BIM, and masonry brickwork has a productivity of 0.2m^3 per crew per day, while prefabricated panels achieve 20 m^2 per crew per day with the same crew size

Example – prefabricated wall panels	Example – clay brick masonry wall
Q = 40 m^2 P = 20 m^2/labour/day N = 4 labourers D = 40 / (20 x 4) = 0.5 days	Q = 40 m^2 or (4 $m^{3;}$ if the wall is 0.1m thickness) P = 0.2 m^3/labour/day N = 4 labourers D = 4 / (0.2 x 4) = **5** days

Scheduling Logic and 4D Simulation

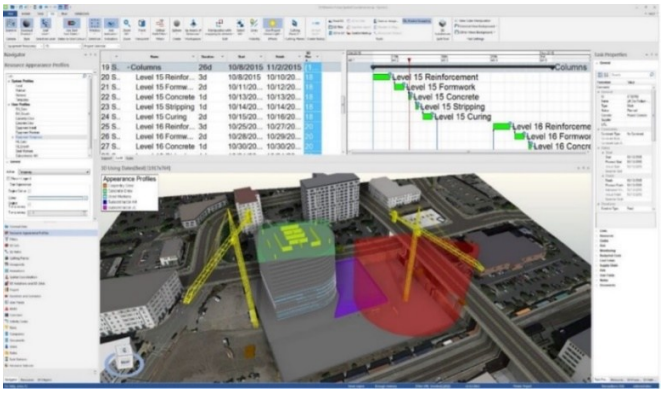


Figure 3.2 - 4D BIM simulation of the construction sequence
Source: 4D BIM Scheduling for Construction Logistics Management

As seen in Figure 3.3, once activity durations have been derived from BIM-based productivity calculations, precedence relationships and a standardized working calendar are applied to generate the project schedule. Activities are structured using Critical Path Method logic and implemented within scheduling software. A uniform working calendar is adopted for all construction alternatives to ensure analytical consistency. The finalized schedule is then linked to the BIM model to create a 4D simulation environment. Model elements, previously organized according to WBS codes, are exported in IFC or other 4D-compatible formats and grouped into selection sets corresponding to scheduled tasks. These sets are connected to activities within the 4D platform, enabling time-based visualization of the construction process.

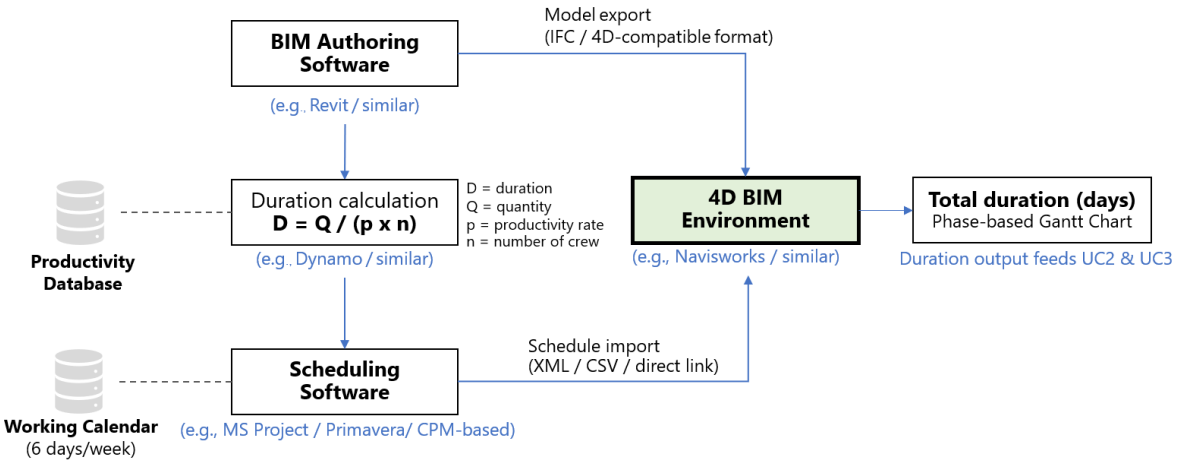


Figure 3.3 – Summary of 4D BIM workflow (UC1).
Source: Thesis Author

Beyond visualization, the 4D simulation serves as an analytical validation tool, enabling: verification of constructability and sequence feasibility, identification of logical conflicts or unrealistic overlaps, and comparison of workflow characteristics between conventional and prefabricated systems. The resulting total duration, phase distribution, and critical activities **provide structured input for UC2 and UC3.**

3.2.2 UC2: COST ESTIMATION (5D)

UC2 translates both material quantity and the time-based analysis of UC1 into a direct cost comparison of the alternative construction scenarios. The scope is limited to direct costs attributable to construction activities: materials, labour, equipment, and transportation. Indirect costs, such as overhead, profit, tax, financing, and design fees, are excluded so that the comparison reflects differences in construction logic rather than project-specific commercial conditions.

Cost categories and data sources

Four cost categories are considered in this study:

- **Material cost** covers the procurement of concrete, reinforcement, masonry, precast elements, finishes, and other construction products. Model quantities are adjusted using material-specific waste potential percentages (for example, cutting and bending losses of reinforcement) to obtain the ordered quantities. Unit prices are then applied to these adjusted quantities and are compiled from official national statistics and market surveys and stored in an external cost database.

$$C_material = Quantity(1 + waste\ rate) \times Price$$

- **Labour cost** is based on daily wage rates for skilled construction workers, classified by trade type and skill level in accordance with national wage regulations. These rates are expressed in Thai Baht per person per day and are applied to the crew compositions defined in UC1.

$$C_labour = Duration_activity \times Crew_size \times Wage_daily$$

- **Equipment cost** includes the rental of major construction machinery such as cranes, concrete pumps, excavators, and dump trucks. Benchmark rental rates are taken from government cost handbooks and updated to the study year using fuel and energy price indices.

$$C_equipment = Duration_equipment \times Rate_equipment$$

- **Transportation cost** covers the delivery of materials to the site and the removal of excavated soil and construction waste. In this study, transportation is modelled explicitly for bulk materials with significant logistical impact, namely excavated soil and heavy prefabricated elements transported from the factory. Transport of conventional components such as bricks, doors, and similar items is omitted, as these products are typically delivered free of charge or with negligible additional cost when ordered in standard quantities in the Thai residential construction context.

$$C_transport = Number\ of\ trips \times Rate_transport$$

where Rate_transport is expressed as a lump-sum rate per trip and already incorporates haul distance.

All unit rates are organized in an external cost database (for example, Excel files or PDF tables) grouped by material code, labour trade, equipment type, and transportation item. This database is not edited manually within the BIM software but is linked through an external calculation layer.

BIM-based demand: QTO

Material demand is defined through BIM-based quantity takeoff at LOD 350, enabling the extraction of quantities per element and per WBS activity. Revit schedules are used to obtain volumes, areas, weights, and counts, including transport-related quantities such as excavated soil or waste material. For materials subject to cutting or fabrication losses, allowance factors are applied to convert net model quantities into ordered quantities before cost calculation.

Schedule-based demand: UC1 scheduling

UC1 provides the temporal and resource framework for cost estimation. For each WBS activity, duration is derived from BIM quantities and productivity rates, together with crew size, equipment, and transport requirements. These outputs are linked to corresponding WBS codes in the BIM model. Labour, material transport, and equipment costs in UC2 are therefore directly dependent on the duration and resource demand established in UC1.

Data link and 5D cost environment

The integration of BIM quantities, the UC1 schedule, and the external cost database is implemented through a data link and an external calculation layer, such as Dynamo. This layer:

(1) maps material, labour, equipment, and transport items to database unit rates;

(2) combines unit rates with QTO and activity duration; and

(3) writes calculated costs back into the 5D cost environment.

From figure 3.4, the 5D environment may be represented by Revit cost schedules, Excel, or similar platforms storing cost parameters at the element or activity level. Activity-level direct cost is obtained by components, while scenario-level cost is calculated by aggregating across WBS activities.

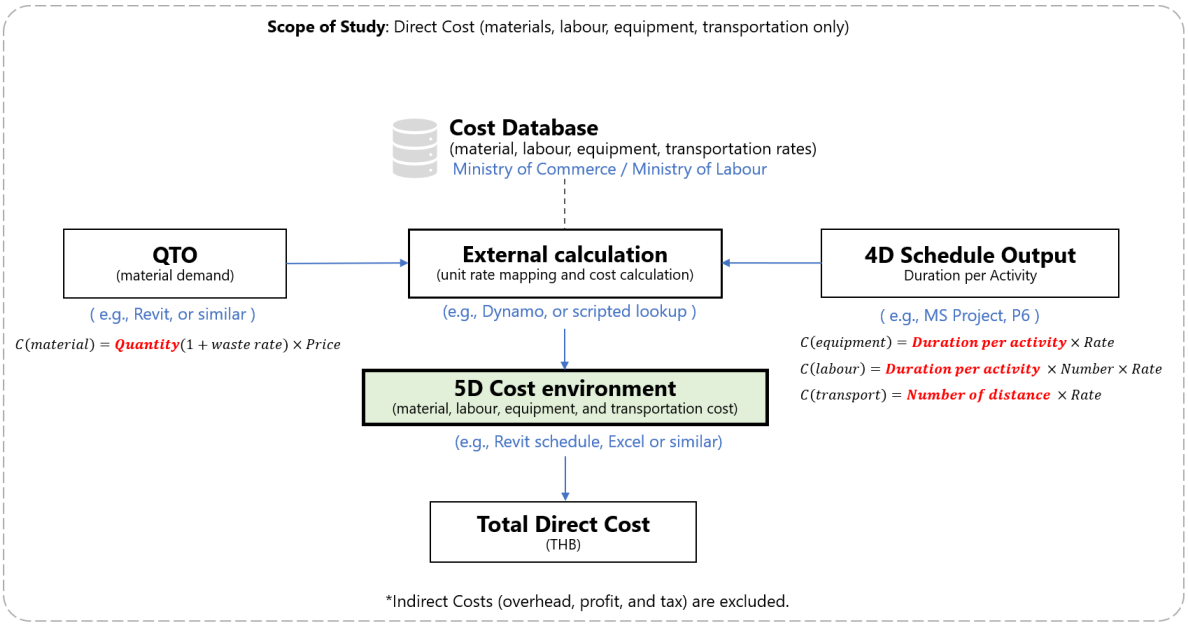


Figure 3.4 - Summary of 5D BIM workflow (UC2)
Source: Thesis author

3.2.3 UC3: ENVIRONMENTAL ASSESSMENT (6D)

UC3 establishes a BIM-integrated environmental assessment framework to quantify and compare the embodied carbon of alternative construction systems for the single-family and standardized emission factors, ensuring methodological consistency across all scenarios. The 6D assessment focuses on upfront embodied impacts and complements the time-based analysis (UC1).

System Boundaries (A1–A5)

The environmental scope is defined in accordance with EN 15804 +A2 and limited to modules A1–A5:

- **A1–A3:** raw material extraction, transport, and manufacturing
- **A4:** transport to the construction site
- **A5:** construction and installation processes

This cradle-to-handover boundary captures the embodied environmental impacts associated with material production and construction activities. Operational (B) and end-of-life stages (C) are excluded to isolate differences attributable solely to construction systems and material configurations. All construction alternatives are evaluated under identical system boundaries to ensure analytical comparability.

Data Sources and Localization Strategy

Environmental impacts are calculated using emission factors compliant with EN 15804 +A2 within a 6D BIM environment (e.g., One Click LCA).

Primary data sources prioritize **Thai national databases**, including:

- Carbon Footprint for Products (CFP) certified by the Thailand Greenhouse Gas Management Organization (TGO)
- Thai Environmental Product Declarations (EPDs)

For typical construction materials such as concrete, cement, steel, and insulation, Thai EPD datasets are generally available and reflect local manufacturing conditions and the national electricity grid mix. The use of localized data improves geographical relevance and reduces distortion caused by generic global datasets.

However, certain TGO-certified products are not directly integrated into international LCA software databases. In such cases, a structured substitution strategy is applied based on:

1. Equivalent production technology
2. Comparable energy system characteristics
3. Geographic proximity, prioritizing Southeast Asia

If no regional dataset is available, the closest EN 15804-compliant dataset is selected and documented transparently. This approach maintains methodological rigor while acknowledging database interoperability limitations.

Waste adjustment

Modules A1 to A3 is product stage which need to be added the waste rate to get an actual material were used.

$$Adjusted\ Quantity\ = BIM\ Quantity \times (1 + Waste\ Percentage)$$

Global warming potential impact

Both product stage (A1-A3) and construction phase (A4-A5) need to be calculated by quantity and emission factor base on it location which EF can be source from and external database or regional

$$GWP_{element} = Q_{adj} \times EF$$

Where:

GWP = Global Warming Potential per element

Q (adj)= Waste-adjusted quantity

EF = Emission factor obtained from EPD or national database

Integration within the BIM-Based Assessment Workflow

The 6D workflow integrates model data and environmental datasets within a structured digital framework:

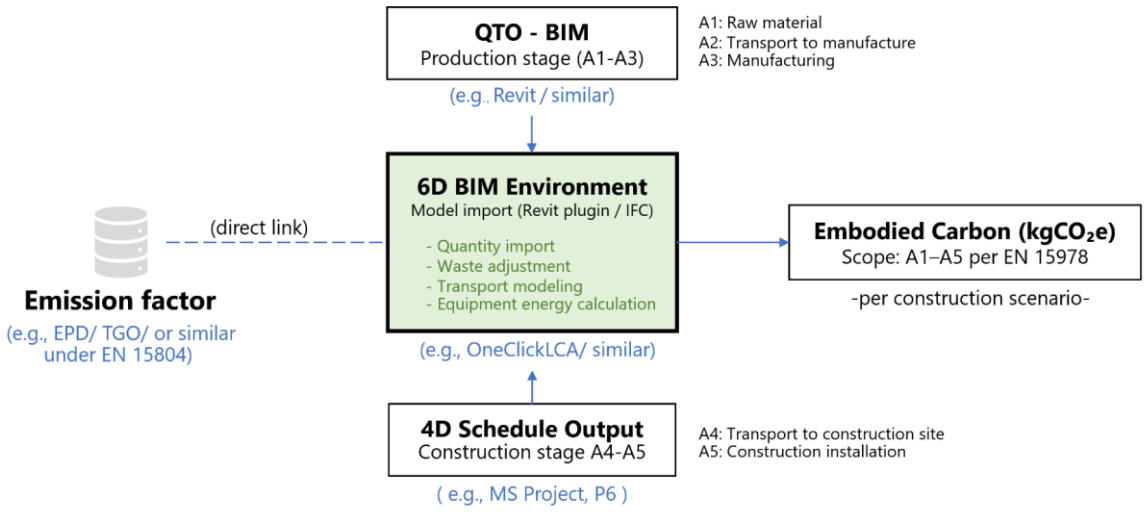


Figure 3.5 - Summary of 6D BIM workflow

Source: Thesis author

The primary output consists of total embodied carbon ($kgCO_2e$) per construction alternative, alongside module-based distribution across A1–A5. These results are subsequently interpreted in conjunction with duration (UC1) and cost (UC2) outcomes to support comparative performance evaluation.

3.2.4 UC4: INTEGRATED SYNTHESIS AND DECISION SUPPORT

UC4 synthesises the quantitative outputs of UC1–UC3 into a unified comparative framework to support evidence-based selection of the most appropriate construction technique under varying decision priorities. The use case does not generate new source data; it converts and integrates current outputs through two consecutive steps: performance normalisation, and trade-off assessment.

Performance Normalisation

To enable comparison across dimensions with different units and scales, all six performance indicators are expressed as a Performance Index relative to TC as the baseline scenario:

$$Performance\ Index_{\mathrm{i}} \ = \ (\ Value_{\mathrm{i}} \ / \ ValueTC\ ) \ \times \ 100$$

An index of 100 sets the baseline with TC. A value below 100 indicates that technique i outperforms TC on that dimension; a value above 100 indicates underperformance.

Six-Dimension Evaluation Framework

UC4 evaluates each scenario across six dimensions, all derived from BIM-based outputs of UC1–UC3. This ensures that every indicator is quantitatively grounded and free from subjective scoring. Table 3.2 presents the full Normalised Performance Matrix, specifying the unit, data source, and derivation formula for each dimension. Index values are representative placeholders; final values are reported in Chapter 5 following application to the case study.

Table 3.2 - Example: Normalised Performance Matrix: structure and simulated index values

Dimension	Unit	Src	Derivation	TC	PF	PP	RS
Index = (Value$_i$ / ValueTC) × 100 · TC = 100 (baseline) · ▼ outperforms TC · ▲ underperforms TC · Green = best; Orange = worst per dimension							
Construction Time	Working days	UC1	∑ Duration$_i$ across WBS activities	100 =	76 ▼	66 ▼	51 ▼
Direct Cost	THB	UC2	∑ (Material + Labour + Equipment + Transport)$_i$	100 =	109 ▲	119 ▲	67 ▼
Embodied Carbon (A1–A5)	$kgCO_2e$	UC3	∑ (Quantity$_i$ × Emission Factor$_i$) across materials and stages	100 =	92 ▼	86 ▼	52 ▼
Waste Ratio	% of total cost	UC2	Waste Cost / Total Direct Cost × 100	100 =	80 ▼	68 ▼	55 ▼
On-Site Labour	Person-days	UC1	∑ (Duration$_i$ × Crew Size$_i$) per WBS activity	100 =	72 ▼	50 ▼	85 ▼
Equipment Dependency	Crane-days	UC1	∑ (Duration$_i$ × Equipment Flag$_i$) for crane-dependent tasks	100 =	140 ▲	160 ▲	20 ▼

Source: Thesis Author

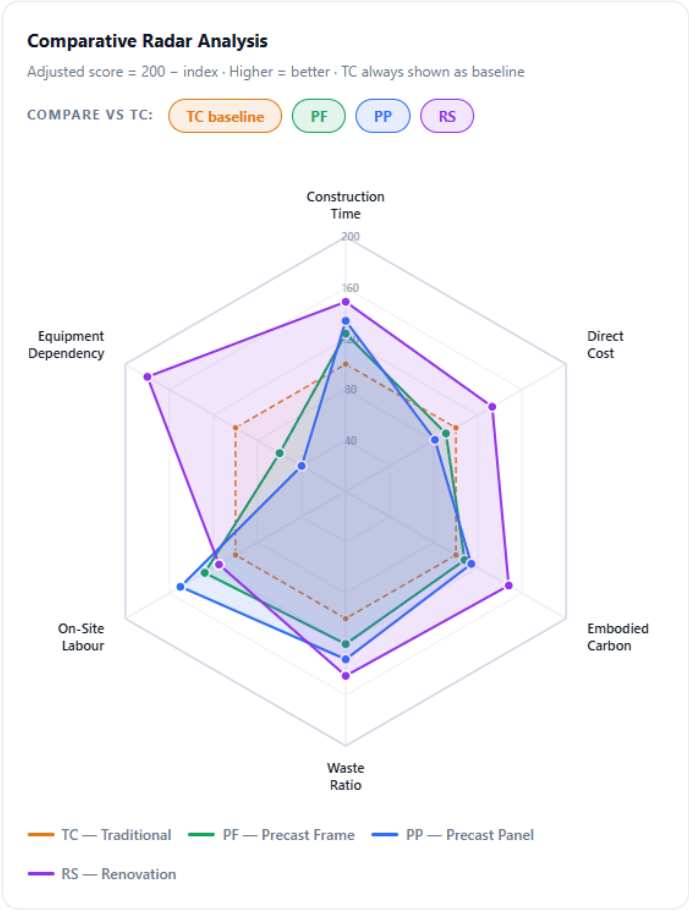
Trade-off Visualisation and Decision Support

The six-dimension comparison is visualised using a radar chart, in which each construction scenario is represented as a polygon across six axes. This forms part of the Multi-Criteria Decision Analysis (MCDA) framework implemented in UC4, where each technique constitutes an alternative and the six performance dimensions represent the evaluation criteria.

Prior to plotting, normalised indices are rescaled using ***Adjusted Score = 200 - Performance Index***, so that outward extent on every axis consistently denotes better relative performance. TC retains a score of 100 on all axes and serves as the reference polygon.

Interpretation follows four principles: radial extent reflects relative performance on each dimension; polygon shape reveals the overall strength profile of each technique; overlap and divergence between polygons identify where one technique outperforms another; and asymmetric or concave polygons signal trade-offs between competing objectives, such as the tension between construction speed and equipment dependency observed in the precast scenarios.

The chart does not impose an aggregated score or weighting scheme. Instead, it provides a transparent, non-aggregative representation to support decision-making under varying priorities, avoiding subjective weighting assumptions at the methodology stage. It is generated directly from the normalised performance matrix and serves as a visual decision-support layer complementing the quantitative analysis reported in Chapter 5.



Source: Thesis Author (generated with AI assistance via Claude, Anthropic, 2026)

Decision Framework

The synthesis concludes with a structured trade-off summary organised around three decision contexts representative of practical constraints in the Thai residential construction sector:

- **Time-critical**: the binding constraint is minimising total construction duration (primary dimension: Construction Time, UC1).
- **Budget-constrained**: the binding constraint is minimising direct construction cost (primary dimension: Direct Cost, UC2).
- **Low-carbon**: the binding constraint is minimising embodied carbon across A1–A5 (primary dimension: Embodied Carbon, UC3).

For each context, the framework identifies the technique with the lowest index on the relevant primary dimension and qualifies the associated trade-offs on secondary dimensions. Outputs are presented as conditional statements — if [constraint], then [preferred technique], subject to [trade-off] — rather than prescriptive rankings, to reflect the context-dependency of construction decisions and to preserve analytical objectivity. Full findings and recommendations are reported in **Chapter 5.**

Input Data and Tools

UC4 requires no additional primary data beyond UC1–UC3. The six dimensions are derived as follows:

- **Construction Time**: total project duration (working days) from the UC1 MS Project schedule, aggregated across WBS activities.
- **Direct Cost**: total direct construction cost (THB) from UC2 cost estimation, aggregated across material, labour, equipment, and transport categories.
- **Embodied Carbon (A1–A5)**: total embodied carbon ($kgCO_2e$) from UC3 LCA outputs, calculated as $\sum (Quantity_i \times Emission\ Factor_i)$ and extracted from OneClickLCA or equivalent platform.
- **Waste Ratio**: waste cost as a percentage of total direct cost, derived from the material waste factor assumptions embedded in the UC2 cost model.
- **On-Site Labour**: cumulative person-days computed as $\sum (Duration_i \times Crew\ Size_i)$ across all UC1 WBS activities, reflecting total on-site human resource demand.
- **Equipment Dependency**: cumulative crane-days computed as $\sum (Duration_i \times Equipment\ Flag_i)$ for activities flagged as crane-dependent in the UC1 schedule, capturing the degree of reliance on heavy lifting equipment.

All normalisation, index calculation, and slope chart visualisation are carried out in Excel using data exported directly from UC1–UC3. This ensures full traceability from BIM model inputs to synthesis outputs and supports independent verification.

3.3 LEVEL OF INFORMATION NEED (LOIN)

The information requirement framework applied in this study is grounded in ISO 19650-1:2018, which defines the Level of Information Need (LOIN) as the specification of what information must be present in a BIM model to satisfy a defined set of information uses. Under this standard, information requirements are established before model development begins, ensuring that only information necessary for the intended analytical purposes is embedded in the model and that the model functions as a data-rich analytical environment rather than a solely geometric representation.

In this thesis, the information uses are defined through three analytical use cases: UC1 (4D construction scheduling), UC2 (5D cost estimation), and UC3 (6D embodied carbon assessment). Together these use cases form the Exchange Information Requirements (EIR) in ISO 19650 terms, setting out what each scenario model must deliver at the point of analytical handover. The LOIN is therefore turned into a structured attribute matrix that maps each Revit element category to the information it must carry, at what level of detail, and for which downstream purpose. This approach ensures that parameter assignment in the BIM model can be traced to an explicit information requirement rather than modelling convention alone.

Beyond geometric detail, the LOIN defines the information attributes essential for downstream analyses. Each element includes in Table 3.3

Table 3.3 - LOIN attribute matrix per element category

LOIN Category	Information Required	Purpose (UC1 / UC2 / UC3)
Geometry	- Length, width, height, thickness - Area / Volume - Opening geometry (doors/windows) - Element type (wall, slab, column, precast panel)	**UC1**: calculate work quantities + sequencing **UC2**: quantity take-off for cost **UC3**: material volume for carbon
Material	- Material name - Density/unit weight - Rebar content - Surface finishing type	**UC2**: material cost classification **UC3**: carbon factor mapping ($kgCO_2e$/unit)
Productivity & Labour	- Productivity rate (m^2/day, m^3/day, kg/day) - Required labour type (mason, carpenter, crane operator) - Machinery needed (crane, mixer, manual)	**UC1**: duration calculation (Quantity ÷ Productivity)
Cost Data	- Unit rate (material, labour, machinery) - Cost category (direct material, installation, transport)	**UC2**: total cost calculation from QTO
Environmental Data	- Material to carbon factor mapping - Unit ($kgCO_2e$ per kg/m^3/m^2) - Transport assumptions (A4)	**UC3**: embodied carbon calculation (A1–A5)

	– Construction stage factors (A5)	
Location / Spatial	- Building storey - Grid/coordinates - Precast element placement	**UC1**: sequencing + crane logic for precast **UC3**: transport/manufacturing scenario distinction
Interoperability	- IFC 4.0 export compatibility - Consistent parameter naming - Schedule / CSV export enabled	Supports all UC workflows across Revit, Excel, MS Project, Navisworks, and OneClickLCA

As shown in Figure 3.6, the geometric fidelity required to satisfy the LOIN was determined by reference to the Level of Development (LOD) framework. LOD is not a separate framework but operationalises the geometrical dimension of the LOIN. A minimum of LOD 300 was adopted to ensure that all major elements have accurate geometry, placement, and material assignments suitable for reliable quantity extraction. However, for elements where the LOIN specifies assembly-level detail, such as precast structural systems, connection components, and masonry ligament configurations, the model was developed to LOD 350, because the comparative analysis depends on element-level detail that affects construction logic, sequencing, and material composition.

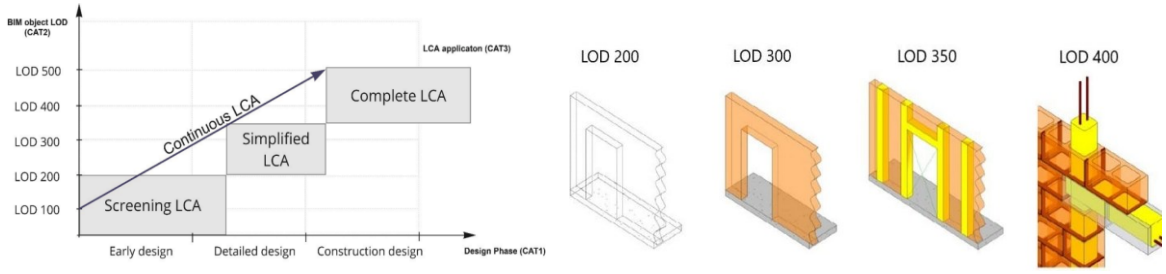


Figure 3.6 - The relationship between the design phase, BIM objects' LOD, and LCA application. Source: (1) Parece, Resende, and Rato (2023). (2) Adapted from Cuneio, T. (2021).

Geometric fidelity also has a measurable effect on the embodied carbon assessment. Because UC3 derives A1 to A3 carbon directly from modelled material quantities, elements represented at insufficient detail would under-report their material mass and therefore their carbon contribution. At LOD 300, reinforcement and precast connection details are absent, so their embodied impact would be omitted from the take-off. The elements that govern the comparison between construction techniques, namely reinforcement, precast panels, and masonry ligaments, were therefore developed to LOD 350 so that the quantity take-off reflects the true material composition of each scenario. This ensures that observed carbon differences derive from genuine construction characteristics rather than from inconsistent modelling resolution.

3.4 REQUIRED BIM PARAMETER

From Figure 3.7, BIM parameters are assigned exclusively to a predefined subset of Revit categories to maintain analytical consistency across the 4D, 5D, and 6D workflows. The structural scope includes **Structural Foundations, Structural Columns, Structural Framing, and Structural Walls**. The architectural scope includes **Floors, Walls, Roofs, Doors, Windows, and Stairs.** Parameter application is strictly limited to these categories to control the modelling boundary and ensure comparability between scenarios

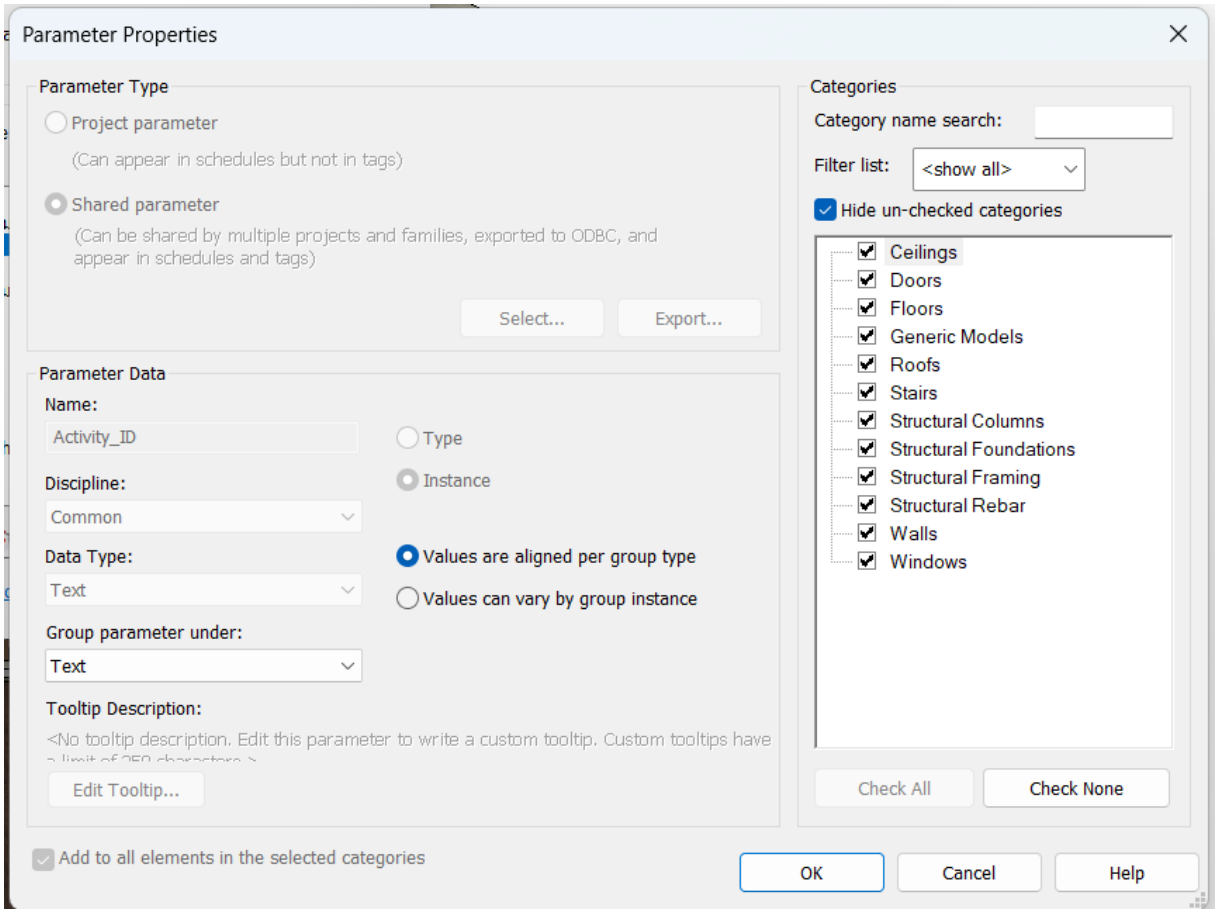


Figure 3.7 - Selected category for each parameter
Source: Thesis Author (Revit 2024)

3.4.1 4D SCHEDULING PARAMETERS

The 4D parameter structure supports the transformation of BIM quantities into construction duration through productivity-based logic. Only classification and productivity parameters are embedded in the BIM model. Activity identifiers are maintained in the BIM model for recheck and directly exported as csv to scheduling software and are not duplicated in the model.

Parameter Name	Type / Instance	Data Type	Group Under	Purpose
WBS_Code	Type	Text	Identity Data	Group elements into construction activities
Construction_Scenario	Type	Text	Identity Data	Distinguish TC / PF / PP / RS scenarios
Productivity_Rate	Type	Number	Construction	Duration calculation input
Crew_Size	Type	Integer	Construction	Duration calculation input
Activity_ID	Type	Text	Identity Data	Link element to scheduled WBS activity row
Duration_Days	Instance	Number	Construction	Calculated duration written back by Dynamo

Dynamo reads WBS_Code from all elements, aggregates quantities per activity, and computes duration using $D = Q / (P \times n)$ as defined in Section 3.2.1. The result is written back to each element as Duration_Days, enabling Revit schedules to display activity durations sorted by WBS code. Duration_Days is defined as an instance parameter to prevent write conflicts when the same element type appears under more than one WBS activity. See 3.2.1 UC1: SCHEDULING (4D)

3.4.2 5D COST PARAMETERS

The 5D parameter structure seperates between model-driven material costs and time-dependent costs calculated externally. Within the BIM model, only material-related cost parameters are embedded. Labour, equipment, and transportation costs are derived externally based on duration outputs from the 4D workflow to avoid duplication of time-dependent logic within the geometric model.

Parameter Name	Type / Instance	Data Type	Group Under	Purpose
WBS_Code	Type	Text	Identity Data	Group elements for cost estimation of each material
Unit_Material_Cost	Type	Currency	Cost	Material price per unit
Waste_Factor	Type	Number (%)	Construction	Quantity adjustment
Adjusted_Quantity	Instance	Number	Construction	Waste-adjusted quantity
Material_Cost	Instance	Currency	Cost	Final material cost per element

Material cost is computed at the element level using quantity and unit price information, with waste adjustment applied before aggregation**.** See 3.2.2 UC2: COST ESTIMATION (5D)

3.4.3 6D ENVIRONMENTAL PARAMETERS

The 6D parameter structure links BIM elements to environmental impact datasets without embedding fixed emission factors directly within the model. Instead of storing numeric carbon values as object attributes, reference-based mapping is applied to ensure dataset flexibility and transparency.

Parameter Name	Type / Instance	Data Type	Group Under	Purpose
Waste_Factor	Type	Number (%)	Construction	Consistency with 5D adjustment

Each element is assigned a material classification and an environmental dataset reference (e.g., EPD or national database entry), enabling automated impact mapping within the LCA software environment. Embodied carbon for each element is calculated externally. See 3.2.3 UC3: ENVIRONMENTAL ASSESSMENT (6D)

3.5 SELECTION AND ROLE OF SOFTWARE TOOLS

This section explains how the selected software tools were connected to execute UC1–UC3. The focus is on data flow and interoperability.

Revit – BIM Modeling and Data Structuring

Selected for its capacity to host LOD 350 geometry and embed parametric information such as productivity rates, cost codes, and material classifications. Revit functions solely as the environment for generating and structuring quantities required for downstream analyses.

Navisworks – Model Aggregation and 4D Simulation

Navisworks is used as a federated model environment capable of reading IFC and native Revit formats, enabling model coordination and linking construction activities for visual 4D simulation. Its Timeliner environment supports validation of sequencing logic, while the scheduling engine itself remains external, ensuring methodological independence.

MS Project – Scheduling Logic Engine

MS Project was selected for its capacity to handle critical path logic and incorporate duration values derived from BIM-based quantities and productivity datasets. It acts as the analytical engine for UC1, while Navisworks serves as the visualization environment.

Excel & Dynamo – Computational and Automation Layer

Excel provides transparent and traceable numerical processing for UC2 and UC3, including cost aggregation and carbon factor calculations. Dynamo is employed to automate repetitive BIM parameter assignments, export structured datasets, and maintain consistency in the model's data architecture.

OneClick LCA – Environmental Database Interface

OneClickLCA enables standardized linkage between extracted material quantities and recognized embodied carbon factors. It serves as the external reference database for UC3, ensuring the environmental assessment follows validated LCA methodologies.

3.6 AI USE DISCLOSURE

In accordance with the MBUILD guidelines on the approved use of AI tools, this section discloses where and how generative AI was applied in the preparation of this dissertation. AI tools were used only for data preparation, translation, language refinement, and visualization support, and not for content writing, discussion, or evaluation, which remain the sole work of the author.

ChatGPT (OpenAI) was used to convert the numerical outputs of Use Cases 1 to 3 into infographic diagrams. The underlying data, values, and interpretations were produced by the author from the BIM-based analysis; the tool assisted only with the visual presentation of these results. Each AI-assisted figure is noted accordingly in its caption.

Claude (Anthropic) was used to consolidate and simplify the quantity take-off spreadsheets exported from the BIM model. Raw Revit schedules may contain minor elements that fall outside the scope of the calculation, such as door hardware and other small components. The tool assisted in cleaning and restructuring these spreadsheets into a clearer, more consistent format for analysis. All quantities and cost values were verified by the author against the source model to ensure accuracy.

Google Translate, Claude (Anthropic), and ChatGPT (OpenAI) were used to support the translation of technical terms from the author's native language and to refine the academic style of the written text. These tools assisted with language and expression only the intellectual content, arguments, and conclusions remain entirely the author's own.

4

CASE STUDY AND APPLICATION

4.1 CASE STUDY DESCRIPTION

Defines the physical, functional, and contextual characteristics of the case study, including scope, constraints, and assumptions applied uniformly across all scenarios.

4.1.1 PROJECT DESCRIPTION AND SCOPE

Five single-family housing projects in the Bangkok Metropolitan Region (BMR) were selected as case studies for this research. The selection criteria followed the 2 to 5 million THB price segment, which represents approximately 41.8 percent of total low-rise unit transfers in the BMR. As documented by the Real Estate Information Center (REIC), this price segment corresponds to usable floor areas of 150 to 200 sqm. The five projects selected for this study, with gross floor areas (GFA) ranging from 185 to 200 sqm as reported by their respective developers, confirming their representativeness of the largest single market segment for low-rise residential construction in the BMR. All five projects are two-storey detached houses drawn from AP Thailand Public Company Limited and Sansiri Public Company Limited, spanning three administrative zones in Samut Prakan Province and Bangkok.

Table 4.1 - Overview of Five Selected Single-Family Housing Projects, Bangkok Metropolitan Region

Model	Developer	Project	Location	GFA (sqm)	BR/BA	Reference
BEA	AP Thailand	MODEN Bangna-Srinakarin	Bangplee, Samut Prakan	185	3/3	AP Thai (2025a)
GARY	AP Thailand	MODEN Bangna-Theparak	Bang Bo, Samut Prakan	185	4/3	AP Thai (2025b)
MUGUET	Sansiri	Saransiri Srinakarin-Phraeksa	Phraeksa, Samut Prakan	200	4/4	Sansiri (2025a)
CHERISH	Sansiri	Setthasiri Phaholyothin	Tha Raeng, Bangkok	186	4/3	Sansiri (2025b)
EDEN	AP Thailand	CENTRO On Nut-Ladkrabang	Ladkrabang, Bangkok	190	4/4	AP Thai (2025c)

Source: Adapted by the thesis author from AP Thailand Public Company Limited (2025) and Sansiri Public Company Limited (2025).

The five projects from Table 4.2 share comparable spatial programmes comprising 3 to 4 bedrooms, 3 to 4 bathrooms, and open-plan ground-floor living arrangements. This internal consistency makes them a cohesive dataset for BIM-based construction performance analysis, while the spread across two developers and three geographic locations ensures that findings are not unduly influenced by a single design tradition or site context.

Table 4.2 - Floor Plan Reference: Ground Floor (F1) and Upper Floor (F2) for Five Case Study Projects

Project	F1 — Ground Floor	F2 — Upper Floor
BEA **185 sqm** 3/3		
GARY **185 sqm** 4/3		
MUGUET **200 sqm** 4/4		

CHERISH **186 sqm** 4/3		
EDEN **190 sqm** 4/4		

Source: Adapted by the thesis author from AP Thailand Public Company Limited (2025) and Sansiri Public Company Limited (2025).

4.1.2 REFERENCE MODEL DEVELOPMENT

The five projects described in Section 4.1.1 serve as spatial reference cases for the construction of a hypothetical Revit BIM model used throughout this study. Rather than replicating any single project directly, the Revit model is calibrated to reflect the aggregate spatial characteristics observed across the five reference cases, including approximate room proportions, room counts, and the design logic governing spatial relationships between rooms.

Specifically, the model adheres to the Thai residential planning convention in which semi-public and service spaces, namely the living area, dining area, kitchen, and guest bedroom, are located on the ground floor, while private bedrooms requiring a higher degree of occupant privacy are positioned on the upper floor. This vertical zoning pattern, consistently observed across all five reference projects, reflects established sociocultural norms of domestic life in Thailand, where the separation of guest-accessible and private zones by floor level constitutes a foundational principle of middle-income. The resulting BIM model is therefore not a project-specific representation but a synthetic archetype that captures the spatial logic and scale of the dominant market segment, providing a credible and contextually grounded basis for the construction performance comparisons presented in subsequent sections.

To illustrate the spatial programme that informs this model, Table 4.3 presents a detailed room-by-room area breakdown for the CHERISH model unit (Sansiri, Setthasiri Phaholyothin-Watcharapol), which serves as the primary spatial reference for the hypothetical BIM model on account of its representative room configuration and GFA of 186 sqm.

Table 4.3 - presents a detailed room area breakdown for the CHERISH model unit (186 sqm.)

No.	Room / Space	Floor	Area (sqm)	% of GFA
Ground Floor (F1)				
1	Living Room (Guest)	F1	14.43	7.8%
2	Dining Area	F1	10.23	5.5%
3	Kitchen	F1	7.28	3.9%
4	Food Preparation Area	F1	8.25	4.4%
5	Bedroom 4 (Guest)	F1	12.87	6.9%
6	Bathroom 3	F1	4.62	2.5%
7	Car Park	F1	33.08	17.8%
8	Entry Veranda	F1	4.80	2.6%
9	Entry Lobby	F1	3.30	1.8%
10	Laundry Area	F1	4.50	2.4%
11	Storage	F1	1.35	0.7%
12	Side Terrace	F1	5.82	3.1%
Upper Floor (F2)				
13	Master Bedroom (Bed 1)	F2	15.41	8.3%
14	Bedroom 2	F2	12.87	6.9%
15	Bedroom 3	F2	9.57	5.1%
16	Master Bathroom (Bath 1)	F2	4.23	2.3%
17	Bathroom 2	F2	3.38	1.8%
18	Dressing Room	F2	4.90	2.6%
19	Family Lounge	F2	12.29	6.6%
20	Balcony	F2	4.07	2.2%

21	Stair and Landing	F2	3.70	2.0%
22	Walls and Structural Elements	F1+F2	5.05	2.7%
	TOTAL GFA	F1+F2	186.00	100.0%

Source: Compiled by the thesis author from the developer-published floor plan for CHERISH (Sansiri, 2025b). Room areas computed from published width-by-depth dimensions.

4.1.3 BIM MODEL DEVELOPMENT



Figure 4.1 - BIM Model Exterior Perspective

The BIM model from Figure 4.1 was developed for this research represents a synthetic archetype derived from the spatial and programmatic characteristics of the five case study projects. The model synthesizes typical design patterns observed across the selected developments to create a representative single-family house aligned with Thai residential norms and the 2–5 million THB market segment in the Bangkok Metropolitan Region. All model geometry, structural systems, and building components were developed independently by the author using Autodesk Revit 2024, with structural components (columns, beams, slabs, walls, connections) modeled to LOD 350 to support scenario differentiation, while substructure (foundation) and architectural elements (doors, windows, partitions, finishes) were modeled to LOD 300 for quantity takeoff and cost estimation. MEP systems are excluded from scope as the research focuses on structural and architectural construction methods.

As seen Figure 4.2-4.3, the project sits on a hypothetical 16 × 16-meter plot (256 sqm) in Pathumthani Province, reflecting the typical land subdivision patterns in peri-urban residential developments. The spatial program has a total Gross Floor Area (GFA) of 188.91 sqm spread across two storeys, with the ground floor holding service, guest, and communal functions, while the upper floor holds private bedroom suites. This vertical zoning strategy reflects sociocultural norms common across the Thai residential market and was consistently seen in all five case study projects. The structural system is organized on a regular column grid to accommodate fabrication and erection constraints across all four construction scenarios, with focus on precast module dimensions and transportation limits for the Precast Frame (PF) and Precast Panel (PP) techniques.

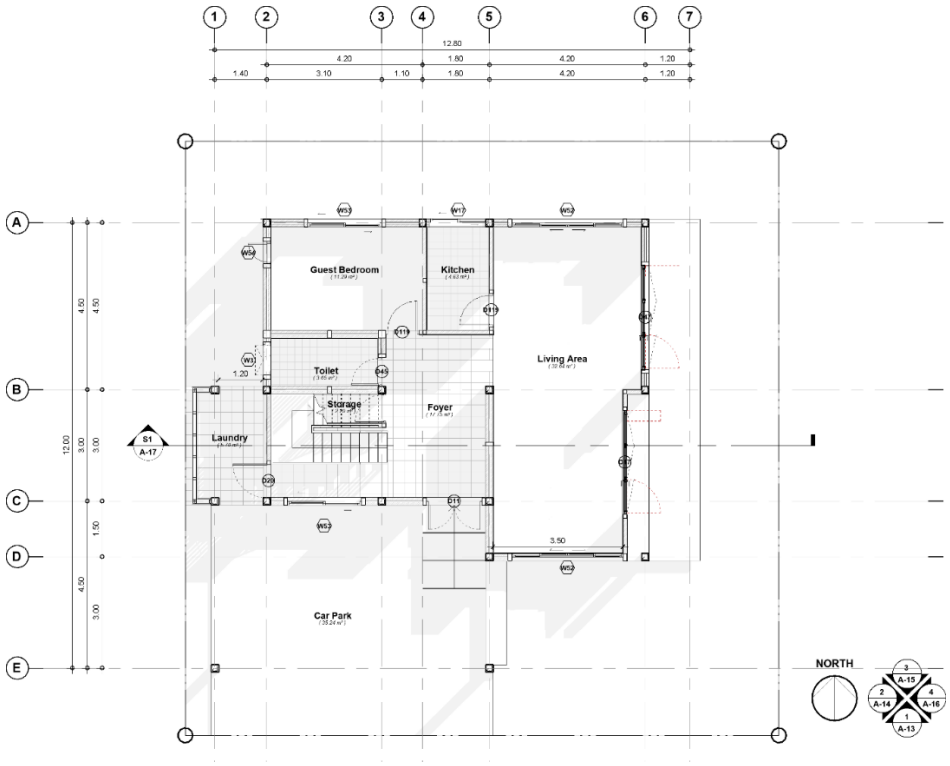


Figure 4.2 - Ground Floor Plan

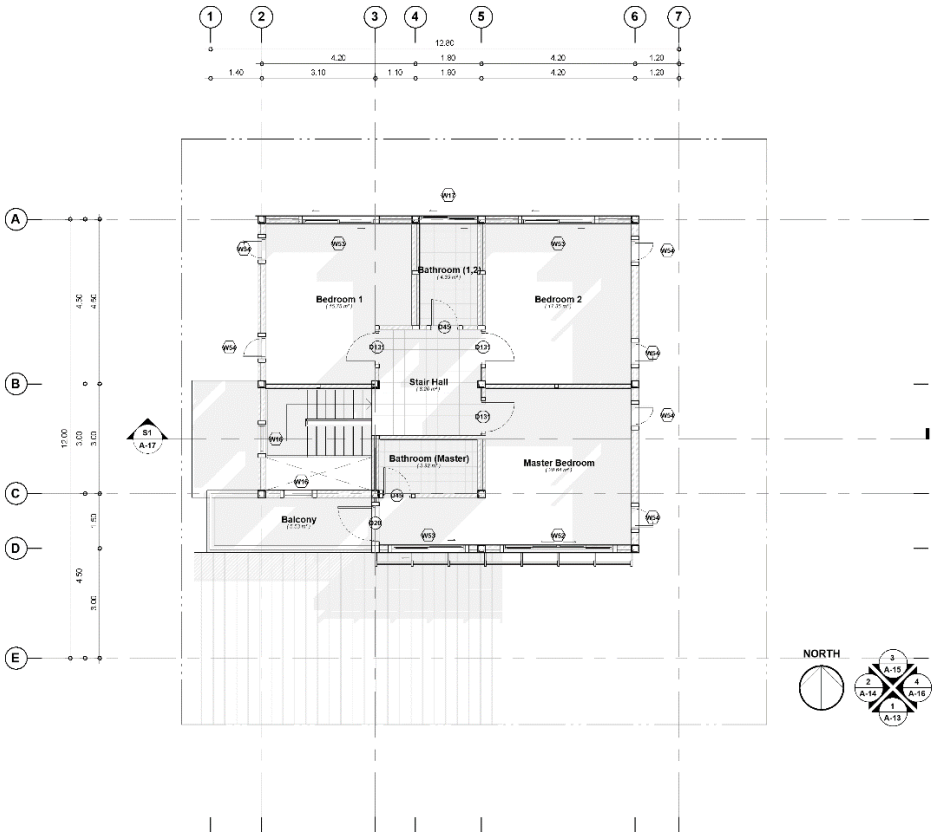


Figure 4.3 - Upper Floor Plan

Table 4.4 - Spatial Program of the Synthetic BIM Model

No.	Room / Space	Floor	Area (sqm)	% of GFA
Ground Floor (F1)				
1	Living Area	F1	32.64	17.3%
2	Kitchen	F1	4.63	2.5%
3	Guest Bedroom	F1	11.29	6.0%
4	Toilet	F1	3.65	1.9%
5	Storage	F1	2.29	1.2%
6	Foyer	F1	17.75	9.4%
7	Laundry	F1	5.70	3.0%
8	Car Park	F1	35.24	18.7%
9	Bathroom (1,2)	F1	4.35	2.3%
Upper Floor (F2)				
10	Master Bedroom	F2	20.64	10.9%
11	Bedroom 1	F2	16.75	8.9%
12	Bedroom 2	F2	17.35	9.2%
13	Bathroom (Master)	F2	3.92	2.1%
14	Stair Hall	F2	8.20	4.3%
15	Balcony	F2	5.53	2.9%
16	Bathroom (1,2)	F2	4.35	2.3%
	TOTAL GFA	F1+F2	188.91	100.0%

Note: GFA calculation is derived directly from Revit Area Schedule.

4.1.4 CONSTRUCTION SCENARIO MODELS

The four construction scenarios differ primarily in their structural systems and degree of prefabrication, as summarized in Table 4.4. Traditional Cast-in-Place (TC) serves as the baseline with entirely site-cast concrete, Precast Frame (PF) prefabricates vertical and horizontal structural members while retaining cast-in-place connections, Precast Panel (PP) extends prefabrication to full-height wall panels minimizing wet trades on site, and the Renovation Scenario (RS) retains the existing TC structure while modifying only non-structural elements including roof cladding and door-window assemblies.

Table 4.5 - Construction Technique Comparison Matrix

Element	TC	PF	PP	RS
Foundation	Rectangular footing + driven precast prestressed concrete pile, I-shape section (0.22 × 0.22 m, L = 12 m)			-
Column	Cast-in-place (200 × 200 mm)	Precast column (200 × 200 mm)	Precast column (200 × 200 mm)	-
Beam	Cast-in-place (200 × 400, 500 mm)	Precast beam (200 × 400, 500 mm)	Precast beam (200 × 400, 500 mm)	-
Slab	Cast-in-place (t = 100 mm)	Precast slab (1–4 pieces per room)	Precast slab (1–4 pieces per room)	-
Stair	Cast in place	Precast stair	Precast stair	-
Wall	AAC block	AAC block	Precast wall panel (t = 100 mm)	Partial demolition of existing AAC wall + new AAC block partition (Living Area)
Roof	Steel structure + roof tile			Replace roof tile cladding
Door-Window	Aluminium frame	Aluminium frame	Aluminium frame	Replace door and window assemblies
Finishes	Plaster + paint	Plaster + paint	Plaster + paint	New paint/tile

Note: "-" indicates elements not modified in the Renovation Scenario (RS), which retains the existing structure. AAC = Autoclaved Aerated Concrete; RC = Reinforced Concrete.

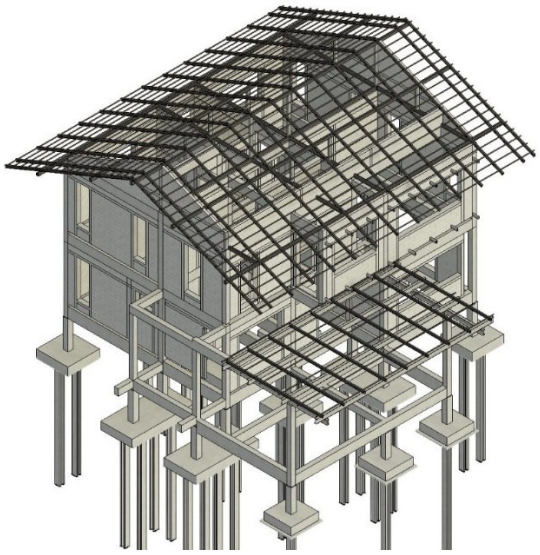


Figure 4.47 - Traditional Cast-in-Place structure (Isometric View)

As illustrated on Figure4.4, the Traditional Cast-in-Place scenario employs a fully monolithic reinforced concrete frame, with columns (200 × 200 mm), beams (200 × 400/500 mm), and a 100 mm flat slab cast sequentially on-site. Walls are constructed from Autoclaved Aerated Concrete (AAC) blocks, and the roof adopts a steel structure with roof tile cladding, representing the conventional construction approach widely practiced in Thailand.

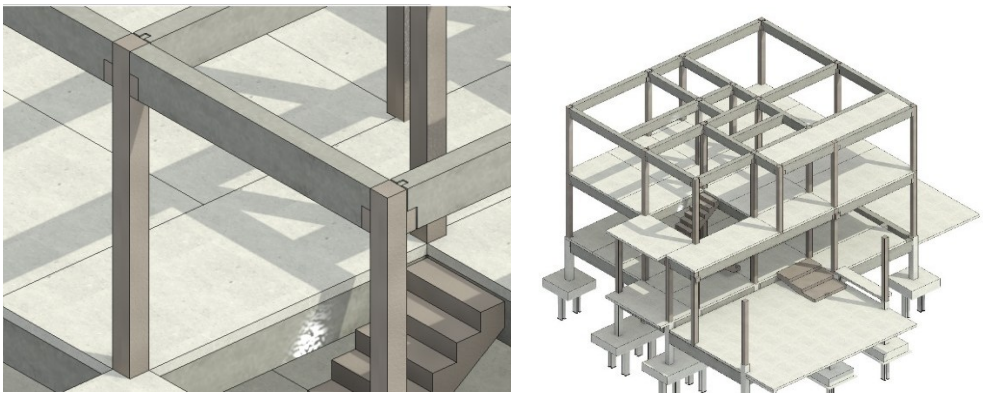


Figure 4.5 – Prefablicated frame structure (Isometric View)

The Prefabricated Frame scenario on Figure 4.5 replaces all cast-in-place structural members with factory-manufactured precast columns, beams, slabs, and stair units, assembled on-site using non-shrink grout connections. Wall infill and roof construction follow the same specification as the TC scenario, isolating the structural frame as the primary variable under comparison.



Figure 4.6 - Prefablicated panel structure (Isometric View)

As seen in Figure 4.6, the Prefabricated Panel scenario adopts a load-bearing precast wall panel system (t = 100 mm), transferring vertical loads directly through the panels to the substructure and eliminating the need for an internal beam-column frame in most zones. Precast beams are retained only where the second-floor wall layout is not aligned with the first floor, and columns are used selectively to support the roof structure over the parking area, preserving the overall building geometry of the original design.



Figure 4.7 - Renovation scenario, fliter only new construction elements (Isometric View)

From Figures 4.7-4.11, the Renovation scenario retains the existing reinforced concrete structure and selectively replaces building components assessed as likely to deteriorate within a 20-year horizon. New works include partial demolition and reconstruction of AAC block partition walls in the living area, replacement of roof tile cladding, installation of new aluminium door and window assemblies, and application of new paint and tile finishes throughout.

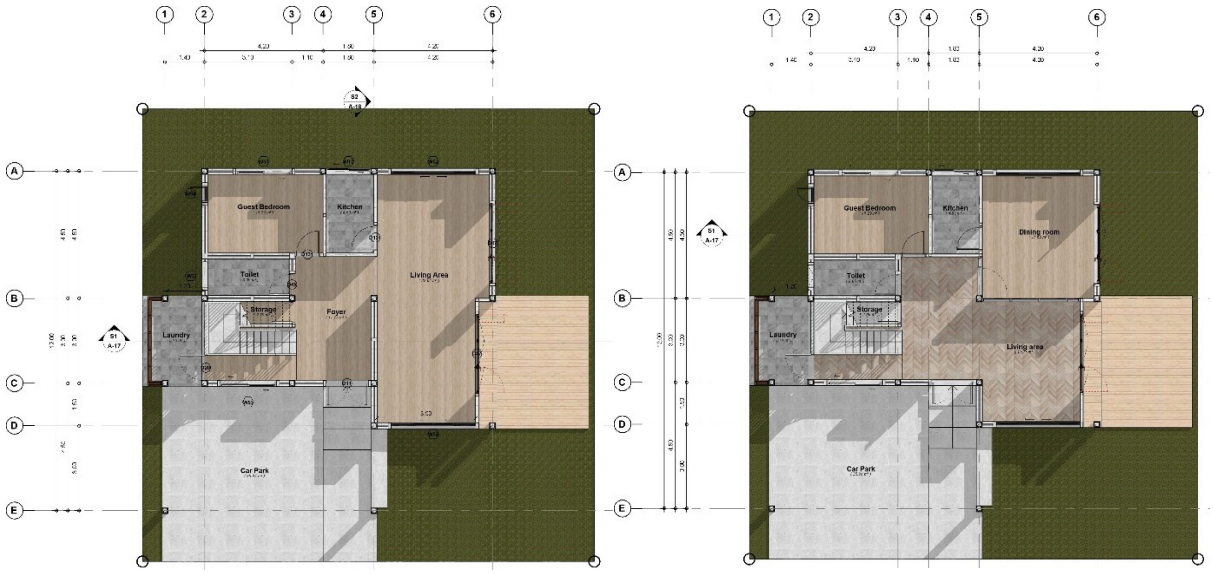


Figure 4.8 - Existing plan (Left) Renovated planing propose (Right)

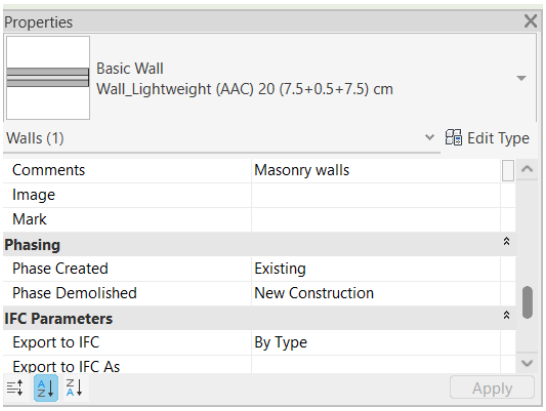


Figure 4.9 - Demolished element setting: Phase created "Existing" and select "New Construction" for Phase demolished

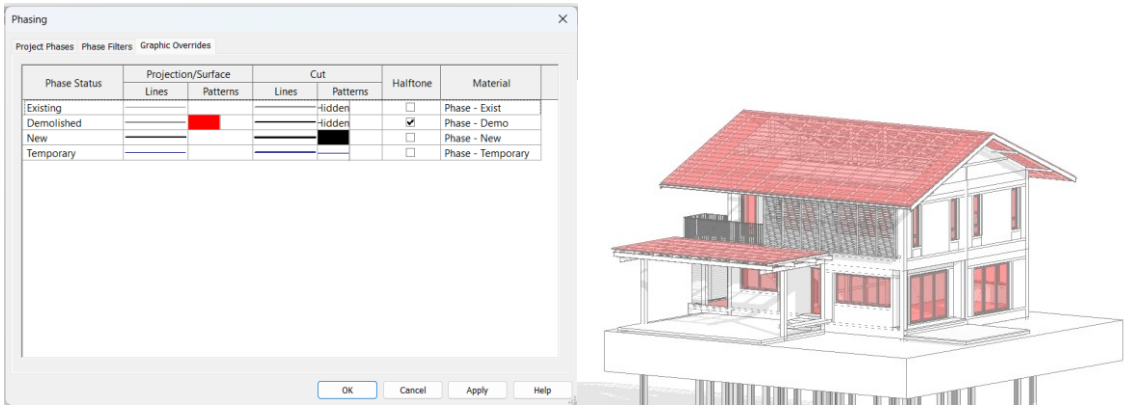


Figure 4.10 - Demolished element setting: Overide red color on demolish element that proposed to be remove base on aged material life cycle

4.2 APPLICATION OF USE CASE

This section describes the structured application of UC1 through UC3 to the case study, following the methodology defined in Chapter 3. The BIM model developed in Section 4.1.3 serves as the central data source, ensuring that differences in scheduling, cost, and environmental outcomes are attributable exclusively to variations in construction technique rather than to building geometry or spatial programme.

4.2.1 UC1 – SCHEDULING ANALYSIS

Use Case 1 (UC1) translates BIM model geometry into a productivity-based construction schedule for each of the four construction scenarios. The objective is to derive activity durations analytically from measured model quantities and standardized productivity rates, as defined in Sections 3.2.1 and 3.5.1, rather than to estimate them manually. The workflow follows a four-stage pipeline from BIM model parameter setup through to output handoff, summarized in Table 4.6 and illustrated in Figure 4.11.

Table 4.6- UC1 Scheduling Workflow: Process Steps and Tools

Step	Process	Description	Tool
1	BIM Model (Revit 2024)	Each scenario (TC, PF, PP, RS) is embedded in a single Revit 2025 model at LOD 300–350. Every element carries six type or instance parameters as listed in Table 4.7.	Revit 2024
2	Element-to-WBS Mapping (Dynamo)	A Dynamo script reads the parameters, aggregates quantities by WBS code and scenario, computes D = Q / (P × n), and writes Duration_Days back to each element. Output is also exported as a CSV keyed by Activity_ID.	Dynamo
3	Schedule Compilation (MS Project)	The duration CSV is imported into MS Project. Predecessor relationships and lag values are applied per scenario to generate the critical path schedule under a uniform 6-day working calendar.	MS Project
4	Output Handoff to UC2 and UC3	Total duration per scenario feeds UC2 as the time basis for labour and equipment cost. Phase durations define the A5 stage boundary for UC3 embodied carbon assessment.	Excel / OneClick LCA

Source: Thesis author

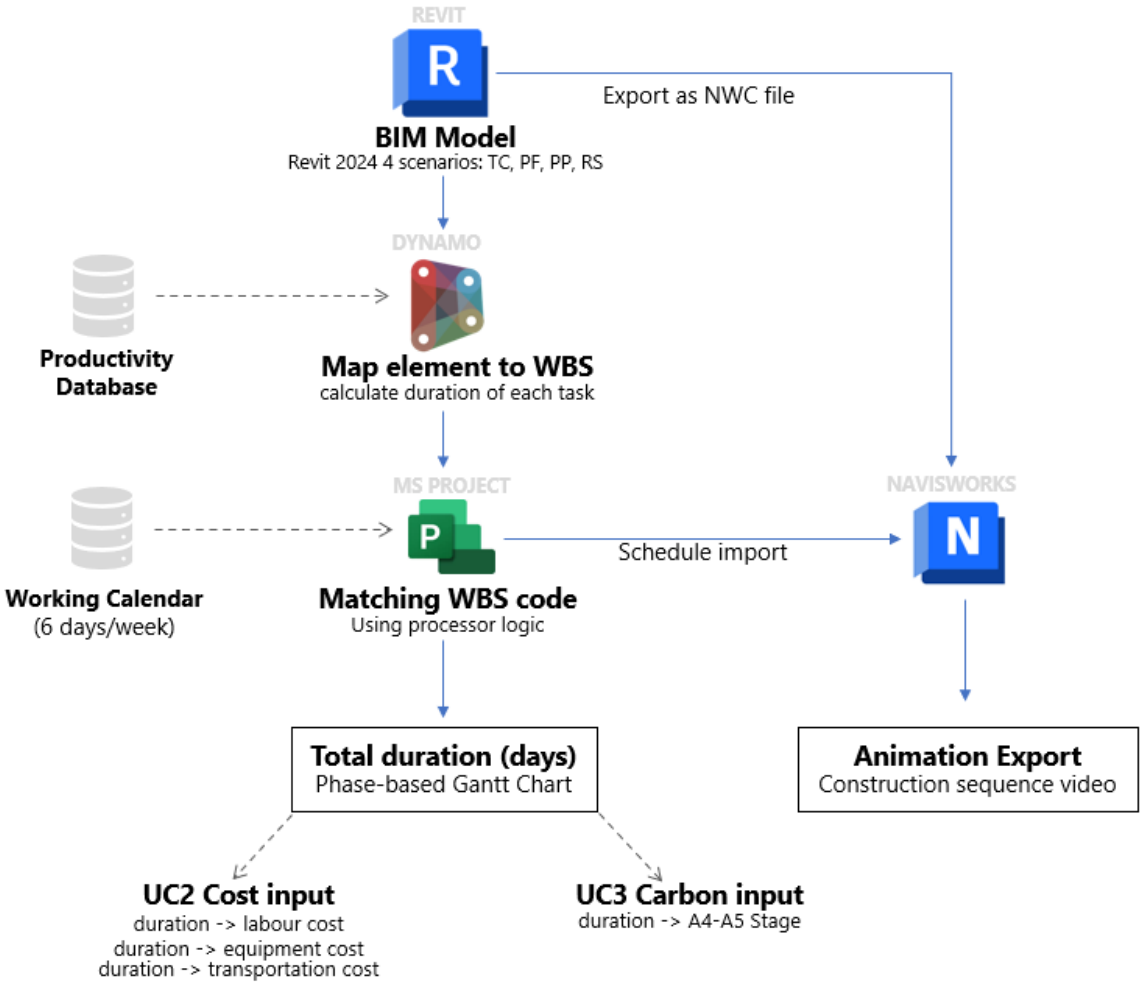


Figure 4.11 - UC1 Scheduling Analysis: Data Flow Diagram
Source: Thesis author

Step 1: BIM Model Parameter Setup

The Revit 2025 model was configured with six parameters assigned to all elements within the analytical scope, as listed in Table 4.7. The first four parameters serve as inputs to the duration formula. Activity_ID links each element group to its corresponding scheduled activity row, and Duration_Days stores the Dynamo-calculated result back in the model to enable Revit schedule output sorted by WBS code.

Table 4.7 - BIM Parameters for 4D Scheduling (UC1)

Parameter Name	Type/Instance	Data Type	Group Under	Purpose
WBS_Code	Type	Text	Identity Data	Group elements into construction activities
Construction_Scenario	Type	Text	Identity Data	Distinguish TC / PF / PP / RS scenarios
Productivity_Rate	Type	Number	Construction	Duration calculation input
Productivity_Unit	Type	text	Construction	Align the quantity with productivity unit
Crew_Size	Type	Integer	Construction	Duration calculation input
Activity_ID	Type	Text	Identity Data	Link element to scheduled WBS activity row
Duration_Days	Instance	Number	Construction	Calculated duration written back by Dynamo

Source: Thesis author; consistent with Section 3.4.1

M41_01_UC1_Duration days per...

<M41_01_UC1_Duration days per activity>

A	B	C	D	E	F	G	H
Acti	WBS_	Construction_Sce	Name of Activity	Productivity_Rate	Productivity_Unit	Crew_Size	Duration_Days
1	S01	TC	Site clearing and setting out	225	m2	3	0
2	S02	TC	Excavation	480	m3	2	0
3	S03	TC	Foundation piles (driven precast)	0.75	piece	5	0
4	S04	TC	Blinding concrete	40	m2	5	0
5	S05	TC	Footings	1	m3	5	0
6	S06	TC	Column stumps	0.17	m3	5	0
7	S07	TC	Ground beams	0.26	m3	5	0
8	S08	TC	Floor structure (F1)	1.34	m3	5	0
9	ST01	TC	Columns 1F	0.17	m3	5	0
10	ST02	TC	Beams 1F	0.26	m3	5	0
11	ST03	TC	Floor structure (F2)	0.47	m2	5	0
12	ST07	TC	Stair construction	0.25	piece	4	0
13	ST04	TC	Columns 2F	0.17	m3	5	0
14	ST05	TC	Beams 2F	0.26	m3	5	0
15	ST06	TC	Floor structure (UpperF2)	0.47	m2	5	0
16	R01	TC	Look detail in QTO roof structure	7.5	m2	5	0
17	R02	TC	Roof covering and waterproofing	12.72	m2	4	0
17	R02	TC	Roof covering and waterproofing (Metal Sheet)	24	m2	4	0
18	A01	TC	Look detail in QTO Tie column and beam	0	m		
18	A01	TC	Masonry walls	8	m2	4	0
19	A02	TC	Plastering and painting (internal + external walls, 12mm)	8.72	m2	4	0
20	A03	TC	Doors and windows	2.5	piece	3	0
21	A04	TC	Floor finishes	14.64	m2	3	0
22	A05	TC	Ceiling installation	36.32	m2	2	0
23	A07	TC	Facade -- subcontract--	12	m2	4	0

Figure 4.12 - Input of 4D Scheduling (UC1) inside Revit 2024

Source: Thesis author; consistent with Section 3.4.1

Step 2: Duration Calculation (Dynamo)

The Dynamo script acts as the computational bridge between the Revit model and the MS Project schedule. It reads BIM element parameters, computes waste-adjusted quantities, derives activity durations from the productivity formula, and writes the results back to the model before exporting a structured CSV for MS Project import. The script is arranged into five node groups, each handling a distinct stage of the calculation pipeline, as shown in Figure 4.13.

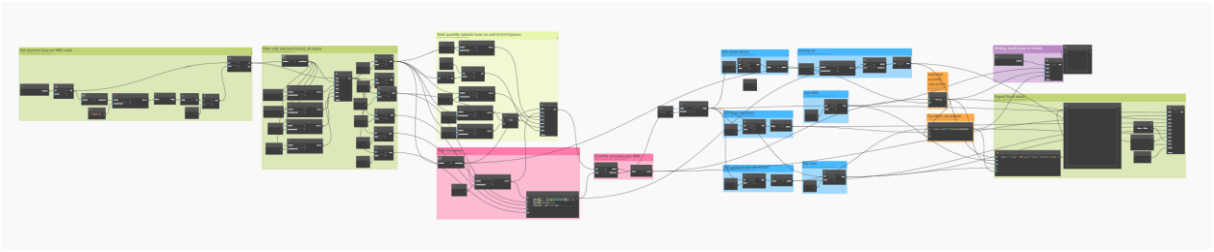


Figure 4.13 - Dynamo Script UC1: Full Workspace Overview

Source: Thesis author (Dynamo, Revit 2025)

Get element base on WBS code collects all elements from the active Revit view, flattens the list, and filters out any element whose WBS_Code parameter is empty, ensuring only analytically scoped elements proceed.

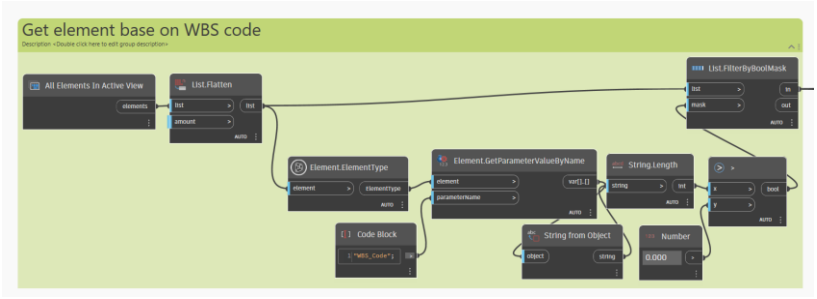


Figure 4.14 - Dynamo Script group: Get element base on WBS code

Source: Thesis author (Dynamo, Revit 2025)

Filter only element having all values reads four scheduling parameters per element: Productivity_Unit, Productivity_Rate, Crew_Size, and Waste_Factor — and excludes any element where one or more values are missing, preventing null propagation through the calculation, as shown in Figure 4.14

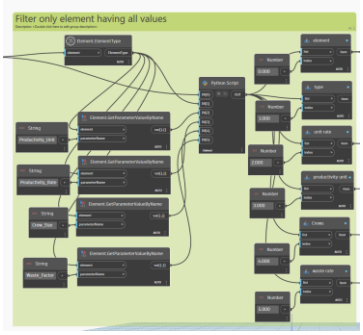


Figure 4.15- Dynamo Script group: Filter only element having all values

Source: Thesis author (Dynamo, Revit 2025)

Total quantity selector base on unit (m2/m3/piece) extracts the appropriate geometric quantity for each element by selecting from Volume, Area, Length, or Width according to the Productivity_Unit value, using a Python Script node to resolve the correct dimension per element.

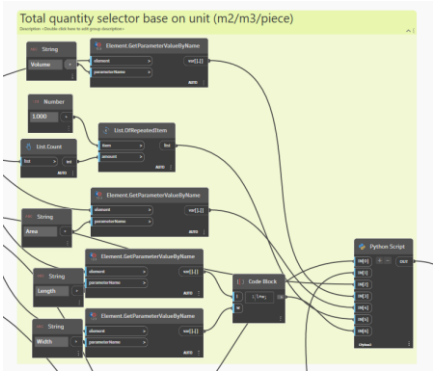


Figure 4.16 - Dynamo Script group: Total quantity selector base on unit (m2/m3/piece)

Source: Thesis author (Dynamo, Revit 2025)

WBS Grouping and **Quantity grouping per WBS** construct a composite key from WBS_Code, unit, rate, crew size, and waste factor using a null-safe Code Block, then aggregate adjusted quantities per WBS activity using List.GroupByKey and Math.Sum.

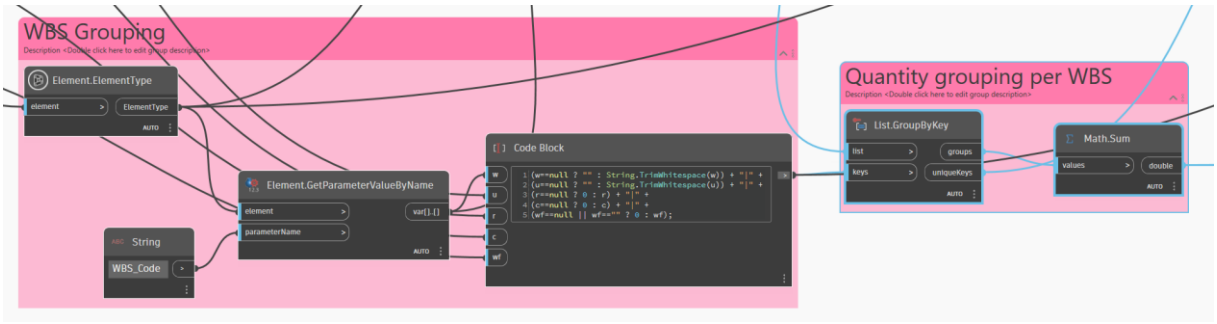


Figure 4.17 - Dynamo Script group: WBS Grouping and Quantity grouping per WBS

Source: Thesis author (Dynamo, Revit 2025)

Adjusted quantity calculation and **Duration calculation** apply the waste adjustment (Adjusted_Quantity = Base_Quantity x (1 + Waste_Factor)) and the productivity formula (D = Adjusted_Quantity / (P x n)) at WBS-code level, resolving Activity_ID per group simultaneously.

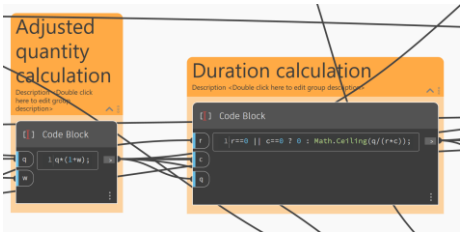


Figure 4.18 - Dynamo Script group: Adjusted quantity calculation and Duration calculation

Source: Thesis author (Dynamo, Revit 2025)

Writing result back to model and Export Excel sheet write Duration_Days and Adjusted_Quantity back to each element as Revit instance parameters via Element.SetParameterByName, and export the aggregated results as a structured Excel file keyed by Activity_ID for MS Project import.

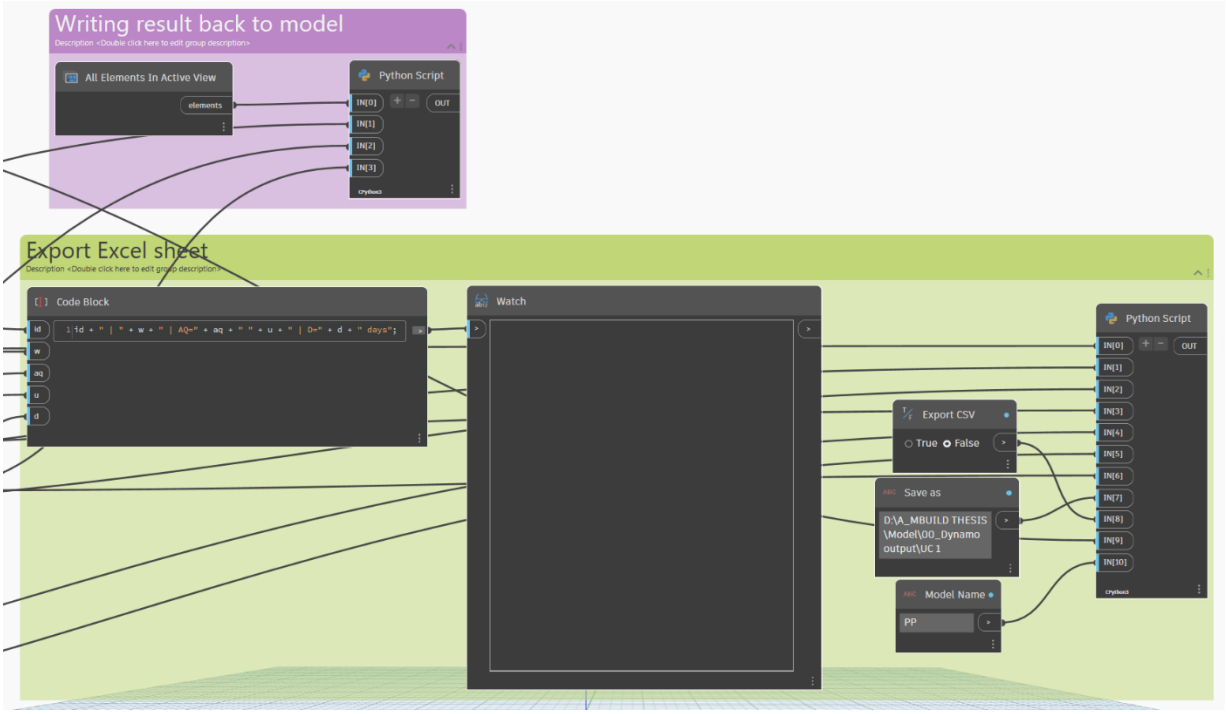


Figure 4.19 - Dynamo Script group: Writing result back to model and Export Excel sheet
Source: Thesis author (Dynamo, Revit 2025)

Step 3: WBS Schedule Tables (MS Project)

The duration CSV exported from Dynamo was imported into MS Project, where predecessor relationships and lag values were applied per scenario to generate the critical path schedule under a uniform 6-day working calendar. Tables 4.8 through 4.11present the complete activity lists, predecessor logic, and lag reasons for each scenario.

Table 4.8 - WBS Activity Schedule: Traditional Cast-in-Place (TC)

Act ID	WBS_Code	Name of Activity	WBS	Predecessors	Lag Reason
1	S01	Site clearing and setting out	1.0 Substructure - Site works	-	-
2	S02	Excavation (bulk + trench)	1.1 Substructure - Earthworks	1FS	-
3	S03	Foundation piles (driven precast prestressed	1.2 Substructure - Foundation piles	2FS	-
4	S04	Blinding concrete	1.3 Substructure - Blinding	3FS	-
5	S05	Footings (rebar + concrete)	1.4 Substructure - Foundations	4FS	-
6	S06	Column stumps (RC cast in-situ)	1.5 Substructure - Column stumps	5FS+2d	Side formwork strip 2d on footing; then build stump
7	S07	Ground beams (rebar + concrete, cast in-situ)	1.6 Substructure - Ground beams	6FS+2d	Side formwork strip 2d on column stump; then ground
8	S08	Ground floor slab (RC cast in-situ)	1.7 Substructure - Ground floor slab	7FS+2d	Side formwork strip 2d on ground beam; backfill + compact
9	ST01	Columns 1F (RC cast in-situ)	2.1 Superstructure - Columns 1F	8FS+7d	Slab-on-grade water curing 7d (soil-supported; less critical
10	ST02	Beams 1F (RC cast in-situ)	2.2 Superstructure - Beams 1F	9FS+2d	Side formwork strip 2d on column; then start beam
11	ST03	Upper slab 1F (RC cast in-situ)	2.3 Superstructure - Floor slab 1F	10FS	Beam + slab poured monolithically (no lag; continuous
12	ST04	Columns 2F (RC cast in-situ)	2.4 Superstructure - Columns 2F	11FS+14d	Suspended slab soffit propping min 14d before upper floor
13	ST05	Beams 2F (RC cast in-situ)	2.5 Superstructure - Beams 2F	12FS+2d	Side formwork strip 2d on column; then start beam
14	ST06	Upper slab 2F (precast plank slab install)	2.6 Superstructure - Upper slab 2F	13FS	Beam + slab poured monolithically (no lag; continuous
15	ST07	Stair construction (RC cast in-situ)	2.7 Superstructure - Stairs	11FS	Stair starts after slab 1F complete (structural connection)
16	R01	Roof primary structure (gable roof truss)	3.1 Roof - Structure	14FS+14d	Upper slab soffit propping min 14d before roof truss load
17	R02	Roof covering and waterproofing	3.2 Roof - Covering	15FS	-
18	A01	Masonry walls (external + internal partitions)	4.1 Architectural - Masonry walls	11SS	Ground floor masonry can start parallel with slab 1F curing
19	A02	Plastering (internal + external walls)	4.2 Architectural - Plastering	17FS	-
20	A03	Doors and windows installation	4.3 Architectural - Openings	18FS	-
21	A04	Floor finishes	4.4 Architectural - Floor finishes	18FS	-
22	A05	Ceiling installation	4.5 Architectural - Ceiling	18FS	-
23	A06	Painting works (interior + exterior)	4.6 Architectural - Painting	19FS	-
24	A07	Facade cladding installation	4.7 Architectural - Facade	16FS	-

Source: Thesis author (MS Project input)

Table 4.9 - WBS Activity Schedule: Precast Frame (PF)

Act ID	WBS_Code	Name of Activity	WBS	Predecessors	Lag Reason
1	S01	Site clearing and setting out	1.0 Substructure - Site works	-	-
2	S02	Excavation (bulk + trench)	1.1 Substructure - Earthworks	1FS	-
3	S03	Foundation piles (bored pile, cast in-situ)	1.2 Substructure - Foundation piles	2FS	-
4	S04	Blinding concrete	1.3 Substructure - Blinding	3FS	-
5	S05	Footings (rebar + concrete)	1.4 Substructure - Foundations	4FS	-
6	S05A	Column stumps (RC cast in-situ)	1.5 Substructure - Column stumps	5FS+2d	Side formwork strip 2d on footing; then build stump
7	P01	Ground beams (precast install, incl. connections)	1.5 Substructure - Ground beams	6FS+2d	Side formwork strip 2d on stump; precast beam rests on
8	S07	Ground floor slab (RC cast in-situ)	1.6 Substructure - Ground floor slab	7FS+1d	Non-shrink grout cure 1d for precast ground beam
9	P02	Columns 1F (precast install)	2.1 Superstructure - Columns 1F	8FS+7d	Slab-on-grade water curing 7d (soil-supported) before
10	P03	Beams 1F (precast install)	2.2 Superstructure - Beams 1F	9FS+1d	Non-shrink grout cure 1d for precast column base
11	P04	Floor slab 1F (precast install)	2.3 Superstructure - Floor slab 1F	10FS+1d	Non-shrink grout cure 1d for precast beam connection
12	P05	Columns 2F (precast install)	2.4 Superstructure - Columns 2F	11FS+7d	Topping concrete (50mm) on precast plank: water curing
13	P06	Beams 2F (precast install)	2.5 Superstructure - Beams 2F	12FS+1d	Non-shrink grout cure 1d for precast column connection
14	P07	Floor slab 2F / roof ring beam (precast install)	2.6 Superstructure - Upper slab 2F	13FS+1d	Non-shrink grout cure 1d for precast beam connection
15	P08	Stair installation (precast)	2.7 Superstructure - Stairs	11FS+7d	Topping concrete curing 7d before precast stair placement
16	R01	Roof primary structure (gable roof truss)	3.1 Roof - Structure	14FS+7d	Topping concrete (50mm) water curing 7d before roof
17	R02	Roof covering and waterproofing	3.2 Roof - Covering	15FS	-
18	A01	Masonry walls (external + internal partitions)	4.1 Architectural - Masonry walls	11SS	Ground floor masonry can start parallel with slab 1F topping
19	A02	Plastering (internal + external walls)	4.2 Architectural - Plastering	17FS	-
20	A03	Doors and windows installation	4.3 Architectural - Openings	18FS	-
21	A04	Floor finishes	4.4 Architectural - Floor finishes	18FS	-
22	A05	Ceiling installation	4.5 Architectural - Ceiling	18FS	-
23	A06	Painting works (interior + exterior)	4.6 Architectural - Painting	19FS	-
24	A07	Facade cladding installation	4.7 Architectural - Facade	16FS	-

Source: Thesis author (MS Project input)

Table 4.10 - WBS Activity Schedule: Precast Panel (PP)

Act ID	WBS_Code	Name of Activity	WBS	Predecessors	Lag Reason
1	S01	Site clearing and setting out	1.0 Substructure - Site works	-	-
2	S02	Excavation (bulk + trench)	1.1 Substructure - Earthworks	1FS	-
3	S03	Foundation piles (driven precast prestressed pile, install)	1.2 Substructure - Foundation piles	2FS	-
4	S04	Blinding concrete	1.3 Substructure - Blinding	3FS	-
5	S05	Footings (rebar + concrete)	1.4 Substructure - Foundations	4FS	-
6	S06	Column stumps (RC cast in-situ)	1.5 Substructure - Column stumps	5FS+2d	Side formwork strip 2d on footing; then build stump
7	B01	Ground beams (precast install, incl. connections/grout)	1.5 Substructure - Ground beams	6FS+2d	Side formwork strip 2d on stump; precast beam rests on
8	S08	Ground floor slab (RC cast in-situ)	1.7 Substructure - Ground floor slab	7FS+1d	Non-shrink grout cure 1d for precast ground beam
9	B02	Beams 1F (precast install, incl. connections/grout)	2.1 Superstructure - Beams 1F	8FS+7d	Slab-on-grade water curing 7d (soil-supported) before
10	W01	External wall panels 1F install (incl. jointing/grouting)	2.2 Superstructure - External walls 1F	9FS+1d	Non-shrink grout cure 1d for precast beam connection
11	W02	Internal wall panels 1F install (incl. jointing/grouting)	2.3 Superstructure - Internal walls 1F	9FS+1d	Non-shrink grout cure 1d for precast beam connection
12	F01	Precast floor slab panels 1F install (incl. joints/grout)	2.4 Superstructure - Floor slab 1F	11FS+1d	Non-shrink grout cure 1d for wall panel connection before
13	B03	Beams 2F (precast install, incl. connections/grout)	2.5 Superstructure - Beams 2F	12FS+7d	Topping concrete (50mm) on precast plank: water curing
14	W03	External wall panels 2F install (incl. jointing/grouting)	2.6 Superstructure - External walls 2F	13FS+1d	Non-shrink grout cure 1d for precast beam connection
15	W04	Internal wall panels 2F install (incl. jointing/grouting)	2.7 Superstructure - Internal walls 2F	13FS+1d	Non-shrink grout cure 1d for precast beam connection
16	F02	Precast floor slab panels 2F install (incl. joints/grout)	2.8 Superstructure - Upper slab 2F	15FS+1d	Non-shrink grout cure 1d for wall panel connection before
17	T01	Stair installation (precast)	2.9 Superstructure - Stairs	12FS+7d	Topping concrete curing 7d before precast stair placement
18	R01	Roof primary structure (gable roof truss)	3.1 Roof - Structure	16FS+7d	Topping concrete (50mm) water curing 7d before roof
19	R02	Roof covering and waterproofing	3.2 Roof - Covering	17FS	-
20	A03	Doors and windows installation	4.3 Architectural - Openings	13FS	-
21	A04	Floor finishes	4.4 Architectural - Floor finishes	19FS	-
22	A05	Ceiling installation	4.5 Architectural - Ceiling	19FS	-
23	A06	Painting works (interior + exterior)	4.6 Architectural - Painting	20FS	-
24	A07	Facade cladding installation	4.7 Architectural - Facade	18FS	-

Source: Thesis author (MS Project input)

Table 4.11 - WBS Activity Schedule: Renovation Scenario (RS)

Act ID	WBS_Code	Name of Activity	WBS	Predecessors	Lag Reason
1	S01	Site setup and protection	1.0 Renovation - Site works	-	-
2	S02	Existing condition survey and measurement	1.1 Renovation - Survey	1FS	-
3	RS01	Remove existing roof covering	2.1 Roof - Removal	2FS	-
4	RS02	Dismantle existing roof structure	2.2 Roof - Structure removal	3FS	-
5	R01	Install new roof primary structure (gable truss)	2.3 Roof - Structure installation	4FS	-
6	R02	Install new roof covering and waterproofing	2.4 Roof - Covering installation	5FS	-
7	RS03	Remove existing floor finishes	3.1 Floor - Removal	2SS	-
8	RS04	Substrate preparation / leveling	3.2 Floor - Preparation	7FS	-
9	A04	Install new floor finishes	3.3 Floor - Installation	8FS+1d	Substrate screed cure 1d (overnight) before floor tile
10	RS05	Demolish existing AAC wall partition (Living Area)	5.1 Wall Modification - Demolition	2SS	Can start after survey complete; parallel with floor/roof
11	RS07	New AAC block partition construction (Living	5.2 Wall Modification - New partition	10FS+1d	Rubble/debris cleared same day (small scope ≤30 m²); 1d
12	ST07	Stair finishes replacement	3.4 Stairs - Finishes	2SS	-
13	A03	Replace doors and windows (frames and leaves)	4.3 Architectural - Openings	2SS	-
14	A05	Local ceiling replacement	4.5 Architectural - Ceiling	2SS	-
15	A06	Painting works (interior + exterior)	4.6 Architectural - Painting	9FS,11FS	-
16	A07	Facade cladding / re-cladding installation	4.7 Architectural - Facade	6FS	-

Source: Thesis author (MS Project input)

Step 4: Handoff to UC2 and UC3

Activity duration per WBS code, combined with crew size and daily wage rates, provides the labour cost basis for UC2. Equipment rental duration is derived from crane-dependent activities identified in the same schedule. For UC3, phase durations define the temporal boundaries of construction stage A5, informing the allocation of on-site equipment emissions across the A4–A5 module. This linkage ensures that cost and carbon differences between scenarios are attributed to construction logic rather than to inconsistent scheduling assumptions.

4.2.2 UC2 – COST ESTIMATION

Use Case 2 (UC2) translates BIM-based quantity take-off and UC1 schedule outputs into a direct cost comparison across the four construction scenarios. The scope covers material, labour, equipment, and transportation costs as defined in Section 3.2.2. Indirect costs are excluded so that differences reflect construction logic rather than project-specific commercial conditions.

UC2 Data Flow Diagram

Figure 4.X illustrates the data flow for UC2, from BIM model and UC1 schedule inputs through Dynamo and MS Project to the final cost output per scenario.

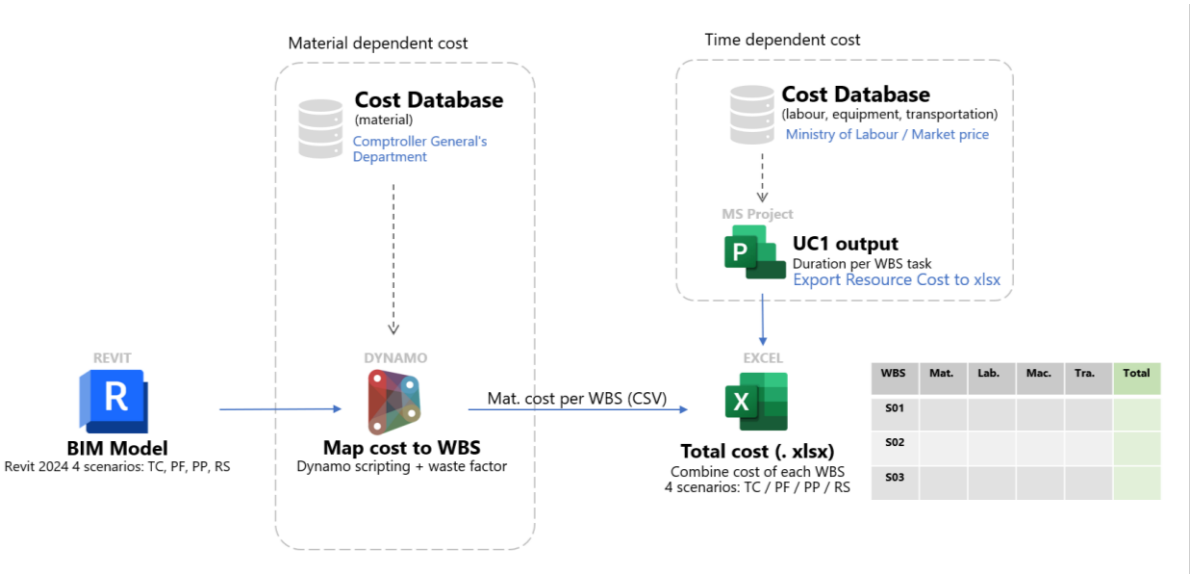


Figure 4.20 - UC2 Cost Estimation: Data Flow Diagram
Source: Thesis author

Step 1: BIM Model Parameter Setup

Five cost-related parameters were embedded in the Revit model as listed in Table 4.X. Only material-related parameters are stored in the model. Labour, equipment, and transportation costs are derived externally from UC1 duration outputs to avoid duplicating time-dependent logic within the geometric model.

Table 4.12 - BIM Parameters for 5D Cost Estimation (UC2)

Parameter Name	Type / Instance	Data Type	Group Under	Purpose
WBS_Code	Type	Text	Identity Data	Group elements for cost estimation
Unit_Material_Cost	Type	Currency	Cost	Material price per unit
Waste_Factor	Type	Number (%)	Construction	Quantity adjustment for material loss
Adjusted_Quantity	Instance	Number	Construction	Waste-adjusted quantity per element
Material_Cost	Instance	Currency	Cost	Final material cost per element

Source: Thesis author; consistent with Section 3.4.2

<M41_02_UC2_Material Cost Estimation per activity>

For the blank unit materil cost: 1. productivity unit and material cost logic is not similar inside WBS code plese find more detail in QTO (A01, R01) 2. Blank unit material cost does not contain material inside activity (S01, S02)

A	B	C	D	E	F	G	H
Acti	WBS_C	Name of Activity	Unit_cost	Cost per unit	Waste_Factor	Adjusted_Quantity	Material_Cost
1	S01	Site clearing and setting out					
2	S02	Excavation					
3	S03	Foundation piles (driven precast)	m	฿2,076.00	0		
4	S04	Blinding concrete	m2	฿123.00	0.075		
5	S05	Footings	m3	฿2,470.60	0.075		
6	S06	Column stumps	m3	฿2,470.00	0.075		
7	P01	Ground beams (precast install, incl. connections) 0.2x0.4	m	฿1,700.00	0		
7	P01	Ground beams (precast install, incl. connections) 0.2x0.4	m	฿2,000.00	0		
8	S08	Ground floor slab (RC)	m3	฿2,470.60	0.075		
9	P02	Floor slab 1F (Precast Install)	m2	฿1,375.00	0		
10	P03	Columns 1F (Precast Install)	m	฿1,000.00	0		
11	P04	Beams 1F (Precast Install)	m	฿1,700.00	0		
12	P05	Floor slab 2F (Precast Install)	m2	฿1,375.00	0		
13	P06	Stair (Precast Install)	piece	฿4,000.00	0		
14	P07	Columns 2F (Precast Install)	m	฿1,000.00	0		
15	P08	Beams 2F (Precast Install)	m	฿1,700.00	0		
16	P09	Floor slab upper 2F (Precast Install)	m2	฿1,375.00	0.075		
17	R01	Roof structure (Look detail in QTO)	<varies>	฿50.00	0.07		
17	R01	Roof structure (Look detail in QTO)	m	฿80.00	0.07		
17	R01	Roof structure (Look detail in QTO)	m	฿546.00	0.07		
18	R02	Roof covering and waterproofing	m2	฿162.00	0.04		
18	R02	Roof covering and waterproofing (Metal Sheet)	m2	฿200.00	0.04		
19	A01	Tie column and beam (Look detail in QTO)	m		0.075		
19	A01	Wall 10cm	m2	฿200.00	0.04		
19	A01	Wall 20cm	m2	฿400.00	0.04		
20	A02	Plastering (internal + external walls, 12mm)	m2	฿100.00	0.075		
21	A03	Doors and windows	piece	฿2,000.00	0		
21	A03	Doors and windows	piece	฿4,000.00	0		
21	A03	Doors and windows	piece	฿6,000.00	0		
21	A03	Doors and windows	piece	฿20,000.00	0		
22	A04	Floor finishes	m2	฿500.00	0.075		
23	A05	Ceiling installation	m2	฿400.00	0.075		
24	A07	Facade					

Figure 4.21 - Input of 5D Material Cost Estimation (UC2) inside Revit 2024
Source: Thesis author; consistent with Section 3.4.2

Step 2: QTO and Material Cost Calculation (Dynamo)

A Dynamo script extracted BIM quantities, applied waste factors to obtain ordered quantities, and calculated material cost per element as defined in Section 3.2.2. The results were written back to Adjusted_Quantity and Material_Cost as instance parameters and exported as CSV for MS Project aggregation.

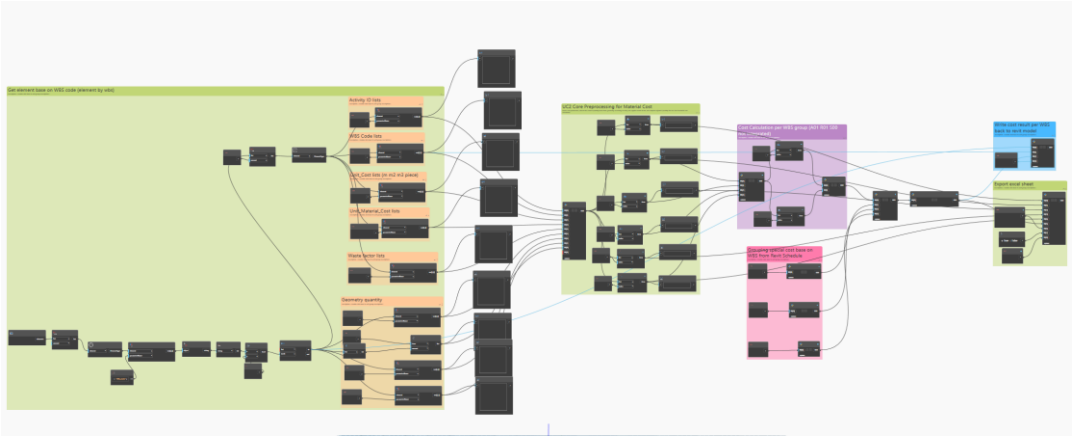
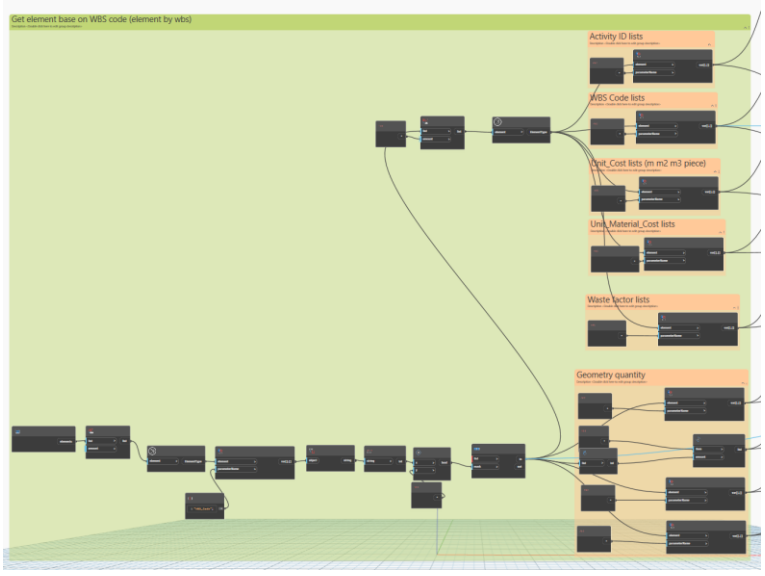


Figure 4.22 - Dynamo Script UC2: Full Workspace Overview

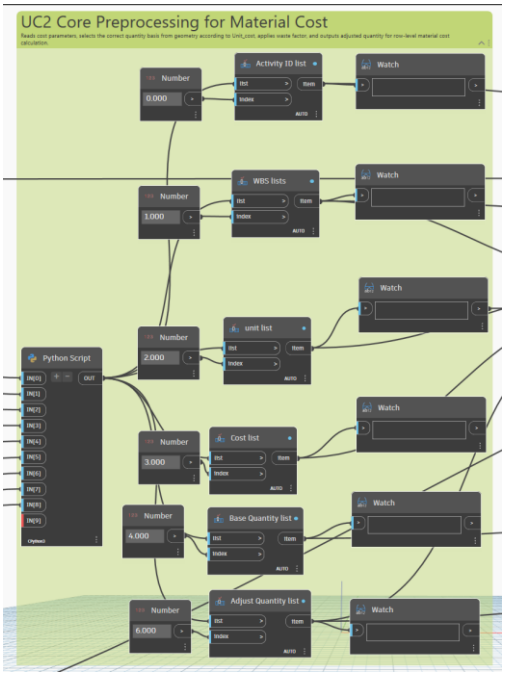
Source: Thesis author (Dynamo, Revit 2025)

Get element base on WBS code follows the same filtering logic as UC1, retaining only elements with the WBS_Code, but extracts Unit_Material_Cost and Geometry quantity in place of the productivity and crew parameters used in UC1.



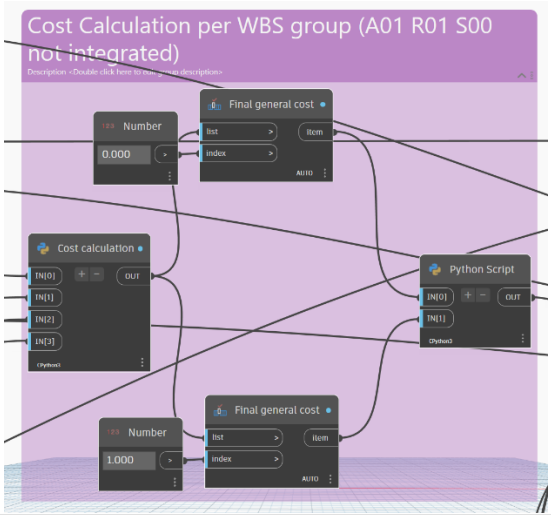
Source: Thesis author (Dynamo, Revit 2025)

UC2 Core Preprocessing for Material Cost acts as the unit resolver and quantity cleaner, selecting the correct geometric dimension per element based on Unit_Cost, applying the Waste_Factor to produce Adjusted_Quantity, and outputting aligned lists for downstream cost computation.



Source: Thesis author (Dynamo, Revit 2025)

Cost Calculation per WBS group multiplies Adjusted_Quantity by Unit_Material_Cost and sums the result per WBS group to produce material cost per activity. Activities A01, R01, and S00 are excluded because each holds several material components with different unit rates inside a single WBS code, which conflicts with the one WBS code per family type logic used throughout the script. In A01 for example, a single tie column-beam family needs separate rates for concrete (THB 2,507/m3) and rebar (THB 40/m), which cannot fit into one Unit_Material_Cost value; these activities are therefore handled separately to keep full per-component cost accuracy.

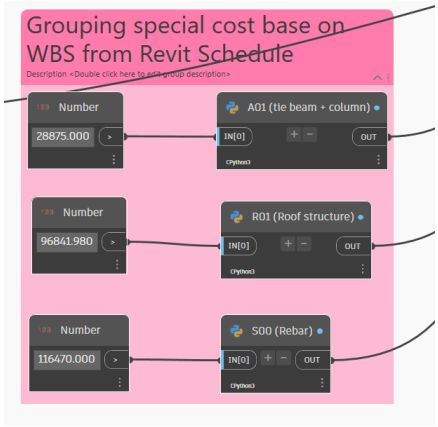


<M41_A01 Quantity takeoff for tie Column - Beam>

A	B	C	D	E	F	G	H	I	J	K	L	M
WBS_Code	Type	Count	Total Length	Area Surface	Volume	Waste_Factor	Adjusted Quantity	4RB9 :1m	Concrete 1m3	Concrete_cost	Rebar_Cost	Tie C-B_Cost
A01	RSB - Tie Column - Beam 10 x 10 cm	41	102.90	0.01 m²	1.03 m³	0.075	1.11 m³	<varies>	₿2,507.00	₿2,773.20	₿3,816.03	₿6,387.10
A01	RSB - Tie Column - Beam 10 x 20 cm	96	233.51	0.02 m²	4.67 m³	0.075	5.02 m³	₿40.00	₿2,507.00	₿12,586.14	₿9,340.27	₿21,926.41
A01	RSB - Tie Column - Beam 20 x 20 cm	2	5.50	0.04 m²	0.22 m³	0.075	0.24 m³	₿40.00	₿2,507.00	₿592.91	₿220.00	₿812.91
Grand total: 139		139	341.91		5.92 m³		6.36 m³			₿15,952.24	₿13,376.30	₿29,126.41

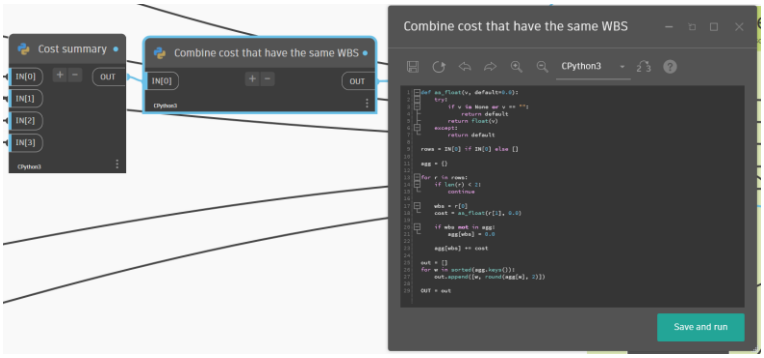
Source: Thesis author (Dynamo, Revit 2025)

Grouping special cost base on WBS from Revit Schedule handles the three excluded activities by insertinging lump-sum values sourced directly from Revit Schedule, bypassing the geometry pipeline entirely, and feeds the results back into the main cost stream at the merge point.



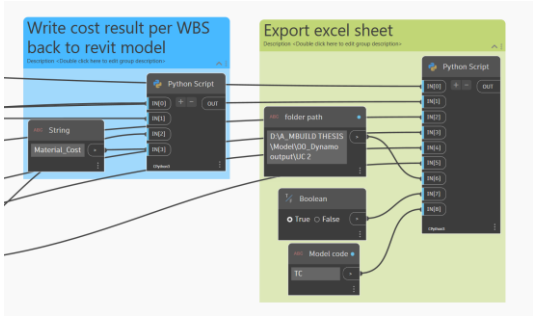
Source: Thesis author (Dynamo, Revit 2025)

Cost summary and Combine cost that have the same WBS merge the general and special cost streams and deduplicate by summing entries sharing the same WBS code, producing one final material cost value per activity.



Source: Thesis author (Dynamo, Revit 2025)

Write the cost result back to the Revit model and export an Excel sheet. Write Material_Cost back to each element instance for Revit schedule visibility, and export the consolidated table as a tagged Excel file per scenario for subsequent merging with labour, equipment, and transportation outputs from MS Project.



Source: Thesis author (Dynamo, Revit 2025)

Step 3: Labour, Equipment, and Transportation Cost (MS Project)

Labour, equipment, and transportation costs were configured in MS Project using three resource types that correspond to the cost categories defined in Section 3.2.2. Work resources (Type = Work) were assigned for labour trades and equipment, with a standard daily rate multiplied automatically by the WBS activity duration from the UC1 schedule. Transportation costs were assigned as Cost resources (Type = Cost), with a lump-sum value per delivery trip calculated. All resources were tagged with a Group field (Labour, Equipment, and transportation) to enable cost category filtering during export.

RESOURCE SHEET

	Resource Name	Type	Material	Initials	Group	Max.	Std. Rate	Ovt. Rate	Cost/Use	Accrue	Base
1	General Labour	Work			Labour	100%	฿400.00/day	฿0.00/hr	฿0.00	Prorated	6day per week
2	Skilled Labour	Work			Labour	100%	฿445.00/day	฿0.00/hr	฿0.00	Prorated	6day per week
3	Pile Operator	Work			Labour	100%	฿515.00/day	฿0.00/hr	฿0.00	Prorated	6day per week
4	Precast Installer	Work			Labour	100%	฿510.00/day	฿0.00/hr	฿0.00	Prorated	6day per week
5	Roof Cover Labour	Work			Labour	100%	฿470.00/day	฿0.00/hr	฿0.00	Prorated	6day per week
6	Mason	Work			Labour	100%	฿510.00/day	฿0.00/hr	฿0.00	Prorated	6day per week
7	Plasterer	Work			Labour	100%	฿455.00/day	฿0.00/hr	฿0.00	Prorated	6day per week
8	Door Window Installer	Work			Labour	100%	฿435.00/day	฿0.00/hr	฿0.00	Prorated	6day per week
9	Floor Ceiling Finishing	Work			Labour	100%	฿485.00/day	฿0.00/hr	฿0.00	Prorated	6day per week
10	Painter	Work			Labour	100%	฿500.00/day	฿0.00/hr	฿0.00	Prorated	6day per week
11	Demolish Labour	Work			Labour	100%	฿400.00/day	฿0.00/hr	฿0.00	Prorated	6day per week
12	Excavator	Work			Equipment	100%	฿5,750.00/day	฿0.00/hr	฿0.00	Prorated	6day per week
13	Pile Machine	Work			Equipment	100%	฿15,000.00/day	฿0.00/hr	฿0.00	Prorated	6day per week
14	Concrete Pump	Work			Equipment	100%	฿500.00/day	฿0.00/hr	฿0.00	Prorated	6day per week
15	Crane (PF)	Work			Equipment	100%	฿5,500.00/day	฿0.00/hr	฿0.00	Prorated	6day per week
16	Crane (PP)	Work			Equipment	100%	฿7,500.00/day	฿0.00/hr	฿0.00	Prorated	6day per week
17	Crane (roof)	Work			Equipment	100%	฿5,000.00/day	฿0.00/hr	฿0.00	Prorated	6day per week
18	Transportation	Cost			Transportation					Prorated	

Figure 4.23 - MS Project Resource Assignment: Labour, Equipment, and Transportation

Source: MS Project Resource Assignment: Labour, Equipment, and Transportation

Step 4: Export and Cost Aggregation (Excel)

Resource cost data were exported from MS Project to Microsoft Excel using the Export Wizard with Assignment mapping, selecting the fields Task Name, Resource Name, Resource Group, and Cost. The exported Assignment_Table sheet contains one row per resource per WBS activity, enabling cost filtering by Group (LAB, MAC, TRA) using SUMIFS formulas. Material cost values from the Dynamo CSV were entered directly into the Material column of the Summary sheet. The Total column is computed as the sum of all four cost categories per WBS activity.

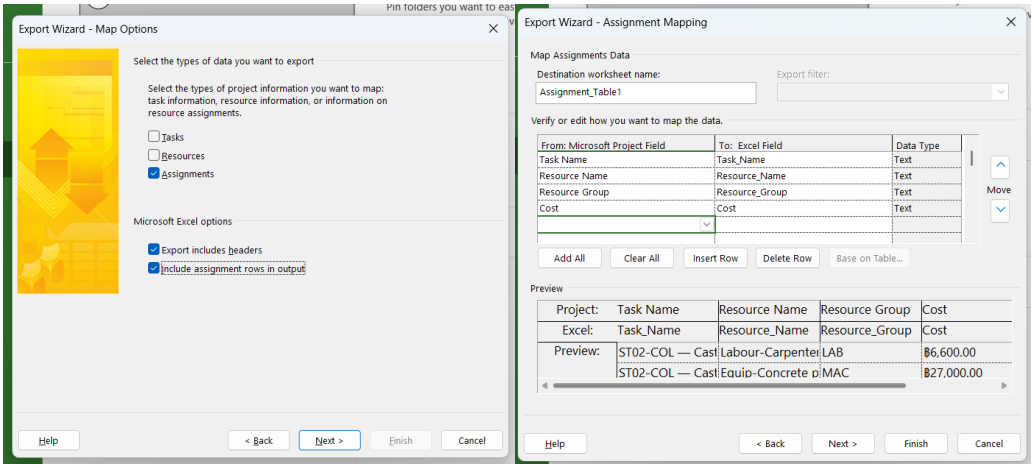
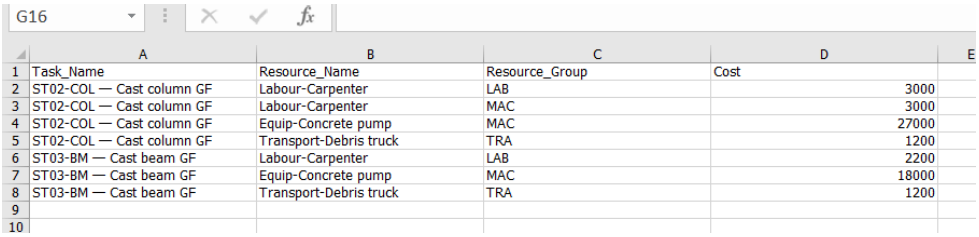


Figure 4.24 - Export Wizard with Assignment mapping (example)
Source: Thesis author (MS Project)



	A	B	C	D	E
1	Task_Name	Resource_Name	Resource_Group	Cost	
2	ST02-COL — Cast column GF	Labour-Carpenter	LAB	3000	
3	ST02-COL — Cast column GF	Labour-Carpenter	MAC	3000	
4	ST02-COL — Cast column GF	Equip-Concrete pump	MAC	27000	
5	ST02-COL — Cast column GF	Transport-Debris truck	TRA	1200	
6	ST03-BM — Cast beam GF	Labour-Carpenter	LAB	2200	
7	ST03-BM — Cast beam GF	Equip-Concrete pump	MAC	18000	
8	ST03-BM — Cast beam GF	Transport-Debris truck	TRA	1200	
9					
10					

Figure 4.25 - Export Wizard with Assignment mapping (example)
Source: Thesis author (MS Project)

The SUMIFS formula applied for each cost category is structured as follows, using wildcard matching to accommodate full task name strings exported from MS Project:

Lab. = SUMIFS(Cost_col, Task_col, "*"&WBS_code&"*", Group_col, "LAB")

Mac. = SUMIFS(Cost_col, Task_col, "*"&WBS_code&"*", Group_col, "MAC")

Tra. = SUMIFS(Cost_col, Task_col, "*"&WBS_code&"*", Group_col, "TRA")

The resulting summary table provides a direct cost breakdown per WBS activity across all four scenarios (TC, PF, PP, RS), forming the primary dataset for UC4 comparative analysis. Table 4.13 presents an excerpt of the output format.

Table 4.26 - UC2 Cost Output: Direct Cost Breakdown per WBS Activity (example)

	A	B	C	D	E	F	G
1	WBS	Task_Name	Lab.	Mac.	Tra.	Materia	Total
2	ST02-COL	Cast column GF	3000	30000	1200	10892	45092
3	ST03-BM	Cast beam GF	2200	18000	1200	8450	29850
4							

Note: Material cost values derived from Dynamo QTO. Labour, equipment, and transportation costs derived from MS Project resource assignment linked to UC1 duration. Values in THB.

4.2.3 UC3 – EMBODIED CARBON ASSESSMENT

Use Case 3 (UC3) quantifies embodied carbon across lifecycle modules A1–A5 for each construction scenario, following the system boundary and data hierarchy defined in Section 3.2.3. The system boundary covers architectural and structural works only; MEP systems and temporary works are explicitly excluded in accordance with the scope defined in Section 3.2.3. Material quantities extracted from the BIM model are mapped to emission factors from EPD and TGO databases, and construction stage emissions are derived from UC1 phase durations and UC2 transportation data. Results are reported in $kgCO_2e$ per complete building per construction scenario, conforming to EN 15978 [functional unit: one complete two-storey single-family house, 150–200 m^2 GFA].

UC3 Data Flow Diagram

Figure 4.X illustrates the data flow for UC3, from BIM model quantities and external emission factor databases through OneClick LCA (v.24.x) to the final embodied carbon output. Material quantities from Revit feed into OneClick LCA for A1–A3 product stage assessment, while activity durations and equipment utilisation hours derived from UC1 (MS Project) provide the basis for A4–A5 construction stage calculations.

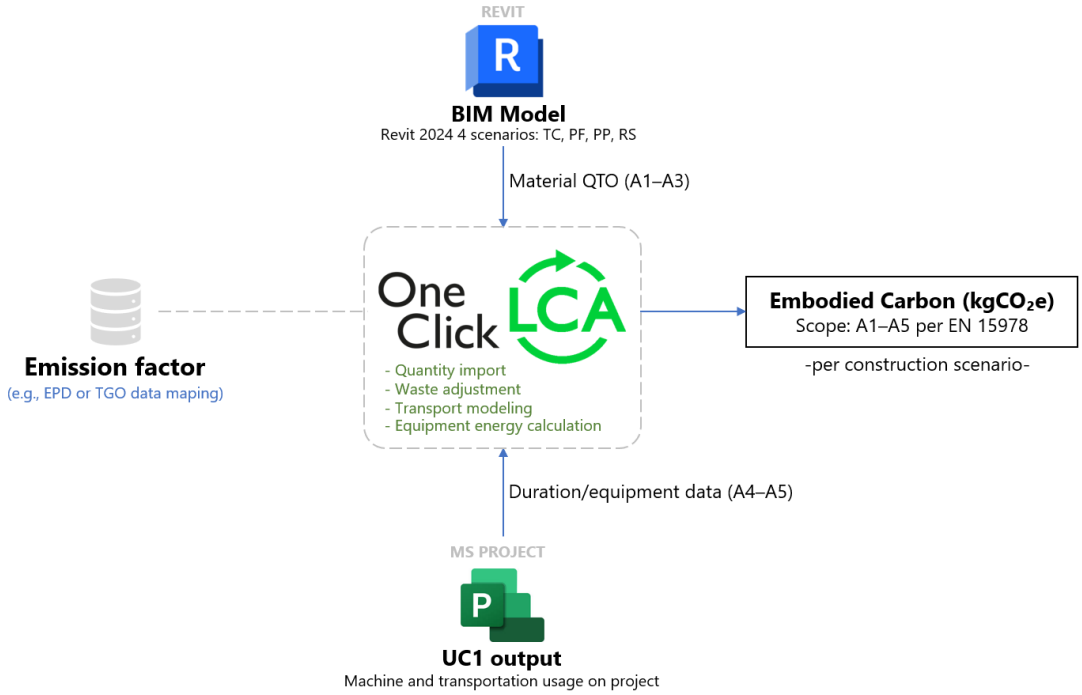


Figure 4.26 - UC3 Embodied Carbon Assessment: Data Flow Diagram
Source: Thesis author

Step 1: Revit Model Preparation

Before initiating the export, the 3D view Visibility/Graphic Overrides is set to display all model categories without exception. This step prevents any building element from being omitted during the quantity extraction, as OneClick LCA captures only elements visible in the active view at the time of export.

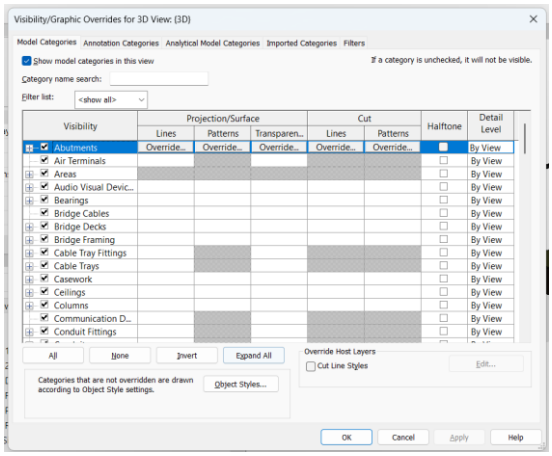


Figure 4.27- Revit Visibility Graphic showing all categories checked

Source: Thesis author

Within the plugin panel, the Models tab is set to Active view (Main model) with both Existing and New Construction phases checked. This configuration is applied consistently across all four scenario models.

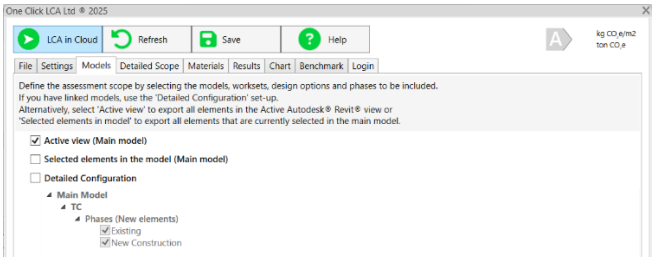


Figure 4.28 - OneClick LCA plugin Models tab showing Active view and phase selection

Source: Thesis author (OneClick LCA)

Step 2: Import Settings

The exported data is assigned to the project MBUILD_M41_Pirawit_2026 and the corresponding design name for each scenario. The scenarios.

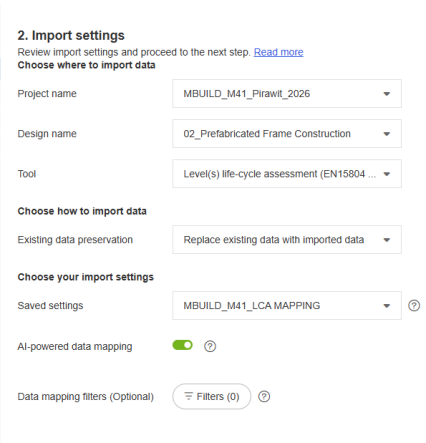


Figure 4.29 - OneClick LCA Import settings showing project, design name, tool selection, and saved settings

Source: Author, via OneClick LCA platform

Step 3: Column Mapping

At the Column mapping step, the MATERIAL field is mapped to Name, VOLUME_M3 to Quantity, and QTY_TYPE to Unit. Additional fields including CLASS, CATEGORY, FAMILY, TYPE, AREA_M2, LENGTH_M, and ELEMENTIDS are assigned as Extra information. Columns not relevant to the LCA calculation are skipped.

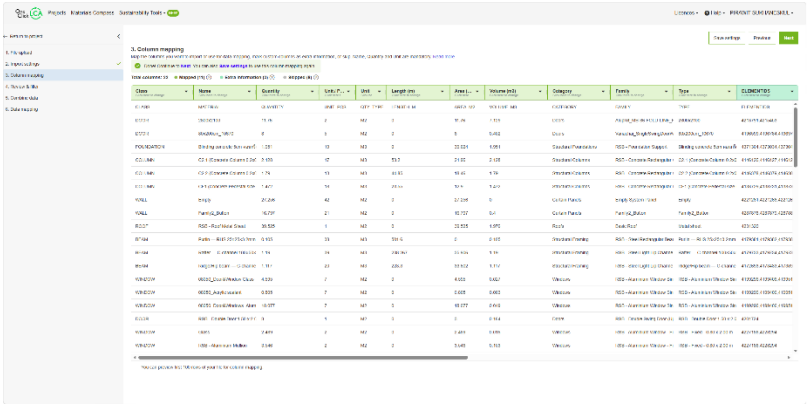


Figure 4.30 - OneClick LCA Column mapping interface

Source: Author, via OneClick LCA platform

Step 4: Material Mapping

At the Data mapping stage, each material name is linked to an EPD or generic dataset. The AI-powered mapping function provides an initial suggestion based on material name and unit compatibility. All mappings are reviewed manually and adjusted where the suggestion does not reflect the Thai construction context.

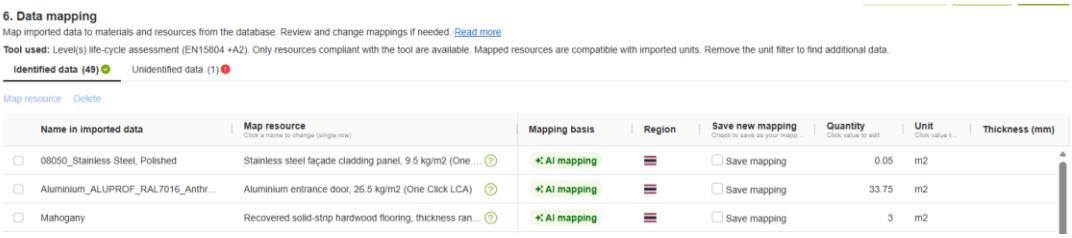


Figure 4.31 - OneClick LCA Data mapping interface with Thailand filter applied, showing AI mapping EPD resources

Source: Author, via OneClick LCA platform

The EPD selection hierarchy prioritizes Thai-specific EPDs first, followed by Thailand-region generic datasets within OneClick LCA (identifiable by the Thai flag icon), Structural concrete is mapped to Ready-mix concrete datasets at the appropriate strength class, *with CPAC entries from The Concrete Products and Aggregate Co., Ltd.* used where available. Reinforcement steel is mapped to generic rebar at 0% recycled content as a conservative baseline. Structural steel sections are mapped to structural steel rolled section datasets. For materials without a direct equivalent, the closest functionally equivalent dataset is selected and recorded as a proxy assignment.

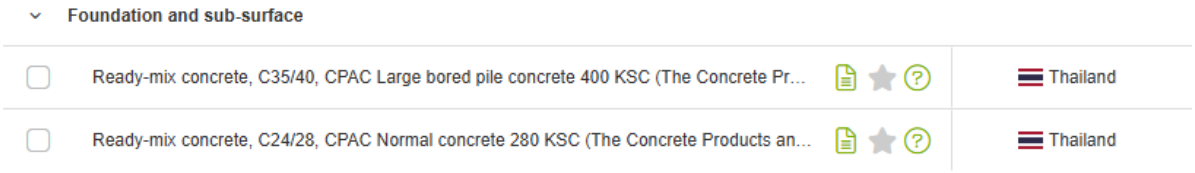
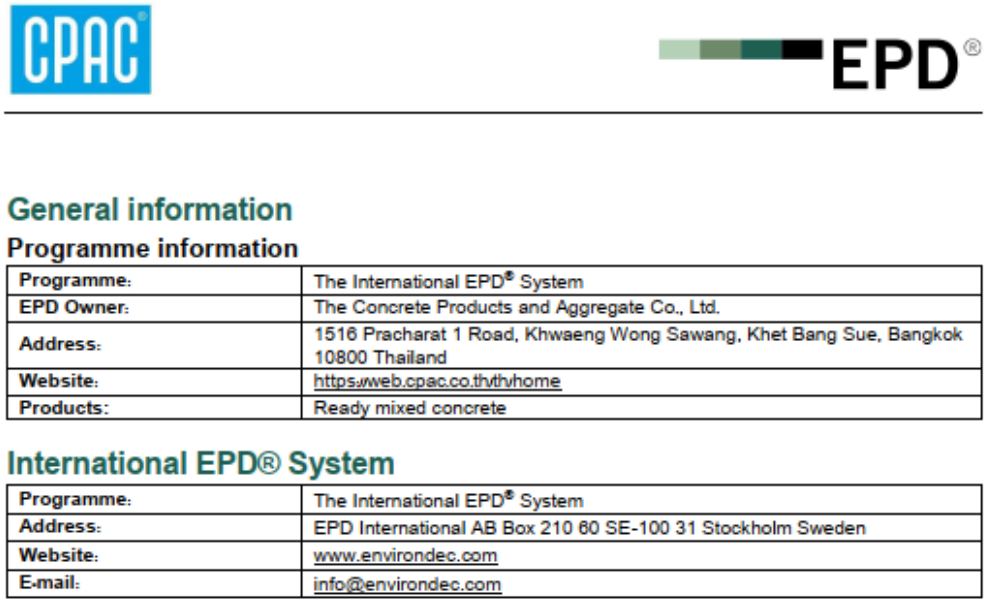


Figure 4.32 - OneClick LCA Data mapping interface with Thailand filter applied, showing material names and mapped EPD resources

Source: Author, via OneClick LCA platform



General information

Programme information

Programme:	The International EPD® System
EPD Owner:	The Concrete Products and Aggregate Co., Ltd.
Address:	1516 Pracharat 1 Road, Khwaeng Wong Sawang, Khet Bang Sue, Bangkok 10800 Thailand
Website:	https://web.cpac.co.th/th/home
Products:	Ready mixed concrete

International EPD® System

Programme:	The International EPD® System
Address:	EPD International AB Box 210 60 SE-100 31 Stockholm Sweden
Website:	www.environdec.com
E-mail:	info@environdec.com

Figure 4.33 The Concrete Products and Aggregate Co., Ltd. (2024) Environmental Product Declaration: Ready Mixed Concrete.

Source: The International EPD System. Available at: https://web.cpac.co.th/th/home

Step 5: A4 and A5 Configuration

After material mapping is complete, transportation distances (A4) and construction site operation parameters (A5) are entered manually at the building part level. Hauling distances for major material groups are estimated based on supplier locations relative to Pathumthani Province. A5 construction process emissions, covering site equipment energy use and construction waste, are informed by the activity durations and equipment schedules established in UC1.

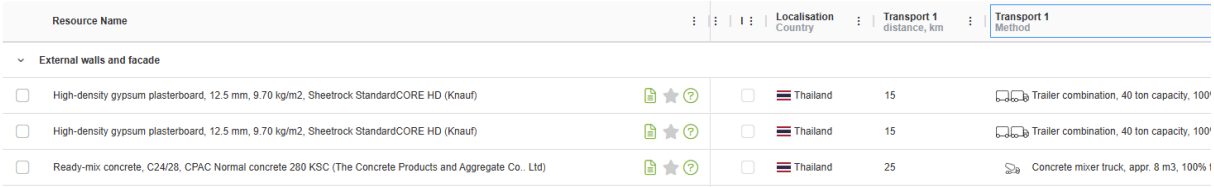
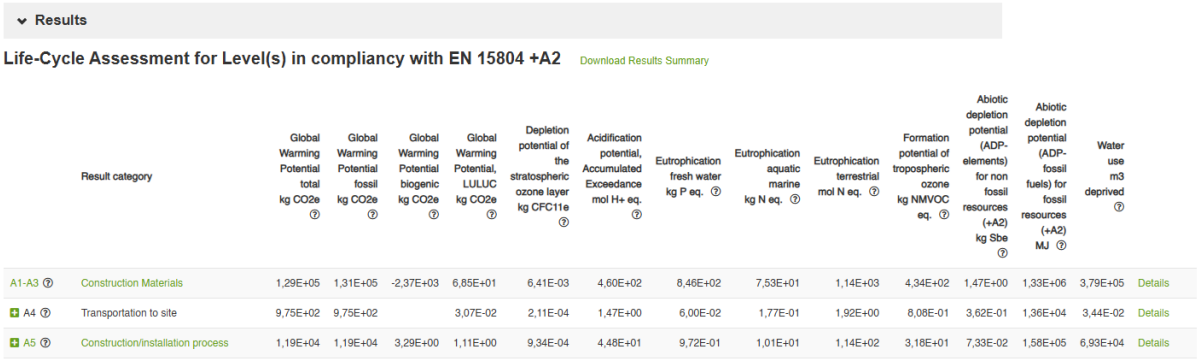


Figure 4.34 - OneClick LCA Data mapping transportation distance

Source: Author, via OneClick LCA platform

Step 6: Calculation and Export

Once all parameters are confirmed, the carbon calculation is run and the results are exported. The output reports total embodied carbon per scenario in kg CO2e, disaggregated by life-cycle module (A1–A3, A4, A5) and building part category, providing the input data required for the comparative analysis in UC4.



Results

Life-Cycle Assessment for Level(s) in compliancy with EN 15804 +A2 Download Results Summary

	Result category	Global Warming Potential total kg CO2e	Global Warming Potential fossil kg CO2e	Global Warming Potential biogenic kg CO2e	Global Warming Potential, LULUC kg CO2e	Depletion potential of the stratospheric ozone layer kg CFC11e	Acidification potential, Accumulated Exceedance mol H+ eq.	Eutrophication fresh water kg P eq.	Eutrophication aquatic marine kg N eq.	Eutrophication terrestrial mol N eq.	Formation potential of tropospheric ozone kg NMVOC eq.	Abiotic depletion potential (ADP-elements) for non fossil resources (+A2) kg Sbe	Abiotic depletion potential (ADP-fossil fuels) for fossil resources (+A2) MJ	Water use m3 deprived	
A1-A3	Construction Materials	1,29E+05	1,31E+05	-2,37E+03	6,85E+01	6,41E-03	4,60E+02	8,46E+02	7,53E+01	1,14E+03	4,34E+02	1,47E+00	1,33E+06	3,79E+05	Details
A4	Transportation to site	9,75E+02	9,75E+02		3,07E-02	2,11E-04	1,47E+00	6,00E-02	1,77E-01	1,92E+00	8,08E-01	3,62E-01	1,36E+04	3,44E-02	Details
A5	Construction/installation process	1,19E+04	1,19E+04	3,29E+00	1,11E+00	9,34E-04	4,48E+01	9,72E-01	1,01E+01	1,14E+02	3,18E+01	7,33E-02	1,58E+05	6,93E+04	Details

Figure 4.35 - OneClick LCA Building materials results view showing mapped resources grouped by building part with CO2e values

Source: Author, via OneClick LCA platform

5

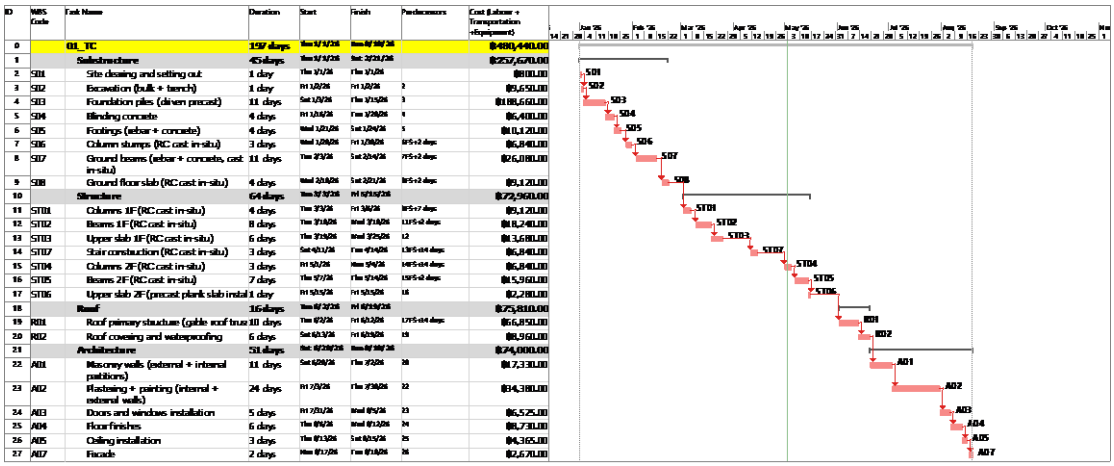
RESULT AND DISCUSSION

5.1 CONSTRUCTION TIME ANALYSIS (UC1)

Analytical comparison based on scheduling results

5.1.1 NEW CONSTRUCTION COMPARISON (TC / PF / PP)

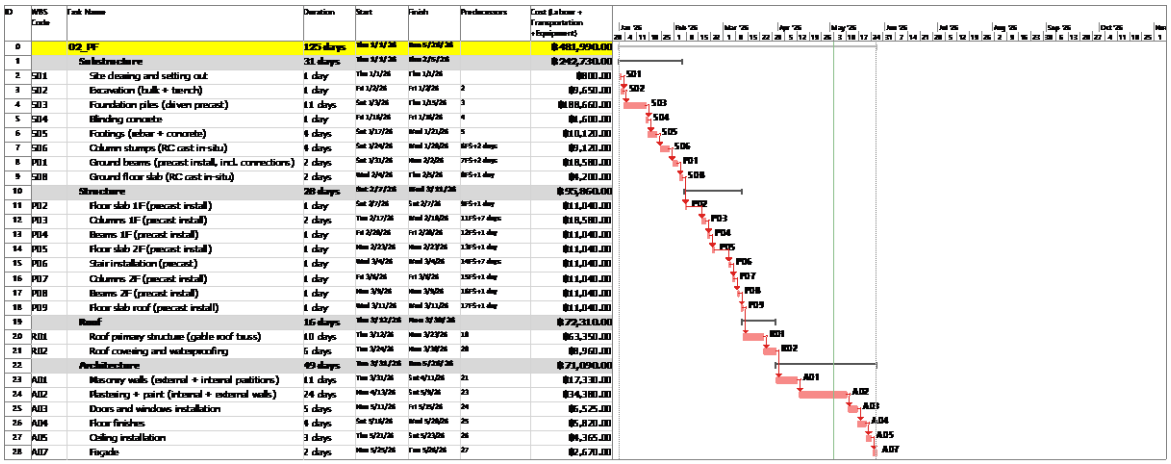
Figures 5.1 through 5.3 present the phase-based Gantt charts for each scenario, exported from MS Project. Each chart illustrates the sequence of activities based on WBS codes, including predecessor relationships and associated lags.



ID	WBS Code	Task Name	Duration	Start	Finish	Predecessors	Cost (Labour + Transportation +Equipment)
0		01_TC	157 days	Mon 1/1/26	Mon 8/10/26		฿480,440.00
1		Substructure	45 days	Mon 1/1/26	Sat 2/28/26		฿257,670.00
2	ST1	Site clearing and setting out	1 day	Thu 1/1/26	Thu 1/1/26		฿810.00
3	ST2	Excavation (bulk + bench)	1 day	Fri 1/2/26	Fri 1/2/26	2	฿9,650.00
4	ST3	Foundation piles (driven precast)	11 days	Sat 1/3/26	Thu 1/15/26	3	฿188,660.00
5	ST4	Blinding concrete	4 days	Fri 1/16/26	Tue 1/20/26	4	฿6,480.00
6	ST5	Footings (rebar + concrete)	4 days	Wed 1/21/26	Sat 1/24/26	5	฿10,120.00
7	ST6	Column stumps (RC cast in-situ)	3 days	Wed 1/28/26	Fri 1/30/26	6FS+2 days	฿6,840.00
8	ST7	Ground beams (rebar + concrete, cast in-situ)	11 days	Thu 2/13/26	Sat 2/28/26	7FS+2 days	฿26,080.00
9	ST8	Ground floor slab (RC cast in-situ)	4 days	Wed 2/18/26	Sat 2/21/26	8FS+2 days	฿9,120.00
10		Structure	64 days	Mon 2/2/26	Fri 5/1/26		฿272,960.00
11	ST01	Columns 1F (RC cast in-situ)	4 days	Thu 2/5/26	Fri 2/6/26	8FS+7 days	฿9,120.00
12	ST02	Beams 1F (RC cast in-situ)	8 days	Thu 2/19/26	Wed 2/25/26	11FS+2 days	฿18,240.00
13	ST03	Upper slab 1F (RC cast in-situ)	6 days	Thu 2/19/26	Wed 2/25/26	12	฿13,680.00
14	ST07	Stair construction (RC cast in-situ)	3 days	Sat 4/11/26	Tue 4/14/26	13FS+14 days	฿6,840.00
15	ST04	Columns 2F (RC cast in-situ)	3 days	Fri 5/1/26	Mon 5/4/26	14FS+14 days	฿6,840.00
16	ST05	Beams 2F (RC cast in-situ)	7 days	Thu 5/7/26	Thu 5/14/26	15FS+2 days	฿15,960.00
17	ST06	Upper slab 2F (precast plank slab instal	1 day	Fri 5/15/26	Fri 5/15/26	16	฿2,280.00
18		Roof	16 days	Mon 6/1/26	Fri 6/19/26		฿75,810.00
19	R01	Roof primary structure (gable roof truss	10 days	Thu 6/2/26	Fri 6/12/26	17FS+14 days	฿66,850.00
20	R02	Roof covering and waterproofing	6 days	Sat 6/13/26	Fri 6/19/26	19	฿8,960.00
21		Architecture	51 days	Sat 6/20/26	Mon 8/10/26		฿24,000.00
22	A01	Masonry walls (external + internal partitions)	11 days	Sat 6/20/26	Thu 7/2/26	20	฿17,330.00
23	A02	Plastering + painting (internal + external walls)	24 days	Fri 7/3/26	Thu 7/30/26	22	฿34,380.00
24	A03	Doors and windows installation	5 days	Fri 7/31/26	Wed 8/5/26	23	฿6,525.00
25	A04	Floor finishes	6 days	Thu 8/6/26	Wed 8/12/26	24	฿8,730.00
26	A05	Ceiling installation	3 days	Thu 8/13/26	Sat 8/15/26	25	฿4,365.00
27	A07	Facade	2 days	Mon 8/17/26	Tue 8/18/26	26	฿2,670.00

Figure 5.1 - Phase-Based Gantt Chart: Traditional Cast-in-Place (TC)

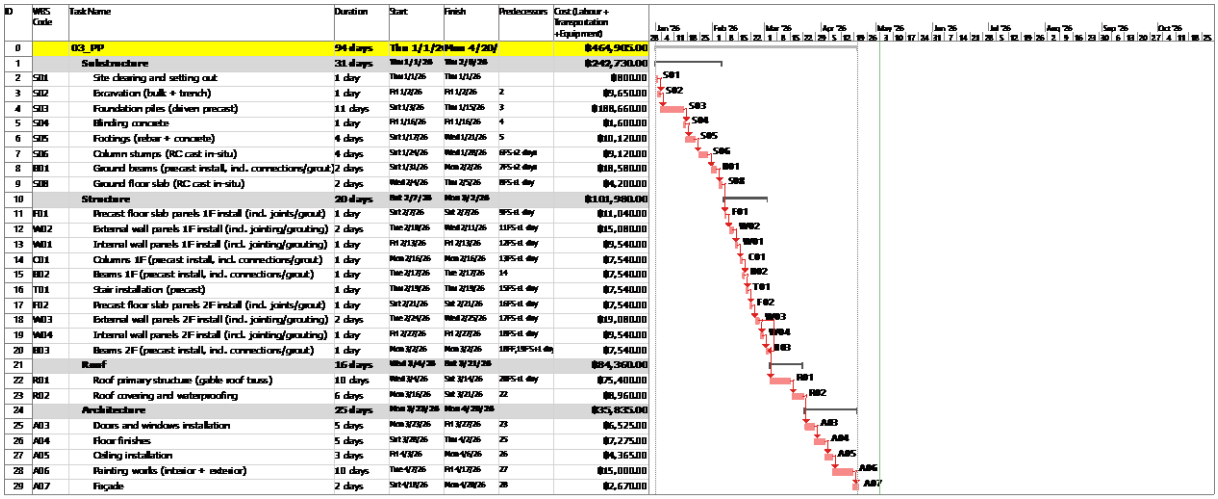
Source: Thesis author (MS Project)



ID	WBS Code	Task Name	Duration	Start	Finish	Predecessors	Cost (Labour + Transportation +Equipment)
0		02_PF	125 days	Mon 1/1/26	Mon 6/29/26		฿481,990.00
1		Substructure	31 days	Mon 1/1/26	Mon 2/9/26		฿242,730.00
2	ST1	Site clearing and setting out	1 day	Thu 1/1/26	Thu 1/1/26		฿810.00
3	ST2	Excavation (bulk + bench)	1 day	Fri 1/2/26	Fri 1/2/26	2	฿9,650.00
4	ST3	Foundation piles (driven precast)	11 days	Sat 1/3/26	Thu 1/15/26	3	฿188,660.00
5	ST4	Blinding concrete	1 day	Fri 1/16/26	Fri 1/16/26	4	฿1,600.00
6	ST5	Footings (rebar + concrete)	4 days	Sat 1/17/26	Wed 1/21/26	5	฿10,120.00
7	ST6	Column stumps (RC cast in-situ)	4 days	Sat 1/24/26	Wed 1/28/26	6FS+2 days	฿9,120.00
8	P01	Ground beams (precast install, incl. connections)	2 days	Sat 1/31/26	Mon 2/2/26	7FS+2 days	฿18,580.00
9	ST8	Ground floor slab (RC cast in-situ)	2 days	Wed 2/4/26	Thu 2/5/26	8FS+1 day	฿6,200.00
10		Structure	28 days	Sat 2/7/26	Wed 3/18/26		฿95,060.00
11	P02	Floor slab 1F (precast install)	1 day	Sat 2/7/26	Sat 2/7/26	8FS+1 day	฿13,040.00
12	P03	Columns 1F (precast install)	2 days	Thu 2/12/26	Wed 2/18/26	11FS+7 days	฿18,580.00
13	P04	Beams 1F (precast install)	1 day	Fri 2/20/26	Fri 2/20/26	12FS+1 day	฿13,040.00
14	P05	Floor slab 2F (precast install)	1 day	Mon 2/23/26	Mon 2/23/26	13FS+1 day	฿13,040.00
15	P06	Stair installation (precast)	1 day	Wed 2/25/26	Wed 2/25/26	14FS+7 days	฿13,040.00
16	P07	Columns 2F (precast install)	1 day	Fri 2/27/26	Fri 2/27/26	15FS+1 day	฿13,040.00
17	P08	Beams 2F (precast install)	1 day	Mon 3/2/26	Mon 3/2/26	16FS+1 day	฿13,040.00
18	P09	Floor slab roof (precast install)	1 day	Wed 3/11/26	Wed 3/11/26	17FS+1 day	฿13,040.00
19		Roof	16 days	Mon 3/2/26	Mon 3/23/26		฿72,310.00
20	R01	Roof primary structure (gable roof truss)	10 days	Thu 3/12/26	Mon 3/23/26	18	฿63,350.00
21	R02	Roof covering and waterproofing	5 days	Thu 3/24/26	Mon 3/30/26	20	฿8,960.00
22		Architecture	49 days	Mon 3/2/26	Mon 5/25/26		฿71,090.00
23	A01	Masonry walls (external + internal partitions)	11 days	Tue 3/31/26	Sat 4/11/26	21	฿17,330.00
24	A02	Plastering + paint (internal + external walls)	24 days	Mon 4/13/26	Sat 5/9/26	23	฿34,380.00
25	A03	Doors and windows installation	5 days	Mon 5/11/26	Fri 5/15/26	24	฿6,525.00
26	A04	Floor finishes	6 days	Sat 5/16/26	Wed 5/20/26	25	฿5,820.00
27	A05	Ceiling installation	3 days	Thu 5/21/26	Sat 5/23/26	26	฿4,365.00
28	A07	Facade	2 days	Mon 5/25/26	Tue 5/26/26	27	฿2,670.00

Figure 5.2 - Phase-Based Gantt Chart: Precast Frame (PF)

Source: Thesis author (MS Project)



ID	WBS Code	Task Name	Duration	Start	Finish	Predecessors	Cost (Labour + Transportation +Equipment)
0		03_PP	94 days	Thu 1/1/26	Mon 4/20/		฿464,905.00
1		Substructure	31 days	Thu 1/1/26	Thu 2/19/26		฿242,730.00
2	S01	Site clearing and setting out	1 day	Thu 1/1/26	Thu 1/1/26		฿800.00
3	S02	Excavation (bulk + trench)	1 day	Fri 1/2/26	Fri 1/2/26	2	฿9,650.00
4	S03	Foundation piles (driven precast)	11 days	Sat 1/3/26	Thu 1/15/26	3	฿188,660.00
5	S04	Blinding concrete	1 day	Fri 1/16/26	Fri 1/16/26	4	฿1,600.00
6	S05	Footings (rebar + concrete)	4 days	Sat 1/17/26	Wed 1/21/26	5	฿10,120.00
7	S06	Column stumps (RC cast in-situ)	4 days	Sat 1/24/26	Wed 1/28/26	6FS+2 days	฿9,120.00
8	S07	Ground beams (precast install, incl. connections/grout)	2 days	Sat 1/31/26	Mon 2/2/26	7FS+2 days	฿18,580.00
9	S08	Ground floor slab (RC cast in-situ)	2 days	Wed 2/4/26	Thu 2/5/26	8FS+1 day	฿4,200.00
10		Structure	20 days	Sat 2/7/26	Mon 3/2/26		฿101,980.00
11	F01	Precast floor slab panels 1F install (incl. joints/grout)	1 day	Sat 2/7/26	Sat 2/7/26	9FS+1 day	฿11,040.00
12	W02	External wall panels 1F install (incl. jointing/grouting)	2 days	Tue 2/10/26	Wed 2/11/26	11FS+1 day	฿15,080.00
13	W01	Internal wall panels 1F install (incl. jointing/grouting)	1 day	Fri 2/13/26	Fri 2/13/26	12FS+1 day	฿9,540.00
14	C01	Columns 1F (precast install, incl. connections/grout)	1 day	Mon 2/16/26	Mon 2/16/26	13FS+1 day	฿7,540.00
15	B02	Beams 1F (precast install, incl. connections/grout)	1 day	Tue 2/17/26	Tue 2/17/26	14	฿7,540.00
16	T01	Stair installation (precast)	1 day	Thu 2/19/26	Thu 2/19/26	15FS+1 day	฿7,540.00
17	F02	Precast floor slab panels 2F install (incl. joints/grout)	1 day	Sat 2/21/26	Sat 2/21/26	16FS+1 day	฿7,540.00
18	W03	External wall panels 2F install (incl. jointing/grouting)	2 days	Tue 2/24/26	Wed 2/25/26	17FS+1 day	฿19,080.00
19	W04	Internal wall panels 2F install (incl. jointing/grouting)	1 day	Fri 2/27/26	Fri 2/27/26	18FS+1 day	฿9,540.00
20	B03	Beams 2F (precast install, incl. connections/grout)	1 day	Mon 3/2/26	Mon 3/2/26	18FF,19FS+1 day	฿7,540.00
21		Roof	16 days	Wed 3/4/26	Sat 3/21/26		฿84,360.00
22	R01	Roof primary structure (gable roof truss)	10 days	Wed 3/4/26	Sat 3/14/26	20FS+1 day	฿75,400.00
23	R02	Roof covering and waterproofing	6 days	Mon 3/16/26	Sat 3/21/26	22	฿8,960.00
24		Architecture	25 days	Mon 3/30/26	Mon 4/20/26		฿35,825.00
25	A03	Doors and windows installation	5 days	Mon 3/30/26	Fri 4/3/26	23	฿6,525.00
26	A04	Floor finishes	5 days	Sat 3/28/26	Thu 4/2/26	25	฿7,275.00
27	A05	Ceiling installation	3 days	Fri 4/3/26	Mon 4/6/26	26	฿4,365.00
28	A06	Painting works (interior + exterior)	10 days	Tue 4/7/26	Fri 4/17/26	27	฿15,000.00
29	A07	Façade	2 days	Sat 4/18/26	Mon 4/20/26	28	฿2,671.00

Figure 5.3 - Phase-Based Gantt Chart: Precast Panel (PP)

Source: Thesis author (MS Project)

Phase Duration Comparison

This table summarizes total duration and phase distribution across TC, PF, and PP scenarios. Durations include non-working days and construction-related lag times, such as curing periods required before proceeding to subsequent activities.

Phase	TC	PF	PF faster than TC	PP	PP faster than TC
Substructure	45	31	14 days / 31.1%	31	14 days / 31.1%
Superstructure	64	28	36 days / 56.3%	20	44 days / 68.8%
Roof	16	16	0 days / 0%	16	0 days / 0%
Architecture	51	49	2 days / 3.9%	25	26 days / 51.0%
Total	197	125	72 days / 36.5%	94	103 days / 52.3%

TC requires 197 working days in total (six-day week). PF reduces this to 125 days (−36.5%, or 72 days shorter), while PP achieves 94 days (−52.3%, or 103 days shorter than TC). The difference is concentrated in the Superstructure and Architecture phases.

Critical Path and Duration Drivers

The critical path of TC runs through the Superstructure phase, which accumulates 64 working days from curing lags distributed across multiple activities: S06FS+2d, S07FS+2d, ST03FS+14d (suspended slab soffit propping), ST04FS+14d, and ST05FS+2d totalling over 30 lag days within this phase alone. Activity S07 (Ground beams, cast-in-situ) further contributes 11 days due to a composite productivity rate that integrates formwork erection, rebar fixing, and concrete casting into a single operation.

PF reduces the Superstructure phase to 28 days by replacing ground beams, columns, beams, and floor slabs with precast elements, each installable within one to two days. However, the Architecture phase of

PF remains at 49 days because masonry walls (A01: 11 days) and plastering plus painting (A02: 24 days) are retained, as in TC.

PP reduces the Architecture phase to 25 days (−51.0% vs TC) because wall panels are already installed during the Superstructure phase, eliminating the need for A01 (masonry) and A02 (plastering). PP therefore benefits from prefabrication at two levels simultaneously: both the structural frame and the building envelope.

Effect of Prefabrication on Schedule

Prefabrication affects the schedule through two principal mechanisms. First, it eliminates on-site curing lags: TC accumulates over 30 lag days in the Superstructure phase, all of which are removed in PF and PP because precast elements complete curing at the factory before delivery. Second, it increases on-site productivity: most PP Superstructure activities (F01, W02, W01, C01, B02, T01, F02, W04, W03, B03) require only one to two days each, compared with six to eleven days for equivalent cast-in-situ elements in TC.

5.1.2 RENOVATION VS NEW CONSTRUCTION (TC / RS)

ID	WBS Code	Task Name	Duration	Start	Finish	Predecessors	Cost (Labour + Transportation + Equipment)
0		**03_RS**	**40 days**	**Thu 1/1/26**	**Mon 2/16/26**		**฿49,440.00**
1		**Demolish**	**12 days**	**Thu 1/1/26**	**Wed 1/14/26**		**฿12,000.00**
2	S01	Site setup and protection	1 day	Thu 1/1/26	Thu 1/1/26		฿800.00
3	RS01	Remove existing roof covering	3 days	Fri 1/2/26	Mon 1/5/26	2	฿3,200.00
4	RS03	Remove existing floor finishes	5 days	Tue 1/6/26	Sat 1/10/26	3	฿4,800.00
5	RS05	Demolish existing AAC wall partition (Living Ar	3 days	Mon 1/12/26	Wed 1/14/26	4	฿3,200.00
6		**New construction**	**28 days**	**Thu 1/15/26**	**Mon 2/16/26**		**฿37,440.00**
7	RI02	Install new roof covering (ceramic tile)	5 days	Thu 1/15/26	Wed 1/21/26	5	฿6,140.00
8	A04	Install new floor finishes	5 days	Thu 1/22/26	Tue 1/27/26	7	฿7,275.00
9	RS07	New AAC block partition construction (Living Area, per gridline)	1 day	Thu 1/29/26	Thu 1/29/26	RS-st day	฿1,530.00
10	RS06	Remove and replace doors and windows (frames and leaves)	6 days	Fri 1/30/26	Tue 2/3/26	9	฿5,720.00
11	A05	Local ceiling replacement	5 days	Wed 2/4/26	Mon 2/9/26	10	฿7,775.00
12	A06	Painting works (interior + exterior)	6 days	Tue 2/10/26	Mon 2/16/26	11	฿9,000.00

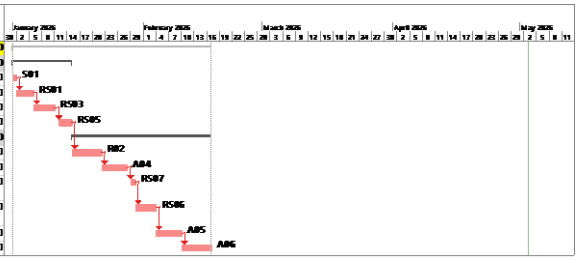


Figure 5.4 - Phase-Based Gantt Chart: Renovation scenarios (RS)

Source: Thesis author (MS Project)

Scope Reduction and Time Impact

RS completes in 40 working days, compared with 197 days for TC (−79.7%). However, this comparison must be considered by scope: RS involves nine activities targeting partial renovation of the ground-floor living area, with no Substructure or Superstructure phase. The RS schedule comprises a Demolition phase (12 days: roof covering, floor finishes, and AAC wall partition removal) followed by a New Construction phase (28 days: six renovation activities).

Challenges in Partial Renovation Scheduling

RS scheduling requires Navisworks TimeLiner to distinguish Demolish task types from Construct task types explicitly. Additionally, the predecessor relationship of RS06 (Replace doors and windows) depending on RS07 (New AAC partition) must be sequenced correctly to prevent interference with the existing structural elements.

5.1.3 KEY FACTORS INFLUENCING TIME PERFORMANCE

Labour Intensity

The TC cast-in-situ system requires formwork erection, rebar fixing, and concrete casting to proceed together for every structural element, resulting in extended durations regardless of crew size. S07 (Ground beams) requires 11 days owing to its composite productivity rate, whereas the equivalent PF precast activity P01 (Ground beams, precast) requires only 2 days. This difference directly reflects the on-site labour demand that needs to be increased for lower-productivity task.

Prefabrication Level

PP achieves the highest prefabrication level, covering both the structural frame and the wall panel system, which reduces the Architecture phase by 51% relative to TC. PF applies precast only to the structural frame; because masonry and plastering remain in the Architecture phase, the reduction in that phase is only 3.9%.

Sequencing Logic

The suspended slab soffit propping lag (FS+14d), applied at ST03 and ST04 in TC, constitutes the primary scheduling constraint of the cast-in-situ Superstructure phase. In PF and PP this lag is replaced by a non-shrink grout curing lag of FS+1d. Correctly designed sequencing logic therefore has a direct and measurable effect on project duration.

5.1.4 SCHEDULING RISKS AND UNCERTAINTIES

Labour Availability

TC and PF require multiple skilled trade categories on site simultaneously. In the semi-rural context of Pathumthani Province, skilled labour shortages during peak construction season may cause actual durations to exceed the estimates adopted in this analysis.

Weather

TC carries a higher weather-related risk than PF and PP because on-site concrete curing and formwork operations are sensitive to rainfall. The TC Superstructure phase spans March to May 2026, coinciding with the onset of the wet season in central Thailand.

Delivery and Dependency Risk

PP has more rigid sequential dependencies in the Superstructure phase than TC, as wall panels must be installed after each floor slab is complete. Any delay in precast factory delivery propagates through the schedule as a chain reaction. By contrast, TC retains greater flexibility to resequencing cast-in-situ activities when disruptions occur

5.2 CONSTRUCTION COST ANALYSIS (UC2)

UC2 results cover the direct construction cost of all four scenarios, disaggregated into Material, Labour, Equipment, and Transportation. Factor F (government budget allowance) is excluded throughout to isolate direct construction costs for scenario comparison. Material quantities are sourced from Dynamo QTO multiplied by unit prices from the Department of Comptroller General 2025 Price List (กรมบัญชีกลาง 2568) and real project budget for prefabricated concrete structure. Labour rates follow the Ministry of Labour Announcement No. 13. Equipment and transportation costs reflect prevailing market rates. All figures are referenced to a gross floor area (GFA) of 188.91 m^2.

5.2.1 SUMMARY OF TOTAL COSTS AND COST PER M^2

Figure 5.5 presents total direct costs disaggregated by category for TC, PF, PP, and RS placed side by side. Material is the category that differs most markedly between the precast scenarios (PF and PP) and the cast-in-situ baseline (TC). RS records the lowest overall cost owing to its limited renovation scope.

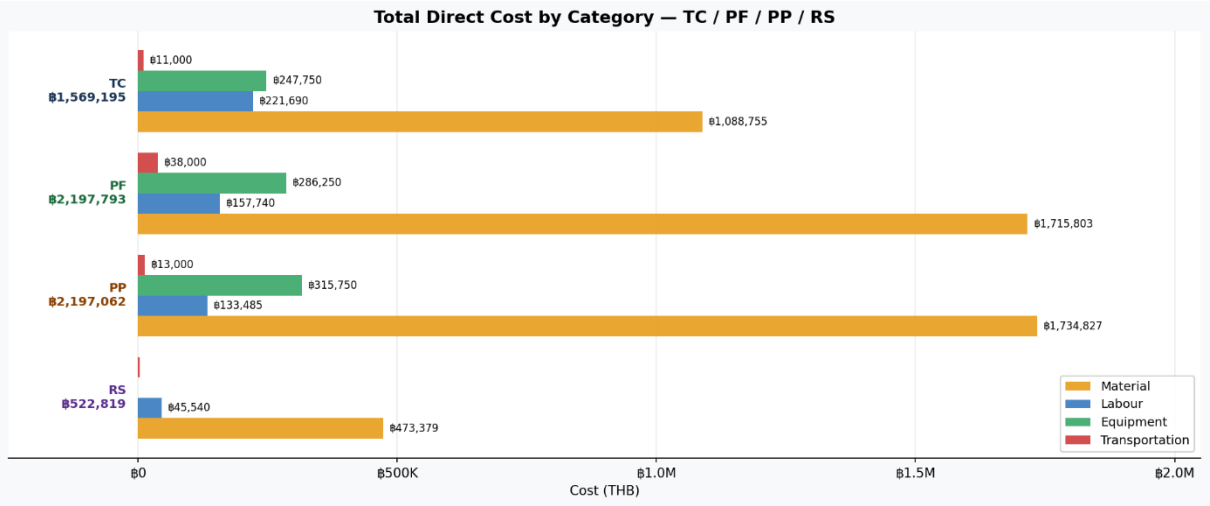


Figure 5.5 - Total Direct Cost by Category: TC / PF / PP / RS
Source: Thesis author (MS Project)

Table 5.1 - Total Direct Cost, Cost per GFA, and Duration by Scenario

Scenario	Direct Cost (THB)	Cost / m^2 (THB)	vs TC	Duration
TC – Traditional Cast-in-Place	1,569,195	8,307	–	197 days
PF – Precast Frame	2,197,793	11,634	+40.1%	125 days
PP – Precast Panel	2,197,062	11,630	+40.0%	94 days
RS – Renovation	522,819	2,768*	−66.7%	40 days

Source: Thesis author

PF and PP have almost identical total costs, differing by only THB 731 (0.03%). Despite this, PP completes 31 days earlier than PF (94 vs 125 days), establishing PP as the dominant option on a combined time-cost basis among the three new-build scenarios. TC has the lowest direct cost but the longest duration.

5.2.2 DIRECT COST BY WBS ACTIVITY

This section presents the direct cost breakdown for each scenario individually. For each scenario, a stacked bar chart (Material: amber; Labour: blue; Equipment: green; Transportation: red) is followed by the complete activity-level cost table, enabling cost outliers and category composition to be identified at the activity level.

5.2.2.1 TC Scenario

Table 5.2 - TC Scenario: Direct Cost Breakdown by WBS Activity

TC Scenario — Direct Cost Breakdown by WBS Activity

*Material: Dynamo QTO × Unit Price (สพช. 2568) | Labour: MOL No.13 | Equipment & Transport: Market Rate | * S00 = Rebar (included in Substructure total)*

Act ID	WBS Code	Activity Name	Material Cost (THB)	Labour Cost (THB)	Equipment Cost (THB)	Transport Cost (THB)	Total Direct Cost (THB)	% of Total
1. SUBSTRUCTURE								
*	**S00**	Rebar — structural reinforcement	116,470	0	0	0	**116,470**	7.4%
1	**S01**	Site clearing and setting out	0	800	0	0	**800**	0.1%
2	**S02**	Excavation	0	400	5,750	3,500	**9,650**	0.6%
3	**S03**	Foundation piles	68,508	22,660	165,000	1,000	**257,168**	16.4%
4	**S04**	Blinding concrete	5,160	6,400	0	0	**11,560**	0.7%
5	**S05**	Footings	36,086	7,120	2,000	1,000	**46,206**	2.9%
6	**S06**	Column stumps	3,908	5,340	1,500	0	**10,748**	0.7%
7	**S07**	Ground beams	25,847	19,580	5,500	1,000	**51,927**	3.3%
8	**S08**	Ground floor slab	41,688	7,120	2,000	0	**50,808**	3.2%
		Subtotal — 1. SUBSTRUCTURE	**297,667**	**69,420**	**181,750**	**6,500**	**555,337**	
2. SUPERSTRUCTURE								
9	**ST01**	Columns 1F	5,735	7,120	2,000	0	**14,855**	0.9%
10	**ST02**	Beams 1F	19,227	14,240	4,000	0	**37,467**	2.4%
11	**ST03**	Upper slab 1F	25,981	10,680	3,000	0	**39,661**	2.5%
12	**ST07**	Stair construction	8,281	5,340	1,500	0	**15,121**	1.0%
13	**ST04**	Columns 2F	4,824	5,340	1,500	0	**11,664**	0.7%
14	**ST05**	Beams 2F	16,064	12,460	3,500	0	**32,024**	2.0%
15	**ST06**	Upper slab 2F	2,452	1,780	500	0	**4,732**	0.3%
		Subtotal — 2. SUPERSTRUCTURE	**82,564**	**56,960**	**16,000**	**0**	**155,524**	
3. ROOF								
16	**R01**	Roof primary structure	96,842	13,350	50,000	3,500	**163,692**	10.4%
17	**R02**	Roof covering and waterproofing	37,660	8,460	0	500	**46,620**	3.0%
		Subtotal — 3. ROOF	**134,502**	**21,810**	**50,000**	**4,000**	**210,312**	
4. ARCHITECTURAL								
18	**A01**	Masonry walls	116,617	16,830	0	500	**133,947**	8.5%
19	**A02**	Plastering + painting	91,280	34,380	0	0	**125,660**	8.0%
20	**A03**	Doors and windows installation	150,000	6,525	0	0	**156,525**	10.0%
21	**A04**	Floor finishes	123,903	8,730	0	0	**132,633**	8.5%
22	**A05**	Ceiling installation	92,222	4,365	0	0	**96,587**	6.2%
23	**A07**	Facade cladding installation	0	2,670	0	0	**2,670**	0.2%
		Subtotal — 4. ARCHITECTURAL	**574,022**	**73,500**	**0**	**500**	**648,022**	
		GRAND TOTAL — TC Scenario (Direct Cost)	**1,088,755**	**221,690**	**247,750**	**11,000**	**1,569,195**	**100.0%**

The TC chart confirms that S03 (Foundation piles) is the single most expensive activity at THB 257,168, of which THB 165,000 (64%) is equipment, namely pile-driving rig hire at THB 15,000 per day for 11 days. This cost recurs identically in PF and PP because all three scenarios use driven precast piles, irrespective of superstructure system choice. Within the Superstructure phase, activities ST01 to ST06 carry a proportionally high Labour share: ST02 (Beams 1F) spends THB 14,240 of its THB 37,467 total (38%) on labour alone, reflecting parallel use of formwork, rebar, and concrete crews. In the Architecture phase, A02 (Plastering and painting) carries the highest single labour cost at THB 34,380, in line with its 24-day duration and skill-intensive wet-finish requirements. S00 (Rebar) at THB 116,470 represents 7.4% of the

TC total; this figure is calculated via a dedicated Revit schedule rather than the standard Dynamo QTO route, as explained in the methodology note below.

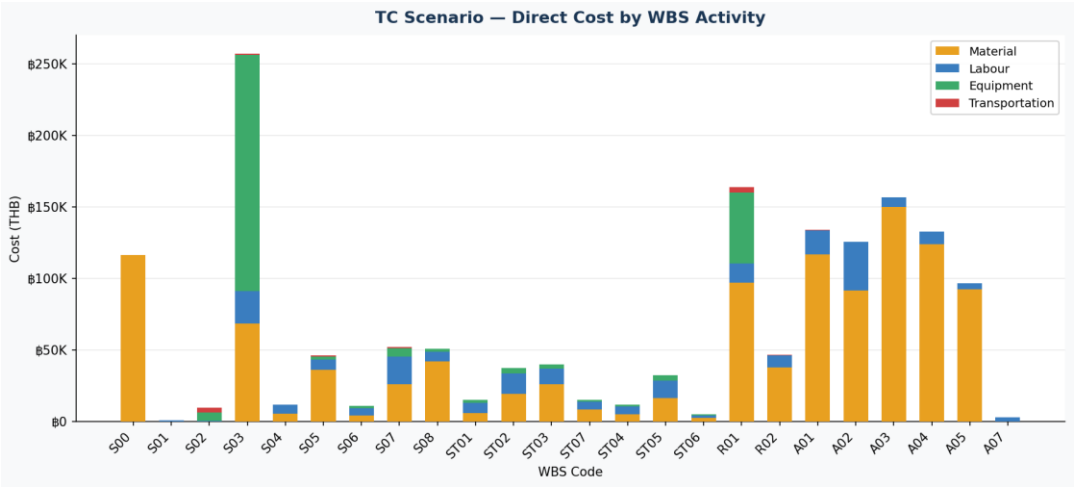


Figure 5.6 - TC Scenario: Direct Cost by WBS Activity
Source: Thesis author (MS Project / Dynamo QTO)

5.2.2.2 PF Scenario

Table 5.3 - PF Scenario: Direct Cost Breakdown by WBS Activity

PF Scenario — Direct Cost Breakdown by WBS Activity

Material: Dynamo QTO × Unit Price (avg. 2568) | Labour: MOL No.13 | Equipment & Transport: Market Rate | Factor F excluded

Act ID	WBS Code	Activity Name	Material (THB)	Labour (THB)	Equipment (THB)	Transport (THB)	Total Direct Cost (THB)	% of Total
1. SUBSTRUCTURE								
1	**S01**	Site clearing	0	800	0	0	**800**	0.0%
2	**S02**	Excavation	0	400	5,750	3,500	**9,650**	0.4%
3	**S03**	Foundation piles	68,508	22,660	165,000	1,000	**257,168**	11.7%
4	**S04**	Blinding concrete	5,341	1,600	0	0	**6,941**	0.3%
5	**S05**	Footings	36,086	7,120	2,000	1,000	**46,206**	2.1%
6	**S06**	Column stumps	5,499	7,120	2,000	0	**14,619**	0.7%
		Subtotal — 1. SUBSTRUCTURE	**115,433**	**39,700**	**174,750**	**5,500**	**335,383**	
2. SUPERSTRUCTURE								
7	**P01**	Ground beams	247,585	4,080	11,000	3,500	**266,165**	12.1%
8	**S08**	Ground floor slab	16,964	3,200	1,000	0	**21,164**	1.0%
9	**P02**	Floor slab 1F	124,746	2,040	5,500	3,500	**135,786**	6.2%
10	**P03**	Columns 1F	57,400	4,080	11,000	3,500	**75,980**	3.5%
11	**P04**	Beams 1F	174,590	2,040	5,500	3,500	**185,630**	8.4%
12	**P05**	Floor slab 2F	137,734	2,040	5,500	3,500	**148,774**	6.8%
13	**P06**	Stair	8,000	2,040	5,500	3,500	**19,040**	0.9%
14	**P07**	Columns 2F	48,800	2,040	5,500	3,500	**59,840**	2.7%
15	**P08**	Beams 2F	135,186	2,040	5,500	3,500	**146,226**	6.7%
16	**P09**	Floor slab roof	13,256	2,040	5,500	3,500	**24,296**	1.1%
		Subtotal — 2. SUPERSTRUCTURE	**964,261**	**25,640**	**61,500**	**31,500**	**1,082,901**	
3. ROOF								
17	**R01**	Roof structure	96,842	13,350	50,000	0	**160,192**	7.3%
18	**R02**	Roof covering	37,660	8,460	0	500	**46,620**	2.1%
		Subtotal — 3. ROOF	**134,502**	**21,810**	**50,000**	**500**	**206,812**	
4. ARCHITECTURAL								
19	**A01**	Masonry walls	116,847	16,830	0	500	**134,177**	6.1%
20	**A02**	Plastering	60,330	34,380	0	0	**94,710**	4.3%
21	**A03**	Doors & windows	150,000	6,525	0	0	**156,525**	7.1%
22	**A04**	Floor finishes	82,222	5,820	0	0	**88,042**	4.0%
23	**A05**	Ceiling	92,208	4,365	0	0	**96,573**	4.4%
24	**A07**	Facade	0	2,670	0	0	**2,670**	0.1%
		Subtotal — 4. ARCHITECTURAL	**501,607**	**70,590**	**0**	**500**	**572,697**	
		GRAND TOTAL — PF Scenario (Direct Cost)	**1,715,803**	**157,740**	**286,250**	**38,000**	**2,197,793**	**100.0%**

In PF, the dominant cost driver shifts from equipment (TC) to material within the Superstructure phase. P01 (Ground beams, precast) reaches THB 266,165, of which THB 247,585 (93%) is material, a direct consequence of the precast bundled unit price that consolidates concrete, reinforcement, formwork, and factory overhead into a single quoted rate. P04 (Beams 1F, precast) at THB 185,630 and P05 (Floor slab 2F) at THB 148,774 follow a similar material-dominant pattern. The Superstructure subtotal of THB 1,082,901 represents 49.3% of the PF total, compared with only 9.9% for the equivalent phase in TC. Architecture costs remain similar to TC because masonry walls (A01: THB 134,177) and plastering (A02: THB 94,710) are both retained. Note that PF carries no S00 entry: precast manufacturer quotes already include reinforcement.

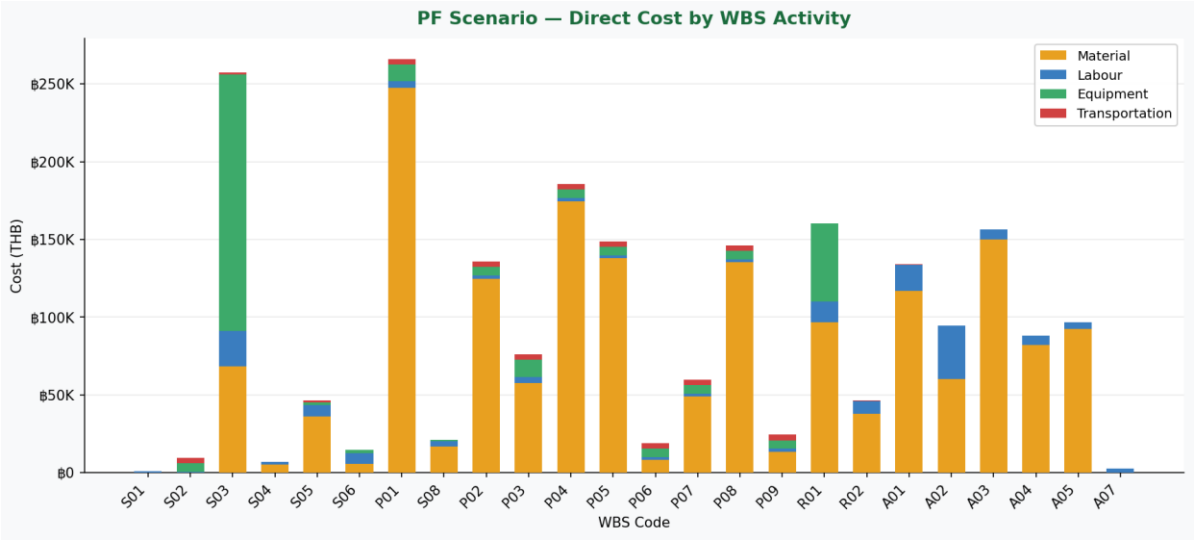


Figure 5.7 - PF Scenario: Direct Cost by WBS Activity
Source: Thesis author (MS Project / Dynamo QTO)

5.2.2.3 PP Scenario

PP Scenario — Direct Cost Breakdown by WBS Activity

Material: Dynamo QTO × Unit Price (avg. 2568) | Labour: MOL No.13 | Equipment & Transport: Market Rate | Factor F excluded

Act ID	WBS Code	Activity Name	Material (THB)	Labour (THB)	Equipment (THB)	Transport (THB)	Total Direct Cost (THB)	% of Total
1. SUBSTRUCTURE								
1	**S01**	Site clearing	0	800	0	0	**800**	0.0%
2	**S02**	Excavation	0	400	5,750	3,500	**9,650**	0.4%
3	**S03**	Foundation piles	68,508	22,660	165,000	1,000	**257,168**	11.7%
4	**S04**	Blinding concrete	5,341	1,600	0	0	**6,941**	0.3%
5	**S05**	Footings	36,086	7,120	2,000	1,000	**46,206**	2.1%
6	**S06**	Column stumps	5,500	7,120	2,000	0	**14,620**	0.7%
		Subtotal — 1. SUBSTRUCTURE	**115,435**	**39,700**	**174,750**	**5,500**	**335,385**	
2. SUPERSTRUCTURE								
7	**B01**	Ground beams	252,885	4,080	11,000	3,500	**271,465**	12.4%
8	**S08**	Ground floor slab	16,850	3,200	1,000	0	**21,050**	1.0%
9	**F01**	Floor slab 1F	124,799	2,040	5,500	3,500	**135,839**	6.2%
10	**W02**	Ext. wall panels 1F	70,655	4,080	11,000	0	**85,735**	3.9%
11	**W01**	Int. wall panels 1F	55,206	2,040	7,500	0	**64,746**	2.9%
12	**C01**	Columns 1F	27,300	2,040	5,500	0	**34,840**	1.6%
13	**B02**	Beams 1F	175,784	2,040	5,500	0	**183,324**	8.3%
14	**T01**	Stair	8,000	2,040	5,500	0	**15,540**	0.7%
15	**F02**	Floor slab 2F	131,093	2,040	5,500	0	**138,633**	6.3%
16	**W04**	Ext. wall panels 2F	85,475	2,040	7,500	0	**95,015**	4.3%
17	**W03**	Int. wall panels 2F	82,361	4,080	15,000	0	**101,441**	4.6%
18	**B03**	Beams 2F	79,167	2,040	5,500	0	**86,707**	3.9%
		Subtotal — 2. SUPERSTRUCTURE	**1,109,577**	**31,760**	**86,000**	**7,000**	**1,234,337**	
3. ROOF								
19	**R01**	Roof structure	96,842	20,400	55,000	0	**172,242**	7.8%
20	**R02**	Roof covering	37,660	8,460	0	500	**46,620**	2.1%
		Subtotal — 3. ROOF	**134,502**	**28,860**	**55,000**	**500**	**218,862**	
4. ARCHITECTURAL								
21	**A03**	Doors & windows	150,000	6,525	0	0	**156,525**	7.1%
22	**A04**	Floor finishes	94,075	7,275	0	0	**101,350**	4.6%
23	**A05**	Ceiling	105,460	4,365	0	0	**109,825**	5.0%
24	**A06**	Painting	25,780	15,000	0	0	**40,780**	1.9%
		Subtotal — 4. ARCHITECTURAL	**375,314**	**33,165**	**0**	**0**	**408,479**	
		GRAND TOTAL — PP Scenario (Direct Cost)	**1,734,827**	**133,485**	**315,750**	**13,000**	**2,197,062**	**100.0%**

PP's Superstructure phase is the most expensive of the three new-build scenarios at THB 1,234,335 (56.2% of total). B02 (Beams 1F, precast) at THB 183,324 is the highest single-activity cost, driven by the large cross-section and reinforcement density of first-floor beams. The wall panel activities (W02 (Ext. wall 1F: THB 85,735), W01 (Int. wall 1F: THB 64,746), W04 (Ext. wall 2F: THB 95,015), and W03 (Int. wall 2F: THB 101,441) that together contribute an additional THB 347,000 that has no equivalent in TC or PF, as these systems use masonry instead. However, the Architecture phase of PP is the cheapest at THB 408,480: the absence of masonry (A01) and plastering (A02) eliminates THB 259,607 relative to TC. As with PF, precast unit prices already include reinforcement; no separate S00 activity is required

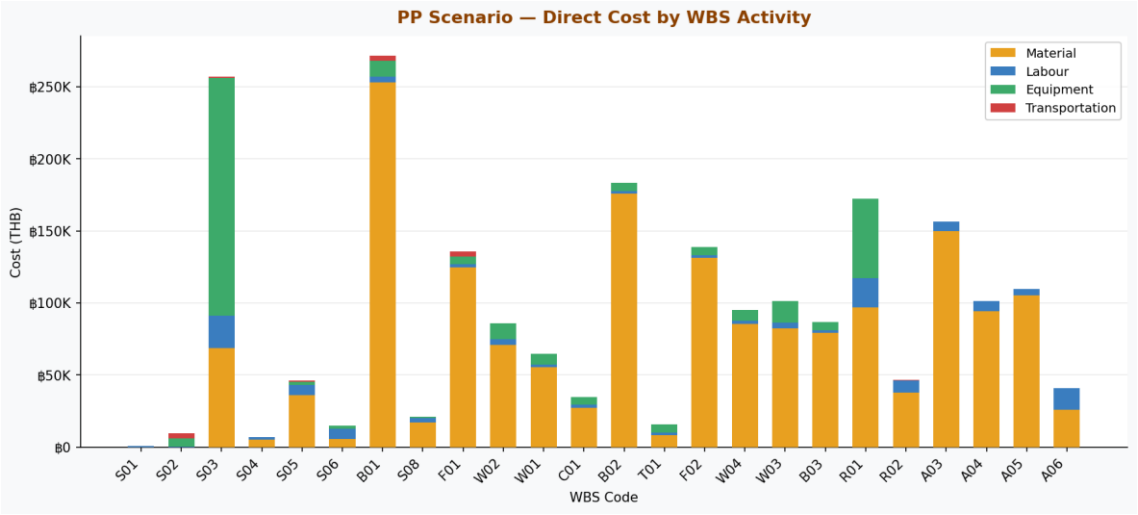


Figure 5.8 - PP Scenario: Direct Cost by WBS Activity
Source: Thesis author (MS Project / Dynamo QTO)

5.2.2.4 RS Scenario

RS Scenario — Direct Cost Breakdown by WBS Activity

Material: Dynamo QTO × Unit Price (สงฆ. 2568) | Labour: MOL No.13 | Equipment & Transport: Market Rate | Factor F excluded

Act ID	WBS Code	Activity Name	Material (THB)	Labour (THB)	Equipment (THB)	Transport (THB)	Total Direct Cost (THB)	% of Total
1. SITE SETUP								
1	**S01**	Site setup and protection	0	800	0	0	**800**	0.2%
		Subtotal — 1. SITE SETUP	**0**	**800**	**0**	**0**	**800**	
2. DEMOLITION								
2	**RS01**	Remove existing roof covering	0	2,400	0	800	**3,200**	0.6%
3	**RS03**	Remove existing floor finishes	0	4,000	0	800	**4,800**	0.9%
4	**RS05**	Demolish AAC wall partition	0	2,400	0	800	**3,200**	0.6%
		Subtotal — 2. DEMOLITION	**0**	**8,800**	**0**	**2,400**	**11,200**	
3. RENOVATION								
5	**R02**	New roof covering	36,231	5,640	0	500	**42,371**	8.1%
6	**A04**	New floor finishes	92,527	7,275	0	0	**99,802**	19.1%
7	**RS07**	New AAC partition	12,032	1,530	0	0	**13,562**	2.6%
8	**RS06**	Replace doors & windows	118,000	5,220	0	500	**123,720**	23.7%
9	**A05**	Ceiling replacement	184,444	7,275	0	500	**192,219**	36.8%
10	**A06**	Painting works	30,145	9,000	0	0	**39,145**	7.5%
		Subtotal — 3. RENOVATION	**473,379**	**35,940**	**0**	**1,500**	**510,819**	
		GRAND TOTAL — RS Scenario (Direct Cost)	**473,379**	**45,540**	**0**	**3,900**	**522,819**	**100.0%**

Source: Thesis author

RS has the simplest cost structure of the four scenarios. All 10 activities are confined to three phases, with no Substructure or Superstructure work. A05 (Ceiling replacement) is the single largest cost at THB 192,219 (36.8% of total), driven by gypsum board, metal framing, and insulation quantities covering the entire ground-floor area. RS06 (Replace doors and windows) at THB 123,720 (23.7%) is the second largest item, reflecting imported frame-and-leaf sets. Together these two activities account for 60.5% of the RS direct cost. Equipment cost is zero throughout: all renovation activities are manual trades that do not require heavy plant.

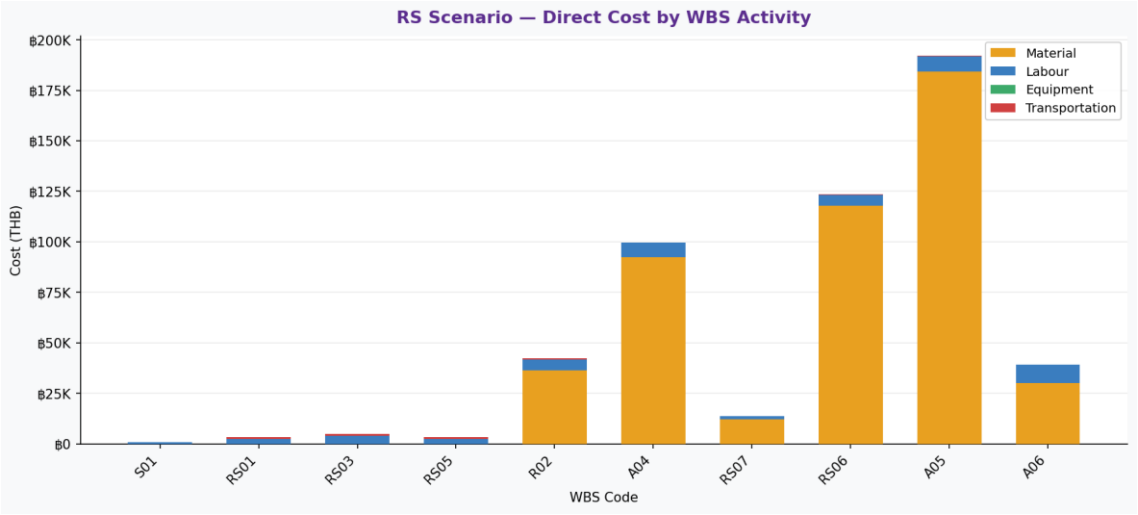


Figure 5.9 - RS Scenario: Direct Cost by WBS Activity
Source: Thesis author (MS Project / Dynamo QTO)

5.2.2.5 Methodology Note: Separate Quantity Calculation for Multi-Family WBS Activities

Certain WBS codes in TC contain elements from more than one Revit family type. Applying a single Dynamo QTO unit rate across mixed families would introduce systematic error, so three activities were extracted separately via dedicated Revit schedules and added to the cost database outside the standard QTO workflow.

- S00: Structural reinforcement (rebar) extracted from schedule M41_S_Rebar_List, covering four bar diameters with individual waste factors. Total: THB 116,470.

<M41_S00_Rebar List>

A	B	C	D	E	F	G
Deformation	Bar Diameter	Quantity	Waste_Factor	Total Bar Length	Unit_Material_Cost	Total Cost
Plain	6 mm	2659	0.075	4217.02 m	฿4.35	฿19,719.83
Plain	9 mm	860	0.075	1486.54 m	฿9.42	฿15,053.40
Deformed	12 mm	781	0.075	2155.64 m	฿16.82	฿38,977.13
Deformed	16 mm	325	0.075	1343.00 m	฿29.59	฿42,719.85
Grand total: 592		4625		9202.19 m		฿116,470.21

- A01: Tie column and beam stirrups extracted from schedule M41_A01_Tie_Column_Beam, covering three stirrup sizes across 139 elements. Total: THB 29,662, consolidated within the A01 cost entry.

<M41_A01 Quantity takeoff for tie Column - Beam>

A	B	C	D	E	F	G	H	I	J	K	L	M
WBS_Code	Type	Count	Total Length	Area Su	Volume	Waste_Factor	Adjusted Quantity	4RB9 :1m	Concrete 1m3	Concrete_cost	Rebar_Cost	Tie C-B_Cost
A01	RSB - Tie Column - Beam 10 x 10 cm	40	97.90	0.01 m²	0.98 m³	0.075	1.05 m³	฿40.00	฿2,507.00	฿2,638.41	฿3,915.97	฿6,554.38
A01	RSB - Tie Column - Beam 10 x 20 cm	96	233.50	0.02 m²	4.67 m³	0.075	5.02 m³	฿40.00	฿2,507.00	฿12,585.73	฿9,339.97	฿21,925.71
A01	RSB - Tie Column - Beam 20 x 20 cm	3	8.00	0.04 m²	0.32 m³	0.075	0.34 m³	฿40.00	฿2,507.00	฿862.41	฿320.00	฿1,182.41
Grand total: 139		139	339.40		5.97 m²		6.42 m³			฿16,086.55	฿13,575.95	฿29,662.50

- R01: Roof primary structure verified from schedule M41_R01_Roof_Structure, confirming steel framing quantities (H-beam, purlin, rafter, ridge) before the 7% waste factor. Total material: THB 94,139, consistent with THB 96,842 in Table 5.3a (TC).

<M41_R01_Quantity takeoff for roof structure>

A	B	C	D	E	F	G	H
WBS_Code	Structure type	U	Length	Waste_Factor	Adjusted_length	Unit_Material_Cos	Cost per material
R01	H Beam 200 x 100 x 18.2 mm		46.18	0.07	49.41	฿546.00	26979.54
R01	Purlin — RHS 25×25×3.2mm		516.13	0.07	552.26	฿50.00	27613.04
R01	Rafter — C-channel 100×50×20×2.3mm	m	238.65	0.07	255.36	฿80.00	20428.69
R01	Ridge/Hip beam — C-channel 100×50×20×2.3mm	m	223.34	0.07	238.98	฿80.00	19118.21
Grand total: 115			1024.31		1096.01		94139.48

5.2.3 PHASE COST COMPARISON: TC, PF, PP, AND RS

Figure 5.3 disaggregates total cost by construction phase for TC, PF, and PP. The chart makes clear that the Superstructure phase is where costs diverge most sharply, and that PP partially offsets its higher Superstructure cost through a lower Architecture cost.

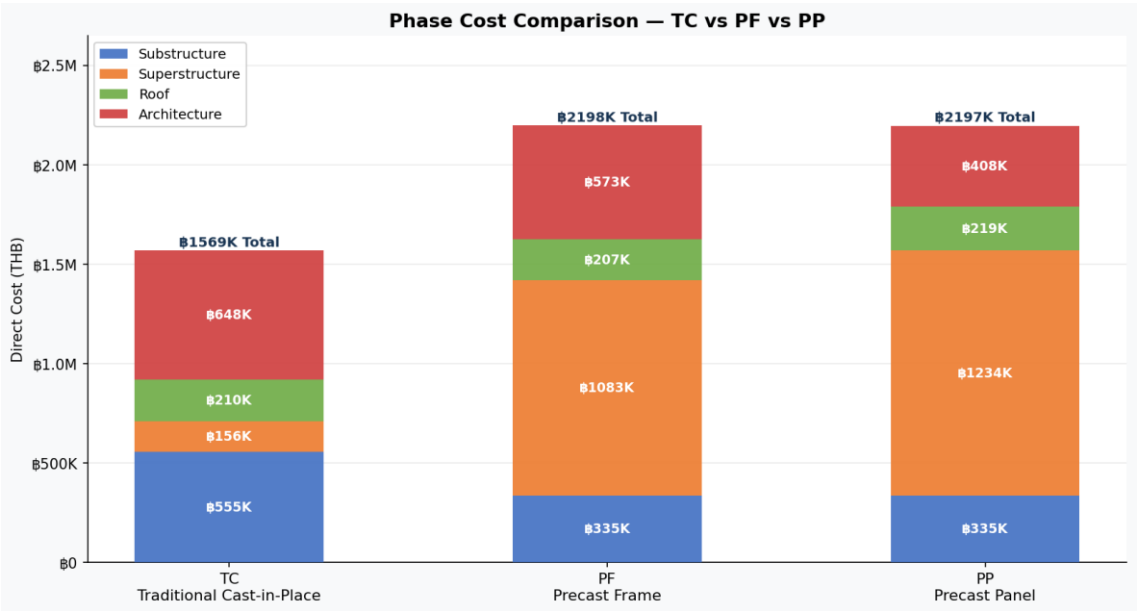


Figure 5.10 - Phase Cost Comparison: TC vs PF vs PP
Source: Thesis author (MS Project / Dynamo QTO)

TC records the lowest Superstructure cost at THB 155,524, reflecting individually priced cast-in-situ components. PF and PP reach THB 1,082,901 (+597% vs TC) and THB 1,234,337 (+694% vs TC) respectively. This premium arises entirely from the precast bundled unit price, which consolidates concrete, reinforcement, formwork, and factory overhead into the quoted rate. Were these components priced separately, as in TC, the Superstructure cost of the precast scenarios would be substantially lower.

PP compensates for its higher Superstructure cost through a significantly lower Architecture phase cost of THB 408,479, which is THB 239,543 less than TC (−37.0%). The saving arises because wall panels installed during the Superstructure phase eliminate the need for A01 (Masonry walls: THB 133,947) and A02 (Plastering and painting: THB 125,660), totalling THB 259,607. PF retains both of these activities and achieves only a modest Architecture cost reduction of THB 75,325 (−11.6% vs TC).

5.2.4 LABOUR AND EQUIPMENT TRADE-OFF

Figure 5.4 illustrates how the balance between on-site labour and mechanical equipment shifts as the prefabrication level increases. The left panel shows combined Labour and Equipment costs; the right panel decomposes equipment cost by phase for TC, PF, and PP, identifying where the equipment increase is concentrated.

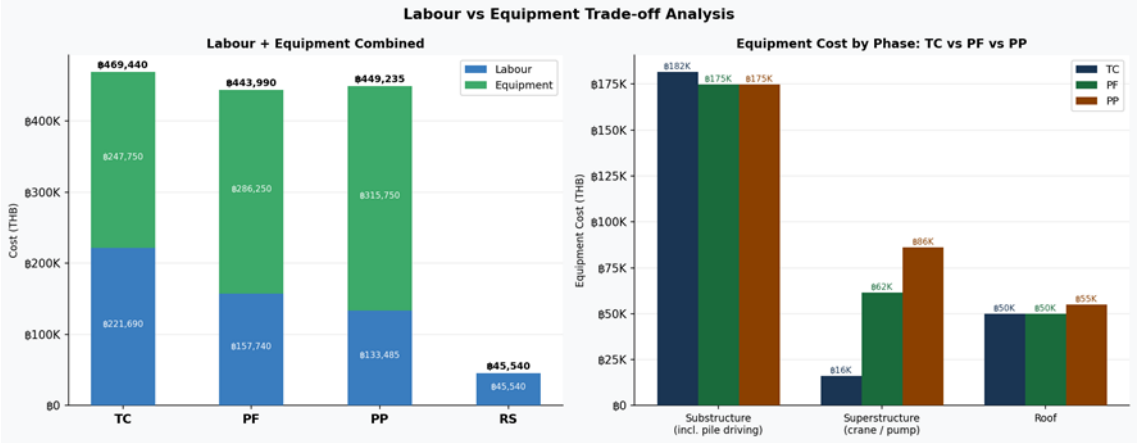


Figure 5.11 - Labour vs Equipment Trade-off: TC / PF / PP / RS
Source: Thesis author

Labour cost drops steadily with increasing prefabrication level: TC (THB 221,690) to PF (THB 157,740, −28.8%) to PP (THB 133,485, −39.8%) to RS (THB 45,540, −79.5%). The savings in PF and PP labour cost come from the precast installation which demand reduced worker hour per activity.

Equipment cost increase mostly in the Superstructure phase: TC employs a concrete pump truck costing THB 16,000 for all cast-in-situ elements, whereas PF and PP require mobile cranes at THB 61,500 (PF) and THB 86,000 (PP) to lift and position precast elements. The higher crane cost in PP reflects the bigger size of lifts required by the panel-based system compared with the frame-based approach of PF.

When Labour and Equipment cost are combined, PF (THB 444,000) and PP (THB 449,235) stay slightly below TC (THB 469,440) by THB 25,440 and THB 20,205 respectively, demonstrating that labour savings exceed the additional equipment expenditure. However, this net saving of THB 20,000 to THB 25,000 does not create impact than the material premium of around THB 627,000 that precast scenarios bear over TC, suggesting that total direct costs remain roughly 40% higher for PF and PP.

5.2.5 RENOVATION VS NEW BUILD (TC / RS)

Figure 5.5 presents the cost composition of TC and RS as pie charts, highlighting the structural difference between a full new build and a partial renovation in terms of cost category distribution.

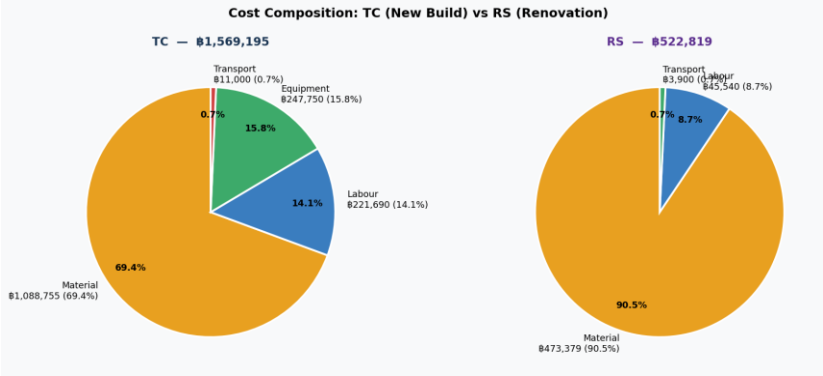


Figure 5.12 - Cost Composition: TC (New Build) vs RS (Renovation)
Source: Thesis author

RS totals THB 522,819, which is 66.7% below TC. The primary reason is the absence of Substructure and Superstructure phases, which collectively account for THB 710,861 (45.3% of the TC total). RS incurs no equipment cost (THB 0) because all renovation activities are classified as light work not requiring heavy plant.

5.2.6 COST-RELATED RISKS AND ECONOMIC TRADE-OFFS

- Precast Advantage vs Time Saving

PF and PP carry a direct cost premium of approximately THB 628,000 over TC while reducing construction duration by 36% and 52% respectively. The decision to specify a precast system therefore depends on the owner's valuation of time. If indirect costs such as temporary accommodation, foregone rental income, and site overhead accumulate at a rate greater than approximately THB 8,700 per day (THB 628,000 divided by 72 days), the precast premium would be recovered by the schedule saving relative to TC. Within the precast options, PP is the more efficient choice: it achieves almost the same direct cost as PF (THB 731 difference) while completing 31 days sooner, and therefore dominates PF on any combined time-cost measure.

- Renovation Uncertainty vs New-Build Predictability

TC offers the highest cost predictability of the four scenarios because its scope covers a completely new building on a clear site, and Dynamo QTO can extract quantities from the Revit model comprehensively. RS carries the highest cost uncertainty due to the unknowable condition of the existing fabric. The estimate of THB 522,819 is therefore treated as a lower-bound figure, valid only under the assumption that no hidden structural or moisture damage is discovered during demolition. The renovation scope is defined on the basis that key finish materials including roofing, floor coverings, ceilings, doors, windows, and AAC partitions, have reached the end of a 20 to 25-year service life, consistent with life-cycle assessment conventions for the Thai climate.

5.3 ENVIRONMENTAL PERFORMANCE ANALYSIS (UC3)

This section presents the results of the life-cycle assessment (LCA) conducted under Use Case 3 (UC3), in accordance with EN 15978 and EN 15804+A2. The primary indicator reported is the Global Warming Potential total (GWP), expressed in kg CO_2e, covering modules A1 through A5 of the cradle-to-practical-completion system boundary. All results from One Click LCA were used, Thai EPD data were available, and generic global datasets where no regional EPD could be identified.

NEW CONSTRUCTION COMPARISON (TC / PF / PP)

This subsection analyses the three new-construction scenarios across modules A1-A3 (product stage), A4 (transport), and A5 (construction stage). Because all three scenarios share an identical steel roof structure, the A1-A3 analysis is presented in two layers: first the full whole-building result, and then a filtered result limited to the structural frame and substructure.

5.3.1.1 Module-Level Summary

Table 5.4 presents the GWP by module for each new-construction scenario. Module A1-A3 (product stage) constitutes the dominant source of embodied carbon in all three cases. A4 transport contributes less than one per cent, and A5 construction-stage electricity and site activities account for the remainder.

Table 5.4 - A1-A5 GWP by module for new-construction scenarios ($kgCO_2e$)

Module	TC ($kgCO_2e$)	PF ($kgCO_2e$)	PP ($kgCO_2e$)	Note
A1-A3 Product Stage	128,596	149,812	154,231	90-93% of A1-A5 total
A4 Transport	975	478	647	<1% of total
A5 Construction	11,868	11,146	8,252	Electricity + crane + pile driving
A1-A5 TOTAL	141,439	161,436	163,130	
Intensity ($kgCO_2e/m^2$)	748.7	854.6	863.5	GFA = 188.91 m^2

Source: Thesis Author, OneClick LCA export, 26 April 2026

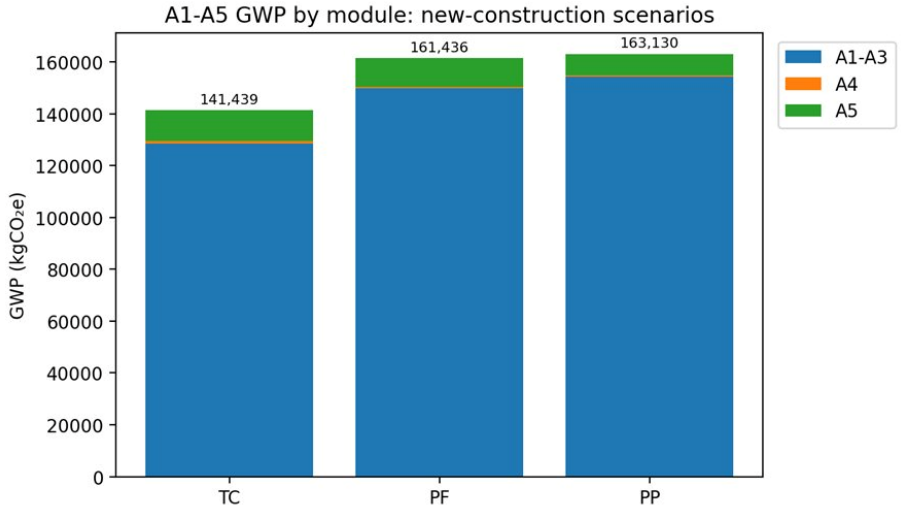


Figure 5.13 - A1-A5 GWP by module for new-construction scenarios TC, PF, and PP.
Source: Thesis Author, OneClick LCA export 26 April 2026. Figures generated from raw Excel data.

5.3.1.2 A1-A3 Product Stage: Simplified Material Group Analysis

The OneClick LCA report is disaggregated into five simplified material groups for comparative clarity: (1) concrete products (combining ready-mix and precast), (2) reinforcement steel and rebar, (3) structural steel including the shared roof structure, (4) AAC masonry, and (5) aluminum and other finishes. All three scenarios use an identical cold-rolled C-channel steel roof system, which contributes approximately 56,000 $kgCO_2e$ across every scenario. Because this element is identical and therefore not a differentiator, a filtered comparison of the structural frame and substructure is also discussed.

Table 5.5 - A1-A3 GWP by simplified material group ($kgCO_2e$)

Material Group	TC	PF	PP	Key observation
Structural Steel (incl. roof)	56,017	56,194	56,017	Identical roof system; not a differentiator across scenarios
Concrete Products (CIP + Precast)	28,557	64,735	83,011	PF and PP use C40/50 precast which already included rebar
Reinforcement Steel	13,148	2,817	2,817	This valued is rebar that be used for concrete cast in place element
AAC Masonry	15,996	15,996	0	PP replaces AAC walls with precast panels
Aluminium / Other Finishes	14,880	10,069	12,386	Aluminium windows and doors; varies by scenario specification
A1-A3 TOTAL	128,596	149,812	154,231	

Source: Thesis Author, OneClick LCA export, 26 April 2026

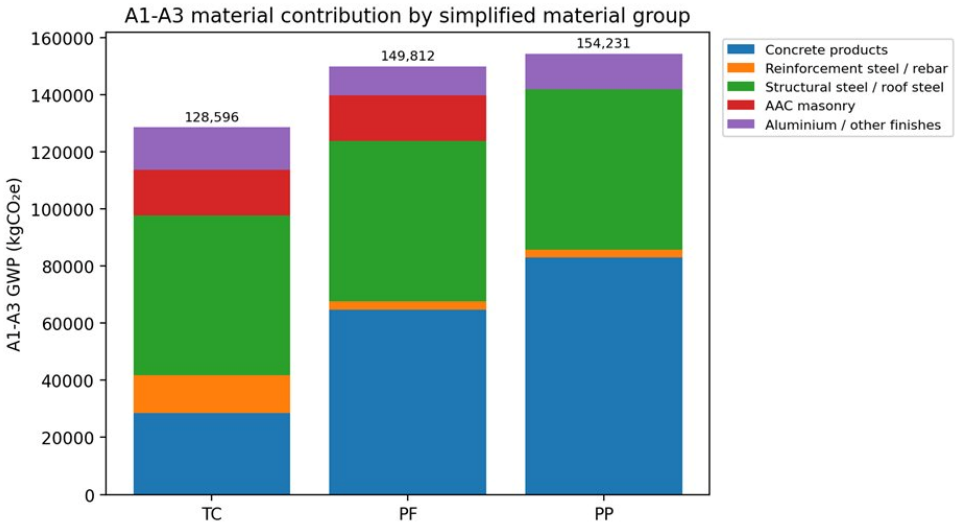


Figure 5.14 - A1-A3 GWP by simplified material group for TC, PF, and PP.
Source: Thesis Author, OneClick LCA export 26 April 2026. Figures generated from raw Excel data.

The dominant A1-A3 contributor across all three scenarios is structural steel, driven almost entirely by the shared roof system. When this common element is set aside, the concrete product group shows the sharpest divergence: TC uses only cast-in-place C24/28 concrete (28,557 $kgCO_2e$), whereas PF combines CIP with C40/50 precast beams and columns (64,735 $kgCO_2e$ total), and PP relies predominantly on large-area precast solid slabs (83,011 $kgCO_2e$). The higher embodied carbon of the precast concrete grade relative to standard CIP concrete explains why PF and PP exceed TC despite the common perception that prefabrication reduces embodied impacts. AAC masonry is identical for TC and PF (15,996 $kgCO_2e$ each, confirming the corrected 421.84 m^2 input), while PP eliminates AAC entirely in precast wall panels.

5.3.1.3 A4 Transport Stage

Transport emissions at A4 are minor in all three scenarios, ranging from 478 to 975 $kgCO_2e$. TC records the highest A4 value (975 $kgCO_2e$) because the larger total volume of site-batched concrete involves more heavy-truck deliveries. PF records the lowest A4 value (478 $kgCO_2e$) because the reduced CIP volume more than compensates for the additional precast element deliveries. The transport dataset applied follows the same three-tier vehicle assumption used throughout: trucks above 32 tonnes for structural concrete and steel, 16-to-32-tonne trucks for AAC and tile materials, and light commercial vehicles below 3.5 tonnes for paint and small accessories.

Table 5.6 - A4 transport GWP results

Scenario	A4 GWP	% of A1-A5	Note
TC	975 $kgCO_2e$	0.7%	Largest total concrete mass
PF	478 $kgCO_2e$	0.3%	Precast element deliveries offset by lower CIP demand
PP	647 $kgCO_2e$	0.4%	267 m^2 precast panels; multiple flatbed deliveries

Source: Thesis Author, OneClick LCA export, 26 April 2026

5.3.1.4 A5 Construction Stage

The A5 module captures site electricity consumption, pile driving, crane operation, and minor waste items. Figure 5.3.3 and Table 5.3.4 present the A5 breakdown for all four scenarios including RS.

Table 5.7 - A5 construction-stage GWP

A5 Item	TC	PF	PP	RS	Note
Site electricity (kWh)	12,576	6,140	4,510	1,920	Thailand grid mix 2022, no renewables
Electricity GWP ($kgCO_2e$)	10,399	5,077	3,729	1,588	Dominant A5 item for all scenarios
Crane GWP ($kgCO_2e$)	0	969	969	0	40 hrs diesel crane, 99 kW; TC and RS require no crane
Pile driving GWP ($kgCO_2e$)	262	262	262	0	396 m pile; RS has no piling
Other A5 ($kgCO_2e$)	1,207	4,838	3,292	1,642	Waste, minor site activities
A5 TOTAL ($kgCO_2e$)	**11,868**	**11,146**	**8,252**	**3,230**	

Source: Thesis Author, OneClick LCA export 26 April 2026

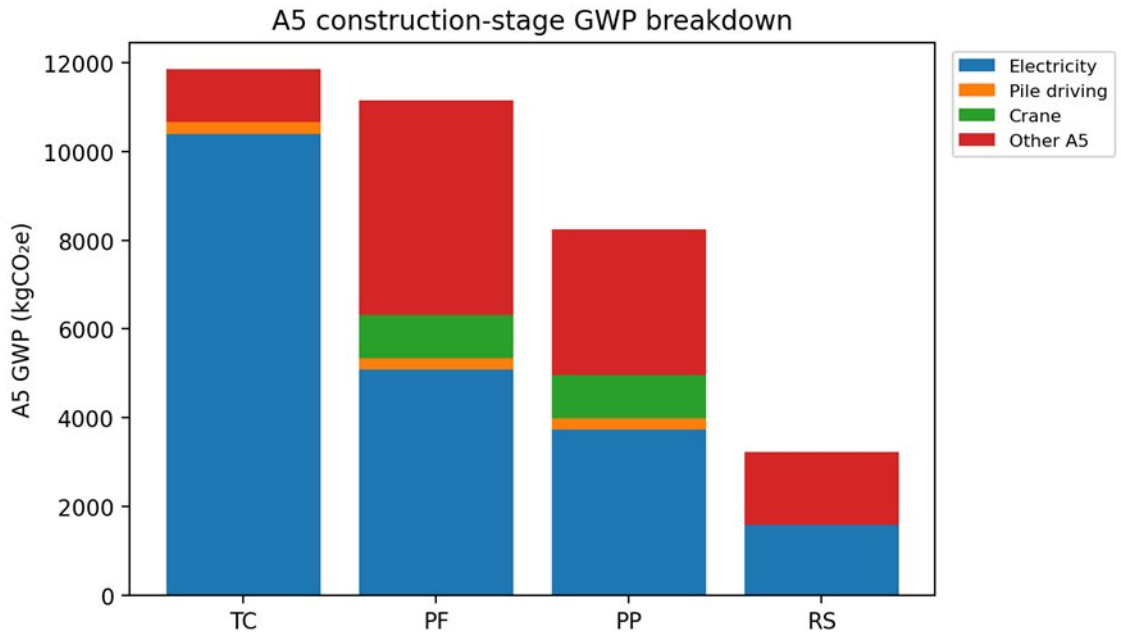


Figure 5.15 - A5 construction-stage GWP breakdown for TC, PF, PP, and RS.
Source: Thesis Author, OneClick LCA export 26 April 2026. Figures generated from raw Excel data.

Site electricity is the dominant A5 item. TC requires the most electricity (12,576 kWh, 10,399 $kgCO_2e$), consistent with its 135-day programme established in Section 5.1. PP achieves the lowest A5 total among new-construction scenarios at 8,252 $kgCO_2e$, reflecting its 77-day programme despite including crane operation. RS records only 3,230 $kgCO_2e$ at A5, consistent with its 33-day renovation programme and the absence of piling and crane activities.

5.3.1 RENOVATION VS NEW CONSTRUCTION (TC / RS)

The RS scenario involves targeted replacement of end-of-life building components rather than construction of a completely new building. A1-A5 total of 50,893 $kgCO_2e$ is approximately 64 per cent lower than TC (141,439 $kgCO_2e$), reflecting the much smaller material scope. Figure 5.3.4 illustrates this comparison.

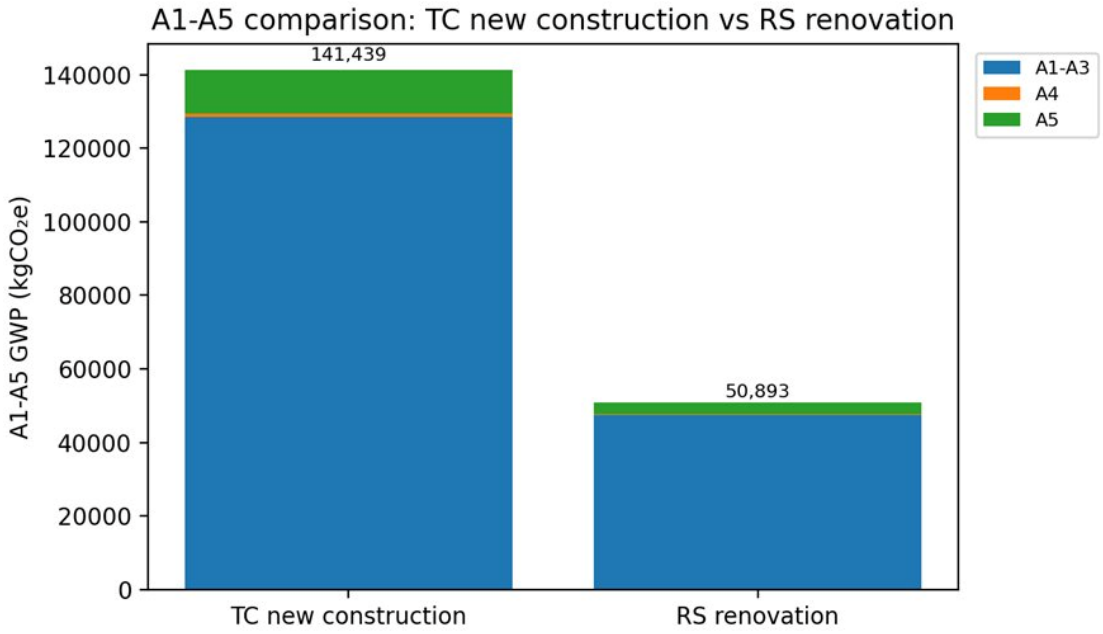


Figure 5.16 - A1-A5 GWP comparison between TC new construction and RS renovation scenario

Source: Thesis Author, OneClick LCA export 26 April 2026. Figures generated from raw Excel data.

The RS A1-A3 profile (47,318 $kgCO_2e$) is dominated by aluminium-related door and window, which together contribute roughly 55 per cent of the RS product-stage total. This results from the replacement of single-glazed aluminium-framed doors and windows with double- or triple-glazed units, which carry a high embodied carbon burden because the production of primary aluminium is so energy-intensive. A5 emissions for RS are 3,230 $kgCO_2e$, reflecting a 33-day site programme with no piling or crane activity

5.3.2.1 Renovation Trade-off Discussion

The principal justification for envelope replacement in a tropical climate such as Pathumthani Province is the potential improvement of thermal performance and reduction of operational cooling energy. Replacing deteriorated single-glazed components with thermally improved glazing is likely to reduce solar heat gain and cooling load, which may justify the embodied carbon investment over the building lifetime. However, this thesis focuses on modules A1-A5 and does not directly quantify operational energy savings; the payback period cannot, therefore, be confirmed from the data available. The RS result must also be interpreted with care: it does not represent a like-for-like comparison with new construction, since RS preserves the existing structural frame and substructure while new construction creates a completely new building asset.

Table 5.8 - A1-A3 GWP by simplified material group for RS.

Material replaced	Reason	A1-A3 GWP ($kgCO_2e$)	Sustainability note
Aluminium triple-glazed patio doors, 56.73 m²	Thermal performance upgrade	15,463	Largest single item. Improved glazing may reduce operational cooling load in tropical climate.
Aluminium entrance doors, 33.75 m²	Security and thermal envelope	12,867	30-year service life; one replacement cycle expected within 50-year lifespan.
Aluminium sheet facade mullions, 0.166 m³	Curtain wall re-framing	5,681	Carbon intensity depends on recycled content; dataset uses 0% recycled aluminium.
Aluminium double-glazed windows, 29.09 m²	Thermal and acoustic improvement	4,820	Operational energy payback period requires confirmation from energy simulation data.
Paint and coatings, 324 m²	External repainting at 10-year cycle	2,114	Recurring B4 impact; repainting every 10 years adds to long-term embodied carbon.
Floor finishes (laminate, vinyl, granite)	Surface wear replacement	1,992	Expected at least once within building lifespan.
RS A1-A3 TOTAL		**47,318**	**64% lower than TC A1-A3 (128,596 $kgCO_2e$)**

Source: Thesis Author, OneClick LCA export 26 April 2026. Figures generated from raw Excel data.

5.3.2 SUSTAINABILITY TRADE-OFFS

The environmental performance analysis reveals six-layered trade-offs relevant to the decision framework in Section 5.4.

1. **Material production:** TC achieves the lowest A1-A5 result because its C24/28 cast-in-place concrete carries a lower carbon intensity per cubic metre than the C40/50 precast concrete used in PF and PP. The precast advantage frequently reported in the literature does not manifest at this building scale, at least on an A1-A3 basis.
2. **Filtering and interpretation:** The shared steel roof system contributes approximately 56,000 $kgCO_2e$ to every scenario and should be isolated when comparing structural systems. Aluminium windows and doors add a further 6,000-7,000 $kgCO_2e$ that is unrelated to the structural system choice and must be acknowledged as a secondary emission hotspot in all scenarios.
3. **Transport:** A4 contributions are marginal (under 1,000 $kgCO_2e$) for all scenarios within the transport distances typical of Pathumthani Province. PF records the lowest A4 value after correction. If precast factories were located at greater distances, the transport sensitivity of PF and PP would increase relative to TC.
4. **Construction stage:** A5 results confirm that TC requires the most site electricity, consistent with its longer construction programme. PP achieves the lowest A5 total among new-construction scenarios. Precast scenarios require crane operation but benefit from the reduced cumulative electricity demand of shorter programmes.
5. **Renovation scope:** RS achieves the lowest absolute embodied carbon (50,893 $kgCO_2e$, 269.4 $kgCO_2e/m^2$) but represents a different scope. The RS comparison cannot be made on a like-for-

like basis with new construction; the result reflects the absence of structural work rather than an inherent environmental advantage of the renovation approach.

6. **Circularity:** Module D may improve the lifecycle interpretation of PF and PP if precast element reuse or recovery can be demonstrated. Until regional EPD data with confirmed Module D values are available, this benefit should be presented as a qualitative scenario assumption rather than a confirmed numerical result.

In summary, the environmental performance analysis does not yield a single clearly superior new-construction scenario. TC offers the lowest A1-A5 embodied carbon at this building scale and specification. However, precast scenarios offer advantages in A5 site emissions, construction programme efficiency, and potential circularity benefits. RS offers the lowest absolute embodied carbon of any scenario but must be evaluated in conjunction with its operational energy performance implications. These findings are integrated into the multi-criteria decision framework presented in Section 5.4.

5.4 INTEGRATED ANALYSIS AND DECISION SUPPORT (UC4)

The preceding sections have presented the results of each use case independently. Section 5.1 examined construction time performance, Section 5.2 analysed direct cost by WBS activity and cost category, and Section 5.3 assessed embodied carbon across the A1-A5 system boundary. This section draws those findings into a unified discussion. UC4 aims to read all integrated results together, to identify the tensions that emerge across dimensions, and to consider what the combined picture implies for construction decision-making.

5.4.1 MULTI-DIMENSIONAL PERFORMANCE NORMALISATION

As each of the results in UC1-UC3 was measured in a different unit: construction duration (days), direct cost (Thai Baht), and embodied carbon in (kilograms of carbon dioxide equivalent). Normalization is used to convert each scenario value relative to a common baseline and make it comparable. In this analysis, TC serves as the reference scenario at an index value of 100. A lower normalized index indicates better performance relative to TC for time, cost, carbon, and on-site labour.

$$\text{Performance Index(i)} = (\text{Value(i)} / \text{Value (TC)}) \times 100$$

In this analysis, TC serves as the reference scenario at an index value of 100. A lower normalised index indicates better performance relative to TC for time, cost, carbon, and on-site labour. Material waste is treated differently, using an inverse ratio so that higher index values reflect less waste generated, which is the more desirable outcome.

The purpose of normalisation in this context is not to produce a single score that ranks all scenarios definitively. It is to make trade-offs visible on a common decision scale, and to allow decision-makers to see simultaneously which scenario performs better or worse on each dimension without having to convert between different units. The normalised performance index does not represent an absolute truth. Its results depend on the indicators selected, the input data used, and the assumptions applied throughout the workflow. A different set of inputs (material prices, EPD dataset, or productivity assumption would shift the index values). This is precisely why the workflow is designed to be transparent and traceable rather than deterministic.

Table 5.9 - Normalised Performance Matrix: Six Dimensions across Four Scenarios

Dimension	TC (Baseline)	PF	PP	RS
Construction Time (days) - UC1	**100** 197 d	**63** 125 d	**48** 94 d	**20** 40 d
Direct Cost (THB) - UC2	**100** 1,569,195THB	**140** 2,197,793THB	**140** 2,197,062THB	**33** 522,819THB
Embodied Carbon A1-A5 (kg CO2e) - UC3	**100** 141,439kgCO2e	**114** 161,436kgCO2e	**115** 163,130kgCO2e	**36** 50,893kgCO2e
Material Waste Cost (THB) * - UC2	**100** 46,213 THB	**56** 31,988 THB	**28** 26,827 THB	**11** 24,451 THB
On-Site Labour (person-days) - UC1	**100** 480 p-days	**69** 330 p-days	**58** 280 p-days	**21** 99 p-days
Crane Dependency (machine-days) ** - UC1	**100** 10 d	**210** 21 d	**240** 24 d	**0** 0 d

Source: Thesis Author

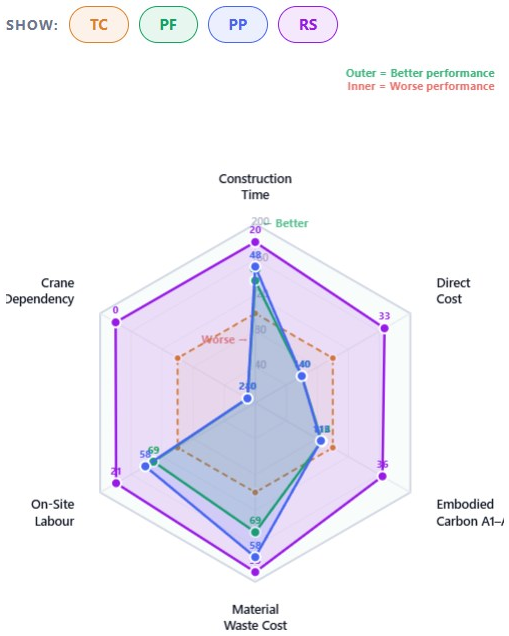


Figure 5.17 Radar chart: Adjusted Score (200 minus Index) for TC, PF, PP, and RS across six dimensions. Source: UC4 Dashboard, Thesis Author 2026.

5.4.2 CROSS-SCENARIO PERFORMANCE COMPARISON

Scenario	Main Strengths	Main Weaknesses	Suitable Project Condition	Key Risks and Uncertainties
TC	Lowest direct cost among new-build options. Lowest A1-A5 embodied carbon among new-build options under assumptions used in this thesis. Widely accessible labour and materials.	Longest construction duration. Higher exposure to on-site uncertainty: curing lags, wet works, weather disruption, multi-trade coordination.	Budget-constrained projects. Flexible delivery programme. Sites with access to local labour and conventional supply chains.	Labour availability risk. Weather-dependent productivity. Curing sequence delays. Site management complexity.
PF	Shorter duration than TC. Reduces wet structural works. Partial	Cost premium close to PP but duration longer than PP. Masonry and wet finishing	Projects where need to be more flexible in term of function as PF allows to create void inside the	Precast delivery scheduling risk. Crane availability. Supplier coordination. Interface risk between precast

	reduction in on-site labour intensity.	trades retained. Less time advantage than PP for the similar cost.	structural framing while PP cannot.	frame and wet finishing trades.
PP	Fastest new-build option. Both structural frame and wall system prefabricated. Lowest on-site material waste among new-build options.	Highest direct cost among new-build options. Highest A1-A3 embodied carbon among new-build options. Highest crane dependency. Strong reliance on factory production schedule and logistics.	Time-critical projects where delayed occupancy or extended site overhead carries high economic cost. Projects with reliable precast supplier access and crane logistics.	Supply chain disruption. Crane availability and sequence risk. Factory production lead time. Higher sensitivity to global material price volatility (steel, concrete grade, aluminium).
RS	Lowest absolute direct cost. Lowest absolute embodied carbon. Shortest duration. No crane required. Extends useful life of existing structure.	Not a new-build equivalent. Low performance figures reflect reduced scope, not superior technology. Existing structure condition is assumed sound.	Existing buildings with avoiding demolition and reconstruction is a sustainability priority.	Hidden structural defects or moisture damage not captured in scope. Unknown site conditions. Performance uncertainty from existing construction quality.

Note: Assessment is based on UC1-UC3 results for a two-storey single-family house in Pathumthani Province under assumptions described in Chapter 4. Results should not be generalised directly to other building types or locations without updating the input data.

Source: Thesis Author.

- TC THE ACCESSIBLE BASELINE

TC represents the most conventional and broadly accessible construction approach among the four scenarios. Under the assumptions used in this thesis, it achieves the lowest direct cost and the lowest A1-A5 embodied carbon among the three full new-build options. These outcomes follow logically from its material and production logic: site-batched concrete does not carry factory manufacturing energy in the A1-A3 module, and its component-level pricing does not include supplier overhead or delivery logistics bundled into a unit rate. TC is therefore well-positioned for projects that face budget constraints, operate with flexible delivery timelines, or rely on conventional local supply chains.

Its principal weakness is duration. TC scheduling is constrained by curing lags from wet work, and the coordination of multiple concurrent trades. These dependencies are inherent to cast-in-situ construction and make the programme sensitive to weather disruption, labour availability, and site management

quality. *In a project context where time is not the primary constraint, this weakness may be acceptable*. Where delays carry direct financial consequences, TC becomes less competitive.

- PF THE INCREMENTAL PRECAST

PF represents a partial transition from conventional construction to prefabrication. By replacing the structural frame with factory-produced elements while retaining masonry walls and wet finishing trades, it achieves a meaningful improvement in construction duration over TC without requiring full system change. This makes it a useful option when complete panel prefabrication is not commercially available, technically feasible, or logistically supported in the project context.

The weakness of PF in this case study is its position relative to PP. Its direct cost is close to that of PP, and its duration is longer. This means that in a straightforward time-cost trade-off between PF and PP, PP tends to dominate: it costs a similar amount but delivers a faster outcome. *PF becomes more attractive when PP is not achievable, for example because panel fabrication capacity is unavailable, crane access is restricted, or the structural system requires wet interface connections that a full panel system cannot accommodate*

- PP THE MAXIMUM PREFABRICATION

PP achieves the fastest construction duration among the new-build scenarios by prefabricating both the structural frame and the wall system. The elimination of masonry and wet plaster from the on-site sequence removes a substantial part of the programme, particularly in the architecture phase, and reduces on-site material waste significantly. For time-critical projects, this performance profile has clear value.

The trade-offs are equally clear. PP carries the highest direct cost among the new-build scenarios, driven by bundled precast pricing that folds factory overhead, quality assurance, transport, and lifting logistics into the unit rate. It also produces the highest A1-A3 embodied carbon among new-build options, because higher-grade precast concrete and the full prefabrication of wall panels raise the manufacturing-stage carbon footprint relative to TC. Additionally, PP depends heavily on crane availability, factory production schedules, and delivery sequencing. Any disruption to these logistics has a more direct and less recoverable impact on programme than an equivalent disruption in TC, where work can often be resequenced around delays.

PP is most suitable when time saving has genuine economic value, such as reduced temporary accommodation costs, earlier occupancy and associated income, compressed financing exposure, or contractual obligations tied to handover dates. Projects selecting PP should treat supplier and logistics management as a primary risk area rather than a secondary concern.

- RS THE RENOVATION REFERENCE

RS should not be compared with TC, PF, and PP as if it were a fourth new-build option competing on equal terms. Its low direct cost and low embodied carbon are genuine outcomes, but they arise primarily from the reduced scope of the intervention rather than from superior construction technology. RS avoids the cost and carbon associated with piling, substructure, superstructure, and roof structure entirely, because these elements already exist in the building being renovated.

The more useful frame for interpreting RS works as a life-extension strategy: it is the right choice when the existing structure is technically sound and when the project goal can be met through targeted replacement of finishes, partitions, and envelope components without structural intervention. RS also carries a form of uncertainty that differs in kind from the risks facing new-build scenarios. Hidden defects, moisture build-up, degraded connections, or undocumented changes to the existing structure may surface only once work begins. This uncertainty is inherent to any renovation project and should be explicitly built into project contingency planning.

5.4.3 TRADE-OFF IMPLICATIONS FOR SCENARIO SELECTION

The scenario profiles in Section 5.4.2 describe each construction approach individually. This section examines the four trade-off that emerge when the scenarios are considered together, each of which reflects a dimension where improvement in one area comes at a cost in another.

TENSION 1: CONSTRUCTION TIME VS DIRECT COST

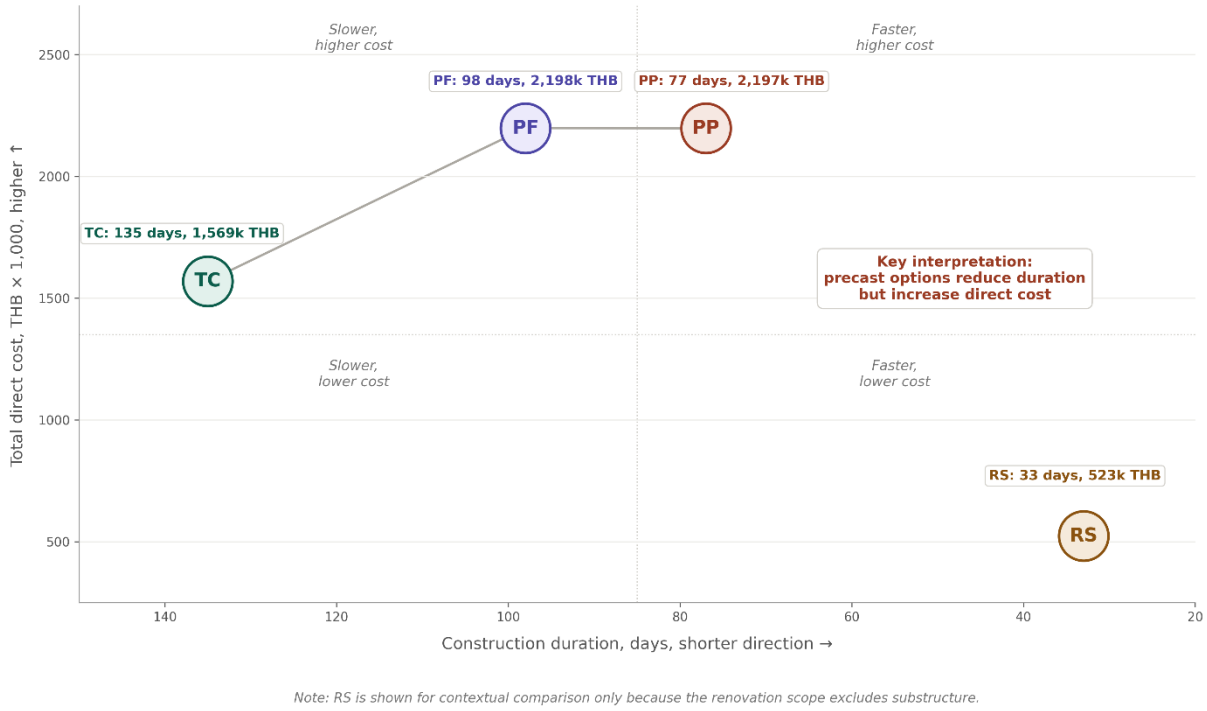


Figure 5.18 - Tension 1: Construction Time versus Direct Cost

Soure: Thesis author (2026). Diagrams generated using Claude (Anthropic, 2025) based on data computed by the author.

The most immediate tension in the results is that faster construction does not correspond to lower direct cost. TC is the cheapest new-build option and the slowest. PP is the fastest and among the most expensive. This relationship reflects the economics of prefabrication: factory-produced elements compress program by removing wet works and curing sequences from the critical path, but they are procured at bundled prices that include overhead and logistics margins unavailable to component-level site procurement.

Whether this time-cost trade-off is worth accepting depends on the value that a specific project places on saved time. For a private residential project where the owner is living in temporary accommodation during construction, each saved week has a real cost in rent and inconvenience. For a project where rental income from the completed building or avoided financing costs is high, the precast premium may be recovered within the savings generated by a shorter program. The analysis in this thesis does not quantify these downstream values because they are project-specific, but it does make the size of the time-cost trade-off visible so that decision-makers can apply their own valuation.

TENSION 2: PREFABRICATION LEVEL VS EMBODIED CARBON

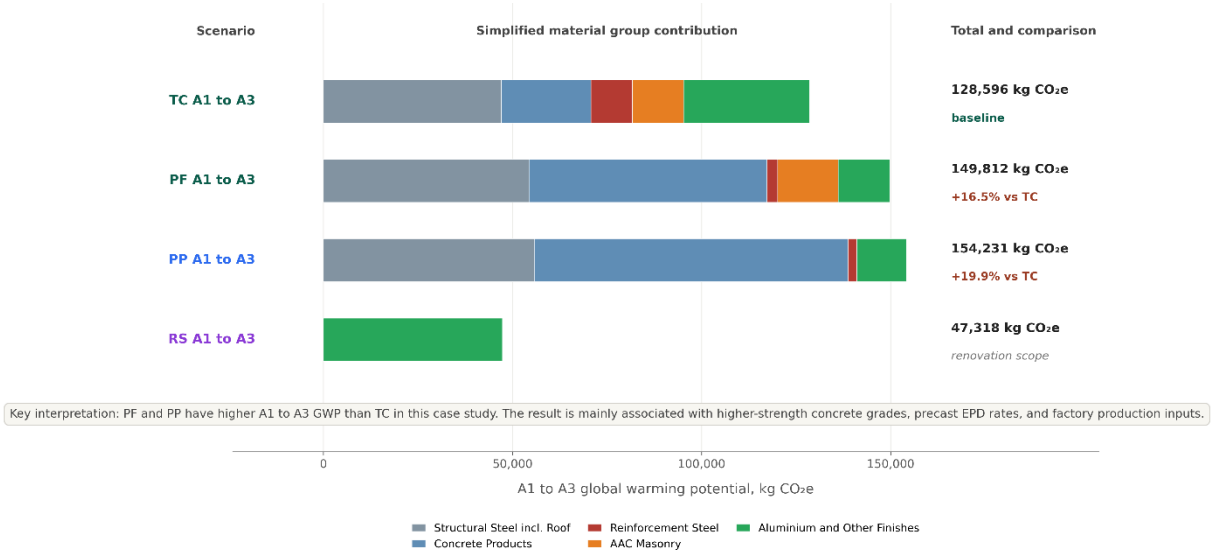


Figure 5.19 - Tension 2: Prefabrication Level versus Embodied Carbon
Source: Thesis author (2026). Diagrams generated using Claude (Anthropic, 2025) based on data computed by the author.

A finding that requires careful communication is that higher prefabrication level is associated with higher, not lower, A1-A3 embodied carbon in this case study. This result runs counter to the common assumption that industrialized construction is environmentally preferable to conventional approaches. The explanation lies in material inputs rather than in construction process efficiency. Factory-precast concrete uses higher-strength grades than site-batched concrete, carries the energy cost of factory production in its emission factor, and, in the case of PP, replaces masonry walls entirely with precast panels that add additional manufactured concrete volume to the A1-A3 total.

This outcome does not mean that prefabrication is being bad choice for embodied carbon. It means that the carbon outcome of prefabrication depends on what materials are used, at what grade, from which suppliers, and under what LCA dataset assumptions. Any projects which aim to claim in reduce embodied carbon through prefabrication should test those claims against project-specific quantities, material specifications, and supplier emission data rather than assuming that prefabrication is inherently low-carbon. Within the A1-A5 boundary applied in this thesis and under the available input data, TC produces the lowest embodied carbon among the new-build scenarios. This should be treated as a case-specific finding, not a universal conclusion.

TENSION 3: ON-SITE LABOUR REDUCTION VERSUS CRANE DEPENDENCY

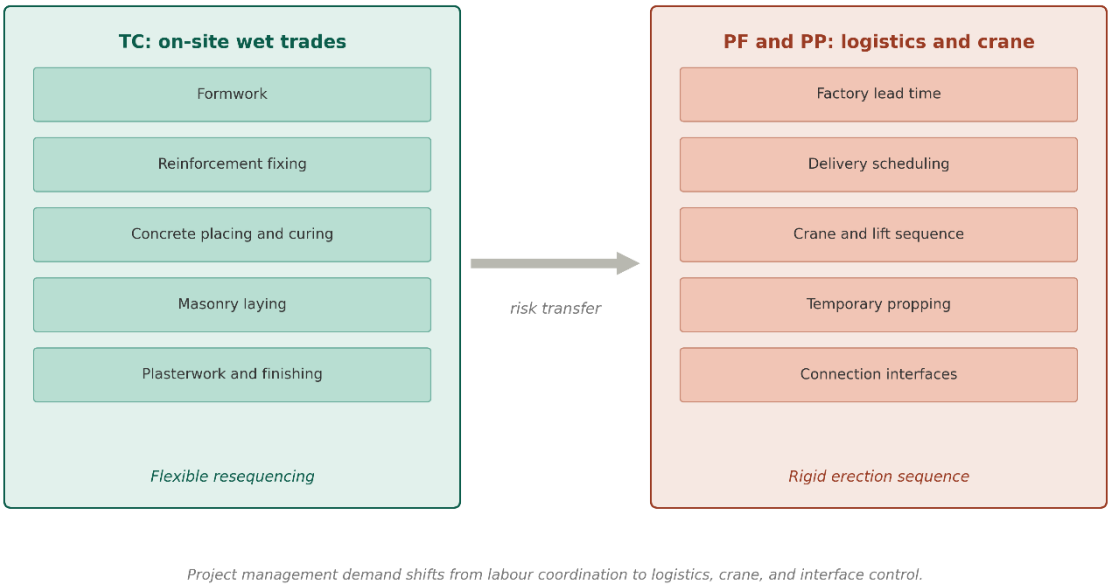


Figure 5.20 - Tension 3: On-Site Labour Reduction versus Crane Dependency
Source: Thesis author (2026). Diagrams generated using Claude (Anthropic, 2025) based on data computed by the author.

Prefabrication lowers on-site labour intensity on wet trades: formwork carpentry, reinforcement fixing, concrete placing, masonry laying, and plasterwork. These activities demand precise coordination between the worker, foreman, and site engineer. Moreover, they are sensitive to weather, curing schedules, and multi-trade sequencing. As these activities are moved off-site, the on-site becomes cleaner and faster.

However, this reduction in labour dependency does not eliminate complexity; it transfers it. PF and PP introduce a different set of dependencies: factory production lead times, precast delivery scheduling, crane availability and lift sequencing, temporary propping coordination, and interface management between precast elements and in-situ connections. A delay in any of these does not allow easy resequencing in the way that a wet trades delay might, because precast erection sequences are typically rigid. The overall effect is a shift in risk profile rather than a reduction in project management demand. Decision-makers who select PF or PP expecting a simpler site environment should plan for logistics management as rigorously as they would plan for labour management in TC.

TENSION 4: WASTE COST REDUCTION VERSUS TOTAL COST PREMIUM

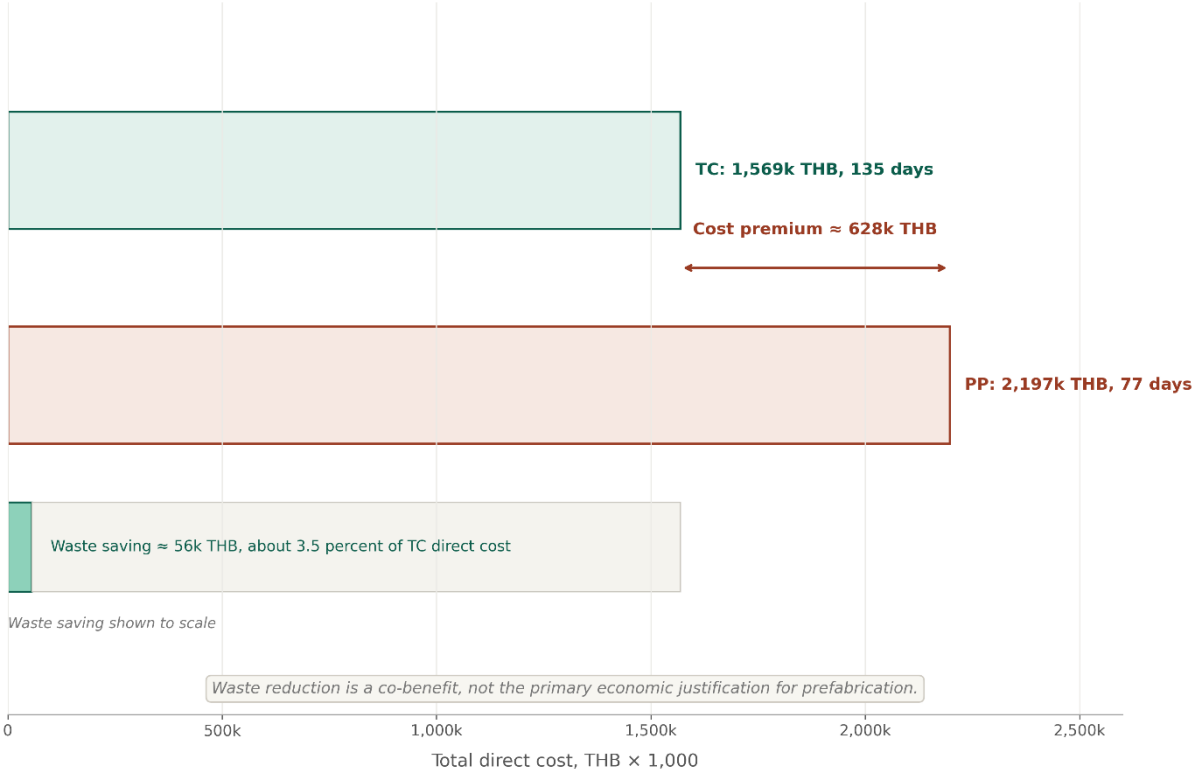


Figure 5.21 - Tension 4: Waste Cost Reduction versus Total Cost Premium

Source: Thesis author (2026). Diagrams generated using Claude (Anthropic, 2025) based on data computed by the author.

Prefabrication produces lower on-site material waste. Factory-produced elements are manufactured to precise dimensions, eliminating the cutting losses associated with reinforcement, formwork, masonry, and concrete over-pour that accumulate on a TC site. This is a genuine benefit, both financially and environmentally, and it is captured in the UC2 waste cost analysis.

The practical limitation is that waste cost saving is relatively small in proportion to the total cost premium introduced by precast procurement. At the project scale analysed in this thesis, the waste savings achievable through prefabrication are significantly outweighed by the bundled unit-rate premium of precast supply.

5.4.4 SUMMARY OF INTEGRATED FINDINGS

- **TC** offers the most cost-efficient and the least carbon-intensive profile among the full new-build scenarios under the assumptions of this analysis, but it requires the longest programme and is most exposed to on-site schedule variability. It is the rational baseline for projects with flexible timelines and budget constraints.
- **PP** achieves the fastest programme and the lowest on-site material waste among new-build options, but introduces a direct cost premium of approximately 40 percent over TC and produces the highest A1-A3 embodied carbon of the three new-build alternatives. Its advantages are meaningful when time has a quantifiable economic value and when logistics can be managed reliably.
- **PF** occupies an intermediate position that is not always clearly advantageous. Because its cost is close to PP while its duration is longer, it is most valuable when PP is not logistically or commercially feasible rather than as a preference in its own right.
- **RS** records the lowest absolute values across cost, carbon, and duration, but these figures reflect a fundamentally narrower project scope. RS is a life-extension strategy, not a new-build equivalent, and its results should be interpreted accordingly.

The central finding of UC4 is not that one scenario is universally better. It is that the relationship between time, cost, and embodied carbon in residential construction involves structural tensions that cannot be resolved by any single method, and that making these tensions visible through a consistent BIM-based framework is itself a contribution to how construction decisions can be approached.

In conclusion, results are sensitively dependent on the quality of the input data used. This analysis draws on government-published material rates, minimum labour costs prescribed under Thai ministerial regulation, and available productivity benchmarks, which represent a transparent and reproducible basis for comparison. In practice, construction costs can vary with a range of project-specific and market conditions. For prefabricated systems in particular, the price of elements is influenced by the number of units ordered and how was a variety required. Having as non-standard or low-volume shapes can increase the tooling and setup costs. Moreover, expenses are also determined by location-distance, material availability, gasoline pricing, and economic circumstances. Materials such as structural steel, aluminium, precast concrete, and petroleum products are particularly sensitive to market. The cost results presented in this thesis should be read as guideline for comparative decision-making, not as a predictor of actual tender prices.

6

CONCLUSION

This chapter draws together the results of the four use cases (UC1 to UC4) into a set of consolidated conclusions. It interprets the meaning of the findings rather than restating the detailed figures presented in Chapter 5, confirms the achievement of the research objectives stated in Chapter 1, sets out the contributions of the study, acknowledges its limitations, and proposes directions for future work.

6.1 SUMMARY OF FINDINGS

The central conclusion of this study is that no single construction technique is superior across all three performance dimensions of time, cost, and embodied carbon. Each scenario carries a distinct profile of advantages and trade-offs, and the value of the BIM based framework lies in making these trade-offs visible through a consistent and reproducible workflow.

Construction time (UC1). The Precast Panel scenario (PP) achieved the shortest programme because it carries the fewest on-site activities and removes most curing lags, with the structural frame and the building envelope prefabricated at the same time. The Precast Frame scenario (PF) reduced the superstructure duration but retained masonry and plastering, leaving its architecture phase close to that of the baseline. The Traditional Cast-in-Place scenario (TC) required the longest programme and is the most exposed to on-site schedule variability. A practical finding is that the speed of PP depends on a high quality of model preparation: precast assemblies must integrate reinforcement, concrete, and MEP within coordinated components, and a single unresolved clash propagates across every repeated unit of the building.

Construction cost (UC2). TC retained the lowest direct cost because material rates dominate the estimate and Thai labour is comparatively inexpensive. This advantage is partly offset in practice by a higher rework and waste exposure, since site labour is largely trained informally and quality depends on close supervision of details such as mortar thickness and brick pre-soaking in a hot climate. Prefabrication addresses these quality gaps but does not deliver a cost saving: precast supply carries a unit-rate premium because manufacturers respond to rising demand for higher productivity. The costs of PF and PP are close to each other and are sensitive to order volume. PP tends to be the more expensive of the two because its panels demand higher precision, whereas PF uses simpler elements but a larger number of connections.

Embodied carbon (UC3). Prefabrication does not always mean lower embodied carbon, which is one of the surprising results of this study. Comparing like for like, at one cubic meter of reinforced concrete, the Thai data actually puts precast above cast-in-place for the A1 to A3 stages, most likely because of how the elements are produced and the standard of the plant they come from. This is why TC ends up with the lowest A1 to A5 carbon of the full new-build scenarios. The steel roof adds a further complication. It is the same across TC, PF, and PP, so it offsets part of the comparison, but it is too large to set aside because the Thai roof form relies on a dense layout of battens and therefore a heavy quantity of reinforcing steel.

Integrated synthesis (UC4). When the three dimensions are placed side by side, TC is the rational baseline for projects with flexible timelines and constrained budgets, PP is justified where time carries a quantifiable economic value and logistics can be managed reliably, and PF is most useful as a fallback when PP is not feasible rather than as a preference in its own right. The Renovation scenario (RS) recorded the lowest absolute values for cost, carbon, and duration, but these results reflect a fundamentally narrower scope. RS is a life-extension strategy and not a new-build equivalent, and its apparent dominance is conditional on the level of intervention required, since works such as structural strengthening would extend both its time and its cost.

6.2 ANSWERS TO THE RESEARCH QUESTIONS

The four research objectives defined in Section 1.2 were met. Each objective was addressed through a dedicated use case, and the outputs are summarized below. A structural strength of the workflow is that UC1 functions as the data spine: the duration results generated in the BIM environment are read automatically through Dynamo and feed directly into the cost and carbon analyses.

SQ1, construction time.

The four techniques spread out widely in build time. PP is quickest at 94 days; PF follows at 125, and TC needs 197. RS sits apart at 40 days, but only because it touches a fraction of the building, so it is not a fair comparison with the new builds (Section 5.1). Most of the gap comes from moving work off site, which strips out site activities and the curing waits that stretch a cast-in-place. That speed is conditional, though. PP only delivers it from a clean model, because one unresolved clash repeats itself across every identical precast unit.

SQ2, construction cost.

On direct cost the order reverses. TC is the most affordable new build at about 8,300 THB/m2, a total of 1,569,195 THB, helped by material rates that dominate the estimate and by relatively cheap site labour. PF and PP both land near 11,600 THB/m2, around 2,197,000 THB each, roughly 40 percent above TC (Section 5.2). The saving in site labour does not close that gap, because the precast units carry the premium themselves. RS is cheapest in absolute terms at about 2,768 THB/m2, again a function of its limited scope. What shifts the figure between scenarios is the structural package, and within it the precast unit rate rather than labour.

SQ3, embodied carbon.

Carbon tracks cost more than speed. Among the new builds TC is lowest at 141,439 kg CO2e, with PF at 161,436 and PP at 163,130; RS records 50,893 under its narrower scope (Section 5.3). The weight sits in product manufacture, modules A1 to A3, where precast concrete on a like-for-like functional unit comes out higher than cast-in-place in the Thai data. One caveat belongs in any comparison of totals: the structural steel roof, about 56,000 kg CO2e, is identical across TC, PF, and PP, so it lifts all three equally and should not be read as a difference between them.

SQ4, integrated comparison.

Placed on a common scale against TC, none of the options is best everywhere (Section 5.4). TC is the sensible default when budget and carbon lead, and the schedule can flex. PP earns its cost and A1 to A3 penalty when time carries a real price and the logistics can be trusted. PF is harder to justify on its own numbers, since it costs nearly as much as PP but takes longer; its case is adaptability. A precast frame lets interior walls be removed or moved in a later renovation without disturbing the load-bearing structure, which is where it pays off, rather than as a first choice for a new build. RS stays in its own category as a life-extension route, read separately from the three new builds.

Global research question.

When building Thai houses, you always have to balance time, cost, and environmental impact—improving one usually affects the other results. The benefit of using a fully connected 4D-to-6D digital model is that it clearly reveals these trade-offs. Because the entire project data is organized under one system, teams can easily test different options and make decisions based on their own specific goals, rather than just following standard defaults.

6.3 RESEARCH CONTRIBUTIONS

The study makes three contributions, addressed to architects, engineers, academics, and policy makers alike.

Methodological. Earlier Thai studies have applied 4D and 5D analysis in the pre-BIM era, and BIM-based research on national housing has focused on 6D alone. This study integrates 4D to 6D within a single BIM workflow for single-family housing in Thailand, which to the author's knowledge has not previously been demonstrated for this building type. The contribution is the integrated and reproducible flow itself, in which one WBS code maps to one family type and links scheduling, cost, and carbon through shared parameters.

Empirical. The study produces a set of comparative benchmarks for four techniques on a real residential layout, calibrated to Thai government rates, ministerial labour costs, and Thai emission data. The most significant empirical insight is that, on a normalised functional unit, precast concrete in the Thai dataset carries higher A1 to A3 embodied carbon than cast-in-place concrete, which challenges the common assumption that prefabrication is inherently lower in carbon.

Practical and policy. The findings show that a claim of zero production waste does not by itself make a system sustainable. The precast scenarios replace only the frame or the panel elements, yet those elements raise the overall A1 to A5 carbon, so reducing factory waste does not offset a higher embodied burden at the unit level. This is directly relevant to the regulatory environment that Thailand is entering. The Climate Change Act is expected to take effect in 2027, introducing a Carbon Tax and an Emission Trading Scheme, under which the real estate sector is anticipated to face a cap-and-trade mechanism set per square metre against the mean emission of each building type. New buildings will also be assessed under the Thailand Taxonomy of the Bank of Thailand, either by meeting a carbon footprint threshold per square metre or by achieving a green building certification such as TREES, LEED, or EDGE. A transparent and traceable carbon accounting workflow, of the kind demonstrated here, supports compliance under both routes, and the study underlines that evidence must be traceable rather than asserted, since manufacturer claims of environmental performance often lack a stated baseline.

6.4 LIMITATIONS OF THE STUDY

The conclusions should be read against the following limitations, which are distinct from the methodological choices set out in Chapter 3 and relate mainly to data availability and scope.

- **Data access.** Thailand has no official standard for prefabricated elements and no published productivity dataset that can be mapped to the WBS logic. Productivity rates were therefore adopted from research conducted on real site projects in Singapore and Malaysia, which were selected as the closest available proxies because they share a similar climate, materials, and construction techniques. This was the best dataset that could be accessed rather than a national reference.
- **Cost data basis.** Government rates are location-specific and updated monthly, but actual prices are also influenced by local suppliers and can exceed the published standard, and precast unit prices are absent from the government database.
- **Boundary conditions.** Precast waste was set at zero percent as a thesis rule and is acknowledged as a boundary condition.

6.5 RECOMMENDATIONS FOR FUTURE RESEARCH

- **AI-assisted analysis.** The full UC1 to UC4 workflow was carried out manually across several software environments. Because every input is machine-readable rather than locked in static documents, an AI-assisted layer could map the datasets and identify the optimal scenario, with the potential to reduce the effort from months to days. The current barrier is that several specialist applications are not yet connected to AI tools, and closing that integration gap is a worthwhile direction.
- **National data development.** Future work should support the creation of Thai-specific productivity benchmarks for prefabricated systems and Thai EPDs for precast elements, which would remove the current reliance on foreign and manufacturer data and improve the accuracy of both UC2 and UC3.
- **Extended life-cycle boundary.** Extending the assessment to operational carbon and end-of-life stages would test whether the embodied advantage of TC, and the apparent advantage of RS, holds over a full-service life of several decades.
- **Complete economic comparison.** Incorporating Factor F and testing the effect of order volume on precast pricing would clarify the conditions under which the fixed setup costs of prefabrication become proportionally justified, for example in multi-unit or repeated-typology projects.
- **Regulatory alignment.** The framework should be connected to TREES for Homes and the Thailand Taxonomy so that it can serve as a readiness tool for the forthcoming carbon regulation, and to help address the shortage of local specialists able to deliver these assessments.

7

REFERENCES

[1] A. Rajapaksha, B. A. K. S. Perera, and T. N. Liyanawatta, "Framework for Avoidance of Disputes Arising in the Construction Industry due to the Economic Crisis," *Journal of Legal Affairs and Dispute Resolution in Engineering and Construction*, vol. 17, no. 1, 2025, doi: 10.1061/JLADAH.LADR-1185.

[2] H. Hegazy *et al.*, "An Exploratory Study on the Impact of the Construction Industry on Climate Change," *Journal of Industrial Integration and Management*, vol. 9, no. 3, pp. 397–418, 2024, doi: 10.1142/S2424862222500282.

[3] Real Estate Information Center (REIC), "Housing Market Situation Analysis in Bangkok Metropolitan Region: Q3 2025 and the First Nine Months of 2025 (January–September)," 2025.

[4] F. Testa, F. Iraldo, and M. K. Frey, "The effect of environmental regulation on firms' competitive performance: The case of the building & construction sector in some EU regions," *J. Environ. Manage.*, vol. 92, no. 9, pp. 2136–2144, 2011, doi: 10.1016/j.jenvman.2011.03.039.

[5] T. K. Chan, "Comparison of precast construction costs - Case studies in Australia and Malaysia," 2011.

[6] P. Srivarasat and W. Wongsurawat, "The bangkok housing market: Past performance and future prospects," *Journal of Applied Business Research*, vol. 35, no. 1, pp. 35–42, 2019, doi: 10.19030/jabr.v35i1.10329.

[7] P. Chinasri and P. Lertwattanaruk, "Guidelines for Integration of Prefabrication Construction Technology for 2 – Storey Residential Building Design and Construction," *Journal of Architectural/Planning Research and Studies*, vol. 18, no. 2, pp. 37–51, 2021, doi: 10.56261/jars.v18i2.240131.

[8] Fao, "300 years of sustainable forestry", [Online]. Available: www.fao.org/forestry/unasylva.

[9] D. Bozsaky, "The historical development of thermal insulation materials," *Periodica Polytechnica Architecture*, vol. 41, no. 2, pp. 49–56, Jun. 2011, doi: 10.3311/pp.ar.2010-2.02.

[10] A. Druckman and T. J. Jackson, "The carbon footprint of UK households 1990-2004: A socio-economically disaggregated, quasi-multi-regional input-output model," *Ecological Economics*, vol. 68, no. 7, pp. 2066–2077, 2009, doi: 10.1016/j.ecolecon.2009.01.013.

[11] M. A. Cole, R. J. R. Elliott, and K. Shimamoto, “Industrial characteristics, environmental regulations and air pollution: An analysis of the UK manufacturing sector,” 2005. doi: 10.1016/j.jeem.2004.08.001.

[12] U. G. D. Weerasinghe and J. Y. Ruwanpura, “Integration of LEED rating system with the project management process,” in *Proceedings, Annual Conference - Canadian Society for Civil Engineering*, 2008, pp. 200–210.

[13] J. Jones and A. Solomon Adewumi, “Exploring the Values of Sustainability and the Cost of Going Green: A Case of Building Research Establishment Environmental Assessment Method (BREEAM),” *Ecological Civilization*, vol. 2, no. 1, pp. 10018–10018, 2025, doi: 10.70322/ecolciviliz.2024.10018.

[14] M. Finkbeiner, A. Inaba, R. B. H. Tan, K. Christiansen, and H. J. Klüppel, “The new international standards for life cycle assessment: ISO 14040 and ISO 14044,” *International Journal of Life Cycle Assessment*, vol. 11, no. 2, pp. 80–85, 2006, doi: 10.1065/lca2006.02.002.

[15] J. D. Silvestre, J. De Brito, and M. D. Pinheiro, “Environmental impacts and benefits of the end-of-life of building materials – calculation rules, results and contribution to a ‘cradle to cradle’ life cycle,” *J. Clean. Prod.*, vol. 66, pp. 37–45, Mar. 2014, doi: 10.1016/J.JCLEPRO.2013.10.028.

[16] Q. B. (China) Luisa F. Cabeza (Spain), “Buildings,” in *Climate Change 2022 - Mitigation of Climate Change*, Cambridge University Press, 2023, pp. 953–1048. doi: 10.1017/9781009157926.011.

[17] K. H. Tiedemann, “Economic and environmental impacts of efficient air conditioning in Thailand,” in *Sustainable World*, 2003, pp. 211–219.

[18] A. Chaichaloempreecha, P. Winyuchakrit, and B. Limmeechokchai, “Long-term energy savings and GHG mitigations in Thailand’s building sector: Impacts of energy efficiency plan,” in *Energy Procedia*, 2017, pp. 847–852. doi: 10.1016/j.egypro.2017.10.110.

[19] S. Chirarattananon, V. D. Hien, and P. Tummu, “Thermal performance and cost effectiveness of wall insulation under Thai climate,” *Energy Build.*, vol. 45, pp. 82–90, 2012, doi: 10.1016/j.enbuild.2011.10.025.

[20] S. Panyakaew and S. A. Fotios, “Agricultural waste materials as thermal insulation for dwellings in Thailand: Preliminary results,” 2008.

[21] N. Bhikhoo, A. Hashemi, and H. J. Cruickshank, “Improving thermal comfort of low-income housing in Thailand through passive design strategies,” *Sustainability (Switzerland)*, vol. 9, no. 8, 2017, doi: 10.3390/su9081440.

[22] N. Limphitakphong, P. Thaipradit, P. Kanchanapiya, T. Tantisattayakul, and O. Chavalparit, “EMBODIED CARBON EMISSIONS OF CONSTRUCTION MATERIALS: A CASE STUDY OF BUILDINGS IN THAILAND,” *International Journal of GEOMATE*, vol. 18, no. 68, pp. 187–193, Apr. 2020, doi: 10.21660/2020.68.9418.

[23] Mordorintelligence, “Thailand Prefabricated Buildings Industry Size & Share Analysis - Growth Trends and Forecast (2026 - 2031),” https://www.mordorintelligence.com/industry-reports/thailand-prefabricated-buildings-industry.

[24] C. Yimprayoon, R. T. Mungkung, P. Takkanon, and S. Intrachooto, “Energy-Saving and Environmentally-Friendly Residential Drawings Certification and Labelling Rating Systems using Energy Simulation and Life Cycle Assessment,” *Journal of Architectural/Planning Research and Studies*, vol. 19, no. 1, pp. 179–200, 2022, doi: 10.56261/jars.v19i1.243880.

[25] C. Mao, F. Xie, L. Hou, W. Peng, J. Wang, and X. Wang, “Cost analysis for sustainable off-site construction based on a multiple-case study in China,” *Habitat Int.*, vol. 57, pp. 215–222, 2016, doi: 10.1016/j.habitatint.2016.08.002.

[26] M. Goh and Y. M. Goh, “Lean production theory-based simulation of modular construction processes,” *Autom. Constr.*, vol. 101, pp. 227–244, 2019, doi: 10.1016/j.autcon.2018.12.017.

[27] Y. Teng and W. Pan, “Systematic embodied carbon assessment and reduction of prefabricated high-rise public residential buildings in Hong Kong,” *J. Clean. Prod.*, vol. 238, 2019, doi: 10.1016/j.jclepro.2019.117791.

[28] C. Ruengorn, R. Awiphan, N. Wongpakaran, T. Wongpakaran, and S. Nochaiwong, “Association of job loss, income loss, and financial burden with adverse mental health outcomes during coronavirus disease 2019 pandemic in Thailand: A nationwide cross-sectional study,” *Depress. Anxiety*, vol. 38, no. 6, pp. 648–660, 2021, doi: 10.1002/da.23155.

[29] REIC Home Construction Cost Index: HCCI, “Analysis: Standard Home Construction Cost Index, Q3 2025,” Sep. 2025.

[30] B. Torut, “Effects of Public Transfers on The Financial Security of Rural Households: Evidence from Thailand,” *International Journal of Economics and Management*, vol. 19, no. 1, pp. 135–147, 2025, doi: 10.47836/ijeam.19.1.09.

[31] C. Denpaiboon, K. Limskul, and / Sarich Chotipanich, “A Low Income Housing Needs and Affordability for thailand’s strategic National Plan During 2017-2037,” 2018.

[32] “Thailand’s leader in the construction sector modernizes building solutions with automated hollow-core production lines; Thailändischer Marktführer in der Baubranche schafft moderne Baulösungen mit automatisierter Hohldecken-Fertigungsanlage,” *Betonwerk und Fertigteil-Technik/Concrete Plant and Precast Technology*, vol. 88, no. 10, pp. 36–40, 2022.

[33] P. Sopon, “Report on the Survey of ‘Vacant Homes’ in Bangkok and Surrounding Areas, 2021.,” *Thai Real Estate Research and Valuation Center*, no. 808/2564, Dec. 2021, Accessed: Jan. 30, 2026. [Online]. Available: https://www.area.co.th/t/5138

[34] REIC Home Construction Cost Index: HCCI, “Analysis: Standard Home Construction Cost Index, Q1 2025,” Mar. 2025.

[35] W. Wuyts, R. Sedlitzky, M. Morita, and H. Tanikawa, “Understanding and managing vacant houses in support of a material stock-type society-The case of Kitakyushu, Japan,” *Sustainability (Switzerland)*, vol. 12, no. 13, 2020, doi: 10.3390/su12135363.

[36] K. B. Kanokporn and V. Iamaram, “Ecological impact assessment; Conceptual approach for better outcomes,” *Int. J. Environ. Res.*, vol. 5, no. 2, pp. 435–446, 2011.

[37] Ministry of Natural Resources and Environment, “Notification of the Ministry of Natural Resources and Environment on the Designation of Projects, Activities, or Operations Required

to Prepare an Environmental Impact Assessment Report, and the Criteria, Procedures, and Conditions for Preparing Environmental Impact Assessment Reports (No. 6), B.E. 2566 (2023)," Bangkok, 2023.

[38] A. Lohmeng, K. Sudasna, and T. Tondee, "State of the Art of Green Building Standards and Certification System Development in Thailand," in *Energy Procedia*, 2017, pp. 417–422. doi: 10.1016/j.egypro.2017.10.188.

[39] W. Shen, W. Tang, A. Siripanan, Z. Lei, C. F. Duffield, and F. K. Peng Hui, "Understanding the green technical capabilities and barriers to green buildings in developing countries: A case study of Thailand," *Sustainability (Switzerland)*, vol. 10, no. 10, 2018, doi: 10.3390/su10103585.

[40] Bangkok Bank, "Bualuang Green Loan for Transition to Environmental Sustainability: Product Information Document," Bangkok. Accessed: Feb. 02, 2026. [Online]. Available: https://www.bangkokbank.com/en/Business-Banking/Finance-My-Business/Loans-for-SMEs/-/media/2376146f1a694ce49f6ae7441cdedd62.ashx

[41] SCBX Group, "Sustainable Products and Services: Growing Economic Resilience," Bangkok, 2024. Accessed: Feb. 02, 2026. [Online]. Available: https://www.scbx.com/en/sustainability/growing-economic-resilience/products-and-services/

[42] Thai Green Building Institute, "Thai Rating of Energy and Environmental Sustainability for New Construction and Major Renovation and Core and Shell Building (TREES-NC/CS)," Bangkok, 2019.

[43] Thai Green Building Institute, *Thai Rating of Energy and Environmental Sustainability for Home (TREES for HOME)*. Bangkok: Thai Green Building Institute (TGBI), 2021. [Online]. Available: www.tgbi.or.th

[44] Frasers Property (Thailand) Public Company Limited, "GUTÉ Sukhumvit 76: TREES for Homes Certified Residential Project." Accessed: Feb. 01, 2026. [Online]. Available: https://home.frasersproperty.co.th/blog/living-ideas/GUT%C3%89-SUKHUMVIT-76-TREES-Home

[45] O. Awadh, "Sustainability and green building rating systems: LEED, BREEAM, GSAS and Estidama critical analysis," *Journal of Building Engineering*, vol. 11, pp. 25–29, 2017, doi: 10.1016/j.jobe.2017.03.010.

[46] H. H. Ali and S. F. Alnusairat, "Developing a green building assessment tool for developing countries - Case of Jordan," *Build. Environ.*, vol. 44, no. 5, pp. 1053–1064, 2009, doi: 10.1016/j.buildenv.2008.07.015.

[47] A. J. Hoffman and R. L. Henn, "Overcoming the social and psychological barriers to green building," *Organ. Environ.*, vol. 21, no. 4, pp. 390–419, 2008, doi: 10.1177/1086026608326129.

[48] L. R. Lima, E. L. G. da Trindade, L. H. Alencar, M. H. Alencar, and L. Silva, "Sustainability in the construction industry: A systematic review of the literature," *J. Clean. Prod.*, vol. 289, 2021, doi: 10.1016/j.jclepro.2020.125730.

[49] “LEED v4.1 RESIDENTIAL DESIGN AND CONSTRUCTION: SINGLE FAMILY HOMES,” 2018.

[50] Thai Green Building Institute, *Thai Rating of Energy and Environmental Sustainability for Home (TREES HOME)*. Bangkok: Thai Green Building Institute (TGBI), 2022. Accessed: Feb. 08, 2026. [Online]. Available: https://tgbi.or.th/trees-home/

[51] Thai Green Building Institute, “Thai Rating of Energy and Environmental Sustainability for New Construction and Major Renovation and Core and Shell Building (TREES-NC/CS),” Bangkok, 2019.

[52] “CPAC PRECAST CONCRETE SYSTEM,” The Concrete Products and Aggregate Co., Ltd. (CPAC). Accessed: Feb. 04, 2026. [Online]. Available: https://web.cpac.co.th/en/product/detail/cpac-precast-concrete-system

[53] N. Ashikin Suhaini, N. H. Abas, S. Nagapan, and K. Nadarason, “Identification of Construction Waste Generated at Precast Concrete Plants: Case study,” in *IOP Conference Series: Materials Science and Engineering*, 2019. doi: 10.1088/1757-899X/601/1/012036.

[54] “Typical Precast Joint,” 2022.

[55] W. Zhou, *Smart Mobile Crane Modelling Strategy on Erection Sequence Generation for Precast Concrete Low-Rise Buildings*, vol. 564 LNCE. 2025. doi: 10.1007/978-981-96-2802-5_28.

[56] K. Phatcharasaengmanat, “Structural Precast Revit Model (Reference Project),” 2024, Revit 2024.

[57] “Method statement for the production &installation of precast concrete,” Random House Audio, Nakhon Ratchasima, Thailand, 2017.

[58] “Comparative Cost Analysis: Conventional vs Precast Systems - A Case Study of a Two-Storey Entrance Building, The Urban Yimjinda Project,” 2022.

[59] X. Li, Y. Geng, Z. Song, Q. Ma, and X. Tian, “Job Stress and Job Satisfaction of Workers in Traditional Cast-in-Situ Projects and Industrialized Projects,” in *ICCREM 2017: Prefabricated Buildings, Industrialized Construction, and Public-Private Partnerships - Proceedings of the International Conference on Construction and Real Estate Management 2017*, 2017, pp. 89–96. doi: 10.1061/9780784481059.009.

[60] *Design guide of high strength concrete to Singapore standard CP 65 : BC 2: 2008*. Building and Construction Authority, 2008.

[61] M. Kajohnboon -Environment, S. Manager, B. Tangsuwan -Environment, and S. A. Manager, “The International EPD ® System Third-party verification LCA Information Title: Life Cycle Assessment of Ready Mix Concrete of The Concrete Products and Aggregate Co., Ltd: 1 m 3 average concrete,” Nov. 2024. [Online]. Available: https://web.cpac.co.th/th/home

[62] S. Kim, W. Hong, J. Kim, and J. T. Kim, “The development of modularized construction of enhanced precast composite structural systems (Smart Green frame) and its embedded energy efficiency,” *Energy Build.*, vol. 66, pp. 16–21, 2013, doi: 10.1016/j.enbuild.2013.07.023.

[63] L. Raghavan and H. Thiagu, “Structural behaviour of conventional and precast panel joints,” *International Journal of Civil Engineering and Technology*, vol. 8, no. 4, pp. 156–162, 2017.

[64] Y. F. M. Badir, M. R. A. Kadir, and A. H. Hashim, “Industrialized building systems construction in Malaysia,” *Journal of Architectural Engineering*, vol. 8, no. 1, pp. 19–23, 2002, doi: 10.1061/(ASCE)1076-0431(2002)8:1(19).

[65] R. J. Guillén-Rujano, S. Vargas-Jara, M. Muñoz-Cayún, and W. S. Velilla-Díaz, “Cable tensions in multi-insert rigging systems for tilt-up panel lifting,” *Materialpruefung/Materials Testing*, 2026, doi: 10.1515/mt-2025-0430.

[66] P. N. Roschke and M. Tiv, “DAMAGE MINIMIZATION FOR PRECAST CONCRETE PANELS.,” 1987.

[67] Z. Li, F. Xue, X. Li, J. Hong, and G. Q. Shen, “An Internet of Things-enabled BIM platform for on-site assembly services in prefabricated construction,” *Autom. Constr.*, vol. 89, pp. 146–161, 2018, doi: 10.1016/j.autcon.2018.01.001.

[68] Nick Bertram, “Capital Projects & Infrastructure Modular construction: From projects to products,” *McKinsey Global Institute*, Jun. 2019.

[69] P. W.-J. Swift, D. Ness, N. Chileshe, K. Xing, J. Gelder, and T. Mcginley, “Unmaking Waste,” 2015.

[70] R. Andersen and K. Negendahl, “Lifespan prediction of existing building typologies,” *Journal of Building Engineering*, vol. 65, Apr. 2023, doi: 10.1016/j.jobe.2022.105696.

[71] C. Fusinpaiboon, “Strategies for the renovation of old shophouses, built during the 1960s and 1970s in Bangkok (Thailand), for mass adoption and application,” *Journal of Asian Architecture and Building Engineering*, vol. 21, no. 5, pp. 1697–1718, 2022, doi: 10.1080/13467581.2021.1942880.

[72] K. Phatcharasaengmanat, “Structural Precast Revit Model (Reference Project),” 2024, Revit 2024.

[73] C. I. De Gaetani, M. Mert, and F. Migliaccio, “Interoperability analyses of BIM platforms for construction management,” *Applied Sciences (Switzerland)*, vol. 10, no. 13, 2020, doi: 10.3390/app10134437.

[74] M. Mayouf, J. Jones, F. Elghaish, H. Emam, E. M. A. C. Ekanayake, and I. Ashayeri, “Revolutionising the 4D BIM Process to Support Scheduling Requirements in Modular Construction,” *Sustainability (Switzerland)*, vol. 16, no. 2, 2024, doi: 10.3390/su16020476.

[75] J. Abeid and D. A. Arditi, “Linking time-lapse digital photography and dynamic scheduling of construction operations,” *Journal of Computing in Civil Engineering*, vol. 16, no. 4, pp. 269–279, 2002, doi: 10.1061/(ASCE)0887-3801(2002)16:4(269).

[76] A. Wahab and J. Wang, “Factors-driven comparison between BIM-based and traditional 2D quantity takeoff in construction cost estimation,” *Engineering, Construction and Architectural Management*, vol. 29, no. 2, pp. 702–715, 2022, doi: 10.1108/ECAM-10-2020-0823.

[77] R. Stanley and D. Thurnell, “The benefits of, and barriers to, implementation of 5D BIM for quantity surveying in New Zealand,” *Australasian Journal of Construction Economics and Building*, vol. 14, no. 1, pp. 105–117, 2014, doi: 10.5130/ajceb.v14i1.3786.

[78] Autodesk Inc., “5D BIM: Precision workflows and cost analysis from design into construction,” Autodesk Inc. Accessed: Feb. 13, 2026. [Online]. Available:

https://www.autodesk.com/solutions/5d-bim#:~:text=5D%20BIM%20allows%20clients%2C%20project,project%20team%20uses%20to%20collaborate.

[79] R. Charef, H. A. Alaka, and S. B. A. Emmitt, “Beyond the third dimension of BIM: A systematic review of literature and assessment of professional views,” *Journal of Building Engineering*, vol. 19, pp. 242–257, 2018, doi: 10.1016/j.jobe.2018.04.028.

[80] S. Azhar, W. A. Carlton, D. A. Olsen, and I. U. Ahmad, “Building information modeling for sustainable design and LEED ® rating analysis,” *Autom. Constr.*, vol. 20, no. 2, pp. 217–224, 2011, doi: 10.1016/j.autcon.2010.09.019.

[81] J. K. W. Wong and J. X. Zhou, “Enhancing environmental sustainability over building life cycles through green BIM: A review,” *Autom. Constr.*, vol. 57, pp. 156–165, 2015, doi: 10.1016/j.autcon.2015.06.003.

[82] Building and Construction Authority, *A guide to help builders measure productivity of various trades*. 2011.

[83] CIDB Malaysia, “Labour Costs and Labour Output Information for Building Construction,” 2007.

[84] D. Lee, D. S. Kim, G. H. Kim, and S. Kim, “Time reduction effect of the enhanced TACT method for high-rise residential buildings,” *Journal of Civil Engineering and Management*, vol. 22, no. 7, pp. 944–953, Oct. 2016, doi: 10.3846/13923730.2014.945949.

[85] A. Najafi and R. Tiong, “Management in Construction Research Association (MiCRA) Postgraduate Conference,” Singapore.

[86] Department of Public Works and Town and Country Planning, “คู่มือการประมาณราคา (Manual for Cost Estimation),” 2012.

[87] B. Viriyaroj, M. Kuittinen, and S. H. Gheewala, “Life-cycle GHG emissions of standard houses in Thailand,” *Buildings and Cities*, vol. 5, no. 1, pp. 247–267, 2024, doi: 10.5334/bc.387.

[88] B. Phrommarat and P. Arromdee, “A life cycle assessment study of pre-stressed concrete poles in Thailand,” *International Journal of Construction Management*, vol. 22, no. 6, pp. 1053–1064, 2022, doi: 10.1080/15623599.2019.1683438.

[89] A. Boonpoke, J. Sriburee, S. Sedpho, and T. Prasertsang, “Environmental impact evaluation of road pavements using life cycle assessment tool,” *Lowland Technology International*, vol. 20, no. 2, pp. 117–124, 2018.

[90] C. R. Orozco, S. Tangtermsirikul, T. Sugiyama, and S. Babel, “Unraveling the environmental and economic impacts of fly ash utilization on mass concrete considering industry practices,” *J. Mater. Cycles Waste Manag.*, vol. 26, no. 3, pp. 1403–1417, 2024, doi: 10.1007/s10163-024-01893-y.

[91] Bangkok Bank, “Bualuang Green Loan for Transition to Environmental Sustainability: Product Information Document,” Bangkok. Accessed: Feb. 02, 2026. [Online]. Available: https://www.bangkokbank.com/en/Business-Banking/Finance-My-Business/Loans-for-SMEs/-/media/2376146f1a694ce49f6ae7441cdedd62.ashx

[92] H. Kara, “LCA Information Title: Life Cycle Assessment of Clinker and Cement production of Siam City Cement Public Company Limited (Thailand): 1,000 kg average Clinker and Cement,” PCR, 2023. [Online]. Available: www.siamcitycement.com

[93] Thailand Environment Institute, “Environmental Product Declaration EPD Thailand.” Accessed: Feb. 06, 2026. [Online]. Available: https://greenlabel.tei.or.th/en/epd-thailand/

[94] “One Click LCA for Autodesk® Revit®.”

[95] A. C. Kumar and T. Reshma, “4D applications of gis in construction management,” *Advances in Civil Engineering*, vol. 2017, 2017, doi: 10.1155/2017/1048540.

APPENDIX A

Figure A.1 - Assessment Framework and Criteria of TREES for Homes (TREES-H)

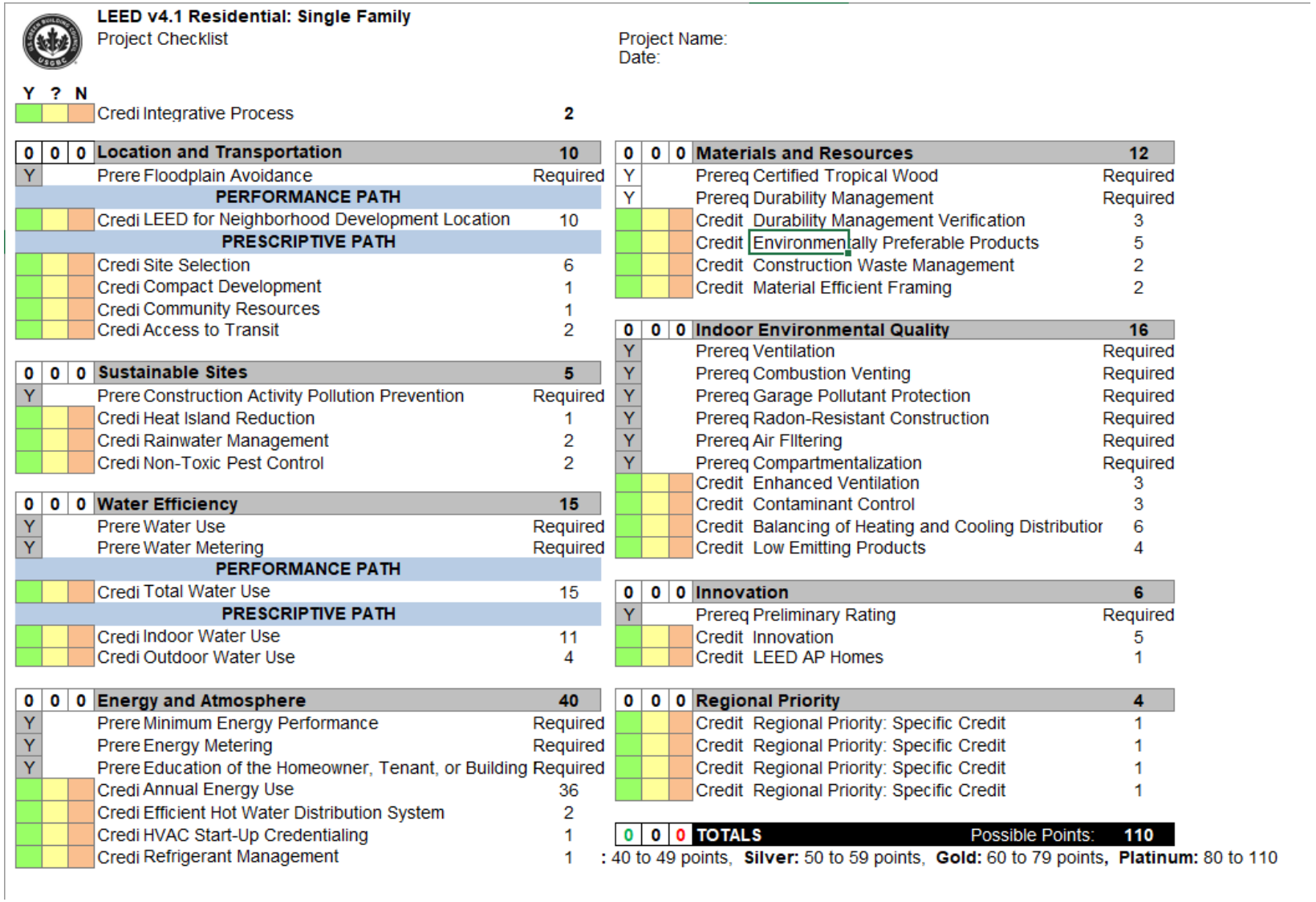
TREES for Homes: Energy-Efficient and Environmentally Friendly Housing Certification Criteria

Y	?	N	Code	Criteria	Max
0	0	0	SL	Sustainable Location and Site	12
Y			SL P1	Appropriate site selection and avoidance of unsuitable construction areas	Required
			SL 1	Development on previously developed land	5
			SL 2	Development within serviced urban areas	2
			SL 3	Residential density: minimum 1 unit per 50 sq.m. of open space (excluding setbacks)	1–2
			SL 4	Use of appropriate building orientation	2
			SL 5	Access to public transportation	1–2
0	0	0	WW	Water, Waste, and Pollution	16
Y			WW	Use of water-efficient fixtures for faucets, showers, and sanitary fittings, certified by Thai	Required
Y			WW	Installation of grease traps for kitchen wastewater	Required
Y			WW	Provision of designated areas for waste separation, including wet and dry waste	Required
			WW 1	Waste separation and construction waste management	6
			WW 2	Provision of waste separation areas at the project level	2
			WW 3	Use of water-saving devices such as sensor taps, automatic shut-off faucets, low-flow showerheads, dual-flush toilets, and irrigation systems, achieving at least a 10%	3
			WW 4	Household waste separation with designated areas for at least two categories or up to	3
			WW 5	Design and construction practices that reduce waste generation, including construction	2
0	0	0	MR	Materials and Resources	16
Y			MR P1	Use of environmentally friendly construction materials	Required
			MR 1	Use of local or low-impact materials	16
0	0	0	EA	Energy Efficiency (30 points)	30
Y			EA P1	Basic building energy performance assessment	Required
Y			EA P2	Use of energy-efficient building envelope	Required
Y			EA P3	Energy-efficient electrical systems	Required
Y			EA P4	Use of energy-efficient appliances	Required
			EA 1	Renewable energy systems	3
			EA 2	Overall thermal transfer value (OTTV)	8
			EA 3	Roof thermal transfer value (RTTV)	4

Y	?	N	Code	Criteria	Max
Y			P5	Use of natural daylight in living rooms, working areas, bedrooms, and window areas in accordance with requirements, with an average **Daylight Factor (DF) ≥ 1.5%**	Required
Y			EA P6	Maximum lighting power density (LPD) not exceeding **8 W/sq.m.**	Required
Y			EA P7	Use of energy-efficient lighting with lamps certified at **Energy Label No. 5**	Required
			EA 4	Use of environmentally friendly lighting systems, including appropriate lighting control	2
			EA 5	Maximum lighting power density (LPD) not exceeding **6.5 W/sq.m.**	5
			EA 6	Use of lighting control systems (lighting sensors) achieving at least **30% reduction in**	3–1
Y			EA P8	Reduction of energy consumption for water pumping, including provision of gravity-fed	Required
			EA 7	Use of renewable energy systems with hot water production from solar energy, including	3
			EA 8	Use of renewable energy, with preparation for installation of renewable electricity	2
			EA 9	Provision of parking spaces for electric vehicles and apartments, with at least **80% of units**	2
0	0	0	IE	Indoor Environmental Quality	Max Points
Y			IE P1	Ventilation rate compliance	Required
Y			IE P2	Indoor air quality management	Required
			IE 1	Daylighting and visual comfort	5–4
			IE 2	Use of low-emission materials	4
			IE 3	Acoustic performance and noise control	5–4
			IE 4	Thermal comfort performance	2–4
0	0	0	IN	Innovation in Design	6
0	0	0	IN	Innovation in Construction	4

Y	?	N	
0	0	0	**รวมคะแนนทงหมด**

Figure A.2 - LEED v4.1 Residential: Single-Family Scorecard and Reference Guide



LEED v4.1 Residential: Single Family
Project Checklist

Project Name:
Date:

Y	?	N		
			Credi Integrative Process	2

0	0	0	**Location and Transportation**	**10**
Y			Prere Floodplain Avoidance	Required
			PERFORMANCE PATH	
			Credi LEED for Neighborhood Development Location	10
			PRESCRIPTIVE PATH	
			Credi Site Selection	6
			Credi Compact Development	1
			Credi Community Resources	1
			Credi Access to Transit	2

0	0	0	**Sustainable Sites**	**5**
Y			Prere Construction Activity Pollution Prevention	Required
			Credi Heat Island Reduction	1
			Credi Rainwater Management	2
			Credi Non-Toxic Pest Control	2

0	0	0	**Water Efficiency**	**15**
Y			Prere Water Use	Required
Y			Prere Water Metering	Required
			PERFORMANCE PATH	
			Credi Total Water Use	15
			PRESCRIPTIVE PATH	
			Credi Indoor Water Use	11
			Credi Outdoor Water Use	4

0	0	0	**Energy and Atmosphere**	**40**
Y			Prere Minimum Energy Performance	Required
Y			Prere Energy Metering	Required
Y			Prere Education of the Homeowner, Tenant, or Building	Required
			Credi Annual Energy Use	36
			Credi Efficient Hot Water Distribution System	2
			Credi HVAC Start-Up Credentialing	1
			Credi Refrigerant Management	1

0	0	0	**Materials and Resources**	**12**
Y			Prereq Certified Tropical Wood	Required
Y			Prereq Durability Management	Required
			Credit Durability Management Verification	3
			Credit Environmentally Preferable Products	5
			Credit Construction Waste Management	2
			Credit Material Efficient Framing	2

0	0	0	**Indoor Environmental Quality**	**16**
Y			Prereq Ventilation	Required
Y			Prereq Combustion Venting	Required
Y			Prereq Garage Pollutant Protection	Required
Y			Prereq Radon-Resistant Construction	Required
Y			Prereq Air Filtering	Required
Y			Prereq Compartmentalization	Required
			Credit Enhanced Ventilation	3
			Credit Contaminant Control	3
			Credit Balancing of Heating and Cooling Distributior	6
			Credit Low Emitting Products	4

0	0	0	**Innovation**	**6**
Y			Prereq Preliminary Rating	Required
			Credit Innovation	5
			Credit LEED AP Homes	1

0	0	0	**Regional Priority**	**4**
			Credit Regional Priority: Specific Credit	1
			Credit Regional Priority: Specific Credit	1
			Credit Regional Priority: Specific Credit	1
			Credit Regional Priority: Specific Credit	1

0	0	0	**TOTALS**	Possible Points:	**110**

: 40 to 49 points, **Silver:** 50 to 59 points, **Gold:** 60 to 79 points, **Platinum:** 80 to 110

APPENDIX B

WBS PRODUCTIVITY AND CREW SIZE TABLE

Productivity references: BCA Singapore (2014) Productivity in Construction; CIDB Malaysia (2006) Productivity Norms for Building Construction

WBS Code	Activity Description	Phase	Unit	Productivity Rate	Unit / Day	Crew Size	Dur. Unit	Source
2.1.1	Driven pile installation (22x22 cm, L=12 m)	Foundation	No.	10	piles	5	day	BCA 2014
2.1.2	Pile integrity test	Foundation	No.	15	tests	2	day	BCA 2014
2.2.1	Pile cap formwork (side)	Foundation	m2	12	m2	3	day	CIDB 2006
2.2.2	Pile cap reinforcement	Foundation	t	0.80	t	4	day	BCA 2014
2.2.3	Pile cap concrete pour	Foundation	m3	8	m3	4	day	BCA 2014
2.3.1	Ground beam formwork	Foundation	m2	15	m2	3	day	CIDB 2006
2.3.2	Ground beam reinforcement	Foundation	t	0.60	t	3	day	BCA 2014
2.3.3	Ground beam concrete	Foundation	m3	8	m3	4	day	BCA 2014
3.1.1	Column formwork (TC)	Superstructure	m2	12	m2	3	day	CIDB 2006
3.1.2	Column reinforcement (TC)	Superstructure	t	0.80	t	4	day	BCA 2014
3.1.3	Column concrete pour (TC)	Superstructure	m3	6	m3	4	day	BCA 2014
3.2.1	Beam formwork (TC)	Superstructure	m2	15	m2	4	day	CIDB 2006
3.2.2	Beam reinforcement (TC)	Superstructure	t	0.70	t	4	day	BCA 2014
3.2.3	Beam concrete pour (TC)	Superstructure	m3	8	m3	5	day	BCA 2014
3.3.1	Suspended slab formwork/propping (TC)	Superstructure	m2	20	m2	5	day	CIDB 2006
3.3.2	Suspended slab reinforcement (TC)	Superstructure	t	0.90	t	4	day	BCA 2014
3.3.3	Suspended slab concrete (TC)	Superstructure	m3	10	m3	5	day	BCA 2014
3.4.1	Slab-on-grade concrete	Superstructure	m2	40	m2	4	day	CIDB 2006
4.1.1	Precast column erection (PF)	Superstructure	No.	8	cols	6	day	BCA 2014
4.1.2	Precast beam erection (PF)	Superstructure	No.	10	beams	6	day	BCA 2014
4.1.3	Non-shrink grout filling (PF)	Superstructure	joint	20	joints	3	day	BCA 2014

WBS Code	Activity Description	Phase	Unit	Productivity Rate	Unit / Day	Crew Size	Dur. Unit	Source
4.2.1	Slab topping concrete (PF)	Superstructure	m3	10	m3	5	day	BCA 2014
5.1.1	Precast wall panel erection (PP)	Superstructure	No.	6	panels	6	day	BCA 2014
5.1.2	Panel joint sealing (PP)	Superstructure	m	30	m	3	day	CIDB 2006
5.1.3	Precast slab panel laying (PP)	Superstructure	No.	8	panels	6	day	BCA 2014
6.1.1	AAC block masonry (external wall)	Enclosure	m2	18	m2	3	day	CIDB 2006
6.1.2	AAC block masonry (internal partition)	Enclosure	m2	20	m2	3	day	CIDB 2006
6.2.1	Cement render/plaster (external)	Enclosure	m2	25	m2	3	day	CIDB 2006
7.1.1	Steel roof structure erection	Roof	t	1.50	t	6	day	BCA 2014
7.1.2	Metal roof deck installation	Roof	m2	100	m2	6	day	BCA 2014
7.2.1	Roof waterproofing membrane	Roof	m2	60	m2	3	day	CIDB 2006
8.1.1	Demolition and stripping (RS)	Renovation	m2	25	m2	4	day	BCA 2014
8.1.2	Wall insulation installation (RS)	Renovation	m2	30	m2	3	day	CIDB 2006
8.1.3	Window replacement (RS)	Renovation	No.	4	windows	3	day	CIDB 2006
8.1.4	Roof insulation layer (RS)	Renovation	m2	50	m2	4	day	BCA 2014

APPENDIX C

COST DATABASE STRUCTURE AND RATE SOURCES

Primary: Comptroller General's Department (CGD) 2568: Banchee Rakha Kawadu lae Kha RaengngaanPi 2568 (Price schedule of materials and labour rates, 2025). Published annually; provides composite unit rates for materials inclusive of supply, delivery to site, and minor installation labour for standard civil works.

Secondary: Ministry of Labour (MOL) Announcement No. 13: Minimum wage and skilled labour rate schedule for the Bangkok Metropolitan Region and Pathumthani Province (effective 2024). Applied to labour line items where CGD rates are insufficient (non-standard activities or renovation works).

Tertiary: Private manufacturer/supplier quotes (2025): Used exclusively for factory-produced precast elements (PF and PP scenarios) and proprietary renovation products. Quotations obtained from a precast manufacturer operating in the Central region of Thailand (commercial terms and prices treated as indicative).

Category	Sub-category	Unit	Rate Source	Remarks
Site Preparation	Clearing and grubbing	m2	CGD 2568 Table 1	Direct cost only; Factor F excluded
Site Preparation	Temporary fencing	m	CGD 2568 Table 1	
Foundation	Driven precast prestressed pile (22x22 cm, L=12 m)	m	CGD 2568 Table 5 / Pile contractor quote	Constant across TC, PF, PP
Foundation	Pile cap concrete (C25/30)	m3	CGD 2568 Table 3	Includes formwork and rebar sub-items
Foundation	Ground beam concrete (C25/30)	m3	CGD 2568 Table 3	
Foundation	Slab-on-grade concrete (C20/25)	m2	CGD 2568 Table 3	Includes sub-base, mesh, and concrete
Structural: TC	Column/beam/slab formwork	m2	CGD 2568 Table 6	Plywood + timber frame
Structural: TC	Column/beam/slab reinforcement SD40	t	CGD 2568 Table 4	Cut, bend, place inclusive
Structural: TC	Ready-mix concrete C25/30 (pump)	m3	CGD 2568 Table 3 + truck mixer rate	Pump surcharge included
Structural: PF	Precast column element (C40)	No.	Private manufacturer quote (2025)	Factory supply and delivery; erection separate
Structural: PF	Precast beam element (C40)	No.	Private manufacturer quote (2025)	Factory supply and delivery; erection separate
Structural: PF	Precast element erection (mobile crane)	No.	CGD 2568 Table 9 + equipment schedule	Crane hire rate per shift
Structural: PF	Non-shrink grout (cement-based)	joint	CGD 2568 Table 3	Per joint including cleaning and cure
Structural: PP	Precast wall panel (C40, sandwich insulated)	No.	Private manufacturer quote (2025)	Panel size as per BOQ
Structural: PP	Precast slab panel (hollow-core)	No.	Private manufacturer quote (2025)	
Structural: PP	Panel erection (mobile crane)	No.	CGD 2568 Table 9	Same crane schedule as PF

Category	Sub-category	Unit	Rate Source	Remarks
Masonry	AAC block 200 mm (external wall)	m2	CGD 2568 Table 7	Block + mortar + labour composite rate
Masonry	AAC block 100 mm (internal partition)	m2	CGD 2568 Table 7	
Masonry	Cement render (external, two-coat)	m2	CGD 2568 Table 7	
Roof	Structural steel roof frame (galvanised)	t	CGD 2568 Table 4	Includes fabrication, delivery, erection
Roof	Metal roof deck (IBR sheet)	m2	CGD 2568 Table 8	
Roof	Roof waterproofing membrane	m2	CGD 2568 Table 8	
Finishes	Ceramic floor tile	m2	CGD 2568 Table 8	
Finishes	Interior paint (emulsion, 2 coats)	m2	CGD 2568 Table 8	
Finishes	Aluminium window (sliding)	No.	CGD 2568 Table 8	
Finishes	Solid timber door (with frame)	No.	CGD 2568 Table 8	
Renovation: RS	Strip and dispose existing finishes	m2	CGD 2568 Table 2 + MOL No. 13	Unskilled labour rate per MOL Annct. No. 13 (THB 353/day)
Renovation: RS	Wall insulation (50 mm EPS board)	m2	Private supplier quote (2025)	Supply and fix rate
Renovation: RS	Window replacement (double glazed)	No.	Private supplier quote (2025)	
Labour — all scenarios	Skilled tradesperson day rate	day	MOL Announcement No. 13 (2024)	THB 353/day minimum; specialist rates up to 2.0x multiplier
Transport — all scenarios	Concrete truck mixer	trip	CGD 2568 Table 9	Per trip, 6 m3 load
Transport — all scenarios	Flatbed truck (precast delivery)	trip	Private freight quote (2025)	Per trip from manufacturer, Pathumthani vicinity

APPENDIX D

EMISSION FACTOR AND EPD SOURCE LIST

Reference standard: EN 15804+A2 (2019+A2:2021) for product-stage factors; EN 15978:2011 for whole-life system boundary and stage definitions.

Grid electricity factor (confirmed): 0.8283 kg CO_2e / kWh (EGAT, 2022). Applied to Stage A5 (construction process electricity consumption) for all four scenarios.

Transport (Stage A4): Delivery distances from supplier/manufacturer to site are scenario-specific. See raw cost files for trip counts; fuel consumption modelled at IPCC AR6 default emission factor for diesel.

No.	Material / Process	GWP Factor	Unit	Declared Unit	Standard	Source / EPD Reference
1	Electricity (site construction process, A5)	0.8283	kg CO2e	kWh	EN 15978 A5	EGAT (2022) Grid Emission Factor / user table
2	Portland cement Type I / CEM I (production, A1-A3)	0.8398	kg CO2e	kg	EN 15804+A2	MPA UK Average CEM I sector EPD as cited by The Concrete Centre
3	Ready-mix concrete C20/25 (A1-A3)	0.0900	kg CO2e	kg	EN 15804+A2	Proxy from CPAC C24/28 EPD in uploaded One Click LCA report, adjusted downward for lower strength
4	Ready-mix concrete C25/30 (A1-A3)	0.1070	kg CO2e	kg	EN 15804+A2	Uploaded One Click LCA report: RMC C25/30 with CEM II/A-S, 10% GGBS
5	Ready-mix / precast concrete C40/50 (A1-A3)	0.3025	kg CO2e	kg	EN 15804+A2	Uploaded One Click LCA report: precast concrete beam C40/50, 25% GGBS
6	Precast concrete element — column, beam (A1-A3)	725.9200	kg CO2e	m3	EN 15804+A2	Uploaded One Click LCA report: precast concrete beam C40/50, 25% GGBS, 2400 kg/m3
7	Precast concrete wall panel — sandwich / wall panel proxy (A1-A3)	500.0000	kg CO2e	m3	EN 15804+A2	Proxy from uploaded precast wall/slab records and generic sandwich wall assumption
8	Precast hollow-core slab panel (A1-A3)	0.1400	kg CO2e	kg	EN 15804+A2	Hollow-core slab EPDs report about 136–143 kg CO2e per tonne A1-A3
9	Mortar and render, cement-based plaster mortar (A1-A3)	0.3497	kg CO2e	kg	EN 15804+A2	Uploaded One Click LCA report: plaster mortar
10	Deformed reinforcement bar SD40 / rebar (A1-A3)	2.3007	kg CO2e	kg	EN 15804+A2	Uploaded One Click LCA report: reinforcement steel rebar, generic, 0% recycled content
11	Structural steel section, galvanised proxy (A1-A3)	2.6470	kg CO2e	kg	EN 15804+A2	Uploaded One Click LCA report: structural steel profiles, 20% recycled content
12	Cold-formed steel / HSS / roof purlin (A1-A3)	2.8937	kg CO2e	kg	EN 15804+A2	Uploaded One Click LCA report: structural hollow steel sections, cold rolled, 20% recycled content

No.	Material / Process	GWP Factor	Unit	Declared Unit	Standard	Source / EPD Reference
13	AAC block, autoclaved aerated concrete (A1-A3)	0.3792	kg CO2e	kg	EN 15804+A2	Uploaded One Click LCA report: autoclaved aerated concrete, calculated average for World
14	Aluminium window frame, anodised / extruded profile proxy (A1-A3)	4.4181	kg CO2e	kg	EN 15804+A2	Uploaded One Click LCA report: extruded aluminium profiles, 80% recycled content
15	Ceramic floor / wall tile, glazed (A1-A3)	0.4517	kg CO2e	kg	EN 15804+A2	Uploaded One Click LCA report: ceramic glazed tile, 20 kg/m2
16	Interior paint, water-based emulsion (A1-A3)	1.3000	kg CO2e	kg	EN 15804+A2	EPD Smart Paint: acrylic water-based emulsion paint A1-A3 GWP total 1.3 kgCO2e/kg
17	EPS insulation board, 50 mm (A1-A3)	3.9000	kg CO2e	kg	EN 15804+A2	EUMEPS EPS rigid foam grey density 15 kg/m3 EPD; A1-A3 converted per kg
18	Double-glazed window unit / aluminium frame window (A1-A3)	4.2932	kg CO2e	kg	EN 15804+A2	Uploaded One Click LCA report: aluminium frame double-glazed non-operable window
19	Diesel fuel combustion, equipment and transport (A4-A5)	2.6800	kg CO2e	L	EN 15978 A4-A5	IPCC default combustion factor proxy for diesel fuel
20	Float glass, single pane 4 mm (A1-A3)	1.2916	kg CO2e	kg	EN 15804+A2	Uploaded One Click LCA report: float glass, single pane, 4 mm
21	Coated glass, single pane 4 mm (A1-A3)	1.3913	kg CO2e	kg	EN 15804+A2	Uploaded One Click LCA report: coated glass, single pane, 4 mm
22	Gypsum plasterboard, regular (A1-A3)	0.3286	kg CO2e	kg	EN 15804+A2	Uploaded One Click LCA report: gypsum plaster board, regular, generic
23	High-density gypsum plasterboard / Sheetrock StandardCORE HD (A1-A3)	0.1595	kg CO2e	kg	EN 15804+A2	Uploaded One Click LCA report: EPD Sheetrock StandardCORE HD, Knauf
24	Fibre cement board, flat coated cladding panel (A1-A3)	0.1038	kg CO2e	kg	EN 15804+A2	Uploaded One Click LCA report: flat fibre cement panels for cladding, coated
25	Porcelain glazed tile (A1-A3)	0.4403	kg CO2e	kg	EN 15804+A2	Uploaded One Click LCA report: porcelain glazed tile, 22 kg/m2
26	Marble / granite floor tile proxy (A1-A3)	0.1180	kg CO2e	kg	EN 15804+A2	Uploaded One Click LCA report: marble floor tile, 18 mm, 48.6 kg/m2
27	High-pressure laminate, HPL 1 mm (A1-A3)	1.7323	kg CO2e	kg	EN 15804+A2	Uploaded One Click LCA report: high pressure laminate, 1 mm, 1.5 kg/m2
28	PVC luxury vinyl tile (A1-A3)	2.8974	kg CO2e	kg	EN 15804+A2	Uploaded One Click LCA report: polyvinyl chloride vinyl tile, CFL EPD Luxury Vinyl Tile
29	Crane, diesel-driven operation (A5 process)	24.2180	kg CO2e	h	EN 15978 A5	Uploaded One Click LCA report: crane diesel-driven operation per hour, Lipasto.fi background

No.	Material / Process	GWP Factor	Unit	Declared Unit	Standard	Source / EPD Reference
30	Ready-mix concrete truck delivery proxy (A4)	7.8000	kg CO2e	m3	EN 15978 A4	Uploaded One Click LCA report: RMC delivery by truck proxy in A4 rows