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Intelligent Structural Design Optimization through Buildability-Based Value Engineering

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Abstract

The structural design phase plays a critical role in determining the cost, constructability, and overall value of construction projects. Value Engineering (VE) provides a systematic approach for achieving required functions while optimizing cost and resource utilization. However, buildability is often insufficiently considered during early structural design, potentially resulting in construction difficulties, increased costs, and delays.

This study presents an intelligent approach to structural design optimization by integrating buildability assessment into the Value Engineering process. A methodological framework is developed to systematically evaluate alternative structural design solutions using a quantitative Buildability Score. The framework considers design simplicity, standardization, construction requirements, material availability, code compliance, and interdisciplinary coordination as key decision criteria. Its applicability is demonstrated through a case study of a multi-story residential building in the Middle East.

The results demonstrate that integrating buildability assessment with Value Engineering provides a systematic basis for comparing structural design alternatives and identifying solutions with improved constructability, resource utilization, and overall project value. The proposed approach provides a practical decision-support framework for incorporating buildability considerations into structural design and supporting informed design decisions at the early project stage.

Keywords: Intelligent Structural Design; Buildability; Constructability; Value Engineering; Structural Design Optimization; Buildability Score; Decision Support.

1. Introduction

The integration of multiple knowledge domains is crucial for achieving optimal outcomes in the construction industry. Among all project phases, the design stage typically involves the lowest cost, making it the most strategic point for implementing Value Engineering (VE) techniques. Early application of VE, particularly during the preliminary design phase, has proven to deliver the most significant benefits [1,16]. Figure 1 illustrates how VE relates to design optimality in construction projects.

As depicted in Figure 1, VE encompasses all key parameters relevant to both the design and construction processes. Design optimality, a critical aspect of effective project planning, can be evaluated during the design stage using tools such as the Building Design Appraisal System (BDAS) to enhance buildability.

During construction, optimality can further be assessed through the Design Quality Indicator (DQI) to support constructability analysis. Understanding the relationship between VE and design optimality requires an in-depth examination of the design process's influence on lifecycle costs, and how early-stage VE can mitigate risks and improve efficiency.

Figure 2 presents the cost distribution across the project lifecycle. Although the design stage represents a smaller portion of the total cost, early construction-related decisions typically drive the majority of expenses. The preliminary design phase, when project requirements, scope, and initial estimates are established, is the ideal window for conducting value analysis. At this stage, alternative design solutions can be examined, and VE teams can propose recommendations that significantly shape the project scope, cost, and functionality [2,17].

Value analysis is a structured, interdisciplinary methodology aimed at enhancing performance while maintaining cost-efficiency. It aligns user needs with functional and economic goals through a systematic process that identifies which activities contribute directly to value. By focusing on necessary functions and eliminating inefficiencies, value analysis supports safer, more reliable, and cost-effective solutions, especially when applied early in the design process (see Figure 3).

This research proposes a conceptual and analytical framework that links design optimality, buildability, and constructability. It emphasizes the role of the Buildable Design Appraisal System (BDAS) in managing the interaction between optimal design and buildability. The core objective is to evaluate buildability during the design phase and understand its implications for construction performance. By identifying key buildability principles and their advantages, the study highlights strategies to ensure timely, cost-effective, and high-quality project delivery.

This research adopts an interdisciplinary approach that combines structural design, construction management, cost optimization, and Value Engineering (VE) principles. Such integration ensures that the proposed framework not only addresses technical design aspects but also considers managerial and economic dimensions, leading to more efficient project delivery.

Ultimately, this paper investigates the relationship between Value Engineering and Design Optimality, interpreting the latter as the buildability of the design during the preliminary phase. The study underscores the necessity of complying with standards such as the Uniform Building Code and achieving functional optimality through informed, collaborative, and regulation-driven design practices.

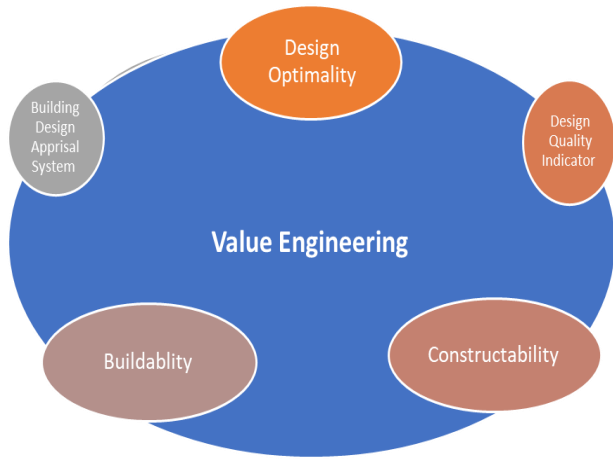


Fig. (1) The relation between Value Engineering and Optimality for construction project

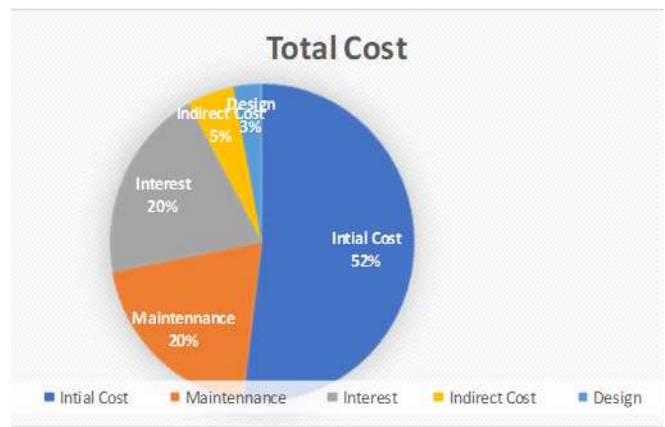


Fig. (2) Total cost of ownership typical office building

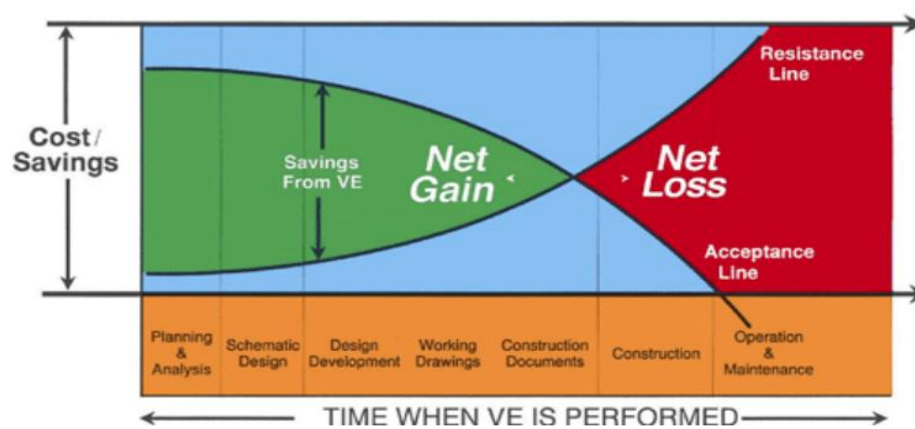


Fig. (3) Potential savings from the Value Engineering study

2. Value Engineering and Buildability Benefits

Value Engineering (VE) is a systematic methodology designed to identify a project's essential functional requirements, whether across the entire scope or within specific component, and deliver them at maximum value. The fundamental objective of VE is to enhance performance while minimizing cost, thereby ensuring efficient resource utilization and meeting or surpassing stakeholder expectations [3,18].

As illustrated in Figure 4, the VE process typically follows a structured sequence comprising several distinct phases: problem definition, information gathering, functional analysis, creative idea generation, evaluation, proposal development, stakeholder presentation, and implementation. Each phase is designed to facilitate informed decision-making and foster the development of optimized design alternatives.

At its core, VE is intrinsically linked to the principle of optimization, which involves achieving target outcomes under various constraints—whether related to budget, material availability, or performance standards. Engineering systems, in particular, must be designed to navigate these constraints without compromising safety, functionality, or economic viability. As illustrated in Figure 5, optimal design approaches often rely on reliable input parameters and may accept minimal risk margins to balance cost-efficiency with structural integrity.

Within this framework, design optimization becomes a foundational component of VE, leading to performance-based decisions that yield measurable construction benefits. One such benefit is buildability, defined as the capacity to execute a construction design efficiently, economically, and with consistent quality. Buildability represents the practical outcome of a well-optimized design strategy.

The Construction Industry Research and Information Association (CIRIA) has identified seven key principles that support buildability in construction projects [3]. These include conducting thorough design and feasibility assessments, ensuring site preparedness and logistical planning, organizing construction activities in a logical sequence, facilitating early enclosure, simplifying on-site assembly processes, standardizing components for repetition, and selecting durable materials compatible with the construction method. When these principles are embedded into the VE framework, the outcome is not merely theoretical optimization but a tangible improvement in construction execution.

Buildability has the potential to improve project performance across all phases; however, its greatest impact is observed when addressed early in the design process. This aligns with the Pareto Principle, which posits that a majority of project outcomes are influenced by a relatively small set of early-stage decisions. Integrating buildability considerations from the outset can lead to significant improvements in project cost, duration, and overall quality.

Research by Lam, Wong, and Chan (2006) confirms that effective buildability management enhances project delivery by improving schedule reliability, reducing construction costs, and ensuring better quality outcomes [4]. Moreover, buildability serves as both a predictive and corrective mechanism within the project lifecycle. Failing to account for buildability, such as through overly complex design features or incompatible construction elements, often results in rework, change orders, project delays, and increased design team workload, which can also impair their availability for future commitments.

To mitigate such risks, project managers and feasibility analysts should be alerted to buildability issues at the earliest stages of planning. Involving key stakeholders, including those responsible for post-occupancy operations during design development, helps ensure that buildability challenges are anticipated and addressed proactively. Additionally, incorporating constructability-focused tools and decision-support methods during the early design phases promotes a more integrated and viable execution strategy [5,19].

The effective integration of buildability into project planning requires coordinated efforts from all stakeholders involved in the design and construction phases. The Construction Industry Institute (CII), through its Constructability Task Force, has developed seven strategic guidelines to strengthen buildability through enhanced planning and scheduling practices [6,20] (see Figure 6). These include preparing a comprehensive construction schedule in advance of finalizing design and procurement, applying backward planning techniques from the intended completion date, and setting clear milestones for system startup, equipment commissioning, and structural readiness.

These guidelines help align design and construction efforts, reduce delays, and enhance resource utilization ultimately supporting successful, efficient, and high-quality project delivery.

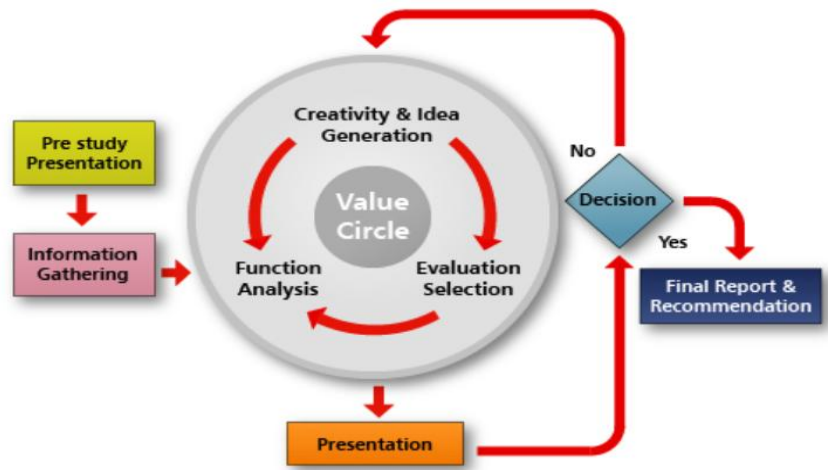


Fig. (4) Life cycle of Value Engineering concept

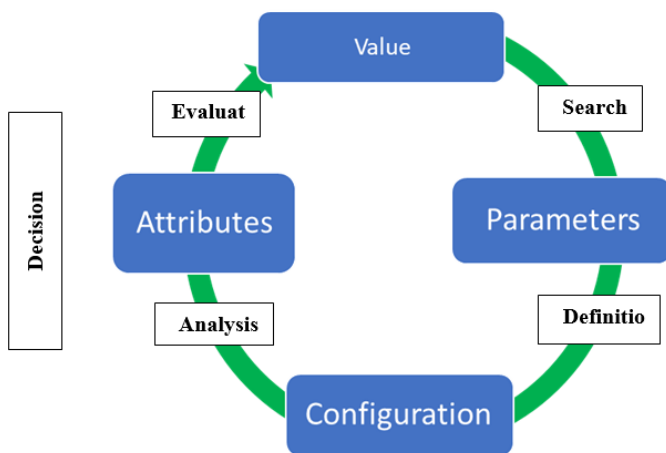


Fig. (5) Formal view of optimal design for construction project

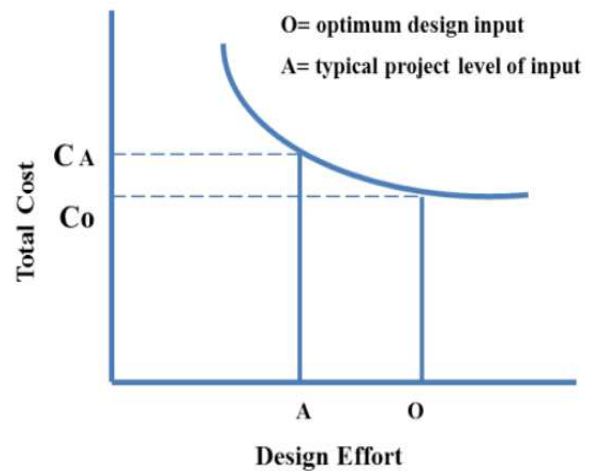


Fig. (6) Relationship for design effect and total cost to define optimum design input [6]

4. Elements Influencing Buildability

The concept of buildability encompasses a wide array of factors that critically affect the efficiency, quality, and feasibility of construction projects. According to Wong et al. [8,21], sixteen key categories of design and site-related variables were identified as having substantial influence on buildability outcomes. Continuous optimization of these factors during the design stage can significantly improve constructability and reduce execution risks. The primary categories are as follows:

4.1 Site-Specific Factors

These include conditions related to the project's location and underground characteristics. Early-stage investigations such as geotechnical testing, geological surveys, utility detection, and structural analysis of adjacent facilities enhance design reliability and reduce unforeseen complications during construction.

4.2 Site Configuration, Environment, and Access

Efficient site planning directly supports buildability. Key considerations include:

- Logical site layout and material storage,
- Reduced dependence on wet trades,
- Adequate access and workspace for labor and equipment,

- Minimization of environmental disruptions (e.g., dust, noise, wastewater),
- Early installation of protective enclosures and permanent access routes.

4.3 Subsurface Works

Subterranean design should:

- Minimize duration and complexity of excavation activities,
- Incorporate safety and environmental considerations,
- Address potential impacts on nearby foundations and utilities.

4.4 Design Coordination

Coordination among disciplines ensures design consistency. This involves:

- Harmonizing architectural, structural, and MEP documents,
- Updating ambiguous or conflicting specifications,
- Standardizing service layouts,
- Clearly indicating routes for mechanical and plumbing systems (e.g., sleeves, vents).

4.5 Detailing

Clear and well-structured detailing promotes execution accuracy. It includes:

- Specified tolerances for all key components,
- Alignment between interconnected systems (e.g., window frames and openings),
- Use of typical or standardized details,
- Visual checks to detect clashes (e.g., services intersecting with reinforcements).

4.6 Design Flexibility

Allowing for interchangeability, such as left-right adaptable fixtures, improves construction adaptability and minimizes potential delays.

4.7 Equipment and Plant Integration

The design should consider:

- Limitations of on-site equipment,
- Accessibility for machinery movement,
- Provisions for temporary anchorages and supports.

4.8 Material and Component Selection

Prioritizing locally available, robust materials enhances supply certainty. Considerations include:

- Anticipated lead times,
- Protection of sensitive components (e.g., precast stairs),
- Ease of maintenance post-construction.

4.9 Resource Utilization

Efficient buildability is supported by:

- Leveraging local labor and equipment,
- Balancing manpower with mechanical solutions.
- Reducing trade overlap and unnecessary material handling.

4.10 Material Systems

Material efficiency can be achieved by:

- Supporting flexibility in material options,
- Utilizing modular systems to reduce waste (e.g., cut losses in tiles, rebar).

4.11 Installation Feasibility

The design must allow:

- Simplified connection systems,
- Field adaptability without significant rework,
- Realistic, buildable tolerances.

4.12 Standardization

Standardized elements and modular design contribute to:

- Repetition and familiarity among labor,
- Higher productivity,
- Streamlined quality control.

4.13 Prefabrication and Offsite Work

Encouraging off-site fabrication, such as modular bathrooms, enhances:

- On-site efficiency,
- Fabrication accuracy,
- Schedule reliability.

4.14 Innovation Integration

Designs should permit:

- Flexibility for alternative construction approaches,
- Adoption of contractor-led innovations.

4.15 Weather Considerations

Weather-sensitive work (e.g., structural framing or external finishes) should be aligned with expected climatic conditions, particularly during rainy or extreme seasons.

4.16 Safety Provisions

Design must integrate safety measures by:

- Allowing early placement of heavy equipment,
- Ensuring component sizes and weights are manageable with typical lifting and handling methods.

5. Causes of Buildability Difficulties

Several studies have underscored the pivotal role of the design phase in enhancing buildability, consistently linking it to reduced project costs and durations, as well as improved safety and quality performance [4,21]. Nonetheless, buildability-related challenges remain prevalent across many construction projects and appear to be increasing in frequency over time [7,22].

Empirical observations indicate that buildability problems often become more pronounced as a project progresses. The incidence of such issues is typically highest after one year of project execution, while significantly fewer occurrences are reported within the first six, three, or one-month periods. A comparative

analysis of perspectives from clients, consultants, and contractors has identified a set of recurring root causes that contribute to buildability difficulties.

5.1 General Causes of Buildability Problems

The following factors have been commonly reported as major contributors to buildability challenges:

- High project complexity
- Incomplete or ambiguous specifications
- Inadequate working drawings
- Client resistance to adopting buildability principles
- Budgetary limitations
- Lack of design standardization
- Separation between design and construction processes
- Limited awareness of current construction technologies
- Poor understanding of the buildability concept
- Deficient communication among stakeholders

In addition to these primary causes, other medium-level contributing factors include:

- Lack of documentation capturing lessons learned
- Adversarial relationships between design and construction teams
- Delayed requests for construction input
- Turnover or loss of key project personnel during critical phases

5.2 Designer Related Causes of Buildability Issues [8]

Several causes of buildability deficiencies have been directly associated with the design team, including:

- Insufficient knowledge or experience in construction methodologies
- Lack of contractor involvement during the design stage
- Increasing complexity in interdisciplinary project coordination
- High technical demands, including advanced systems and building automation
- Weak collaboration and minimal consideration of contractor feedback
- Bureaucratic delays in obtaining governmental approvals for design modifications
- Compressed schedules for design and tendering, leading to inadequate time for detailing and cost estimation
- Fragmentation of consultant responsibilities, which limits cohesive efforts to implement buildability improvements

5.3 Regional Case: Malaysian Construction Industry

A sector-specific study conducted within the Malaysian construction industry identified 19 critical buildability attributes associated with the building design process. Among these, the most important factor—according to clients, consultants, and contractors—was the provision of comprehensive and unambiguous design documentation. On the other end of the spectrum, minimizing underground construction work was rated as the least significant.

This alignment among stakeholders highlights a notable consensus on the key drivers of buildability performance in practice. It also emphasizes the importance of clear communication, well-defined documentation, and coordinated planning as foundational elements for successful buildability integration.

6. Enhancing Buildability Quality During the Design Phase

The quality of design output is often shaped by a balance of multiple, and sometimes conflicting, requirements. This outcome is influenced by the individual interpretations, preferences, and professional biases of various project stakeholders [8]. As the design process is inherently collaborative, it is significantly impacted by human interaction and the dynamics of multidisciplinary engagement [9,23].

However, in many instances, building design is treated predominantly as a creative or artistic exercise, with insufficient attention given to the practical realities and challenges encountered during construction. Consequently, contractors are frequently excluded from the early design development phases, which limits their ability to contribute valuable insights on constructability [9,10].

Recurring issues in modern construction projects include the prevalence of complex or impractical designs, as well as the delivery of design information that is delayed, incomplete, or poorly coordinated. A study by Coles [11] identified three principal deficiencies in design process management:

- Ineffective communication and briefing procedures,
- Limited technical knowledge among design professionals,
- Inadequate pre-planning and lack of schedule assurance for design activities.

These challenges affect all members of the project team, underscoring the pressing need for enhanced design management practices. In particular, there is growing recognition of the importance of incorporating buildability considerations directly into design deliverables from the outset.

To address these shortcomings, Glavinich (1995) emphasized the necessity of structured scheduling for the design process and advocated for continuous assessment of buildability throughout all internal design stages [12]. In a related effort, Mokhtar et al. (2000) proposed a computer-aided system to preempt construction issues arising from late-stage design changes—such as clashes between building components or incompatibility with construction constraints [13,14].

Furthermore, Gray and Hughes (2001) developed a buildability checklist intended to support designers in systematically evaluating their design proposals. Their work emphasized that the assessment of construction feasibility requires substantial site experience, and they encouraged the adoption of designs that are as simple to construct as possible [9].

Collectively, these contributions reflect a growing awareness of the need for specialized tools and frameworks to support effective design management. Such systems should also be flexible enough to accommodate evolving team roles and responsibilities across different stages of the project lifecycle [8].

7. Case Study

This case study explores the assessment of buildability within construction projects in a Middle Eastern context by applying the **Buildable Design Appraisal System (BDAS)** to calculate the buildability score

or design optimality index. The primary objective is to determine whether the evaluated designs require improvement through the application of value engineering (VE) methodologies.

By quantifying the design optimality index, decision-makers can assess the need for implementing VE to enhance the design’s functionality, improve construction productivity, and optimize resource utilization. The overall aim is to improve design quality and building performance while reducing total project cost and time.

The first step in this methodology is the formation of a multidisciplinary **Value Engineering Team**, which typically includes the following members:

- 1. Design Manager
- 2. Owner’s Representative
- 3. Structural Engineer
- 4. Architectural Engineer
- 5. MEP Engineer
- 6. Cost Estimator

This VE team is responsible for analyzing a representative sample of projects ranging from commercial and residential buildings to industrial facilities using the **Buildable Design Appraisal System** to compute the corresponding buildability scores.

Table (1) Value engineering implementation

Sr.	Items	Direction	Effect
1	Safety and Quality	↑↑	More increasing
2	labor Production	↑↑	More Increasing
3	Project Time	↓	Decrease till 30%
4	Project Cost	↓	Decrease till 10%

Table 1 illustrates the outcomes of applying value engineering (VE) in terms of time and cost savings across various construction scenarios. While the initial project budget may increase due to the adoption of higher-quality materials, the long-term benefits include enhanced durability, reduced rework, and improved project performance. To maximize these advantages, it is essential to raise awareness about the buildability concept among project teams through technical presentations that clarify its goals and practical benefits. The methodology for implementing the value engineering approach using the buildability score consists of the following steps:

- 1. The **Value Engineering Team determines** the minimum acceptable buildability score during the design review phase, based on factors such as building type, total floor area, and classification.
- 2. The **Supervision Department** is tasked with developing a comprehensive database containing the number of projects, their classifications, and corresponding design optimality indices. This dataset is used to evaluate the impact of design decisions on project completion times and total costs.

3. The **Value Engineering Team** evaluates and monitors project performance using this information and revises the design strategies accordingly.
4. The team also conducts comparative analyses between conventional and advanced construction systems. For example, traditional systems involving carpentry and in-situ concrete works are contrasted with more efficient alternatives such as precast elements. These modern systems have shown to deliver substantial savings in both time and cost when adopted appropriately [14].

7.1 Elements Positively Influencing the Buildability Score

The following design and construction choices have a positive impact on the buildability score:

- Glass cladding and curtain wall systems
- Precast structural and non-structural elements
- Aluminum cladding
- Ready wall systems
- Steel structural frameworks
- Metal roofing systems
- Enlarged wall openings
- Standardized and uniformly sized openings
- Advanced systems such as post-tensioning and tunnel formwork
- Uniformity in the size and dimensions of vertical elements
- Consistency of grid axes in both directions
- Preassembled service units (e.g., mechanical rooms)
- Adoption of new technologies for finishing works such as automated plastering and painting

7.2 Elements Negatively Influencing the Buildability Score

Conversely, the following elements tend to reduce the buildability score due to their complexity, labor intensity, or incompatibility with modern construction efficiencies:

- Manual plastering
- Stone cladding
- Complex architectural façade treatments
- Load-bearing blockwork
- Extensive use of cast-in-situ concrete
- Two-way beam structural systems

Figure 7 illustrates the relationship between manpower and construction activities, highlighting how labor-intensive systems correspond to lower buildability scores and increased resource demands.

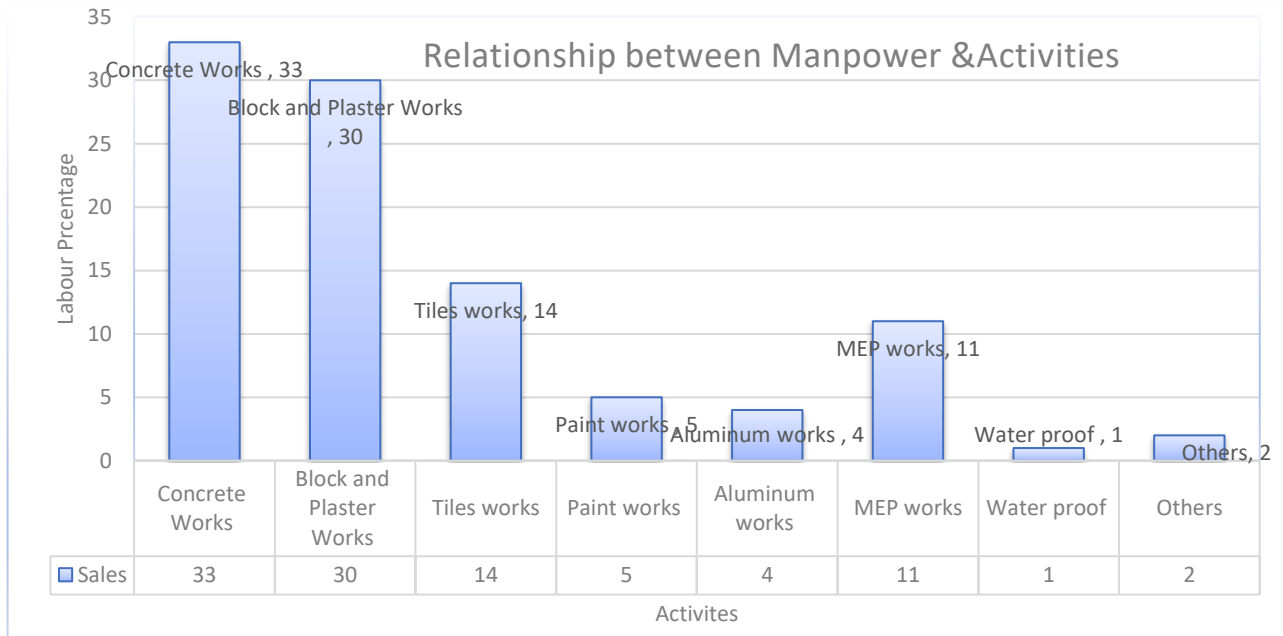


Fig. (7) Relationship between Manpower and Activities for construction project

7.3 Case Study for Calculating the Buildability Score

a) Project Description

This case study evaluates the buildability score for a single-block residential building project. The key features of the project are as follows:

- The building comprises **10 floors**, with **4 apartment units per floor**.
- The structure does **not include a basement**.
- The **slab structural system** is composed of **reinforced concrete (RC)**.
- For analytical consistency, it is assumed that the layout of each typical floor is identical, **except for the ground (first) floor and the roof**.
- The **typical floor-to-floor height** is **3.3 meters**, while the **first floor** has a height of **4.0 meters**.

Table 2 presents the total floor area allocated for apartments, the lift lobby, and general circulation on each level. These spatial allocations form the basis for calculating the Buildability Score using the BDAS framework.

Table (2) Total area for apartments

Item	Quantity
Total floor area of Apartments = 10 x 667.40 m ²	6,674.0 m ²
Total floor area of Lift Lobby = 10 x 86.6 m ²	866.0 m ²
Roof slab area (assume same as typical floor)	754.0 m ²
Ast: Total floor area of building including roof area	8,294.0 m ²

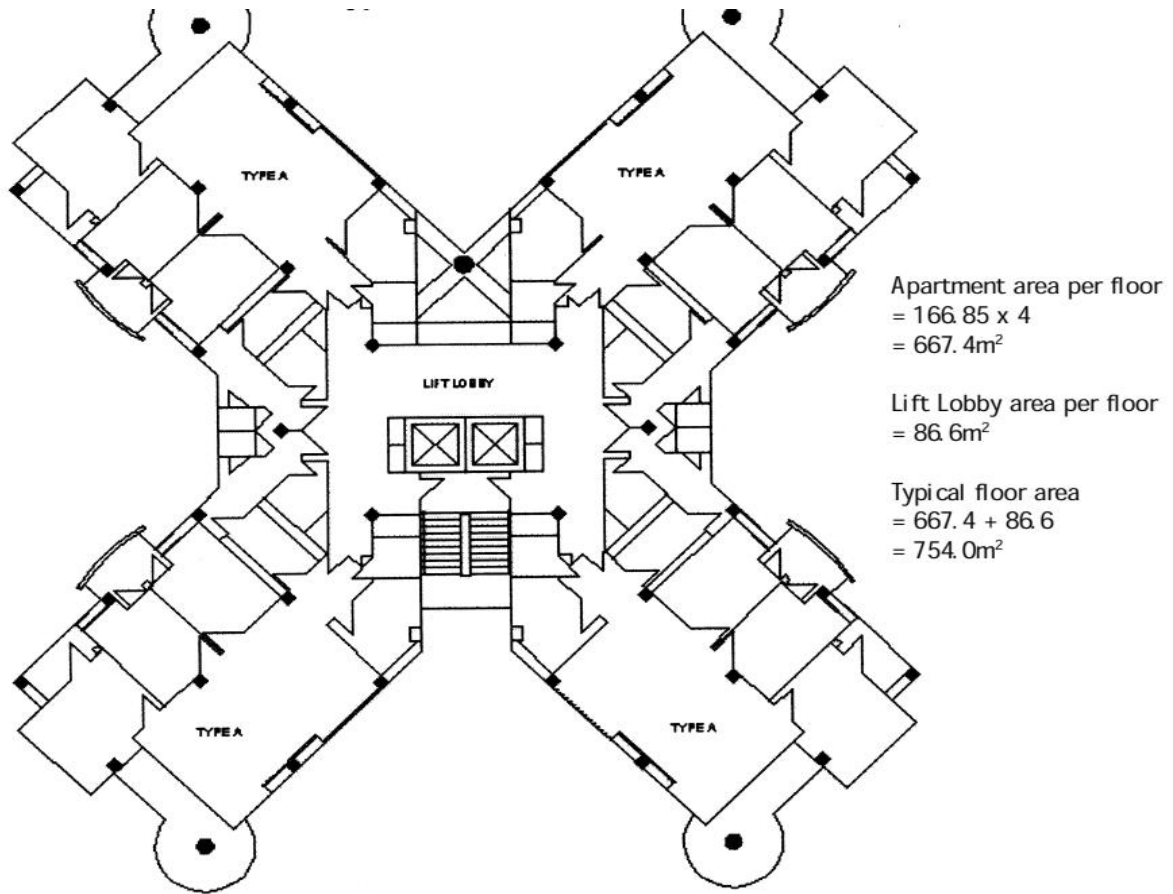


Fig. (8) Typical floor Plan for studied case

b) Formula for Buildability Score

To quantify the impact of a building's design on labor productivity, the **Building and Construction Authority (BCA)** developed the **Buildable Design Appraisal System (BDAS)**. The outcome of this assessment is expressed as the **Buildable Design Score**, which reflects how efficiently labor can be utilized during construction. A higher score generally indicates a design that promotes improved site productivity through reduced labor intensity and simplified construction processes.

The **BDAS** is structured to evaluate a building design's effect on labor efficiency across three main components:

1. **Structural System** – Maximum of 50 points (including the roof structure)
2. **Wall System** – Maximum of 40 points
3. **Other Buildable Design Features** – Maximum of 10 points, with potential bonus points awarded for the use of fully integrated components

The **Buildability Score (BS)** is computed using the following equation:

$$\text{BS} = \text{BS_structural} + \text{BS_wall} + \text{BS_other_features}$$

Where:

- **BS_structural** = Score attributed to the structural system
- **BS_wall** = Score attributed to the internal and external wall systems

- **BS_other_features** = Score assigned to additional buildable design elements and any qualifying bonus components

This framework provides a standardized, objective method for appraising how a building's design translates into construction efficiency, with direct implications for time and cost savings [15].

$$BS = 50[\sum (As \times Ss)] + 40[\sum (Lw \times Sw)] + N$$

Where:

As: The extent to which a particular structural system or prefabricated reinforcement is used. This is expressed as a percentage of the total floor area of the building in the case of structural system and the extent of coverage of use in each cast in-situ component in the case of prefabricated reinforcement.

Ss: A Labour-Saving Index for the particular structural system and prefabricated reinforcement. The labour-Saving Indices for the various structural systems and prefabricated reinforcement. (BCA 2011, Table No. 1)

Lw: The degree of utilization of a specific internal or external wall system. This is given as a percentage of the building's overall wall length.

Sw: A Labor-Saving Index specific to the internal or external wall system in question. The various wall systems' labor-saving indices. (BCA.2011, Table No. 2)

N: Bonus points given to simple building designs without high voids and complex design forms. Depending on the design simplicity, different points are given up to a maximum of 5 (BCA.2011, Table no 3).

Ss, Sw and N values are given in tables in Code of practice BCA. (2011). Code of Practice on Buildability. Building and Construction Authority.

c) Various Design Choices

To evaluate the impact of different structural configurations on the buildability score, four distinct design alternatives were considered for the same building type:

- **Option 1:** A conventional **reinforced concrete (RC) frame** structure utilizing both **external and internal brick walls**. This represents the traditional construction method.
- **Option 2:** A **flat plate slab system** combined with **interior precision block partitions**, **external brick walls**, and **cast in-situ columns**. This configuration improves buildability slightly through simplified slab and partition systems.
- **Option 3:** A **hybrid system** featuring **precast external wall panels**, **interior precision block partitions**, and a **flat plate slab** supported by **cast in-situ columns**. This design significantly enhances buildability by reducing on-site labor and construction complexity.
- **Option 4:** A **composite system** utilizing **cast in-situ columns**, **precast beams**, and **precast slabs**, in combination with **precision block partitions** and **external brick walls**. This approach increases the degree of offsite fabrication and modularity.

Table 3. Comparative Buildability Scores of Design Alternatives

Option	Structural System Description	Key Features	Buildability Score
Option 1	RC Frame + Brick Walls	Conventional cast in-situ, high labor demand	60.50
Option 2	Flat Plate + Brick Walls	Simplified slab, improved internal layout	77.95
Option 3	Flat Plate + Precast Walls	Precast exterior, modular internal layout	83.35
Option 4	Precast Slabs + Beams	Hybrid cast/precast with block partitions	81.60

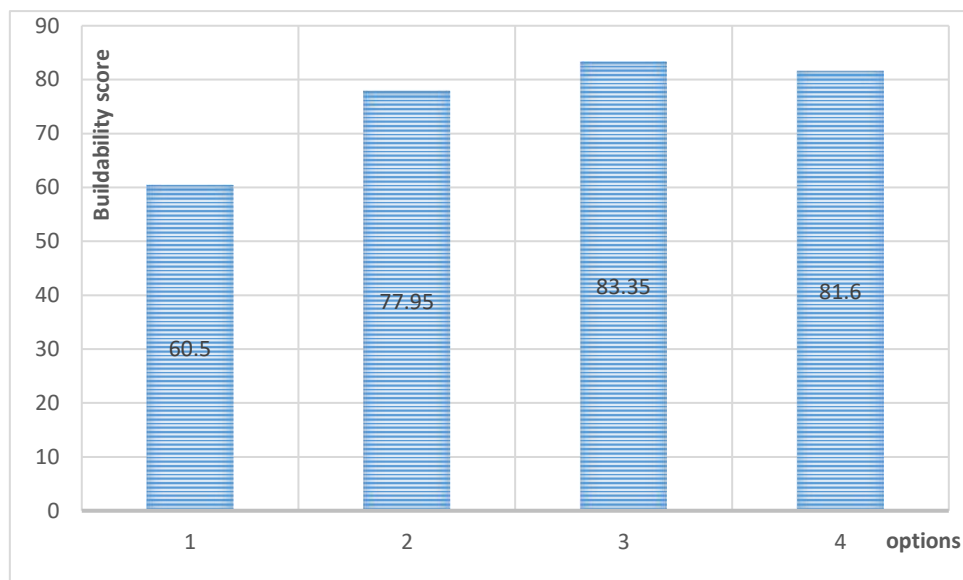


Fig (9). Comparative Buildability Scores of Design Alternatives

The comparative analysis presented in Table 3 and figure 9 reveals significant variations in buildability performance across the four proposed structural design alternatives. The scores, calculated using the Buildable Design Appraisal System (BDAS), highlight a strong correlation between the degree of design industrialization and the resulting buildability index.

Option 3, which employs a flat plate slab system with precast exterior walls and modular internal partitions, achieved the highest Buildability Score (**83.35**). This outcome clearly illustrates a strong positive relationship between the **Labour Saving Index (LSI)** and the overall buildability performance. The design demonstrates a high degree of **standardization**, **modularity**, and **industrialized construction**, all of which reduce dependency on manual labor, simplify construction logistics, and enhance dimensional accuracy—ultimately contributing to improved constructability and faster execution.

Option 4, which integrates precast slabs and beams with traditional wall systems, performed slightly lower (**81.60**), indicating the benefits of partial prefabrication. However, the continued reliance on **labour-intensive block work** limits its efficiency compared to Option 3.

Option 2, featuring a simplified flat plate system and conventional brick walls, scored **77.95**. While the structural simplification provides some efficiency gains, the traditional wall system remains a bottleneck due to its high labor demands.

Conversely, **Option 1** recorded the lowest Buildability Score (**60.50**), reflecting its dependence on **cast in-situ concrete and brick wall systems**—both of which are labor-intensive and prone to execution variability. The lack of prefabrication and standardized design patterns further contributed to its lower performance.

These findings reinforce the value of **modern construction techniques**, such as **precast elements** and **industrialized systems**, which reduce the need for on-site manual labor while leveraging specialized expertise. By enhancing work efficiency, improving construction quality, and optimizing resource utilization, these systems contribute to significantly higher buildability scores.

Overall, the results emphasize the critical importance of **adopting innovative, constructability-driven design strategies** early in the project lifecycle. Designs that integrate **repeatable components, modular systems**, and **value engineering principles** are demonstrably more successful in delivering projects that meet time, cost, and quality expectations.

Conclusions

This study examined the application of buildability scoring as an effective decision-support mechanism for implementing value engineering (VE) during the early design stages of construction projects. Through the application of the Buildable Design Appraisal System (BDAS), the research sought to enhance design optimality, improve labor efficiency, and reduce both time and cost associated with project delivery.

Based on the analysis and findings, several key conclusions can be drawn:

- 1. Standardization of Design Tools:**

The use of structured and standardized checklists contributes to improved alignment and consistency across design documentation. Such tools also facilitate future adaptability of the design for modifications, renovation, or change of use.

- 2. Integration of Construction Knowledge:**

Early-stage consideration of contractor expertise, available construction resources, and coordination of multidisciplinary documentation enhances overall constructability and supports efficient project execution.

- 3. Buildability as a Pillar of Value Engineering:**

Buildability should be recognized as a fundamental criterion in achieving optimal design. Its integration promotes effective value engineering by reducing design redundancies and enabling better-informed decision-making during early design phases.

- 4. Design–Construction Synergy and Market Awareness:**

Strengthening collaboration between design and construction stakeholders, alongside informed material selection based on current market data, leads to more responsive and sustainable design solutions.

- 5. Importance of Site Assessment and Component Repetition:**

Conducting thorough site investigations at the conceptual stage reduces unforeseen complications

during construction. Additionally, repetition and standardization of frequently used components support material efficiency and streamline construction workflows.

6. Correlation Between Industrialization and Buildability:

The findings demonstrated a strong positive correlation between the degree of design industrialization—particularly the use of precast systems—and the resulting buildability score. Designs that incorporate modular components and off-site fabrication consistently outperform traditional systems in labor efficiency, quality, and execution speed.

7. Effectiveness of the BDAS as a Diagnostic Tool:

The Buildable Design Appraisal System (BDAS) proved to be an effective framework for quantitatively assessing design decisions and their impact on construction performance. It offers a structured methodology to guide design optimization and prioritize constructability-related improvements.

8. Practical Implications for Design Decision-Making:

By integrating buildability scoring into early design reviews, project teams can make more informed trade-offs between cost, complexity, and performance. This proactive approach supports better risk management and improves the overall feasibility of construction plans.

9. Value Engineering as a Continuous Process:

Rather than being a one-time exercise, value engineering should be viewed as an ongoing process that begins in conceptual design and continues through execution. The integration of buildability assessments at each stage enhances the adaptability and long-term efficiency of the design.

10. Although this study focused on applying VE and BDAS for buildability assessment, the integration of digital tools such as Building Information Modeling (BIM) and Artificial Intelligence (AI) could further enhance methodological depth. Future research should explore how these technologies can support automated evaluation, real-time data analysis, and decision-making, thereby improving the practical implementation of VE and buildability assessment in structural design.

11. The findings of this study demonstrate strong technical and industrial relevance, as the proposed framework directly addresses common design inefficiencies, reduces project time and cost, and improves buildability. These outcomes emphasize the practical applicability of the approach for enhancing construction performance in real projects."

Recommendations for Future Research

To advance this line of inquiry, future studies are recommended to:

- Investigate buildability classification systems across various building typologies and functional categories.
- Examine the quantitative relationship between the **Design Quality Indicator (DQI)** and **Buildability Score**, particularly as predictors of project success.
- Explore the impact of early collaboration between designers and contractors on the buildability of design deliverables.

Final Remark

Overall, this study contributes a practical and scalable framework for integrating buildability into early-stage design decisions. By linking design quality with labor efficiency and value engineering principles, it provides a structured path for enhancing project

Data Availability

The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

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Appendix – Buildability Evaluation Tables

Appendix1

Option 1: A traditional RC frame building with exterior and interior brick walls

Sr	Description	Area (m ²)	Coverage %	Labour Saving Index	Buildability Score
A	Structural System:				
A-1	RC slab cast on site with slab area divided by the number of beams larger than 10 $A_{\text{Roof Slab Area}} = 10 \times 754.0 = 7,540 \text{ m}^2$	7,540.00	91	$S_s=0.65$	29.60
	RC roof slab	754.00	9	$S_s=0.65$	2.90
A-2	Total	8294	100		32.50
B	Wall System				
B-1	Windows & doors area	1675.00	25	$S_w=1.00$	10.00
B-2	Brick wall with plaster & paint finish	5025.00	75	$S_w=0.40$	12.00
	Total	6700.00	100		16.5
C	Other Buildable Feature				
C-1	Standardization of columns 3S@ 90%		90		N= 2.00
C-2	Standardization of beams 3S @ 85%		85		N= 1.50
C-3	Standardization of door leaf openings (width). 3S at 95%		95		N=1.00
C-4	Standardization of windows 3S @ 95%		95		N=1.00
C-5	Repeating horizontal grids (one meter) 75% of the time (three most popular dimensions)		75		N=1.50
C-6	Repeating the height difference between floors (0.5M) 90%		90		N= 2.00
C-7	Structural floor plan duplication in the vertical 82%		82		N=1.50
C-8	Using ground beams atop pile caps @85%		85		N=1.0
	Total				11.5
Buildability Sore in the project = $50[\sum (A_s \times S_s)] + 40[\sum (A_w \times S_w)] + N$					60.5

Appendix2

Option 2: A flat plate with interior precision block partitions and exterior brick walls with cast in-situ columns

Sr	Description	Area (m ²)	Coverage %	Labour Saving Index	Buildability Score
A A-1	Structure: Apartment's flat plate area is 7,341.4 m ² (Assume Roof area equal to typical floor $A_{SA} = 11 \times 667.4$).	7,341.40	89	$S_s=0.85$	37.8
A-2	Beam/Area for RC slab for lift lobby +Roof area $A_{SA} = 11 \times 86.6 = 952.6\text{m}^2$, Slab area/no. of beams less than 10	952.60	11	$S_s=0.50$	2.75
	Total A_{ST}	8294.00	100		40.55
B B-1	Wall System Windows & doors area	1675.00	25	$S_w= 1.00$	10.00
B-2	Brick wall with plaster & paint	3015.00	45	$S_w= 0.40$	7.20
B-3	Apply a paint finish and a skim coat to the precision blocks.	2010.00	30	$S_w= 0.60$	7.20
	Total	6700.00	100		24.40
C-1	Other Buildable Feature Column 3S standardization at 90%		90		N = 2
C-2	Standardization of beams 3S at 85%		85		N = 1.50
C-3	Standardization of door leaf openings (width).3S @95%		95		N = 1.0
C-4	Standardization of Windows 3Sat 95%		95		N = 1.0
C-5	Repeat of horizontal grids(1m)75% (3 most common dimensions)		75		N = 1.50
C-6	Repeat of floor-to-floor height (0.5 m) 90%		90		N = 2.0
C-7	The structural floor layout's vertical repeat is 82%.		82		N = 1.50
C-8	Welded mesh for floor casting at site 89%		89		N = 1.50
C-9	GB on top of pile caps		85		N = 1.0
Buildability Sore in the project = $50[\sum (A_s \times S_s)] + 40[\sum (A_w \times S_w)] + N$					77.95

Appendix3

Option 3: Precast exterior walls, interior precision block partitions and a flat plate with cast in-situ columns.

Sr	Description	Area (m ²)	Coverage %	Labour Saving Index	Buildability Score
A	Structure:				
A-1	Flat plate for apartment area+ roof Assume roof area equal to typical floor $A_{SA} = 11 \times 667.4 = 7,341.4\text{m}^2$	7341.4	89	$S_S = 0.89$	37.8
A-2	Beam/Slab for lift lobby area +Roof $A_{SA} = 11 \times 86.6 = 952.6\text{m}^2$, Value of slab area over number of beams less than 10 Note: - Roof design as in 1 & 2	952.60	11	$S_S = 0.5$	2.75
	Total A_{ST}	8294	100		40.55
B	Wall System				
B-1	Windows & doors area	1675	25	$S_W = 1.00$	10
B-2	Precast concrete panel with paint finish	2010	30	$S_W = 0.85$	10.2
B-3	Brick wall with plaster & paint finish	1005	15	$S_W = 0.40$	2.40
B-4	Skim coat and paint finish on precisely sized blocks	2010	30	$S_W = 0.60$	7.2
	Total	6700	100		29.80
C	Other Buildable Feature				
C-1	Standardization of columns 3S @90%		90		N = 2.00
C-2	Standardization of beams 3S @85%		85		N = 1.50
C-3	Standardization of door leaf openings (width). 3S @95%		95		N = 1.00
C-4	Standardization of windows 3S@95%		95		N = 1.00
C-5	Repetition of horizontal grids(1m)75% 3 most common dimensions		75		N = 1.50
C-6	Repetition of floor-to-floor height (0.5m) @90%		90		N = 2.00
C-7	1 repetition vertically of structural floor layout @82%		82		N = 1.50
C-8	Welded mesh for casting slab @89%		89		N = 1.50
C-9	Ground beams on top of pilecaps @85%		85		N = 1.00
	Total				13
Buildability Sore in the project = $50[\sum (A_s \times S_s)] + 40[\sum (A_w \times S_W)] + N$					83.35

Appendix4

Option 4: A RC construction with cast-in-situ columns, precast beams, and precast slabs with precision block partitions inside and external brick walls.

Sr	Description		Area (m ²)	Coverage %	Labour Saving Index	Buildability Score
A	Structural System:					
A-1	Pre cast concrete beam and Pres cast concrete slab		7540	91	$S_S = 0.9$	40.95
A-2	RC flat slab for roof (Value of slab area /number of beams) > 10		754	9	$S_S = 0.65$	2.75
	Total Ast		8294	100		43.70
B	Wall System					
B-1	Windows & doors area		1675	25	$S_W = 1.00$	10.00
B-3	Brick wall with plaster & paint finish		3015	45	$S_W = 0.40$	7.20
B-4	Precision blocks with skim coat and paint finish		2010	30	$S_W = 0.60$	7.20
	Total		6700	100		24.400
C	Other Buildable Feature					
C-1	Standardization of columns 3S at 90%			90		N = 2.00
C-2	Standardization of beams 3S @			85		N = 1.50
C-3	Standardization of door leaf openings (width). 3S @100%			100		N = 1.00
C-4	Standardization of windows 3Sat @95%			95		N = 1.00
C-5	Repetition of horizontal grids(1m)75% 3 most common dimensions			75		N = 1.50
C-6	Repetition of floor-to-floor height (0.5m) @90%			90		N = 2.00
C-7	Vertical repetition of structural floor layout @82%			82		N = 1.50
C-8	Standard precast staircase@90%			90		N = 2.00
C-9	Ground beams on top of pilecaps @85%			85		N = 1.00
	Total					13.50
Buildability Sore in the project = $50[\sum (A_s \times S_s)] + 40[\sum (A_w \times S_W)] + N$						81.60