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RESEARCH ARTICLE

Development of an Efficient Spatial Configuration Matrix for Modular Component Factories in Nigeria

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Abstract

The growing adoption of modular construction has increased the need for efficient factory layouts that enhance manufacturing productivity, workflow continuity, and operational flexibility. However, there is currently no standardized framework for evaluating the spatial performance of modular component factories in Nigeria. This study developed an Efficient Spatial Configuration Matrix (ESCM) to support the planning, evaluation, and optimization of modular manufacturing facilities. A qualitative multiple-case study design was adopted, involving ten modular component factories purposively selected from major industrial centres across Nigeria. Data was collected through field observations, architectural layout assessments, workflow mapping, factory documentation, and photographic records. A Spatial Configuration Performance Index (SCPI) comprising ten spatial indicators was developed to transform qualitative observations into standardized performance scores. The findings revealed that Mechanical, Electrical, and Plumbing (MEP) integration recorded the highest performance (100%), followed by safety (86.7%), while functional zoning, workflow continuity, and material handling each achieved 80.0%. In contrast, environmental responsiveness (66.7%), flexibility (63.3%), vertical space utilization (60.0%), and future expandability (60.0%) demonstrated comparatively lower performance, indicating opportunities for improving long-term adaptability and sustainable factory design. These findings informed the development of the ESCM, an evidence-based decision-support framework integrating architectural spatial planning principles with manufacturing performance indicators. The framework provides measurable criteria for evaluating existing facilities and guiding the design of future modular component factories. This study contributes to industrial architecture and modular construction literature by bridging the gap between spatial planning and manufacturing performance and offers a practical tool for architects, industrial planners, manufacturers, and policymakers seeking to improve modular factory design in Nigeria and similar emerging economies.

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1. INTRODUCTION

The global construction industry is undergoing a profound transformation from labour-intensive, site-based production towards industrialized and factory-based manufacturing systems. Among the emerging approaches, modular construction has gained considerable attention because it enables substantial improvements in productivity, quality assurance, construction speed, occupational safety, and environmental sustainability through the off-site manufacture of standardized building components (Innella *et al*., 2019; Yang & Lu, 2023). Unlike conventional construction methods, modular construction relocates a significant proportion of fabrication and assembly activities from construction sites to controlled factory environments, thereby minimizing weather-related disruptions, reducing material waste, improving quality control, and shortening project delivery periods (Pan *et al*., 2012; Bataglin *et al*., 2025).

The success of modular construction, however, depends not only on manufacturing technologies but also on the efficiency of the production environment in which modular components are fabricated. Modular component factories are complex industrial facilities comprising interconnected production zones for raw material reception, fabrication, assembly, quality control, storage, logistics, administration, and dispatch. Within such environments, spatial organization directly influences production efficiency by determining material flow, worker movement, equipment accessibility, operational flexibility, safety, and future expandability (Hillier, 1996; Koren & Shpitalni, 2010). Consequently, factory layout has become a critical determinant of manufacturing performance and an essential consideration in industrial facility planning.

Research in industrial engineering has consistently demonstrated that well-designed factory layouts reduce transportation distances, eliminate workflow interruptions, minimize production bottlenecks, improve labour productivity, and optimize resource utilization (Yang & Lu, 2023). Contemporary approaches to facility planning increasingly integrate Lean Manufacturing principles, Building Information Modelling (BIM), Design for Manufacture and Assembly (DfMA), simulation modelling, and digital manufacturing technologies to enhance production performance and support informed decision-making (Singh, 2025; Laovisutthichai & Lu, 2026). These approaches collectively emphasize the need for production environments that support continuous workflow, efficient circulation systems, adaptable manufacturing spaces, and integrated service infrastructure.

Despite these advances, most existing studies have approached factory planning primarily from manufacturing engineering and operations management perspectives, focusing on production scheduling, automation, equipment optimization, and material handling systems. Comparatively limited attention has been devoted to the architectural dimensions of factory planning, particularly the influence of spatial configuration on manufacturing performance. Issues such as functional zoning, spatial connectivity, circulation hierarchy, environmental responsiveness, flexibility of internal layouts, and integration of building services remain insufficiently explored despite their direct implications for operational efficiency (Hillier & Hanson, 1984; Hillier & Iida, 2005). This imbalance has resulted in the absence of comprehensive architectural frameworks capable of guiding the planning and evaluation of modular manufacturing facilities.

The challenge is particularly evident in developing economies such as Nigeria, where modular construction is increasingly recognized as a viable strategy for addressing the country's growing housing deficit, accelerating infrastructure delivery, and improving construction productivity. However, the adoption of modular construction remains relatively limited owing to several institutional, technological, financial, and organizational constraints, including inadequate industrial infrastructure, low awareness, insufficient technical expertise, and limited implementation of digital construction technologies (Awodele *et al*., 2023; Saka *et al*., 2024). Existing modular manufacturing facilities have largely evolved independently to satisfy individual operational requirements, resulting in substantial variations in factory layouts, production sequencing, storage systems, circulation networks, and service integration. Consequently, there is currently no standardized framework for evaluating or guiding the spatial planning of modular component factories within the Nigerian context.

Although several studies have investigated modular construction adoption, sustainability performance, facility layout optimization, and BIM implementation, no study has comprehensively integrated architectural spatial planning principles with manufacturing performance indicators to develop a structured decision-support framework specifically for modular component factories in Nigeria. Existing evaluation approaches also lack measurable spatial performance indicators capable of objectively assessing the efficiency of industrial layouts and informing future factory design. This represents a significant knowledge gap in industrial architecture and modular manufacturing research.

To address this gap, this study develops an Efficient Spatial Configuration Matrix (ESCM) based on empirical evidence obtained from comparative assessments of ten modular component factories distributed across major industrial centres in Nigeria. The study synthesizes principles from industrial architecture, facility layout planning, Lean Manufacturing, Space Syntax Theory, and Reconfigurable Manufacturing Systems to establish a comprehensive framework for evaluating spatial performance. A Spatial Configuration Performance Index (SCPI) is first developed to assess critical dimensions of factory performance, including functional zoning, workflow continuity, material handling efficiency, circulation systems, flexibility, environmental responsiveness, building services integration, safety, vertical space utilization, and future expandability. These indicators are subsequently integrated into the proposed ESCM, which serves as a practical decision-support tool for architects, factory planners, industrial developers, and policymakers involved in the planning, evaluation, and expansion of modular manufacturing facilities.

The principal contribution of this study, therefore, extends beyond conventional facility layout assessment by introducing a context-specific architectural framework that quantitatively links spatial configuration with manufacturing performance. By providing standardized evaluation criteria and evidence-based design recommendations, the proposed ESCM contributes to improved industrial facility planning, supports the wider adoption of modular construction in Nigeria, and offers a transferable framework that may be adapted to other emerging modular manufacturing contexts.

The objective of this study is to develop and validate an Efficient Spatial Configuration Matrix (ESCM) for modular component factories in Nigeria by integrating architectural spatial planning principles with manufacturing performance indicators derived from comparative multiple-case analysis.

2. LITERATURE REVIEW

2.1 Modular Construction and Factory-Based Manufacturing

Modular construction is an industrialized building approach in which building components or volumetric modules are manufactured under controlled factory conditions before transportation to the construction site for installation. By transferring a substantial proportion of construction activities from site-based operations to factory production, modular construction enhances productivity, quality control, occupational safety, schedule certainty, and environmental sustainability (Pan *et al*., 2012; Bataglin *et al*., 2025). Compared with conventional construction, factory-based production enables standardized manufacturing processes, improved precision, reduced material waste, and greater opportunities for automation and digital integration.

The rapid global adoption of modular construction has been driven by increasing demand for affordable housing, labour shortages, sustainability targets, and advances in manufacturing technologies. Recent developments have incorporated Lean Manufacturing principles, robotics, Building Information Modelling (BIM), Digital Twins, and Design for Manufacture and Assembly (DfMA) to improve production efficiency and product quality (Innella *et al*., 2019; Laovisutthichai & Lu, 2026). These innovations have transformed modular factories from simple fabrication workshops into sophisticated manufacturing environments requiring carefully planned spatial organization to support continuous production.

Despite these advances, the performance of modular manufacturing systems depends not only on production technologies but also on the physical arrangement of manufacturing spaces. Inefficient spatial layouts increase travel distances, interrupt production flow, create congestion, reduce operational flexibility, and increase production costs, whereas well-designed factory layouts facilitate smooth material movement, efficient supervision, safer working environments, and higher production throughput (Yang & Lu, 2023).

2.2 Spatial Configuration in Industrial Architecture

Spatial configuration refers to the organization, connectivity, accessibility, and functional relationships among spaces within the built environment (Hillier, 1996). Within industrial architecture, spatial configuration determines how production spaces interact to support manufacturing activities, logistics, maintenance, and personnel movement. Effective spatial planning therefore extends beyond the placement of machinery to encompass functional zoning, circulation systems, storage organization, service integration, safety provisions, and future expansion capacity.

Space Syntax Theory provides one of the most influential theoretical perspectives for understanding the relationship between spatial organization and human movement. The theory proposes that the configuration of spaces influences accessibility, visibility, movement patterns, and interaction among users (Hillier & Hanson, 1984; Hillier & Iida, 2005). Although originally developed for architectural and urban analysis, its principles have increasingly been applied to industrial facilities to explain how spatial layouts affect workflow continuity, operational coordination, supervision, and manufacturing efficiency.

In modular manufacturing environments, spatial configuration must simultaneously accommodate raw material reception, fabrication, assembly, quality inspection, storage, packaging, dispatch, administrative functions, and utility services. The effectiveness of these interdependent activities depends on maintaining logical spatial relationships that minimize unnecessary movement while ensuring operational flexibility and safety. Consequently, factory planning has become an important component of industrial architecture rather than merely engineering exercise.

2.3 Facility Layout Planning and Manufacturing Efficiency

Facility Layout Planning (FLP) seeks to determine the optimal arrangement of production facilities, workstations, machinery, storage areas, and circulation routes to maximize operational performance. The primary objectives include minimizing material handling costs, reducing travel distances, eliminating workflow interruptions, improving worker safety, and enhancing production flexibility (Yang & Lu, 2023).

Several layout strategies have been adopted in manufacturing systems, including product layouts, process layouts, cellular layouts, and fixed-position layouts. Product layouts are generally preferred where standardized, repetitive production requires continuous workflow and high throughput, while cellular layouts provide greater flexibility for manufacturing diverse products and responding to changing production requirements (Koren *et al*., 1999; Koren & Shpitalni, 2010). Recent simulation studies indicate that hybrid arrangements combining the efficiency of linear production with the flexibility of cellular manufacturing are particularly suitable for modular construction because they support standardized production while accommodating product variability (Yang & Lu, 2023). This perspective helps reconcile the apparent distinction between cellular manufacturing and linear production flow that has been identified in previous studies and aligns with contemporary modular manufacturing practices.

Lean Manufacturing further reinforces the importance of efficient spatial planning by emphasizing the elimination of non-value-adding activities such as unnecessary transportation, waiting time, excessive movement, and inventory accumulation (Innella *et al*., 2019; Singh, 2025). Factory layouts that support uninterrupted workflow and efficient material handling contribute directly to improved productivity, reduce operational costs, and enhanced manufacturing performance.

2.4 Modular Manufacturing in Nigeria and Research Gap

The Nigerian construction industry continues to face increasing pressure to deliver affordable housing and infrastructure efficiently. Modular construction has been identified as a promising strategy for improving construction productivity and reducing project delivery time; however, its adoption remains relatively slow due to limited industrial infrastructure, inadequate technical expertise, insufficient policy support, and low levels of digital technology implementation (Awodele *et al*., 2023; Saka *et al*., 2024).

Existing Nigerian studies have predominantly focused on the adoption of modular construction, sustainability performance, barriers to implementation, and BIM utilization. Comparatively little attention has been devoted to the architectural planning of modular manufacturing facilities or to the influence of spatial configuration on factory performance. Furthermore, no standardized framework currently exists for evaluating the spatial efficiency of modular component factories within the Nigerian context. The absence of objective spatial performance indicators limits the ability of architects, industrial planners, and policymakers to assess existing facilities and guide the planning of future modular manufacturing plants.

This study addresses these shortcomings by developing an Efficient Spatial Configuration Matrix (ESCM) grounded in empirical evidence obtained from a comparative analysis of ten modular component factories across Nigeria. Unlike previous studies, which largely examine production engineering or technology adoption, the proposed framework integrates architectural spatial planning principles with measurable manufacturing performance indicators to provide a practical decision-support tool for industrial facility planning.

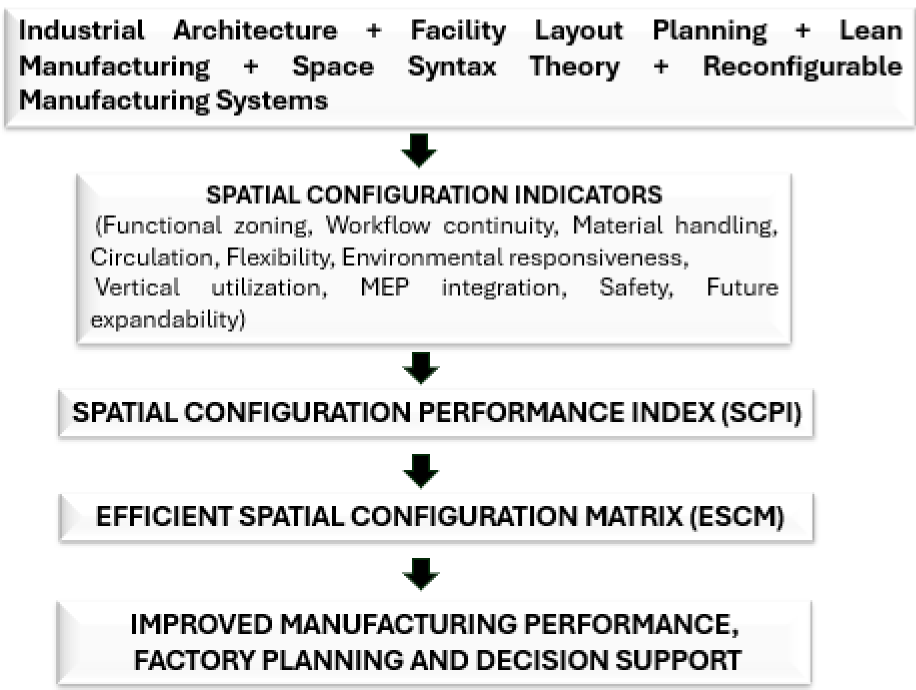

Figure 1. Conceptual framework for developing the Efficient Spatial Configuration Matrix (ESCM).

3. MATERIALS AND METHODS

3.1 Research Design

This study adopted a qualitative multiple-case study design to investigate the spatial configuration characteristics of modular component factories in Nigeria and to develop an Efficient Spatial Configuration Matrix (ESCM). A multiple-case approach was considered appropriate because it enables systematic comparison across different industrial facilities while preserving the operational characteristics of individual factories. Compared with single-case investigations, multiple-case studies provide stronger analytical generalization by identifying recurring spatial patterns and validating observations across diverse production environments (Yin, 2018).

The research was exploratory and evaluative in nature. Rather than assessing production output alone, the study examined how architectural spatial planning influences manufacturing efficiency through the organization and interaction of production spaces. Consequently, the investigation integrated principles from industrial architecture, facility layout planning, Lean Manufacturing, Space Syntax Theory, and Reconfigurable Manufacturing Systems to establish a comprehensive framework for evaluating spatial performance.

3.2 Selection of Case Studies

Ten modular component manufacturing facilities distributed across Nigeria were purposively selected for the investigation (Table 1). Purposive sampling was adopted because only a limited number of operational factories undertake modular or prefabricated building production within the country. The selected facilities represent different categories of modular manufacturing, including volumetric modular construction, precast concrete production, prefabricated building systems, steel fabrication, panelized construction, and industrialized building components.

To improve representativeness and mitigate location-specific bias, factories were selected from major industrial centers across six geopolitical regions. The selection was guided by specific criteria requiring that the facilities had active modular or prefabrication manufacturing operations, established production plants with identifiable functional zones, and physical accessibility for field observation and documentation. Additionally, selected factories had to exhibit variation in their production systems and layouts, alongside an institutional willingness to participate in the study. Ultimately, this broad geographical distribution enabled a comprehensive comparison of diverse spatial planning approaches.

Table 1. Selected Modular Component Factories Used as Case Studies

S/N	Case Study	Location	Role in Study
1	Modular Tekniqs Factory	Lagos	Primary Case
2	Karmod Nigeria Facility	Abuja	Primary Case
3	Zeberced Group Precast	Abuja	Primary Case
4	Liquidfire Nigeria Modular	Lagos	Primary Case
5	Metal Berg Manufacturing Company Factory	Lagos	Primary Case
6	Local Precast Concrete Plants	Lagos	Primary Case
7	Prefab & Modular Contractor Sites	Ibadan	Primary Case
8	Construction Prefab Workshops	Port Harcourt	Primary Case
9	Pre-Engineered Building Production Facilities	Kaduna	Primary Case
10	Industrial Zones with Concrete Block & Panel Plants	Enugu	Primary Case

3.3 Data Collection

Data was collected between January and April 2026 using multiple sources of evidence to enhance research credibility through methodological triangulation. Primary data were gathered through direct field observations of factory operations, walkthrough assessments of production environments, and detailed architectural layout and photographic documentation. This was further enriched by systematic workflow mapping and informal discussions with facility managers and production supervisors.

Secondary data included architectural drawings, factory reports, production manuals, technical documents, published journal articles, industrial reports, and relevant policy documents.

Using multiple sources of evidence enabled cross-validation of observations and strengthened the reliability of the findings by reducing dependence on a single data source.

Table 2. Sources of Data and Purpose

Data Source	Purpose
Field observations	Assessment of operational spatial arrangement
Architectural drawings	Spatial analysis and zoning evaluation
Photographs	Visual verification
Factory documents	Production workflow information
Literature	Development of an evaluation framework
Industrial reports	Contextual validation

3.4 Development of the Spatial Configuration Evaluation Framework

A structured evaluation framework was developed through synthesis of previous studies on industrial architecture, facility layout planning, modular construction, Lean Manufacturing, and Space Syntax Theory. Ten spatial configuration indicators consistently identified in the literature as determinants of manufacturing efficiency were adopted for assessment.

The evaluated indicators comprised functional zoning, workflow continuity, material handling efficiency, and circulation efficiency. Additionally, the assessment incorporated spatial performance factors, including flexibility, vertical space utilization, environmental responsiveness, and mechanical, electrical, and plumbing (MEP) integration, alongside critical structural metrics like safety and future expandability. These indicators collectively represent the principal architectural characteristics influencing operational efficiency within modular manufacturing facilities.

Table 3. Spatial Configuration Indicators and Assessment Criteria

Indicator	Description	Assessment Focus
Functional zoning	Logical separation of production spaces	Operational organization
Workflow continuity	Sequential production movement	Production efficiency
Material handling	Ease of material movement	Logistics
Circulation	Worker and vehicle movement	Accessibility
Flexibility	Ease of layout modification	Adaptability
Vertical space utilization	Efficient use of building height	Capacity
Environmental responsiveness	Daylighting, ventilation and thermal performance	Sustainability
MEP integration	Coordination of building services	Operational support
Safety	Worker protection and circulation safety	Risk reduction
Future expandability	Provision for future growth	Long-term adaptability

3.5 Spatial Configuration Performance Index (SCPI)

To enable objective comparison among factories, a Spatial Configuration Performance Index (SCPI) was developed. The SCPI converts qualitative field observations into quantitative performance scores using a weighted multi-criteria assessment approach.

Each indicator was evaluated using a five-point ordinal scale:

Score	Interpretation
1	Very Poor
2	Poor
3	Fair
4	Good
5	Excellent

For each factory, indicator scores were assigned based on predefined assessment criteria developed from the literature and verified during field observations. Scores from all assessed factories were subsequently aggregated and converted into percentage performance values using Equation (1):

$$SCPI_i = \frac{\sum S_i}{5N} \times 100$$

where:

- $SCPI_i$= performance score for indicator *i*;
- S_i= observed score assigned to each factory;
- N= number of factories assessed (10).

This standardization permits direct comparison among indicators irrespective of their absolute scores.

3.6 Indicator Weighting

Recognizing that spatial characteristics contribute differently to manufacturing performance, weighted importance values were assigned to each indicator through literature synthesis supported by expert consultation involving architects, industrial planners, production engineers, and modular construction specialists.

Higher weights were assigned to indicators consistently identified as having the greatest influence on production efficiency, workflow optimization, and operational performance. The final weighting scheme totaled 100%.

Table 4. Indicator Weights Used in the SCPI

Indicator	Weight (%)
Functional zoning	15
Workflow continuity	12
Material handling	11
Circulation efficiency	10
Flexibility	10
Environmental responsiveness	9
Safety	9
Vertical space utilization	8
MEP integration	8
Future expandability	8

Unlike purely engineering-based facility assessment methods, these weights reflect the combined influence of architectural functionality and manufacturing performance.

3.7 Reliability and Validation

To improve methodological rigor, the evaluation framework was subjected to expert validation before implementation. Five professionals with expertise in industrial architecture, modular construction, manufacturing engineering, and factory planning independently reviewed the evaluation indicators, scoring criteria, and weighting structure.

Their recommendations resulted in the refinement of several assessment descriptors and confirmation that the selected indicators adequately represented critical dimensions of spatial performance. To minimize observer bias, all case studies were evaluated using identical assessment procedures, standardized field observation checklists, and consistent scoring criteria. Multiple sources of evidence, including field observations, architectural drawings, and photographic records, were triangulated during the assessment process.

3.8 Data Analysis

Qualitative observations were first organized according to the ten spatial indicators and subsequently transformed into quantitative performance scores using the SCPI methodology. Descriptive statistics, percentage analysis, and cross-case comparison were then employed to evaluate similarities and differences among the case studies.

The validated performance indicators were finally synthesized into the proposed Efficient Spatial Configuration Matrix (ESCM), which serves as a practical decision-support framework for evaluating existing modular factories and guiding the planning of future manufacturing facilities.

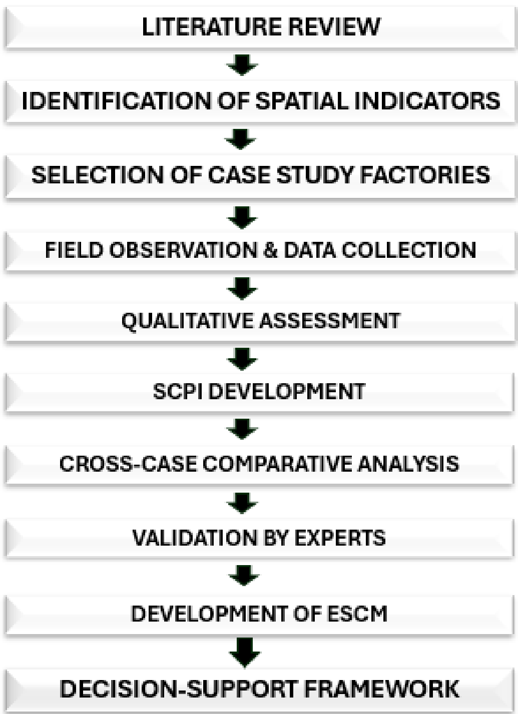

Figure 2. Research methodology adopted in developing the Efficient Spatial Configuration Matrix (ESCM).

4. RESULTS AND DISCUSSION

4.1 Spatial Configuration Performance of Modular Component Factories

The comparative assessment of the ten modular component factories revealed considerable variation in the implementation of architectural spatial planning principles across the selected case studies. Although all factories were designed to support modular manufacturing, differences were observed in functional zoning, production workflow, circulation systems, material handling arrangements, environmental responsiveness, flexibility, and provisions for future expansion. These variations demonstrate that factory performance is influenced not only by manufacturing technology but also by the quality of spatial organization.

To facilitate objective comparison, the Spatial Configuration Performance Index (SCPI) developed in this study was applied to each of the ten spatial indicators. The SCPI transformed qualitative observations into standardized percentage scores, enabling systematic evaluation of the relative performance of each spatial characteristic across all factories.

Table 5. Overall Spatial Configuration Performance of the Assessed Factories

Spatial Indicator	Performance (%)	Rating
MEP Integration	100.0	Excellent
Safety	86.7	Excellent
Functional Zoning	80.0	Very Good
Workflow Continuity	80.0	Very Good
Material Handling	80.0	Very Good
Circulation Efficiency	73.3	Good
Environmental Responsiveness	66.7	Moderate
Flexibility	63.3	Moderate
Vertical Space Utilization	60.0	Moderate
Future Expandability	60.0	Moderate

Source: Author's field survey (2026).

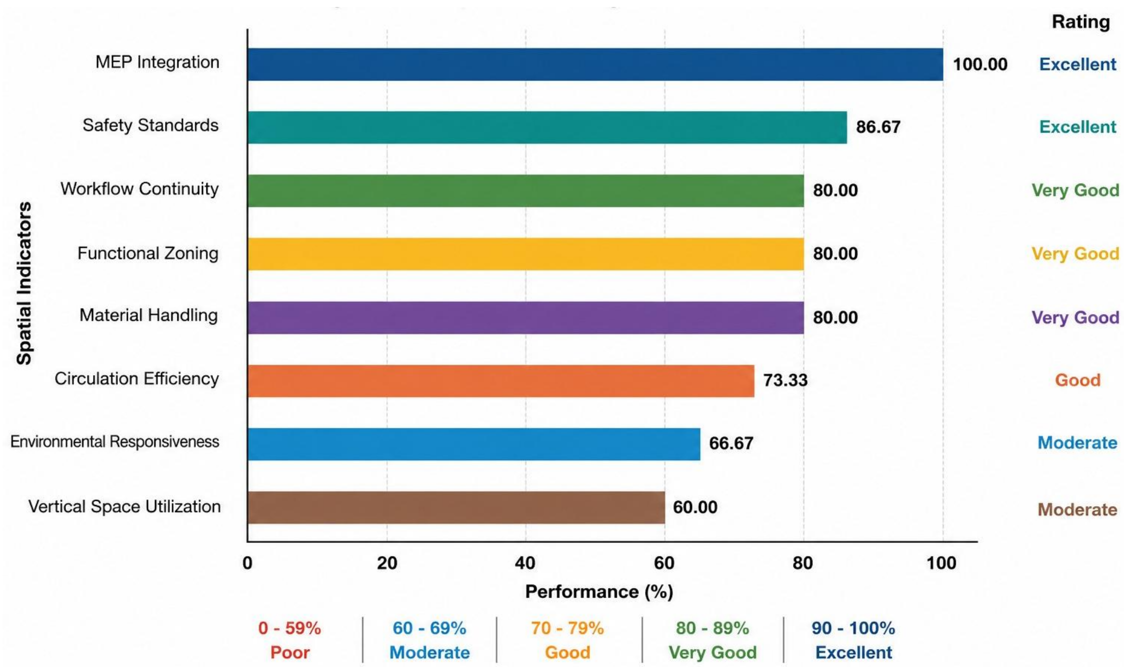

Figure 3. Overall Spatial Configuration Performance of Modular Component Factories

Author's Field Survey (2026)

The findings indicate that MEP integration achieved the highest performance score (100%), demonstrating that all assessed factories had adequately coordinated mechanical, electrical, and plumbing systems to support manufacturing operations. Effective service integration minimizes operational disruptions, facilitates equipment maintenance, and enhances production continuity. Similar observations have been reported in digitally integrated manufacturing environments, where coordinated service infrastructure contributes significantly to production efficiency and operational reliability (Laovisutthichai & Lu, 2026).

Safety also recorded a high-performance score (86.7%), suggesting that most factories incorporated basic occupational health and safety measures such as designated circulation routes, emergency exits, fire protection systems, and controlled operational zones. This finding reflects increasing industry awareness of workplace safety as a critical component of sustainable industrial development and aligns with Lean Manufacturing principles that advocate safe and organized production environments (Singh, 2025).

Functional zoning, workflow continuity, and material handling each recorded performance levels of 80%, indicating that most factories maintained logical sequencing of production activities. In these facilities, raw material receiving areas were appropriately connected to fabrication zones, assembly stations, quality inspection areas, storage facilities, and dispatch points, thereby reducing unnecessary transportation and production delays. Similar relationships between efficient spatial organization and manufacturing productivity have been reported in modular factory layout studies, which emphasize the importance of uninterrupted production flow and minimized material handling distances (Yang & Lu, 2023).

By contrast, environmental responsiveness (66.7%), flexibility (63.3%), vertical space utilization (60.0%), and future expandability (60.0%) exhibited comparatively lower performance. Many factories relied predominantly on horizontal expansion, with limited provision for mezzanine floors, overhead storage systems, or adaptable production spaces. Furthermore, passive environmental strategies such as natural ventilation, daylight optimization, and thermal performance considerations were inconsistently incorporated into factory designs.

The relatively low flexibility scores further indicate that several facilities would have trouble accommodating changes in production volume, manufacturing processes, or product types without extensive structural modification. According to Reconfigurable Manufacturing Systems Theory, adaptability is essential for maintaining long-term competitiveness in dynamic manufacturing environments (Koren *et al*., 1999). The limited provision for future expansion similarly suggests that factory planning has generally focused on immediate operational requirements rather than long-term industrial growth.

These findings demonstrate that while Nigerian modular component factories have made notable progress in production organization and operational safety, considerable opportunities remain for improving architectural spatial planning. Specifically, greater attention should be devoted to flexible production layouts, efficient utilization of vertical space, environmentally responsive factory design, and strategic planning for future expansion. These improvements would not only enhance manufacturing efficiency but also increase the resilience and adaptability of modular production systems.

The results further demonstrate the usefulness of the proposed SCPI as an objective evaluation tool capable of identifying strengths and deficiencies within industrial facilities. Unlike conventional facility assessments that emphasize production capacity or equipment performance, the SCPI integrates architectural and operational considerations into a single performance framework. Consequently, it provides a robust evidence base for the development of the Efficient Spatial Configuration Matrix (ESCM), which is presented in the subsequent section as a practical decision-support tool for factory planning and evaluation.

The findings make three important contributions to knowledge. First, they confirm that architectural spatial configuration significantly influences manufacturing performance in modular construction facilities, complementing earlier studies that primarily focused on production engineering. Second, the inclusion of flexibility and future expandability as measurable performance dimensions broadens existing facility evaluation frameworks by recognizing the importance of long-term adaptability in industrial architecture. Third, the proposed SCPI provides a reproducible and standardized approach for assessing factory layouts, thereby laying the empirical foundation for the development of the ESCM.

4.2 Development of the Efficient Spatial Configuration Matrix (ESCM)

The principal contribution of this study is the development of the Efficient Spatial Configuration Matrix (ESCM), a structured decision-support framework that integrates architectural spatial planning principles with manufacturing performance indicators for modular component factories. Unlike conventional facility layout evaluation methods that primarily assess production efficiency or equipment utilization, the ESCM provides a comprehensive framework for evaluating the spatial quality of industrial facilities by combining functional, operational, environmental, and adaptability considerations into a single assessment model.

The ESCM was developed through the synthesis of three complementary sources of evidence. First, theoretical principles derived from industrial architecture, Space Syntax Theory, Lean Manufacturing, and Reconfigurable Manufacturing Systems established the conceptual basis for identifying critical spatial variables. Second, empirical observations from the ten Nigerian case studies provided practical evidence of the strengths and weaknesses associated with existing factory layouts. Third, the Spatial Configuration Performance Index (SCPI) quantified the relative importance and performance of each spatial indicator, thereby providing an objective basis for assigning priorities within the framework.

The resulting matrix therefore represents an evidence-based integration of theory and practice rather than a purely conceptual model. It translates observed spatial characteristics into measurable design criteria that can be applied during factory planning, facility evaluation, expansion projects, and post-occupancy assessments.

4.3 Efficient Spatial Configuration Matrix (ESCM)

Table 6. Proposed Efficient Spatial Configuration Matrix (ESCM)

Spatial Variable	Weight (%)	Performance Objective	Recommended Design Strategy	Expected Operational Benefit
Functional zoning	15	Logical separation of production activities	Sequential production zones arranged according to manufacturing sequence	Reduced operational conflicts and improved workflow
Workflow continuity	12	Continuous movement of products	Linear production flow with minimal backtracking	Increased productivity and shorter production cycles
Material handling	11	Efficient movement of materials	Dedicated loading, unloading and internal transport routes	Reduced handling time and transportation cost
Circulation efficiency	10	Safe movement of workers and vehicles	Separate pedestrian and vehicular circulation networks	Improved safety and reduced congestion
Flexibility	10	Adaptability to changing production needs	Modular production cells and reconfigurable workspaces	Improved responsiveness to changing demand
Environmental responsiveness	9	Sustainable production environment	Natural lighting, cross-ventilation and thermal control strategies	Lower energy consumption and improved worker comfort
Safety	9	Occupational health and risk reduction	Clearly designated emergency routes and safety zones	Enhanced operational safety
Vertical space utilization	8	Efficient use of building volume	Mezzanine floors, overhead cranes and vertical storage systems	Increased storage capacity without additional land requirements
MEP integration	8	Coordinated building services	Centralized service corridors with integrated maintenance access	Improved maintenance efficiency and operational reliability
Future expandability	8	Long-term adaptability	Reserved expansion zones and modular structural systems	Reduced future expansion costs

The matrix demonstrates that functional zoning, workflow continuity, and material handling collectively account for 38% of the overall assessment, highlighting their dominant influence on manufacturing efficiency. These indicators directly affect production sequencing, transportation distances, and operational coordination, making them the primary determinants of spatial performance within modular manufacturing environments.

Conversely, environmental responsiveness, vertical space utilization, and future expandability received comparatively lower weights because they generally influence long-term operational sustainability rather than immediate production performance. Nevertheless, their inclusion ensures that the framework evaluates factory performance holistically by considering both present operational requirements and future industrial resilience.

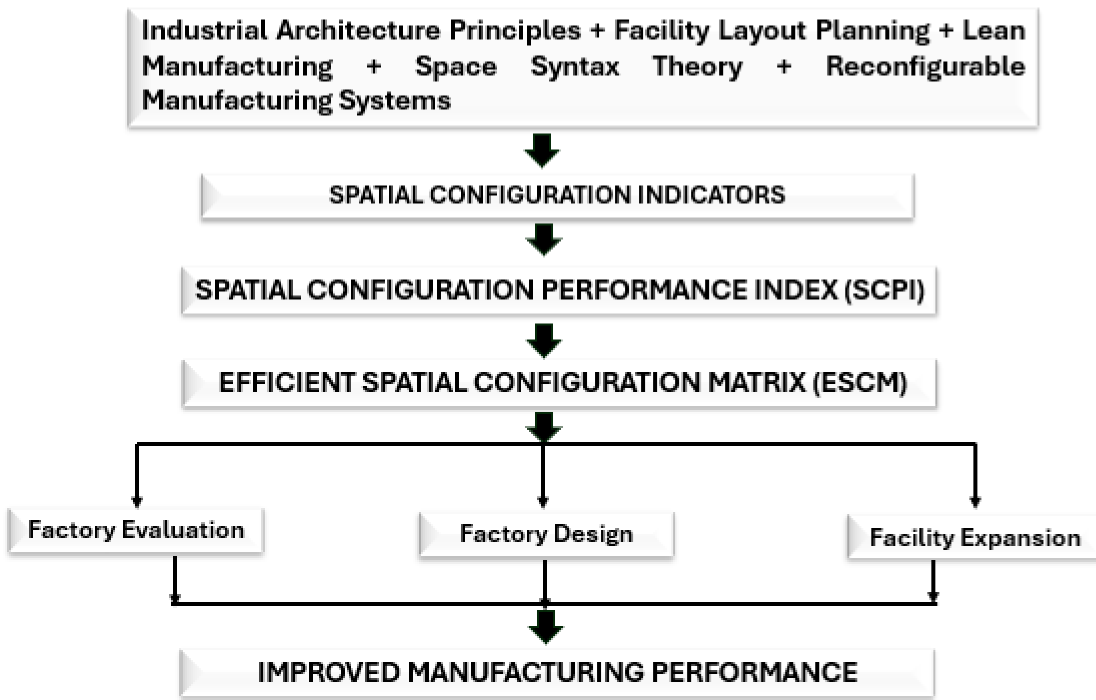

Figure 4. Efficient Spatial Configuration Matrix Framework

4.4 Comparison with Existing Factory Planning Frameworks

The proposed ESCM extends existing approaches to industrial facility planning in several important respects. Traditional facility layout planning techniques primarily focus on minimizing transportation costs, improving equipment arrangement, or optimizing workflow through simulation-based methods (Yang & Lu, 2023). Similarly, Lean Manufacturing emphasizes waste elimination by reducing unnecessary movement, waiting time, and inventory (Innella *et al*., 2019; Singh, 2025), while Reconfigurable Manufacturing Systems focus on flexibility and rapid adaptation to changing production requirements (Koren *et al*., 1999).

Although these approaches have significantly improved manufacturing efficiency, they generally evaluate production systems from engineering and operational perspectives. Architectural considerations such as functional zoning, spatial connectivity, circulation hierarchy, environmental quality, and building service integration receive comparatively less attention despite their substantial influence on production performance.

The ESCM addresses this limitation by explicitly integrating architectural design principles into factory performance assessment. Rather than replacing existing engineering approaches, it complements them by providing a structured framework through which architects, engineers, and industrial planners can jointly evaluate factory layouts during planning, construction, and post-occupancy stages.

Furthermore, unlike generic industrial layout guidelines, the ESCM has been developed from empirical evidence collected within Nigerian modular manufacturing facilities. Consequently, it reflects the operational realities of an emerging industrial economy while remaining sufficiently flexible for adaptation to similar contexts in other developing countries.

4.5 Practical Implications

The proposed ESCM has important implications for industrial practice, policy, and research.

For architects and factory designers, the framework provides measurable criteria for evaluating spatial organization during the design stage, thereby facilitating evidence-based planning decisions. For manufacturing organizations, the matrix offers a practical benchmarking tool for identifying operational deficiencies and prioritizing layout improvements. Policymakers and regulatory agencies may utilize the framework to support the development of national guidelines for modular manufacturing facilities, thereby promoting greater standardization across the construction industry.

ESCM also contributes to sustainable industrial development by encouraging factory layouts that improve workflow efficiency, reduce unnecessary material movement, enhance worker safety, optimize building services, and provide flexibility for future technological advancement. Such improvements are particularly relevant within developing economies where industrial infrastructure continues to evolve in response to increasing demand for modular construction.

Finally, the framework provides a methodological foundation for future research integrating BIM, Digital Twins, simulation modelling, and artificial intelligence into factory planning and spatial optimization. These digital technologies could further enhance the predictive capability of the ESCM by enabling virtual testing of alternative layout scenarios before physical implementation.

4.6 Study Limitations

Several limitations should be acknowledged when interpreting the findings. First, the study was based on ten modular component factories located within Nigeria. Although these facilities represent the country's major modular manufacturing operations, the findings may not fully capture spatial planning practices in other industrial sectors or geographical contexts. Second, the SCPI relied primarily on structured field observations and expert-informed assessments rather than continuous operational performance data such as production rates, equipment utilization, or manufacturing cycle times. Consequently, the framework emphasizes architectural and spatial performance rather than detailed production engineering metrics.

In addition, the weighting scheme used in the SCPI was derived through literature synthesis and expert consultation. While this approach provides a robust basis for comparative evaluation, alternative weighting methods, such as the Analytic Hierarchy Process (AHP), Delphi surveys, or multi-objective optimization techniques, may produce different priority rankings under varying industrial conditions.

5. CONCLUSION AND RECOMMENDATIONS FOR FUTURE RESEARCH

5.1 Conclusion

This study developed an Efficient Spatial Configuration Matrix (ESCM) to support the planning, evaluation, and optimization of modular component factories in Nigeria. Using a qualitative multiple-case study approach, ten modular manufacturing facilities were comparatively assessed through a Spatial Configuration Performance Index (SCPI) comprising ten spatial indicators representing functional, operational, environmental, and adaptability characteristics of factory layouts. The integration of these indicators provided a systematic basis for evaluating spatial performance and identifying design attributes that influence manufacturing efficiency.

The findings demonstrate that spatial configuration plays a fundamental role in the operational effectiveness of modular manufacturing facilities. Among the assessed indicators, MEP integration, safety, functional zoning, workflow continuity, and material handling exhibited the highest levels of performance, indicating that most factories have adopted appropriate production sequencing and basic operational infrastructure. Conversely, flexibility, environmental responsiveness, vertical space utilization, and future expandability showed comparatively lower performance, suggesting that existing factory layouts place greater emphasis on immediate production requirements than on long-term adaptability and sustainable industrial development.

A major contribution of this study is the development of the ESCM, which integrates architectural spatial planning principles with manufacturing performance indicators into a practical decision-support framework. Unlike conventional facility layout assessment methods that focus predominantly on engineering and production efficiency, ESCM incorporates broader architectural considerations, including functional zoning, circulation systems, environmental quality, building services integration, and future expansion capability. Consequently, the framework provides a more comprehensive basis for evaluating industrial facilities and guiding evidence-based factory planning.

The proposed SCPI further enhances the contribution of this research by providing a standardized and reproducible approach for assessing spatial performance. The index enables objective comparison among manufacturing facilities while identifying specific areas requiring design improvement. Collectively, the SCPI and ESCM establish an integrated methodology that bridges the gap between industrial architecture and manufacturing engineering, thereby extending current approaches to facility planning.

From a practical perspective, the findings have important implications for architects, industrial planners, manufacturing organizations, and policymakers. The ESCM can be applied during the planning of new modular factories, the evaluation of existing facilities, post-occupancy assessments, and industrial expansion projects. The framework also has the potential to inform national guidelines and design standards for modular manufacturing facilities, thereby supporting the broader adoption of industrialized construction systems in Nigeria and other emerging economies.

5.2 Recommendations for Future Research

Future investigations should validate the ESCM across a larger number of modular manufacturing facilities within and outside Nigeria to assess its wider applicability. Comparative studies involving different industrial sectors, including precast concrete production, steel fabrication, timber prefabrication, and volumetric modular construction, would further strengthen the framework's generalizability.

The integration of digital technologies also presents significant opportunities for extending this research. Building Information Modelling (BIM), Digital Twins, Geographic Information Systems (GIS), discrete-event simulation, and artificial intelligence-based optimization techniques could be incorporated to evaluate alternative factory layouts before physical implementation. Such approaches would improve predictive capability and support real-time decision-making in industrial facility planning.

Finally, future studies should investigate the relationship between spatial configuration and measurable operational outcomes such as production throughput, labour productivity, energy efficiency, logistics performance, maintenance costs, and worker satisfaction. Establishing these quantitative relationships would further validate the ESCM and strengthen its application as a comprehensive framework for industrial facility design and performance evaluation.

REFERENCES

Awodele, I. A., Mewomo, M. C., & Eze, E. C. (2023). Inhibitors to the adoption of Building Information Modelling in modular construction: A case study of the Nigerian construction industry. *Journal of Construction in Developing Countries, 28*(2), 19–36. https://doi.org/10.21315/jcdc-01-22-0004

Bataglin, F. S., Formoso, C. T. & Viana, D. D.. (2025). Model for Production System Design in Modular Construction Projects. In Seppänen, O., Koskela, L., & Murata , K. (Eds.), *Proceedings of the 33rd Annual Conference of the International Group for Lean Construction (IGLC 33)* (pp. 388–399). https://doi.org/10.24928/2025/0165

Hillier, B. (1996). *Space is the machine: A configurational theory of architecture*. Cambridge University Press.

Hillier, B., & Hanson, J. (1984). *The social logic of space*. Cambridge University Press.

Hillier, B., & Iida, S. (2005). Network and psychological effects in urban movement. In A. G. Cohn & D. M. Mark (Eds.), *Spatial information theory* (pp. 475–490). Springer.

Innella, F., Arashpour, M., & Bai, Y. (2019). Lean methodologies and techniques for modular construction: Chronological and critical review. *Journal of Construction Engineering and Management, 145*(12), 04019076. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001712

Koren, Y., Heisel, U., Jovane, F., Moriwaki, T., Pritschow, G., Ulsoy, G., & Van Brussel, H. (1999). Reconfigurable manufacturing systems. *CIRP Annals, 48*(2), 527–540. https://doi.org/10.1016/S0007-8506(07)63232-6

Koren, Y., & Shpitalni, M. (2010). Design of reconfigurable manufacturing systems. *Journal of Manufacturing Systems, 29*(4), 130–141.

Laovisutthichai, V., & Lu, W. (2026). Design for manufacture and assembly (DfMA) for modular buildings: An analytical framework. *Journal of Asian Architecture and Building Engineering, 25*(1), 247–261. https://doi.org/10.1080/13467581.2025.2455028

Pan, W., Gibb, A. G., & Dainty, A. R. (2012). Strategies for integrating the use of off-site production technologies in house building. *Journal of construction engineering and management*, *138*(11), 1331-1340. https://doi.org/10.1061/(asce)co.1943-7862.0000544

Saka, A. B., Chan, D. W. M., & Ajayi, S. O. (2024). Institutional isomorphism and adoption of Building Information Modelling (BIM) in small and medium-sized enterprises of the Nigerian construction industry. *Engineering, Construction and Architectural Management, 31*(1), 179–199. https://doi.org/10.1108/ECAM-02-2022-0188

Singh, J. (2025). Lean construction principles and practices. In *Handbook of Construction Project Management* (pp. 941-968). Singapore: Springer Nature Singapore. https://doi.org/10.1007/978-981-96-7631-6_30.

Yang, Z., & Lu, W. (2023). Facility layout design for modular construction manufacturing: A comparison based on simulation and optimization. *Automation in Construction, 147*, 104713. https://doi.org/10.1016/j.autcon.2022.104713

Yin, R. K. (2018). *Case study research and applications: Design and methods* (6th ed.). Sage Publications.