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MULTI-CRITERIA ASSESSMENT FOR FLEXIBILITY IN MODULAR TIMBER SCHOOL PROJECT BASED ON AHP-TOPSIS

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ABSTRACT: Sustainable development has been one important transition goal worldwide. The flexible design extends the frequency and lifespan of buildings by meeting the ever-changing needs of users to increase building sustainability. In this research, module coordination is selected to balance the modularity and flexibility of the modular timber school project. Functional flexibility is quantified by the AHP method based on a three-layer tree diagram assessment framework. The criteria and indicators are determined from the literature following the PRISMA systematic review process. According to the British Educational Building Design Code on area, the common module of school buildings is summarised by comparing the basic spatial dimensions of school buildings of different scales. Six modular grid sizes are selected as the scenarios for comparing the overall flexibility and flexibility in production, construction and service supported by the TOPSIS multi-criteria decision-making method. The ranking for the six sets of the modular grid for timber school classroom unit are summarized in different perspectives.

KEYWORDS: Flexibility, School project, Timber, Modular Construction, Quantification

1 INTRODUCTION

The UN document on sustainable development emphasizes the importance of building connections across economic, social, and environmental sustainability [1]. According to the report [2] and research studies [3], the construction industry consumes up to 35%-40% of the world's energy and generates 36% of greenhouse gas emissions [4], which can contribute to air pollution and material waste [5]. Decarbonization and achieving net-zero emissions have become new standards for the construction industry. The goals of sustainability and decarbonization are closely linked, both of which aim to reduce CO2 emissions for a sustainable future society and economic development.

To lower the impact of the construction industry on the environment, a variety of sustainable approaches have been proposed, e.g., industrial building system (IBS) andof industrialization and standardization in construction has proven to be an effective way of reducing time and waste [9]. Compared to traditional on-site construction methods, prefabrication and modular design/construction are more efficient in terms of time and materials [10,12].

To increase the sustainability of buildings and align with the UK's national strategies for Net Zero, Circular Economy, and Build Back Greener [13], one potential approach is to improve the flexibility of modular design to accommodate varying climates and conditions [14]. Architectural flexibility refers to a space's capacity to accommodate various customizations and layouts [15]. The degree of flexibility and adaptability in a building's design is crucial to meet its users' evolving social and environmental needs [16]. By repurposing existing structures, adaptive reuse can considerably minimize waste and help conserve the energy typically required for material manufacturing and construction [17].

The flexibility of the building can be achieved through design for adaptivity and modular construction [16,18].

The key challenge in designing a new construction project, particularly in the field of the school building, is to achieve flexibility at the design stage. This flexibility is essential in extending the lifespan of the building and meeting sustainability and Net Zero targets[19]. New design models and workflows must be developed to address the challenges posed by the new teaching, learning, and working patterns of a dynamic society in an ever-changing environment. In the post-pandemic era, it is crucial for new school buildings to be adaptable to their users' needs, with dynamic rather than static designs, taking into account the unique characteristics and requirements of the school community.

In the UK, the Department of Education (DfE) builds up to 200 new schools each year in order to fulfil the demand for student places and maintain its inventory. To optimize the learning and working environment, the DfE envisions better design methods, more efficient manufacturing

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processes, increased productivity, and zero carbon emissions, enabling faster construction while promoting sustainability [20]. In the UK, the demands for mass construction and rebuilding of schools prioritize sustainability and addressing climate change [21]. Correspondingly, timber has been gradually applied in different types and different scale of projects worldwide because of its sustainable properties and reliable structural behaviours [22,24].

In modular construction of timber school buildings, the relationship between modularity and flexibility is a critical consideration. The principles of flexibility in construction, specifically the evolution for different users and usage rearrangement in the whole lifecycle [15, 25-26], provide a conceptual framework for understanding the meaning of "flexibility" in construction. his research aims to determine the quantified relationship between flexibility and the module of timber school buildings, enabling them to adapt to different functional requirements and meet sustainable construction needs. The study involves comparing module series of school-type buildings, beginning with the determination of an AHP tree to scope the criteria and impact factors of flexibility, followed by comparisons between different module sets using TOPSIS. Based on the simulated results, a numerical relationship between flexibility and module can be obtained, which can inform module coordination strategies.

2 METHODOLOGY

To quantify the flexibility, which is commonly defined qualitatively, the criteria and factors are retrieved from the literatures using PRISMA [27]. Based on the retrieved literatures, the assessment framework for flexibility of timber schools would be developed.

2.1 CRITERIAL AND INDICATORS RETRIEVAL

The identification for PRISMA is shown in Figure 1. Scopus and Web of Science (WoS) are selected as the database for searching. The Boolean syntax is applied for scoping the keywords, setting as follows: TITLE-ABS-KEY (‘Flexibility’ OR ‘ADAPTABILITY’ OR ‘REVERSABILITY’) AND TITLE-ABS-KEY (‘BUILIDNG’ AND ‘DESIGN’) AND TITLE-ABS-KEY (‘ASSESSMENT’). The range for the publication year is (2010,2022). The workflow for determining the final articles for reviewing is shown in Figure 2.

A total number of 617 literatures are selected after the first step of searching. 21 Literatures are selected for reviewing following main procedures of identification (536), screening (136), eligibility check (45) and final inclusion. The research area, title, keywords, and abstracts are checked throughout the whole workflow.

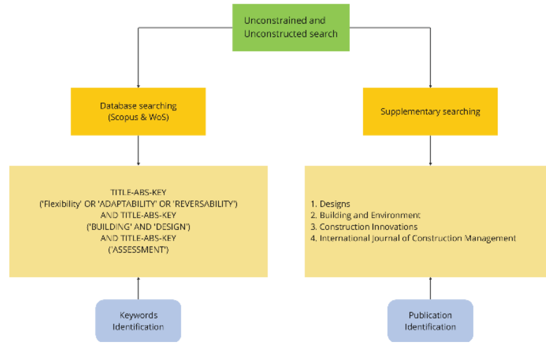

Figure 1: *Identification phase of PRISMA Method*

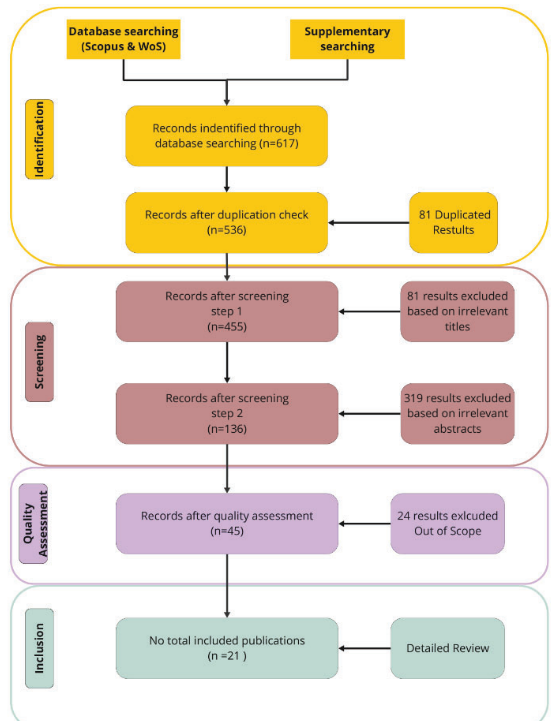

Figure 2: *Workflow for literatures retrieval*

2.2 FLEXIBILITY ASSESSMENT FRAMEWORK

The AHP-Tree Diagram assessment framework including the criteria and indicators are shown in Table 1. To cover the main stages of a cradle-to-cradle whole life cycle related to school building, three criteria have been established: Production, Construction, and Service [28]. The criteria and indicators identification follows the generic principles of flexibility [19, 29] the factors that influence the flexibility of school-type projects are selected from soft aspects [30]. For example, school buildings cater to a wide range of users with age-specific usage requirements, which is why multi-purpose spaces and components are highly demanded to meet their various needs. Under this consideration, the versatile

functionality and structural components are selected as the important indicators (Product types (C_2) and Potential for multifunctional use of space (C_{14})).
Following the AHP Tree Diagram, the weights are determined by collected 12 rating scale questionnaires. After the consistency check for the three factors in criterial level and the 16 factors in indicator level, the weights for the assessment framework ARE summarised in Figure 3.

Table 1: *Flexibility Assessment Framework for Timber School*

Target Level (A)	Criteria(B)	Indicators (C)	Reference
Flexibility	Production (B_1)	Pre-fabrication level (C_1)	[31]
		Product types (C_2)	[30]
		Specific connection (C_3)	[32]
		Structure layers (C_4)	[30]
		Geometry of plan (C_5)	[33]
	Construction (B_2)	Technological flexibility related to the easy installations (C_6)	[34]
		Installation Workflow (C_7)	[30]
		Modular Construction (C_8)	[35]
		System Interaction (C_9)	[36]
		System Zones(C_{10})	[37]
		Ease for deconstruction or disassembly (C_{11})	[38]
	Services(B_3)	Position of technical services (C_{12})	[33]
		Achieved degree of freedom of interior space(C_{13})	[33]
		Potential for multifunctional use of space (C_{14})	[33]
		Planning for future changes and service life (C_{15})	[30]
		Easy maintenance of installations (C_{16})	[34]

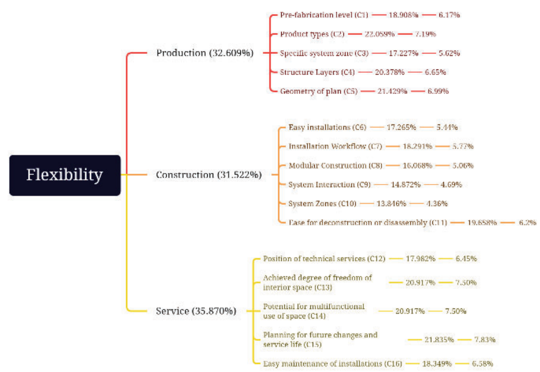

Figure 3: *Weights of the AHP Tree Diagram*

3 TOPSIS FLEXIBILITY ASSESSMENT

Based on the assessment framework, the multi-criteria assessment would be operated using TOPSIS based on the selected scenarios. The scenarios would follow the Net Capacity Guidance for the Mainstream School Design Guidelines from DfE [39]. In this research, the net area for teaching area is selected to determine the initial grid size scenarios. According to the net area guidance, the area for the same functions in primary school and secondary school are different, which are summarised in table 2 and table 3.

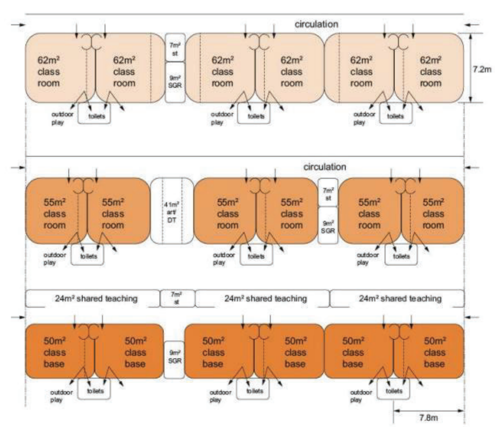

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Figure 4: *Options for arranging basic teaching area, and associated storage, toilets and group rooms, in primary schools[39].*

The determination of grid size scenarios is based on the net area requirements for classrooms and group rooms in primary and secondary schools, listed in [39].

Table 2: *Teaching Space in Primary School*

Zone	Area Name	Size used in a SoA tool	Grid Size $(m \times m)$
B	Large group room	27m2 for 15	7.2×7.8
B	Classbase without/with sink	50 m2 for 30	7.2×7.2
C	Junior classroom	55m2 for 30	7.2×7.8
D	Reception classroom	62m2 for 30	7.8×7.8 7.6×8.4
D	ICT rich practical room	62m2 for 30	7.8×7.8 7.6×8.4

The common grid size ranges from $7.2m \times 7.2m$ to $8.4m \times 8.4m$. According to normal module coordination set 300mm as the basic unit, then the modules for the timber floor could be 7.2, $7.2 + (2 \times 0.3)$, $7.2 + (4 \times 0.3)$. Timber manufacturing company would list the geometry size of their products. For example, the width of CLT floor panels from HESS timber is 2.2-3.2m with length up to 20m, which satisfies the module of gird size in this research. Based on the module range, six grid size scenarios for TOPSIS assessment are set. After the sum of squares normalization process, the TOPSIS assessment results for the six grid size scenarios are shown in Table 4-6. The positive ideal solution $A+$ for construction criteria is: $[0.474, 0.557, 0.461, 0.522, 0.476]$ and the negative ideal solution $A-$ for construction criteria is $[0.355, 0.318, 0.329, 0.326, 0.317]$. The positive ideal solutions $A+$ for the other two criteria are $[0.522, 0.546, 0.551, 0.493, 0.486, 0.508]$ and $[0.497, 0.497, 0.555, 0.547, 0.476]$ respectively. The negative ideal solutions $A-$ for construction and service criteria are $[0.326, 0.273, 0.344, 0.302, 0.324, 0.318]$ and $[0.331, 0.311, 0.277, 0.328, 0.357]$. The ranking for different grid size scenarios in different criteria are presented in Table 4-6.

4 MULTI-CRITERIA DECISION MAKING FOR FLEXIBILITY

Previous part operates the TOPSIS assessment for the six scenarios from production, construction and service criteria. When determining the module of grid size, for stakeholders from different fields, they would have different focuses on different criteria. Multi-criteria decision making (MCDM) could provide a comprehensive analysis for the flexibility of timber school.

Table 3: *Teaching Space in Primary School*

Zone	Area Name	Size used in a SoA tool	Grid Size $(m \times m)$
C	General classroom	55m2 for 30	7.2×7.8
D	Extensive classroom	62m2 for 30	7.8×7.8 7.6×8.4
D	ICT-rich classroom	62m2 for 30	7.8×7.8 7.6×8.4
D	Music classroom	62m2 for 30	7.8×7.8 7.6×8.4
E	Science studio	69m2 for 30	8.4×8.4

Table 4: *TOPSIS Results for Production Criteria*

Module Scenario	Positive ideal distance $D+$	Negative ideal distance $D-$	Relative closeness C	Ranking
7.2×7.2	0.284	0.266	0.484	2
7.2×7.6	0.272	0.180	0.398	4
7.2×7.8	0.252	0.162	0.391	5
7.6×7.8	0.277	0.216	0.438	3
7.8×8.4	0.287	0.180	0.386	6
8.4×8.4	0.246	0.290	0.541	1

Table 5: *TOPSIS Results for Construction Criteria*

Module Scenario	Positive ideal distance $D+$	Negative ideal distance $D-$	Relative closeness C	Ranking
7.2×7.2	0.243	0.438	0.643	1
7.2×7.6	0.241	0.294	0.549	2
7.2×7.8	0.291	0.224	0.435	3
7.6×7.8	0.352	0.198	0.360	5
7.8×8.4	0.441	0.211	0.324	6
8.4×8.4	0.399	0.252	0.388	4

Table 6: *TOPSIS Results for Service Criteria*

Module Scenario	Positive ideal distance $D+$	Negative ideal distance $D-$	Relative closeness C	Ranking
7.2×7.2	0.432	0.119	0.216	6
7.2×7.6	0.358	0.116	0.245	5
7.2×7.8	0.328	0.129	0.282	4
7.6×7.8	0.243	0.230	0.486	3
7.8×8.4	0.213	0.259	0.549	2

$\mathbf{8.4 \times 8.4}$	0.119	0.432	0.784	1

Table 7: Weights of Entropy Method

Indicator	Information entropy value e	Weights
C_1	0.9975	6.15%
C_2	0.9982	4.49%
C_3	0.9980	4.96%
C_4	0.9977	5.68%
C_5	0.9960	9.76%
C_6	0.9984	3.98%
C_7	0.9977	5.74%
C_8	0.9960	9.78%
C_9	0.9947	12.93%
C_{10}	0.9992	2.08%
C_{11}	0.9980	4.93%
C_{12}	0.9965	8.59%
C_{13}	0.9990	2.32%
C_{14}	0.9976	5.88%
C_{15}	0.9988	2.88%
C_{16}	0.9960	9.84%

For the comprehensive assessment framework, entropy method is selected to determine the weights for all the 16 indicators, shown in Table 7. After the sum of squares normalization process for the values of six scenarios, the comprehensive positive ideal solution $A+$ and negative ideal solution $A-$ are: $[0.474, 0.557, 0.461, 0.522, 0.486, 0.522, 0.546, 0.551, 0.483, 0.486, 0.508, 0.497, 0.497, 0.555, 0.547, 0.476]$ and $[0.355, 0.318, 0.329, 0.326, 0.324, 0.326, , 0.273, 0.344, 0.302, 0.324, 0.318, 0.331, 0.311, 0.277, 0.328, 0.357]$. Based on the ideal solutions, the results for TOPSIS assessment for flexibility are shown in Table 8.

Table 8: TOPSIS Results for Flexibility Assessment

Module Scenario	Positive ideal distance $\boldsymbol{D+}$	Negative ideal distance $\boldsymbol{D-}$	Relative closeness $\boldsymbol{C}$	Ranking
$\mathbf{7.2 \times 7.2}$	0.573	0.526	0.479	2
$\mathbf{7.2 \times 7.6}$	0.511	0.364	0.416	4
$\mathbf{7.2 \times 7.8}$	0.514	0.291	0.361	6
$\mathbf{7.6 \times 7.8}$	0.510	0.373	0.423	3
$\mathbf{7.8 \times 8.4}$	0.568	0.381	0.401	5
$\mathbf{8.4 \times 8.4}$	0.483	0.580	0.545	1

The relative closeness and ranking of three main criteria and comprehensive flexibility for the six scenarios are summarised in Table 9, where S means the scenarios, the same as Table 8; C means relative closeness; R means ranking; B_1 to B_3 means criteria following Table 1.

Table 9: TOPSIS Results for Whole Assessment Framework

S	B_1		B_2		B_3		Flexibility	
	C	R	C	R	C	R	C	R
S1	0.484	2	0.643	1	0.216	6	0.479	2
S2	0.398	4	0.549	2	0.245	5	0.416	4
S3	0.391	5	0.435	3	0.282	4	0.361	6
S4	0.438	3	0.360	5	0.486	3	0.423	3
S5	0.386	6	0.324	6	0.549	2	0.401	5
S6	0.541	1	0.388	4	0.784	1	0.545	1

The rankings are demonstrated in Figure 5. For production, the 7.2×7.2 and 8.4×8.4 grid sizes rank top whereases 7.2×7.8 and 7.8×8.4 have less flexibility in production. For construction, the smallest modular grid size has the biggest flexibility in construction. With the increase of grid size, construction flexibility gradually decreases, but it shows an increasing trend when it reaches the maximum size. The scores for services increase as the grid size enlarges, showing a positive correlation. The highest level of flexibility for both the minimum and maximum grid sizes is observed. However, as the grid size increases, the construction flexibility gradually decreases until it reaches a minimum value, after which it begins to increase. The overall trend of flexibility is similar to that of production. Specifically, flexibility exhibits a pattern of decreasing, increasing, decreasing, and then increasing again.

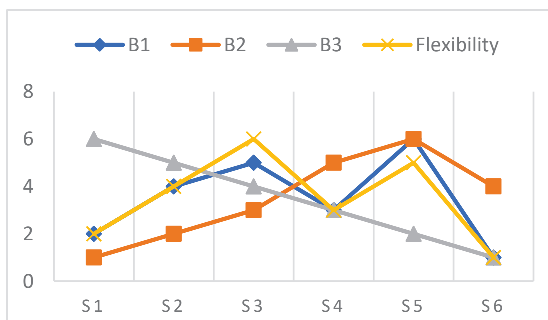

Figure 5: Ranking for different Scenarios

5 DISCUSSION AND CONCLUSIONS

This research develops a framework to quantify flexibility by identifying the criteria and indicators selected from the literatures aiming to cover cradle-to-cradle life cycle. Six modular grid sizes are set as the scenarios for comparisons following the net area design guidance of DfE of UK for primary and secondary schools. AHP is utilized to determine the weights of the tree diagram of the

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assessment framework and TOPSIS is applied to finalise the value of different modular grid size scenarios. The MCDM results demonstrates that the biggest grid size 8.4×8.4 in this case has the biggest flexibly in production, services and comprehensive flexibility. The reason might be the bigger size provide more potential in layout changing for different functionalities. Modular grid size 7.2×7.2 ranks top in construction flexibility mainly because of the geometry size is easy to assemble. The comprehensive flexibility has the similar trend of production flexibility means the production pre-dominate the overall flexibility performance.

Based on the TOPSIS assessment results, for timber school projects, to achieve the maximum flexibility, module coordination [35] can be operated following the rules adjusted from the general rules :

- Delineation of hierarchy of the space;
- Define the zones for different functions;
- Select the area with demands/potential for flexibility as the reference system;
- Situated the components in different size according to the reference system;
- Choose one module series including the basic, multi- and sub module;
- Coordinate the module according to the function requirements.

Future work would be focusing on the specific workflow of module coordination for flexibility based on the TOPSIS assessment framework by setting 7.2-9m as a range to coordinate the module for maximum flexibility.

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