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ISOMORPHISM OF STANDARD TO DESIGN ADJUSTED, RESOURCES UTILIZATION EFFICIENCY AS A NEXUS FOR BUILDABILITY EVALUATION

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ABSTRACT

In spite of the importance of the concept of design buildability, it has found little application in construction management because the concept is yet to be validly measured. It is for this purpose that this study aims at developing an evaluation technique that is mathematically valid, to generate a metric for measuring buildability which does not only preserve transitive order but that also measures distance. Buildability was modeled into the Resources Utilization Efficiency (RUE) equation as a disturbance (ε) for each construction activity, using mathematical theory of lattice algebra. The disturbance was isolated, through analytical estimating and mapped to standard RUE lattice as an isomorphic image. The isomorphism was therefore evaluated and used as the nexus for buildability evaluation. The study found that buildability is defined by the isomorphism of the design adjusted RUE lattice mapped to standard RUE lattice.

Buildability metric would find application in Construction Management as a parameter in Management Information System (MIS) for evidence-based decision making in areas of tender adjudication, estimating, construction programming, project planning and design comparison.

Stems from the development of an interval scale for measuring buildability concept that generates a metric that preserves order and measure distance from an assumed origin of the standard RUE.

Keywords: Isomorphism, Buildability, Standard, Resources, Efficiency

1. INTRODUCTION

Designs have decisive effects on buildability, and buildability influences construction. However, in building construction some salient design features are not fully put into consideration in its management. Designs are only used in the preparation of Bill of Quantities (BOQ). Whereas quantities alone does not capture the full essence of construction operation. Design concept affects the level of waste, it defines the level of productivity, determines the safety of operation, influences the project duration, and ultimately affects the cost of the project. While BOQ that forms the basis of construction planning and costing is based on quantities of construction works, all other factors of buildability are consigned to estimating, to be determined or factored into the operation. Estimating too on the other hand is based on generalized standards rather than specific design consideration. Meanwhile, standard productivities are set based on certain presumption on design concepts. Consequently, construction management is based on generalization as presented by various standards, productivity standards, standard cost, standard rating, standard equipment, standard time. Without adjustments or modification for design consideration, this standardization injects complex imbalances into the construction operations, and this underscores the need for buildability concept.

Buildability is defined as the extent to which the design of a building facilitates ease of construction subject to the overall requirement for the completed building CIRTA (1983). Illingworth (1993) defined Buildability as design and detailing which recognizes the assembly process in achieving the desire result safely and at least cost to the client. Frimpong et al. (2012) also defined buildability as a measure of ease or expediency with which a facility can be constructed. Fergusson (1989) referred to buildability as the ability to construct a building efficiently, economically and to agreed quality levels from its constituent materials, components and sub-assembles. These various definitions of buildability have established that there is a relationship between building design on one hand and the safety of construction operation, the cost of construction, the ease of construction and the duration for construction on the other hand. It is therefore pertinent to explore this relationship for effective construction management.

Morris and Hough (2016) takes the definition further by not only recognizing the effect of building design on construction alone but also recognizes the existence of standards used in construction and also alluded to danger of simplification when buildability is defined as a design philosophy which recognizes and addresses the problems of the assembly process in achieving the construction of the design product safely and without resort to standardization or project level simplification. Francis et al. (1999) submitted that better buildability could contribute to early completion of project. Jergeas and Vander Put (2011) showed that buildable design would lead to saving in project cost.

Wong et al. (2011) in an intensive study on buildability attributes of design, identified sixty-three buildability attributes. These attributes were grouped under headings and sub-divided into two categories: buildability attribute related to the design process and buildability attributes related to the design output. Wong et al. (2011) concluded that buildability is an abstract concept that can underpin the sustainable development of building design as long as the factors affecting it are identified and clearly defined. Out of the nine consolidated key buildability factors to which the buildability attributes were grouped, the one ranked the highest is the economic use of contractors' resources which confirms the central roles of resources efficiency in the concept of buildability. Poh and Chan (1998) posited that buildability has proven impact on productivity and hence cost and project duration. In the opinion of Tatum et al. (1986) it was opined that by avoiding buildability problems, design would be easier to build. This opinion was corroborated by Trevor (2003) and added that this will create less waste in construction operations.

In further linking buildability with productivity Dog (1996) submitted that improved construction productivity can be achieved through design simplication, which is mainly accomplished through the implementation of the buildability principles like rationalization, standardization, and repetition of elements. Fu (2010) also submitted that there has been more drive to ensure that upstream designs consider productivity concept early, so that construction downstream can be carried out safely and efficiently. While Nina et al. (2005) concluded after their study on a major bridge project that constructability input can affect project budget and schedule during the construction phase.

Importance of buildability has reflected on the volume of literatures on the subject, however only few researchers have addressed the theoretical procedure to analyse and implement these aspects on a design Jergers (1989), Fisher and Aalami (1994). Majority of the research works on buildability have provided the industry with general guidelines on what needs to be done to improve design buildability and why the implementation of buildability is important in a project life cycle. Gray (1983) highlighted that there was no simple answer to the problem of evaluating the construction implication of design since "the construction process is extremely complex in nature". The complexity of the construction process information was reiterated by Samson and Lema (2012) who found that traditional performance measurement system has problem because of large and complex amount of information with the absence of approaches to assist decision maker understand, organize, and use such information to manage organizational performance.

From the foregoing, buildability concept would be of little benefit if the concept cannot be validly measured. Some attempt at buildability assessment include Building Design Appraisal System (BDAS) developed by the Australia Building and Construction Authority. The system used to measure the potential impact of a building design on the usage of site labour. A design with a higher buildable design score will result in more efficient labour usage in construction and therefore higher site labour productivity Building and Construction Authority (BCA). (2011). Buildable Design Appraisal System (BDAS) which quantifies the Buildability of design based on three principles; standardization, simplicity and single integrated element was developed in Singapore Building and Construction Authority (BCA) (2005a), Lam, 2000). These two techniques are assessment tools while Buildability Assessment Model (BAM) which aspires to quantifying buildability of designs (Wong et al., 2003) is still a proposition.

Zainnuddin (1997) conducted an extensive review of Computer Application System for Buildability Assessment, identified five different systems; Project Early Design-Stage Indicative Construction Time Estimate (PREDITE), The Intelligent Knowledge Based System (IKBS), Construction Knowledge Expert (COKE), The Dimensional Bay Design System (DBDS), Constructability Assessment for Design System (CADDS) and Model Based Constructability Analysis (MOCA). It was concluded that majority of buildability evaluation methods do not perform the design evaluation in an integrated approach. While these evaluation systems together with the CONPLAN system proposed by Zainnuddin (1997) are largely intended for the use of designers and therefore do not possess the validity expected of a sound measurement necessary for management decision support. This study therefore intends to develop a Buildability Evaluation Technique that is based on valid mathematical principles for generating transitive metric of buildability. With the specific objective to:

1) develop the mathematical model for buildability.
2) deduce the nexus for buildability evaluation.
3) develop the buildability measuring scale.

2. METHODOLOGY

2.1. DESIGN APPRECIATION FOR BUILDABILITY

Process of buildability evaluation started with design appreciation. Design appreciation relies on the knowledge and experience of competent construction professionals in areas of construction technology, construction management, analytical estimating, construction health and safety management as well as material management, to be able to identify buildability issues of the design from the drawing and have the competence to be able to deduce the implication for resources utilization efficiency at the construction stage. Buildability issues range from; extent of conversion work required, effects of complexity of geometry, provision for tolerance, number of varieties in materials, extent of standardization, scope of modularity of the design and re-usability of formwork among other indicative factors of buildability that have direct effects on labour and plant productivity as well as material usage efficiency.

2.2. RESOURCES UTILIZATION EFFICIENCY (RUE) AND BUILDABILITY

Resources utilization efficiency of a construction activity was modeled as a function of labour productivity, plant, and equipment productivity as well as material usage efficiency which are the three resources in construction. Buildability as well affect resources utilization efficiency but as buildability cannot be directly observed and measured, it was not included as another variable in the model. Since buildability auto correlates with all other variables of the model; labour productivity, plant and equipment productivity and material usage efficiency, it was therefore treated as a disturbance or an unobserved variable in the model.

$$R = \gamma_1 X_1 + \gamma_2 X_2 + \gamma_3 X_3$$

Where R is the Resources Utilization Efficiency, that is, resources required for one unit of the construction activity. X_1, X_2 and X_3 are labour, plant and material resources respectively required to achieve the activity while $\gamma_{1,}$ γ_2 and γ_3 are Resources Utilization Efficiency Factors (RUEF) which are the quantity of labour, plant and material respectively required for one unit of the activity in manhour, plant hour and the appropriate unit for the material.

2.3. BUILDABILITY AS UNOBSERVED VARIABLE/DISTURBANCE (ε)

Concept of unobserved variable was introduced to the model for buildability as a disturbance in the model i.e., variable that is not considered in the model - designed buildability represented in the model equation as ε.

$$R = \gamma_1 X_1 + \gamma_2 X_2 + \gamma_3 X_3 + \varepsilon$$

where ε is the unobserved variable – buildability. When the design has no buildability issue that is $\varepsilon = 0$, the resources utilization efficiency is considered to be standard, that means the activities was carried out in standard times, with standard rating and standard productivity. This takes place under presumption for design that facilitates the attainment of standard level of performance. This means that standard RUE are attainable ceteris paribus. However, when design has buildability issue, ceteris paribus would no longer hold that is $\varepsilon \neq 0$, consequently this violation of ceteris paribus injects imbalance in the RUE model and therefore transforms the model from linear algebra into a lattice algebra with development of inner products through orthogonality and orthocomplementary of the lattice space. The approach in this evaluation technique once the buildability issues were identified with the attendant potential imbalance, these imbalances were resolved by adjusting for them in; labour productivity, plant productivity and material utilization efficiency i.e RUEF; $\gamma_1, \gamma_2, \gamma_3$ in order to restore the disturbance ε back to zero. The adjusted RUE was therefore mapped to standard RUE to evaluate the magnitude of the disturbance i.e the buildability of the design. Thus, correlated effects of buildability in RUEF have been indirectly isolated.

The subspaces $\{A_i\}$ are said to be orthogonal if and only if

$\mathbb{A}_i \subseteq A_j^{\perp}$ holds for all $i \neq j \therefore \mathbb{A}_i \perp \mathbb{A}_j$

Orthomodularity holds if $\mathbb{A} \subseteq \mathbb{B} \Rightarrow \mathbb{B} = \mathbb{A} \boxplus (\mathbb{A}^{\perp} \cap \mathbb{B})$

2.4. AGGREGATION OF CONSTRUCTION ACTIVITIES

Each construction activity was modelled as an algebraic lattice of the same variety that is containing the same types of variables X_1, X_2 and X_3. These varieties of algebras are then grouped as a class of subalgebras to model the entire construction activities of the design for the proposed project. RUE of each of the construction activities are isomorphic images of their corresponding standard RUE. Equally RUE of the class of the entire construction activities is also an isomorphic image of the class of the standard RUE for the entire construction activities.

$A \in I(k)$ *iff* A *is isomorphic to* K

$A \in S(k)$ *iff* A *is subalgebra to* K

$\bigvee_{i \in \mathrm{I}} \theta_i = \bigcup[\theta_{io} \circ \theta_{i1} \circ \cdots\cdots \theta_{ik} : \mathrm{io} \cdots\cdots \mathrm{ik} \in I, \mathrm{k} < \infty]$

$\alpha_i : \mathrm{A} \rightarrow \mathrm{A}_i, i \in \mathrm{I}$

$\alpha : \mathrm{A} \rightarrow \prod_{i \in \mathrm{I}} \mathrm{A}_i$

3. BUILDABILITY EVALUATION CONCEPTUAL FRAMEWORK

Buildability evaluation conceptual framework is given by the flowchart in Fig 1. The flowchart diagram traced the buildability evaluation process from the design appreciation for identification of buildability issues in a design by identifying the indicative factors. These were then traced to resources utilization implication and through estimating, the variances between the standard resource's utilization efficiency and design imposed resources utilization efficiency were evaluated. The two levels of efficiency were then mapped by the isomorphism.

Figure 1

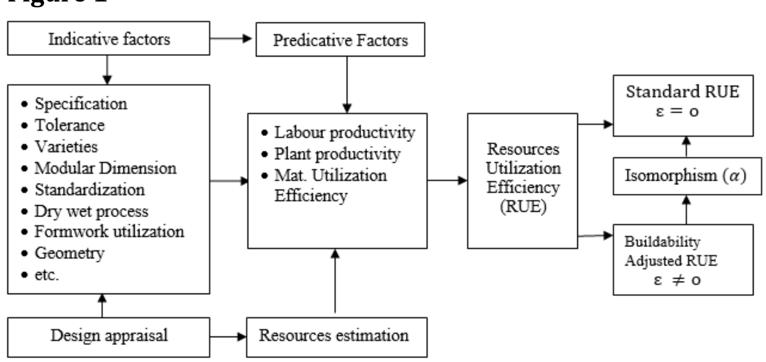

Figure 1 Buildability Evaluation Conceptual Framework

Resources Utilization Efficiency RUE for construction activities was modeled as an algebraic lattice, as a function of labour productivity, plant and equipment productivity and material utilization efficiency, treating buildability as a disturbance in the model

$$R = \gamma_1 X_1 + \gamma_2 X_2 + \gamma_3 X_3 + \varepsilon$$

When the design has no buildability issue, $\varepsilon \neq 0$ and the RUE is standard i.e the resources are employed at the standard level of productivity i.e ceterus parabus is holding and all the inner products are zero.

$$R = S = \begin{bmatrix} \gamma_1 & 0 & 0 \\ 0 & \gamma_2 & 0 \\ 0 & 0 & \gamma_3 \end{bmatrix}$$

When the design has one or more buildability issue, the ceterus parabus is no longer holding i.e., $\varepsilon \neq 0$, thus creating imbalance in RUE and therefore will tend to transform the RUE via the inner product, through orthogonality, orthocomplementary and orthomodularity leading to indeterminate and possibly geometric change in RUE.

$$R = \begin{bmatrix} \gamma_1 & \gamma_1\gamma_2 & \gamma_1\gamma_3 \\ \gamma_2\gamma_3 & \gamma_2 & \gamma_2\gamma_3 \\ \gamma_3\gamma_1 & \gamma_3\gamma_2 & \gamma_3 \end{bmatrix}$$

The approach in this evaluation technique is to resolve the buildability issue of the design proactively. The Resources Utilization Efficiency (RUE) imbalance was therefore resolved through re-estimation of resources inputs. By adjusting the resources input to realistic level of productivity and efficiency after putting the buildability into consideration, the imbalances would be resolved and the disturbance ε would be restored back to zero. This proactive approach to buildability would yield arithmetic increase in the input resources unlike geometric changes if allowed to fester on its own.

$$R^* = \begin{bmatrix} (\gamma_1 + \Delta\gamma_1) & 0 & 0 \\ 0 & (\gamma_2 + \Delta\gamma_2) & 0 \\ 0 & 0 & (\gamma_3 + \Delta\gamma_3) \end{bmatrix}$$

Where R*is the buildability adjusted RUE. If $\gamma_1^* = (\gamma_1 + \Delta\gamma_1)$, $\gamma_2^* = (\gamma_2 + \Delta\gamma_2)$ and

$$R^* = \begin{bmatrix} \gamma_1^* & 0 & 0 \\ 0 & \gamma_2^* & 0 \\ 0 & 0 & \gamma_3^* \end{bmatrix}$$

Buildability adjusted RUE (R*) is an isomorphic image of standard RUE (S). RUE lattices for all construction activities were modeled as a class of subalgebras of activities RUEs presented as a diagonal, partitioned matrix n x n for n number of activities.

$$\mathbb{R}^* = \begin{bmatrix} R_{11} & 0 & \cdots & 0 \\ 0 & R_{22} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & & R_{nn} \end{bmatrix}$$

Where Rij is the RUE for ij construction activities for all i = j since the class of all activities was modeled as a class of disjoint lattices of each construction activity RUE since each activity is independent of the others in terms of resources utilization. The partitioned matrix was therefore presented as a diagonal matrix of nxn, for n number of activities. While class of standard RUE was also presented by as a lattice (matrix) of the same type

$$\mathbb{S} = \begin{bmatrix} S_{11} & 0 & \cdots & 0 \\ 0 & S_{22} & \cdots & 0 \\ \vdots & \ddots & \vdots & \\ 0 & 0 & & S_{nn} \end{bmatrix}$$

3.1. EVALUATION OF ISOMORPHISM

Standardized buildability adjusted, Resources Utilization Efficiency (RUE) in given by the standard quotient i.e., ratio of adjusted Resources Utilization Efficiency Factor (RUEF) to the corresponding standard RUEF.

$$= \begin{bmatrix} \frac{\gamma^*_{i1}}{\gamma_{i1}} & 0 & 0 \\ 0 & \frac{\gamma^*_{i2}}{\gamma_{i2}} & 0 \\ 0 & 0 & \frac{\gamma^*_{i3}}{\gamma_{i3}} \end{bmatrix}$$

Isomorphism of activity i is given by the direct product of the standardized RUEF. Aggregate isomorphism for the entire design assessment is given by the product of individual activities isomorphism.

$$\alpha_i = \frac{\gamma^*_{i1}}{\gamma_{i1}} \circ \frac{\gamma^*_{i2}}{\gamma_{i2}} \circ \frac{\gamma^*_{i3}}{\gamma_{i3}}$$

$$\alpha = \prod \alpha_i$$

3.2. BUILDABILITY MEASURING SCALE

Design Buildability was measured by the isomorphism mapping the aggregate standard RUE ($\mathbb{S}$) to the aggregate buildability adjusted RUE ($\mathbb{R}$).

$$\alpha\, \mathbb{S} = \mathbb{R}^*$$

This study has established a measuring scale with the standard RUE as the assumed origin of an interval scale for buildability evaluation. Having introduced buildability concept as a disturbance ε in the RUE model and indirectly measured it through buildability adjustment to RUE through re-estimation of RUEF. By using isomorphism to map the adjusted RUE to standard RUE, the isomorphism is therefore the distance between the assumed origin; standard RUE to the design buildability, which could be perceived as the deviation from the standard which is the origin. Since Buildability metric $\mathbb{B}$ is inversely proportional to the isomorphism of standard RUE to buildability adjusted RUE. Buildability metric($\mathbb{B}$), expressed as a percentage of standard RUE is given by.

$$\mathbb{B} = 100\ Log\ \frac{1}{\alpha}$$

where α is the isomorphism of standard RUE to buildability adjusted RUE. The evaluation techniques is based on sound measurement criteria premised on mathematical principles in algebra. The buildability measuring scale is an interval scale with standard RUE as the assumed origin ($\varepsilon = 0, \alpha = 1$) where there are no buildability issues in the design and the RUE is at the standard level with isomorphism of unity, from which buildability of the design is measured. Isomorphism of the adjusted RUE to standard RUE is the distance from the origin that measures the buildability when ($\varepsilon \neq 0$) that is when there are buildability issues in the design, ($\varepsilon < 0$) i.e. negative buildability indicates lower resources efficiency while ($\varepsilon > 0$) positive buildability means an improvement in Resources Utilization Efficiency through innovative and creative design concept resulting in higher productivity above established standard.

4. CASE STUDY

Buildability appraisal was conducted on a design, the design concept was found to have buildability issues with six construction activities out of twenty five construction activities identified on the design. The activities with their design adjusted RUEF as well as their corresponding standard RUEF were presented in Table 1.

Table 1

Table 1 Activities with Buildability issues with their Resources Utilization Efficiency Factors

S/n	Construction Activities	Buildability Issue	Standard RUEF			Design Adjusted RUEF		
			γ_1	γ_2	γ_3	γ_1	γ_2	γ_3
1.	Beam Steel Reinforcement	Modular dimension	0.41	-	24.7	0.53	-	44.8
2.	Block work	Geometry	0.36	-	10	1.00	-	19
3.	Arc Formwork	Span and geometry	0.10	-	0.90	0.42	-	3.50
4.	Ceiling	Storey height	0.10	-	1	0.50	-	1
5.	Column	Storey height	0.22	0.22	2	0.45	0.45	2
6.	Roof Structure	Span and storey height	0.2	0.2	10	0.50	0.50	20

Table 2 presents, the standardized RUEF together with the corresponding isomorphism for each of the construction activities identified with buildability issues. Direct product of standardized RUEF gives isomorphism α_i of each construction activity i while direct product of activities isomorphism gives the aggregates isomorphism of the class of activities α.

Table 2

Table 2 Activities with Buildability Issues and Their Corresponding Standardized RUEF and Isomorphism

S/n	Activities	Standardized RUEF			Isomorphism α_i
		γ_1	γ_2	γ_3	
1.	Beam Reinforcement	1.29	-	1.81	2.3349
2.	Block work	2.78	-	1.90	5.2820
3.	Arc Formwork	4.20	-	3.89	16.3380
4.	Ceiling	5.00	-	1.00	5.0000
5.	Column	2.05	2.05	1.00	4.2025
6.	Roof Structure	2.50	2.50	1.00	6.2500
7.	Aggregate Class Isomorphism ($\alpha = \prod \alpha_i$)				26,462

Buildability of the design $\mathbb{B}$ is given by $log\ ^1/_\alpha$ = - 4.423

Buildability presented in form of percentage % $\mathbb{B}$ = - 442%

Buildability metric adjusted for proportion of activities with buildability issues is given by:

$$\frac{\text{No of activities with Buildability Issues}}{\text{Total Number of construction activity}} \times \text{\% Buildability}$$

= 0.24 x - 442

= -106 %

The result shows that the buildability issues identified in the design has plummeted the Resources Utilization Efficiency in four folds. When other activities without buildability issues were put into consideration, Resources Utilization Efficiency Factor (RUEF) of the design otherwise known as design buildability because of six activities out of twenty-five activities was also depressed by 106%.

5. DISCUSSION

Buildability is one concept with the promise of linking designs with management of construction of construction operations. This potential of buildability concept would not be realized until design is fully integrated into the construction management processes via a buildability metric as a parameter in Management Information System (MIS). Most of the tools employed in construction processes are treated as a stand-alone tool, thus limiting the potential of these tools by creating information gaps in management decision-making and as a result, most of the management decisions are made without recourse to these fundamental construction tools which are the bases of construction operation as the fundamental domain operational assets. Drawing is an important construction production information document and as such should be one of the bases for vital management decision making as it is the basis for construction. This underscores the magnitude of the disruptive effect of buildability issues of a design on construction processes which is quite enormous than appreciated because the theories surrounding the investigation are yet to be fully explored.

Reactive approach to buildability issues allows the disturbance to fester and become more difficult to tame when it would have transformed the resources efficiencies from what could have been just arithmetic changes in the plan to a geometric or even exponential alteration to operational efficiency. For instance, if the design, because of modular dimension, creates more unavoidable wastages, leading to shortage of material and disruption in construction programme. This could lead to delay in project completion and redundancy of labour and equipment. Extra costs of ordering of material, additional carrying cost and unbudgeted extra purchasing cost would be incurred leading to increase in project cost. These are the sources of sundry inner products explained in the lattice theory through orthogonality and orthocomplement theorems of lattices. Alternatively, if the buildability is proactively managed by identifying the buildability issues beforehand and adjusted for, increase in material would have been identified and ordered at once, with the additional labour cost and extra plant hour considered at the planning stage, all sundry collateral costs of shortage and delay in form of liquidated damages or dispute on contract could be avoided.

In this study the direct effect of buildability on productivity and resources efficiency were recognized but since buildability cannot be directly measured it was introduced into the Resources Utilization Efficiency RUE model as a disturbance. The actual magnitude of this disturbance is indeterminate as it can transform from the infimum lattice to supremum lattice via the inner products. The approach in this evaluation techniques is to make buildability adjustment for the RUE by estimating the infimum transformation of RUE due to design buildability and mapped it to the standard RUE. This means that the technique used the greatest least bound (glb) of the RUE lattice to carry out the evaluation. It is therefore instructive to known that the effect of buildability could be far greater as the proactive approach used for the evaluation is based on the infimum RUE estimation. Infimum transformation of RUE was adopted because it is estimable, relying on the experience and expertise of the construction professionals. On the contrary supremum transformation of RUE is in the area of risk evaluation which are stochastic and cannot be accurately determined.

Evaluation techniques used in this study for measurement of buildability meets the three major characteristics for measurements: in terms of validity, reliability, and practicality. Validity of the measuring tools stems from its content validity which is total as all construction activities in the design are considered for the buildability assessment and evaluation without an exemption thereby eliminating any form of bias. Criterion related validity was established through the perfect correlation existing between the buildability and the labour productivity, plant productivity and material utilization efficiency, the three variables used for modeling resources utilization efficiency (RUE). Construct validity of the evaluation method rests on the mathematical theories of lattice algebra that was used to explain the behaviour of buildability and deployed for building of interval scale based on assumed origin and the distance from the origin measured by the isomorphism. The only reservation in the validity is the subjective human judgement in identifying the buildability issues on the design and the RUE adjustment. Subjective variance can be greatly minimized through a well-structured process for design appreciation. This will lead to better reliability of the measuring tool by ensuring measurement stability, equivalence, and consistency.

Practicality of the evaluation techniques is based on the interpretability of the Buildability metric, which is expressed as a real number, and can also be expressed as a percentage. Negative value is a negative buildability that is reduction in resources utilization efficiency about standard while positive value is a positive buildability, that is, improvement in RUE above established standard. Buildability metric has value of zero at the standard level of RUE which is the origin of the scale.

6. CONCLUSION

Buildability was identified as a disturbance in the Resources Utilization Efficiency RUE model which prevents the attainment of standard level of Resources Utilization Efficiency RUE, and which perfectly correlates with all the three variables of RUE: labour productivity, plant productivity and material utilization efficiency. Proactive approach to treatment of buildability through adjustment to RUE gives determinate, infimum, and largely arithmetic change to RUE whereas reactive approach to buildability leads to indeterminate supremum transformation of RUE, largely geometric changes, leading to lower efficiency and productivity, resulting in project cost overrun, largely as a result of collateral effects of disruption caused by buildability issues.

Buildability is therefore defined by the isomorphism of infimum transformation of Resources Utilization Efficiency as a result of buildability issues in the design, mapped to standard Resources Utilization Efficiency. Buildability metric which is inversely proportional to isomorphism is therefore the nexus for measuring buildability. Buildability metric is given as the logarithm of the inverse of the isomorphism of adjusted RUE to standard RUE. Thus, the higher the value of the Buildability Metric the better the design buildability. The evaluation techniques is non-prescriptive and non-judgemental as it does not impose design option but rather just appraises the design for resources efficiency in form of resources requirement for 1 unit of the project compared to standard.

Buildability metric would have practical application in different areas of Construction Management like tender adjudication, estimating, construction planning, construction programming, construction productivity evaluation and design comparison. The integration of design buildability concept into the decision making are expected to enrich the evidence-based decision making through inclusion of buildability metric in Management Information System (MIS) as a parameter for decision support. Equally the methodology for design buildability evaluation can be modified for adoption for other design appraisal concepts like maintainability and sustainability evaluation.

CONFLICT OF INTERESTS

None.

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