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Design and Evaluation of an Overall Construction Safety Management System for Residential Construction Sites: A Graph Theoretic Approach

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Abstract:
The present work depicts a systematic approach for development of a benchmarked model for a safety oriented residential construction site or project analysed up to the sub-component level. For the evaluation of the benchmarking model, attributes governing the safety management issues on the residential construction sites have been identified. An attribute digraph for the characteristics of the construction safety management systems has been developed. The inheritances and inter-dependencies of the governing attributes have been rated using weighted approach. The sensitivity analysis for the developed benchmarked model has been carried out by calculation of the permanents of a typical safety oriented construction site management system.

Keyword: construction safety benchmarking model, construction safety issues, matrix function, graph theoretic approach

I. INTRODUCTION

The cost saving and time performance are usually essential to all parties who are involved in a residential construction project, that is owner, contractor, subcontractor. The main causes of disputes in construction projects involve delay and failure to complete the work in the specified cost and time frame. While meeting the deadlines, every stakeholder work under huge pressure to deal with handling construction issues with utmost safety at site but compact schedules lead to happening of accidents with unforeseen accidental costs in terms of labour, work handling and the material handling. Safety of the constructed facility is normally the responsibility of the architect and engineer, whereas safety of the construction process is conventionally considered to be the contractor's responsibility. This proposed work discusses a concept of rethinking construction safety management system for residential projects through the development of a safety oriented benchmarking model for residential construction sites. For the development of the proposed model, various attributes have been identified based on the stress given in the historical data sheets, research papers, monographs etc. Apart from a lot of research carried out on construction safety management issues in last few decades, the publications related to development of total construction safety management system for residential construction projects are very few and are of restricted usage type. Since in a construction safety management system, various processes or work schedules are to be executed simultaneously, every work schedule may be independent of other work schedules in the same construction projects with total responsibility of execution of project with safety at site, a combined effort of the overall construction safety management system design is the need of the present scenario. For the overall construction safety management system design performance evaluation, since the system is to be analysed to its sub- component level, the literature survey is carried out for individual sub-components of such systems pertaining to residential construction projects and emphasis is to be given for the new methodologies to be adopted which are presently being used successfully for other types of system designs. [**Koushki *et.al.*,2005**] identified that the three main causes of time-delays included changing orders, owners' financial constraints and owners' lack of experience in the construction business. Regarding cost overruns, the three main causes were identified as contractor-related problems, material-related problems and, again, owners' financial constraints. [**Moselhi, 1997]** revealed that the current allowance as contingency is 5% of the base line estimates while additional cost is 18% which implies a shortfall of 13%. Furthermore, the study shows that the relationship among contingencies, base line estimates and final cost is statistically significant at 0.01. [**Serpella *et.al.*, 2014]** stated that that risk management in construction projects is still very ineffective and that the main cause of this situation is the lack of knowledge. It is expected that the application of the presented work will allow clients and contractors to develop a project's risk management function based on best practices, and also to improve the performance of this function. [**Alarcon *et.al.*, 2016]** revealed in a study that states that over the years many prevention management practices have been implemented to prevent and mitigate accidents at the construction site. The higher the percentage of prevention practices implemented in a strategy, the lower the accident rate. [**Misiurek & Misiurek , 2017]** proved that human errors, and not technical problems, have the greatest impact on the occurrence of accidents and concluded that three main root causes of human errors are lack of or poorly led training, badly defined and developed work standards and also a lack of supervision of employees. [**Kaskutas *et. al.*, 2016]** described that falls from heights account for 64% of residential construction worker fatalities and 20% of missed work days. It has been hypothesized that worker safety would improve with foremen training in fall prevention and safety communication. It was also found that inexperienced workers are exposed to many fall hazards that they are often not prepared to negotiate. [**Saurin, 2016]** emphasised the safety inspections carried out by government officers are important for the prevention of accidents, there is little in-depth knowledge on their outcomes and processes leading to these. This research deals with this gap by using systems thinking (ST) as a lens for obtaining insights into safety inspections in construction sites. [**Guo *et.al.*, 2017]** suggested that visualization technology can improve safety management by aiding safety training, job hazard area (JHA) identification and on-site safety monitoring and warnings. [**Aguilar & Hewage, 2013]** proposed a system development that transmits safety related information of multiple construction projects into a centralized database, where real-time safety indicators are generated. The system provides safety indicators related to an individual project or industry-wide figures. On site managers can use such real-time information for informed decisions in work sites. Apart from these, a significant work related to implementation of decision making techniques like graph theoretic approach [**Grover *et.*al., 2004], [Venkatasami & Agrawal, 1995]]** and ISM **[Tilakraj *et.* al., 2008]** for solving engineering system problems related to quality systems and manufacturing environment.

CHARACERTISTICS OF CSMS

The construction safety management system (CSMS) is a measure of all its attributes that affect its overall performance level through best matching compromise of performance levels of its subsystems analysed through the outcomes of interdependencies of all such attribute groupings to achieve common goals or objectives of the design of such systems. Through the exhaustive evaluation of various attributes identified by the researchers affecting the construction safety management system irrespective of their domain of influence, all such attributes are categorized in seven broad groupings i.e. Project associated Costs (PAC), Unrealistic Project schedules (UPS), Supervisory competency (SPC), Manpower skills (MPS), Upkeepment of equipment (UKE), Inadequate safety devices (ISD) and Degraded Building material (DBM).

In many cases, it has been observed that projects are delayed due to unorganised process planning and unrealistic project cost estimations. Since every construction company want to reduce the overheads by mitigating the bottlenecks of insufficient funds and time delays, the scheduled time delays in activity durations are crashed to some extent at the cost of operational safety. The strengthening of expertise at the project planning and cost assessment department may reduce the occurrence of unforeseen delays in project schedules and project associated costs (PAC). An organised training at the supervisor level and clarity in flow of instructions/formation from supervisory cadre (SPC) to worker level at construction site would reduce the chances of accidents and help in skill enhancement of the workers (MPS) for similar project executions. Use of latest technology based safety devices at workplace and proper upkeepment of existing ones helps to create more reliable and trustworthy environment with enhanced operational safety, resulting in less unforeseen damage costs to the projects. Proper grade quality material checked at random in mix mode can mitigate the chances of usage of degraded material at construction site planned to meet the requisite standards. Since a number of system variables or the attributes are interdependent, it makes all the quality characteristics also interdependent in one way or the other. A close relationship of such interdependencies among the attributes or the characteristics cannot be established in the form of universal empirical relations; hence, the visual means of representation of such systems like digraph representation plays an important role in understanding and analyzing the performance of construction safety management system.

CONSTRUCTION SAFETY MANAGEMENT SYSTEM (CSMS) DIGRAPH

A digraph is made to show the attributes and their interdependencies within the system. A graph with directed edges is known as digraph. The nodes in the construction safety management system evaluation digraph represent the qualitative measure of the attributes (D_i's) and edges show the interdependencies of the attributes (D_{ij}'s). The digraph consists of a set of nodes V= $\{V_i\}$, with i=1,2,3,…..7 and a set of directed edges D= $\{D_{ij}\}$. A node V_i represents the i^{th} qualitative attribute and the edges represents the relative importance among them. The number of nodes represents the total number of attributes considered for the evaluation of the construction safety management system. If a node '*i*' shows the relative importance over node '*j*', then a directed edge is drawn from node '*i*' to node '*j*' (i.e. D_{ij}). A typical digraph is shown in fig.1 with 7 attributes. Similarly if node '*j*' shows relative importance over node '*i*' then a directed edge is drawn from node '*j*' to node '*i*' (i.e. D_{ji}).

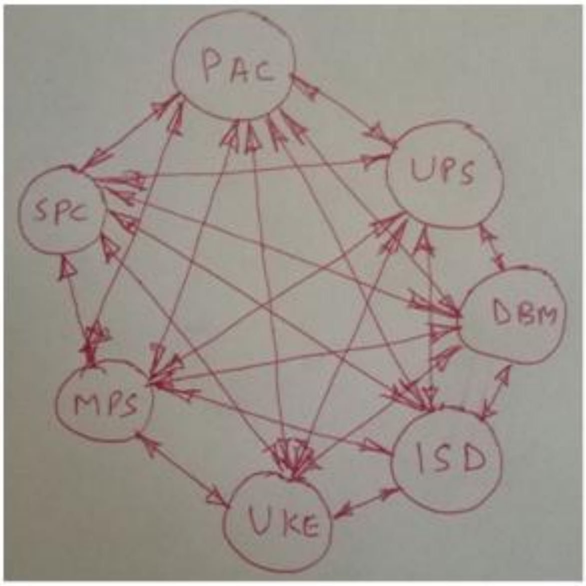

Figure.1. Attribute Digraph

MATRIX REPRESENTATION OF CSMS DIGRAPH

The Digraph representation gives visual analysis. Moreover, for mathematical analysis, the digraph should be represented in the matrix form. The matrix represents all the attributes and their interrelations. Hence a matrix called construction safety management system attribute matrix, [A] is defined. Here in this matrix 'D_i' represents the i^{th} evaluation attribute represented by the node 'V_i' and 'D_{ij}' represents the relative importance among the attributes and is represented by the edge drawn from i to j in the digraph. The determinant of this matrix will give important information regarding the evaluation of attributes. But it will contain negative terms so some useful information will be lost. To solve this problem, researchers have used permanent function of the matrix. The only difference between determinant and permanent function is in the signs of the coefficients. Where determinant has both negative and positive signs in the terms, there only positive signs appears in the permanent function, which ensures that complete objective for the evaluation of the attribute is fulfilled and no information is lost. Permanent is a standard matrix function and is used in combinatorial mathematics.

$$
A = \begin{array}{c} attributes \\ PAC \\ UPS \\ SPC \\ MPS \\ UKE \\ ISD \\ DBM \end{array}
\begin{array}{c}
\begin{array}{ccccccc} PAC & UPS & SPC & MPS & UKE & ISD & DBM \end{array} \\
\begin{bmatrix}
D_1 & a_{1,2} & a_{1,3} & a_{1,4} & a_{1,5} & a_{1,6} & a_{1,7} \\
a_{2,1} & D_2 & a_{2,3} & a_{2,4} & a_{2,5} & a_{2,6} & a_{2,7} \\
a_{3,1} & a_{3,2} & D_3 & a_{3,4} & a_{3,5} & a_{3,6} & a_{3,7} \\
a_{4,1} & a_{4,2} & a_{4,3} & D_4 & a_{4,5} & a_{4,6} & a_{4,7} \\
a_{5,1} & a_{5,2} & a_{5,3} & a_{5,4} & D_5 & a_{5,6} & a_{5,7} \\
a_{6,1} & a_{6,2} & a_{6,3} & a_{6,4} & a_{6,5} & D_6 & a_{6,7} \\
a_{7,1} & a_{7,2} & a_{7,3} & a_{7,4} & a_{7,5} & a_{7,6} & D_7
\end{bmatrix}
\end{array} \tag{1}
$$

PERMANENT FUNCTION OF THE ATTRIBUTE MATRIX

The permanent function of the attribute matrix is represented as Per (A). It contains N! terms. Equation 2 shows the sigma form of the permanent function for 7 attributes.

$$
\begin{aligned}
per\,A = {} & \prod_{i=1}^{7} D_i + \sum_i\sum_j\sum_k\sum_l\sum_m\sum_n\sum_p (a_{ij}a_{ji})D_kD_lD_mD_nD_p \\
& + \sum_i\sum_j\sum_k\sum_l\sum_m\sum_n\sum_p (a_{ij}a_{jk}a_{ki} + a_{ik}a_{kj}a_{ji})D_lD_mD_nD_p \\
& + [(\sum_i\sum_j\sum_k\sum_l\sum_m\sum_n\sum_p (a_{ij}a_{ji})(a_{kl}a_{lk})D_mD_nD_p \\
& + \sum_i\sum_j\sum_k\sum_l\sum_m\sum_n\sum_p (a_{ij}a_{jk}a_{kl}a_{li} + a_{il}a_{lk}a_{kj}a_{ji})D_mD_nD_p\,] \\
& + [\sum_i\sum_j\sum_k\sum_l\sum_m\sum_n\sum_p (a_{ij}a_{ji})(a_{kl}a_{lm}a_{mk} + a_{km}a_{ml}a_{lk})D_nD_p \\
& + \sum_i\sum_j\sum_k\sum_l\sum_m\sum_n\sum_p (a_{ij}a_{jk}a_{kl}a_{lm}a_{mi} + a_{im}a_{ml}a_{lk}a_{kj}a_{ji})D_nD_p\,] \\
& + [\sum_i\sum_j\sum_k\sum_l\sum_m\sum_n\sum_p (a_{ij}a_{ji})(a_{kl}a_{lm}a_{mn}a_{nk} + a_{kn}a_{nm}a_{ml}a_{lk})D_p \\
& + \sum_i\sum_j\sum_k\sum_l\sum_m\sum_n\sum_p (a_{ij}a_{jk}a_{ki})(a_{lm}a_{mn}a_{nl})D_p \\
& + \sum_i\sum_j\sum_k\sum_l\sum_m\sum_n\sum_p (a_{ij}a_{ji})(a_{kl}a_{lk})(a_{mn}a_{nm})D_p \\
& + \sum_i\sum_j\sum_k\sum_l\sum_m\sum_n\sum_p (a_{ij}a_{jk}a_{kl}a_{lm}a_{mn}a_{ni} + a_{in}a_{nm}a_{ml}a_{lk}a_{kj}a_{ji})D_p\,] \\
& + [(\sum_i\sum_j\sum_k\sum_l\sum_m\sum_n\sum_p (a_{ij}a_{ji})(a_{kl}.a_{lm}.a_{mn}.a_{np}.a_{pk}) \\
& + \sum_i\sum_j\sum_k\sum_l\sum_m\sum_n\sum_p (a_{ij}a_{jk}a_{ki})(a_{lm}a_{mn}a_{np}.a_{pl}) \\
& + \sum_i\sum_j\sum_k\sum_l\sum_m\sum_n\sum_p (a_{ij}a_{jk}a_{kl}.a_{lm}a_{mn}a_{np}.a_{pi})]
\end{aligned} \tag{2}
$$

In this total (n+1) i.e (7+1) groupings have been made. These groups represent the measure of attributes and the relative importance. Here total 7 groups have been made and their importance is discussed below.

1. The first grouping represents the measures of inheritance level of implementation factors.
2. The second grouping is absent as there is no self-loop in the digraph.
3. The third grouping contains interrelationships between the subfactors (i.e. a_{ij} a_{ji}) and measures of five remaining factors.
4. The fourth grouping represents a set of three factors relative importance loop and measure of four factors.
5. The fifth grouping contains two sub groups. The terms of the first subgroup represents the relative importance among the two factors and other two factors and the measure of three implementation factors. The second subgroup contains the relative importance among the four factors and the measure of the three implementation factors.
6. The sixth grouping contains two sub groups. The first subgrouping is a set of 2 factor interdependence, i.e. $a_{ij}a_{ji}$, a set of 3 factor interdependence, i.e. $a_{kl}a_{lm}a_{mk}$ or its pair $a_{km}a_{ml}a_{lk}$ and measure of remaining two implementation factor. The second sub-grouping is a set of five implementation factors interdependence, i.e. $a_{ij}a_{jk}a_{kl}a_{lm}a_{mi}$ or its pair $a_{im}a_{ml}a_{lk}a_{kj}a_{ji}$ and measure of remaining two implementation factor.
7. The seventh grouping analyses sub-grouping in terms of a set of two and two factor interdependence; two and four factor interdependence, 2 – three behavioural factor interdependence and one implementation factors in each term.
8. Similarly, the eighth grouping analyses subgrouping in terms of a set of two and five behavioural factor interdependence, three and four behavioural factor interdependence and seven behavioural factor interdependence.

CONSTRUCTION SAFETY MANAGEMENT SYSTEM INDEX

Numerical evaluation index as defined in the equation 2 is used for the evaluation as it contains all the attributes and their relative importance. The numerical value of the permanent function gives the overall numerical evaluation index. As the permanent function contains only positive values, so higher the value of the inheritance level (D_i) and the relative importance (D_{ij}), higher will be the value of numerical evaluation index. To get the appropriate value of the numerical evaluation index, value of D_i and D_{ij} should be chosen judiciously through detailed discussions among the practitioners. This information may be qualitative or quantitative in nature. In case, the quantitative value is not available for the D_i, then a ranked value judgment on a scale i.e. 0 to 1 is adopted. Further, the information available for different Di’s may have difference nature and carry different kind of units. In such cases, it is desirable to normalize the quantitative values of the Di’s on the same scale as the qualitative values i.e. 0 to 1. Since the nature of the Di’s plays an important role during the process of normalization, it is advisable to categorize the benefit type and cost type attributes prior to normalization. An attribute can be considered as benefit type of attribute, if its positive variation results in increase of the permanent function and vice-versa. Similarly, an attribute can be considered as the cost type attribute, if its positive variation results in decrease in the value of the permanent function and vice-versa. For example, if an attribute is of benefit type i.e. increase or decrease in the attribute value contributes in the same sense as that of the objective or index of the problem then the assigned values (Di’s) within the limits of 0-1 are normalized using the relation:

$D_i = (10/D_{iu})*D_{ii}$ for $D_{ii}=0$

and

$D_i = \{10/(D_{iu}-D_{il})\}*(D_{ii}-D_{il})$ for $D_{ii}>0$ (3)

Where

D_{il}= lowest range value of the attribute

D_{iu} : highest range value of the attribute

D_{ii}: value of the attribute (diagonal value in the matrix representation D(MxM), M is the order of the Matrix

However, if the attribute is of cost type, then the normalization of the attribute value is generally done over range of 0-0.5 by using the following relation:

$D_i = 10(1-D_{ii}/D_{iu})$ for D_{ii}=0 and

$D_i= \{10/(D_{iu}-D_{il})\}*(D_{iu}-D_{ii})$ for $D_{ii}>0$ (4)

Where notations have their usual meanings. **Table 1** suggests the equivalent value over a scale of 0-1 for the qualitative measure of an attribute.

TABLE 1: INHERITANCE NORMALIZED VALUES OF ATTRIBUTES

Qualitative measure of attributes	Assigned value of the attributes (Di)
Exceptionally low	0.05
Extremely low	0.1
Very low	0.2
Low	0.3
Below normal	0.4
Normal	0.5
Above normal	0.6
High	0.7
Very high	0.8
Extremely high	0.9
Exceptionally high	0.95

Similarly, the relative importance between the two characteristics or attributes is also assigned a value on a scale of 0-1 and is arranged into classes as mentioned in Table 2.

Table. 2. Relative Importance of the Attributes

Sl. No.	Class description	Relative importance	
		a_{ij}	a_{ji} = 1- a_{ij}
1	Two attributes are equally important	0.5	0.5
2	One attribute (i) is slightly more important over the other (j)	0.6	0.4
3	One attribute (i) is strongly important over the other (j)	0.7	0.3
4	One attribute (i) is very strongly important over the other (j)	0.8	0.2
5	One attribute (i) is extremely important over the other (j)	0.9	0.1
6	One attribute (i) is exceptionally more important over the other (j)	1.0	0.0

Due to complexity of the system as a whole, it becomes infeasible to calculate the relative inter- dependency of one attribute over the other. However, for simplicity, a relationship has been suggested in the literature for such cases which assigns the relative importance of ith attribute over jth attribute and vice-versa as under:

$$\left.\begin{aligned} D_{ij} &= 1 - D_{ji} \\ D_{ji} &= 1 - D_{ij} \end{aligned}\right\} \qquad (5)$$

The construction safety management system index for each type of available Construction safety management system is evaluated by using equation (2) by substituting the values of Di's and Dij's. The Construction safety management systems may be arranged in the ascending order or descending order of the evaluated Construction safety management system index. The construction safety management system which has highest quality index is considered to be the best choice as per the qualitative standards. Since, the graph theoretic approach as adopted can incorporate more number of attributes during the modeling and matrix representation of the Construction safety management systems; it becomes easier to upgrade such systems with modifications in the attribute constraints represented in matrix form.

IDENTIFICATION AND COMPARISON OF CONSTRUCTION SAFETY MANAGEMENT SYSTEMS

The construction safety management system function is useful for identification and comparison of construction safety management systems for a given set of performance ascertaining attributes. The number of terms in each grouping of the construction safety management system function for all kind of construction safety management systems for a given set of such attributes will be same. However, their values will be different. Construction safety management systems may be similar from the qualitative aspects, if their system quality attribute digraphs are isomorphic. Two such digraphs are isomorphic, if they have identical permanent function matrix set representation. This means not only the number of terms in the groupings as well as sub-grouping as same but also their values are also same. Based on this, system quality identification set of the construction safety management systems is represented as:

$$[(J_1^T /J_2^T /J_3^T /J_4^T /J_{51}^T /J_{52}^T /J_{61}^T /J_{62}^T /J_{71}^T /J_{72}^T /J_{73}^T /J_{74}^T /J_{81}^T/J_{82}^T /J_{83}^T /J_{84}^T) (V_1^T /V_2^T /V_3^T/V_4^T /V_{51}^T /V_{52}^T /V_{61}^T /V_{62}^T /V_{71}^T /V_{72}^T /V_{73}^T /V_{74}^T /V_{81}^T /V_{82}^T/V_{83}^T /V_{84}^T] \qquad (6)$$

Where J_i^T represents the total number of terms in the 'ith grouping, J_{ij}^T represents the total number of terms of the Jth sub-grouping in the ith grouping. Similarly, V_i^T represents the numerical value the 'ith grouping and V_{ij}^T represents the numerical value of the jth sub-grouping in the ith grouping. Numerical values of the D_i's and D_{ij}'s are substituted in the sub-grouping or the grouping to obtain the permanent construction safety management system index.

II. METHODOLOGY

The graph theoretic approach evaluates the permanent qualitative index of a construction safety management system in terms of single numerical index, which takes into account the all qualitative measures and their interdependencies while analyzing and evaluating the system. The various steps of the proposed approach, which would be helpful in evaluation of the permanent qualitative index of the construction safety management systems, are enlisted in sequential manner as below:

1. Identify the various characteristics or the broad attributes of the construction safety management system which are responsible for defining the system quality as a whole. On the basis of application domain and the operational constraints, different types of construction safety management systems may have different characteristics or the attributes specifying its quality.

2. Classify the various characteristics or the attributes into clusters such that each cluster of attributes represents or exhibits a common set of characteristics of the system pertaining to its quality. These clusters may be treated as groupings and the constituent attributes of these clusters may be termed as factors or subsystems responsible for performance or response of the grouping.

3. Logically develop a diagraph between the factors as well as the broad attributes or the characteristics depending upon their interdependencies.

4. Develop a variable permanent function matrix at the system level on the basis of digraph developed in step 3.

5. Identify the subfactors affecting each factor.

6. For each factor, develop the digraph among the subfactors based on the interactions among them.

7. Develop a variable permanent matrix at the subsystem level for each factor on the basis of subfactors level digraphs developed in step 6.

8. Using the logical values of the quality measures as well as their interdependencies, obtain the permanent functions at the system as well as subsystem level. The off- diagonal elements of the matrix representation may be obtained from the graphs, knowledge database interpretation or from the excerpts of the expert's opinion.

9. Evaluate the permanent of the variable permanent function at the macro system level i.e. construction safety management system using the permanent functions developed at system level. This permanent has been obtained by analyzing, retrieving and processing the qualitative data of the gas turbine systems without losing any information as per the combinatorial practices of graph theory.

10. Various construction safety management systems can be compared on the basis of permanent system quality index thus obtained. Necessary improvement strategies may be implemented ahead for enhancing the quality of the construction safety management system.

EXAMPLE

To demonstrate the proposed benchmarking index evaluation of the construction safety management systems, an illustrative example is given in the following sections. In this example, the graph theoretic based construction safety management system quality evaluation has been carried out for the qualitative attributes of the construction safety management system. The broad performance characteristics of the construction safety management system have been used to model and analyze the qualitative aspects of the system. A comparison has been made for the qualitative similarity and dissimilarity of the construction safety management systems has also been carried out. The various steps of the methodology adopted are described as below:

1. First, the various characteristics of the construction safety management system have been identified which decides the quality of the construction safety management system and various contributing factors that give the required characteristic of the construction safety management system. The various characteristics as identified are same as mentioned in construction safety management system digraph representation. These are Project associated Costs (PAC), Unrealistic Project schedules (UPS), Supervisory competency (SPC), Manpower skills (MPS), Upkeepment of equipment (UKE), Inadequate safety devices (ISD) and Degraded Building material (DBM).

2. During the characteristics based evaluation, each and every characteristics of the system acts as an attribute. Each characteristic itself represents a cluster of sub-attributes or the subfactors which contribute to the impact of that cluster or characteristic in the qualitative analysis of the construction safety management system. However, the criterion for approximating the inheritance of these characteristics towards qualitative evaluation of the said system is given in Table 1. Similarly, the qualitative dependence of the quality measures is also mentioned in Table 2.

3. In order to develop a logical digraph for all significant characteristics as the construction safety management system attributes, a typical construction safety management system is studied from Macroscopic level to Microscopic level i.e. construction safety management system level to sub-component level and the interdependency of the attributes or such characteristics are analyzed. The probable level of interdependency between the attributes is qualitatively expressed over the normalized scale using the contributing sense of the attribute(s) or the Characteristic(s) towards the desired objective function for benchmarking analysis.
On the basis of the operational strategies and expert's opinions, the level of quality measures of the construction safety management system attributes as well as their dependencies have been specified in Table 3. The graph theoretic representation of these quality characteristics or the attributes of the construction safety management system is already shown in Figure 1.

4. The digraph at the system level developed at step 3 is represented in matrix form, where the order of the matrix is the number of attributes responsible for quality characteristics of the system. The diagonal elements of this matrix are the inheritance values of the system quality characteristic attributes and the off- diagonal elements are the interdependency values of these attributes. Using Table 3 and equation (1), the equivalent matrix representation of the system quality characteristic diagraph is given as:

$$A = \begin{array}{c} \\ PAC \\ UPS \\ SPC \\ MPS \\ UKE \\ ISD \\ DBM \end{array} \begin{array}{c} \begin{array}{ccccccc} PAC & UPS & SPC & MPS & UKE & ISD & DBM \end{array} \\ \begin{bmatrix} 0.8 & 0.4 & 0.3 & 0.2 & 0.4 & 0.4 & 0.6 \\ 0.6 & 0.5 & 0.4 & 0.3 & 0.4 & 0.6 & 0.3 \\ 0.7 & 0.6 & 0.4 & 0.6 & 0.7 & 0.4 & 0.6 \\ 0.8 & 0.7 & 0.4 & 0.9 & 0.3 & 0.3 & 0.7 \\ 0.6 & 0.6 & 0.3 & 0.7 & 0.6 & 0.4 & 0.7 \\ 0.6 & 0.4 & 0.6 & 0.7 & 0.6 & 0.7 & 0.5 \\ 0.4 & 0.7 & 0.4 & 0.3 & 0.3 & 0.5 & 0.6 \end{bmatrix} \end{array} \quad (7)$$

5. The construction safety management system characteristics or the attributes are critically examined from the system level to its subsystem level (i.e. the component level) in the form of subfactors. These subfactors also contribute towards the achievement of maximum system quality through their characteristic normalized values placed in the system quality function matrix. The Table 4 enlists a number of such subfactors contributing towards impact of system characteristics:

6. These subfactors which affect the characteristic attributes have similar kind of inheritance as well as interdependency among each other as the quality characteristics of the construction safety management system have with respect to each other. The level of inheritance and interdependency of such subfactors is also evaluated using the same criteria as adopted for system attributes or quality characteristics.

In order to develop a logical digraph for a particular characteristic attribute, the rational interdependency of the subfactors affecting the system characteristic attribute is analyzed and a qualitative representation of such interdependencies is carried out using the same normalization techniques as used for the system characteristic attributes.

8. Since the variable permanent function matrix for the functional performance attribute is of the order of 7, the permanent for this function will contain 7! terms and is represented by equation (2). The permanent of the above subsystem permanent function is a numerical value and is responsible for judgment of inheritance factors of the main system quality attribute i.e. the functional performance. Similarly, the permanent related to other subsystem matrices are also calculated. In present case, the permanent value as calculated for the functional performance of the construction safety management system matrix is 5.145329 for a given set of attribute normalized set.

9. After normalizing and evaluating the weightage of inheritance of system characteristic attributes on the basis of their permanents obtained from the respective governing subsystem permanent functions, the permanent of the construction safety management system function matrix is obtained. The value of the permanent thus obtained is called construction safety management system benchmarking Index and is to be used further for the comparison of various construction safety management systems quality.

10. The identification set for the construction safety management system quality functions is represented as below: $[(J_1^T / J_2^T / J_3^T / J_4^T / J_{51}^T / J_{52}^T / J_{61}^T / J_{62}^T / J_{71}^T / J_{72}^T / J_{73}^T / J_{74}^T / J_{81}^T / J_{82}^T / J_{83}^T / J_{84}^T)\ (V_1^T / V_2^T / V_3^T / V_4^T / V_{51}^T / V_{52}^T / V_{61}^T / V_{62}^T / V_{71}^T / V_{72}^T / V_{73}^T / V_{74}^T / V_{81}^T / V_{82}^T / V_{83}^T / V_{84}^T]$: [(1/ 0/ 66/ 440/ 1485/ 2970/ 15940/ 19008/ 13860/ 83160/ 36960/ 110880/ 166320/ 399168/ 332640/ 570240/ ….terms in higher order subgroupings)(0.0037340357/ 0/ 0.1089119/ 0.3355173/ 1.009191/ 1.275905/ 4.623179/ 4.369334/ 3.554557/ 12.83652/ 4.29211/ 13.11733/ 16.65007/ 30.5394/ 19.08051/ 32.87354/ … sum of higher order subgrouping terms)] (8)

where Ji^T represents the total number of terms in the 'ith grouping, $J_{ij}{}^T$ represents the total number of terms of the jth subgrouping in the ith grouping. Similarly, Vi^T represents the numerical value the 'ith grouping and Vij^T represents the numerical value of the jth subgrouping in the ith grouping.

III. CONCLUSION

In the present work, a methodology for evaluation and benchmarking model of Construction safety management system is proposed. This is based on digraph and matrix methods by considering the significant characteristics of the Construction safety management system. The seven characteristics which parameterized the quality of the Construction safety management system are identified. The graph theoretical methodology consists of Construction safety management system digraph, Construction safety management system matrix and the Construction safety management system function. The Construction safety management system function is a realistic mathematical quality model. The matrix functions are representative function of the quality and are useful for the characterization, comparison, analysis and evaluation of the quality of such systems. The quality characterization and isomorphism are used for the comparison of the Construction safety management system based on performance parameters. The Construction safety management system index, which is the permanent value of the Construction safety management system matrix, is identified. The step by step procedure for the Construction safety management system evaluation is explained considering different cases. The methodology is explained by taking a typical example for a residential construction site issues. This procedure is not only useful for designers in the development of reliable and robust Construction safety management systems but also to diagnose the failures of such systems. This methodology has been appreciated by the experts of domain as a self assessment tool, since this tool provides sufficient information at various levels for analyzing such cases.

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