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STRUCTURAL ANALYSIS, MODELLING AND DEVELOPMENT OF ALOGRITHM OF A ROBOTIC SYSTEM

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ABSTRACT
This paper presents an efficient methodology for structural modelling and analysis of a robot selection system. The methodology is based on graph theory and is termed as Graph Theoretical Methodology (GTM). In one way, the graphical models i.e. structural digraphs have been prepared for a robot selection system considering various criteria and sub-criteria and their interdependencies which affect the evaluation and selection of the robots for any organization. On the other hand, mathematical models have been developed for conversion of structural digraphs into matrix form and then this matrix into a mathematical function called variable permanent function (VPF). The methodology finally leads to the structural identification and comparison of various robots.

1.0 INTRODUCTION
A relationship always exists between the structure of a system and its performance characteristics. Two such projects QSPR (quantitative structure properties relationship) and QSAR (quantitative structure activity relationship) are actively pursued all over the world. The robot selection for any industry is also a complex problem where a number of selection criteria and sub-criteria affect the selection of any robot. However, no methodology has been evolved till date for structural modelling and analysis wherein all criteria, sub-criteria and their relative importance are considered; the need arises and is proposed using graph theory.

1.1 LITERATURE REVIEW
Robot selection is a difficult decision for industrialists and researchers. Sugeno [1974] introduced the concept of fuzzy integral. Although the initial research was far from being application-oriented, fuzzy integrals have later been used in decision making. Kamali et al. [1982] looked at the problem from the point of view of selecting a robot from among other alternative means of production such as manual or hard auto machines. Hinson [1983] stated that the working environment of the robot is a major factor for selection of robots.
Huang and Ghandforoush [1984] presented a procedure for evaluation and selection of robots based on the investment and budget requirements. Goh [1997] had addressed the problem of robot selection using AHP (Analytical Hierarchy Process) to give a new direction for robot selection and used repeatability, cost, load capacity and velocity as selection criteria. Parkan and Wu [1999] dealt the problem of robot selection using OCRA(Operational Competitiveness Rating Analysis), DEA, utility model and TOPSIS(technique for Order Preference by Similarity to an Ideal Solution) .Layek and Lars [2000] solved the problem of robot's selection using DSS(Decision Support System) .Khouja et al. [2000] has addressed the problem of robot selection using Statistical approach to give a new direction for robot selection .Bhattacharya et al. [2004] used integrated AHP with QFD (Quality Function Deployment) for robot selection under requirement perspective.. Karsak [2008] introduced a decision model for robot selection based on quality function deployment (QFD) and fuzzy linear regression. Kumar and Garg [2010] developed a deterministic quantitative model based on the Distance Based Approach (DBA) method for evaluation, selection and ranking of robots. Chatterjee et al. [2009] attempted two methods 'VIsekriterijumsko KOmpromisno Rangiranje' (VIKOR) and 'ELimination and Et Choice Translating REality' (ELECTRE) and compared their relative performance for a given industrial application. However, VIKOR and ELECTRE methods are outranking methods, having no axiomatic foundation, and require comparatively more

computation. Devi [2011] used fuzzy VIKOR method in intuitionistic fuzzy environment for robot selection . Tao et al. [2012] applied an integrated multiple criteria decision making model applying axiomatic fuzzy set theory .
Karsak [2012] has addressed the problem of robot selection using fuzzy regression-based decision-making approach to give a new direction for robot selection .Vahdani et al. [2013] presented soft computing based on new interval-valued fuzzy modified multi-criteria decision-making method (Fuzzy TOPSIS). The evaluation and selection of robots is mainly dependent on different criteria and sub-criteria e.g. robot type (articulated, SCARA, etc.), degrees of freedom, pay load, horizontal reach, vertical reach, repeatability, power supply, program steps, memory size, control system and cost etc. which directly or indirectly affect the selection process. Therefore, the structural analysis becomes very important and essential which is mainly dependent on the proper identification of these criteria and sub-criteria and their relative importance.

1.2 STRUCTURAL ANALYSIS

In the present paper, the structural analysis of robot selection system is being carried out using a unified and efficient structural approach called GTM (Graph Theoretical Methodology). It is important to consider only the physical structure to explain the methodology in detail. For further analysis in which the abstract structure is necessary, the abstract structure with / without physical structure is considered. The methodology of arriving at an optimal selection is complex not only because of the arithmetic involved but also because of many qualitative judgments. Further, the complexity also increases due to increase in number of the contributing selection criteria/sub-criteria.

2.0 METHODOLOGY

2.1.1 Graph Theory

In order to evaluate the influence of various criteria and sub-criteria on robot selection, a model is developed using Graph Theory. Graph Theory serves as a mathematical model of any system that includes multiple relations among its constituent elements because of its diagrammatic representations and aesthetic aspects. Graph Theory is a subject of combinatorial mathematics and draws a lot from matrix theory. It consists of the digraph representation, matrix representation and permanent function representation. The digraph is the visual representation of the factors and their interdependencies which affects the performance measure. The matrix converts the digraph into mathematical form. The permanent function is a mathematical model that helps to determine numerical value, called performance index.
Graph theoretic approach assumes systems perspective and considers various factors/ nodes and interdependencies among them. It is a three stage unified system approach.

1. Modelling of systems in terms of nodes and edges gives a structural representation to the system and results in a directed graph. This representation is suitable for visual analysis and understanding the interrelationships among various nodes.
2. For further analysis, digraph representation is converted to matrix form, which makes it suitable for computer processing. However the matrix representation is not unique as changing the labelling of nodes can change it.
3. Analysis of matrix model results in permanent function model, which is in the expression form. The permanent function model analyse various combinations among the factors and their interrelationships. Simplified permanent function expression is represented in terms of a single numerical index.

In this work a methodology for the structural analysis and modelling of a robot selection system is presented. In this methodology, a system is analyzed developing the following models in succession:

1 *Graphical Model*
2 Mathematical Model

2.1.1.1 Graphical Model

Graphical Model of the system is developed for its evaluation and analysis in terms of its characteristics using graph theory. Graph Theory has been used extensively in various disciplines. Agrawal and Rao [1987, 1989]; Gandhi and Agrawal [1994]; Garg et al. [2007], etc. have solved different types of real life problems using this theory. They presented models for these problems using graph theory and later analyzed them on a computer.

2.1.1.2 Digraph Representation

A system is defined as a set of interconnected elements. The elements here mean replaceable units i.e. criteria and sub-criteria affecting the evaluation and selection of robots. The system structure is modeled by structure digraph (SG_s). Mathematically, $SG_s = [V_i, E_i]$, where V_i is a node and E_i is an edge. The nodes and the edges are shown in the structure digraph by circles and the straight lines, respectively. The nodes correspond to the criteria/sub-criteria and the edges correspond to the interdependencies between them. In this section, it is proposed to consider only the physical structure to explain the concept of graph theory. The system structure digraph is a graphical representation of the system. The complexity of the structure digraph increases with an increase in the number of subsystems i.e. robot selection criteria/sub-criteria in a system. This also complicates the visual understanding of the structure digraph. A structure digraph corresponding to 3 – criteria is shown in Fig. - 1.1.

The subsystem structure is also modeled by its corresponding structure digraph similar to that of system structure digraph as explained above. It is represented by SG_{ss} and mathematically as: $SG_{ss} = [V_j^*, E_j^*]$, where V_j^* is a node and E_j^* is an edge that represents the sub-criterion and its connectivity, respectively.

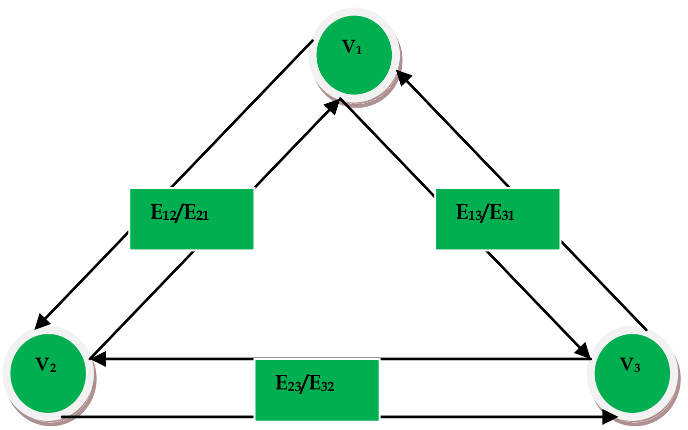


Fig. 1.1 Three Criteria Structure Digraph

2.2.1.3 Mathematical Model

Digraph is a useful entity for representation and visual analysis of a system but not suitable for computer processing. To overcome this problem, the mathematical models of the system are developed using matrix methods. In mathematical modeling, the digraph is represented by an equivalent matrix for developing an algebraic algorithm. Matrices lend themselves easily to mechanical manipulations. Hence the expressions for the analysis and for evaluating the characteristics of a given system (or subsystem) are obtained. Various matrices of the digraph have been defined on the lines of graph theory, Deo [1974] leading to the development of the structural model.

2.3.1.4 Matrix Representation

This matrix, known as variable permanent matrix, is a variant of the structure digraph and is suitable for automatic computation, storage and retrieval of information. The variable permanent matrix corresponding to the structure digraph with 'N' number of nodes is written as given in 1.1.

The elements of a variable permanent matrix, if constructed for a criterion shall represent the characteristics of the sub-criteria and their interdependencies and so on.

$$\begin{bmatrix} V_1 & E_{12} & E_{13} & E_{14} & - & - & E_{1N} \\ E_{21} & V_2 & E_{23} & E_{24} & - & - & E_{2N} \\ E_{31} & E_{32} & V_3 & E_{34} & - & - & E_{3N} \\ E_{41} & E_{42} & E_{43} & V_4 & - & - & E_{4N} \\ - & - & - & - & - & - & - \\ - & - & - & - & - & - & - \\ E_{N1} & E_{N2} & E_{N3} & E_{N4} & - & - & V_N \end{bmatrix} \quad (1.1)$$

2.3.1.5 Variable Permanent Function (VPF)

Both digraph and matrix representations are not unique as they changes by changing the numbering of nodes. To develop a unique representation, a permanent function of the variable permanent matrix is proposed. Permanent is a standard matrix function and is used in combinatorial mathematics, Jukrat [1996]. The permanent function is obtained in a similar manner as its determinant but with all signs positive. The computation process results in a multinomial whose every term has a physical significance. This multinomial representation includes all the information regarding selection criteria and is called variable permanent function of robot selection system, also known as permanent of C (Per C). It is a mathematical expression in symbolic form which considers the presence of all selection criteria and their interdependencies for performance evaluation of robots in terms of a numerical index. The variable permanent function of an N^{th} order square matrix with diagonal elements as V_i's and non-diagonal elements as E_{ij}'s, where i, j = 1, 2, 3, ……N, is written as:

$$\begin{aligned}
\text{VPF} \quad &= f_1 (V_1, V_2, \ldots, V_N) \\
&+ f_2 (0) \\
&+ f_3 (L_2, V_1, V_2, \ldots\ldots\ldots, V_{N-2}) \\
&+ f_4 (L_3, V_1, V_2, \ldots\ldots\ldots, V_{N-3}) \\
&+ f_5 (L_4, V_1, V_2, \ldots\ldots\ldots, V_{N-4}) \\
&+ f_6 (L_5, V_1, V_2, \ldots\ldots\ldots, V_{N-5}) \\
&: \\
&: \\
&+ f_N (L_{N-1}, L_{N-3}, \ldots\ldots\ldots, L_2, V_1) \\
&+ f_{N+1} (L_N, L_{N-2}, \ldots\ldots\ldots, L_2)
\end{aligned} \quad (1.2)$$

Here, Vi and Li represents the characteristic structural feature of the i^{th} criteria and its connectivity loop, respectively. The VPF of a criterion can also be defined on the same line and this process can be extended further for sub-criterion, sub sub-criterion etc. The variable permanent function for 'N' number of selection criteria is written in sigma form as:

$$\begin{aligned}
\text{Per}\, C = &\prod_{i=1}^{N} V_i + \sum_i \sum_j \sum_k \sum_l \ldots\ldots \sum_N \left(E_{ij}E_{ji}\right) V_k V_l V_m \ldots\ldots V_N \\
&+ \Big(\sum_i \sum_j \sum_k \sum_l \ldots\ldots \sum_N \left(E_{ij}E_{jk}E_{ki}\right) V_l V_m \ldots\ldots V_N \\
&+ \sum_i \sum_j \sum_k \sum_l \ldots\ldots \sum_N \left(E_{ik}E_{kj}E_{ji}\right) V_l V_m \ldots\ldots V_N \Big) \\
&+ \Big(\Big\{ \sum_i \sum_j \sum_k \sum_l \ldots\ldots \sum_N \left(E_{ij}E_{ji}\right)\left(E_{kl}E_{lk}\right) V_m V_n \ldots\ldots V_N \Big\} \\
&+ \Big\{ \sum_i \sum_j \sum_k \sum_l \ldots\ldots \sum_N \left(E_{ij}E_{jk}E_{kl}E_{li}\right) V_m V_n \ldots\ldots V_N \\
&+ \Big(\sum_i \sum_j \sum_k \sum_l \ldots\ldots \sum_N \left(E_{il}E_{lk}E_{kj}E_{ji}\right) V_m V_n \ldots\ldots V_N \Big\} \Big) \\
&+ \Big(\Big\{ \sum_i \sum_j \sum_k \sum_l \ldots\ldots \sum_N \left(E_{ij}E_{ji}\right)\left(E_{kl}E_{lm}E_{mk}\right) V_n V_o \ldots\ldots V_N
\end{aligned}$$

$$+\sum_i\sum_j\sum_k\sum_l........\sum_N\left(E_{ij}E_{ji}\right)\left(E_{km}E_{ml}E_{lk}\right)V_nV_o........V_N\}$$

$$+\left\{\sum_i\sum_j\sum_k\sum_l........\sum_N\left(E_{ij}E_{jk}E_{kl}E_{lm}E_{mi}\right)V_nV_o.........V_N\right.$$

$$+\sum_i\sum_j\sum_k\sum_l........\sum_N\left(E_{im}E_{ml}E_{lk}E_{kj}E_{ji}\right)V_nV_o.........V_N\}) \tag{1.3}$$

3.1 STRUCTURAL MODELLING OF ROBOT SELECTION SYSTEM

To meet the objectives and to carry out structural analysis, the robot selection system is given a typical hierarchical structure identifying various selection criteria and sub-criteria. In the present thesis the whole robot selection system is divided into two levels i.e. criteria level and sub-criteria level. The criteria considered are ‘Physical and General’, ‘Static Performance Characteristics’, ‘Dynamic Performance Characteristics’, ‘Robotic Architecture’, ‘Operating Environment’, ‘Instrumentation and control system, and ‘Application’. The hierarchical structure is shown in Fig. - 1.2.

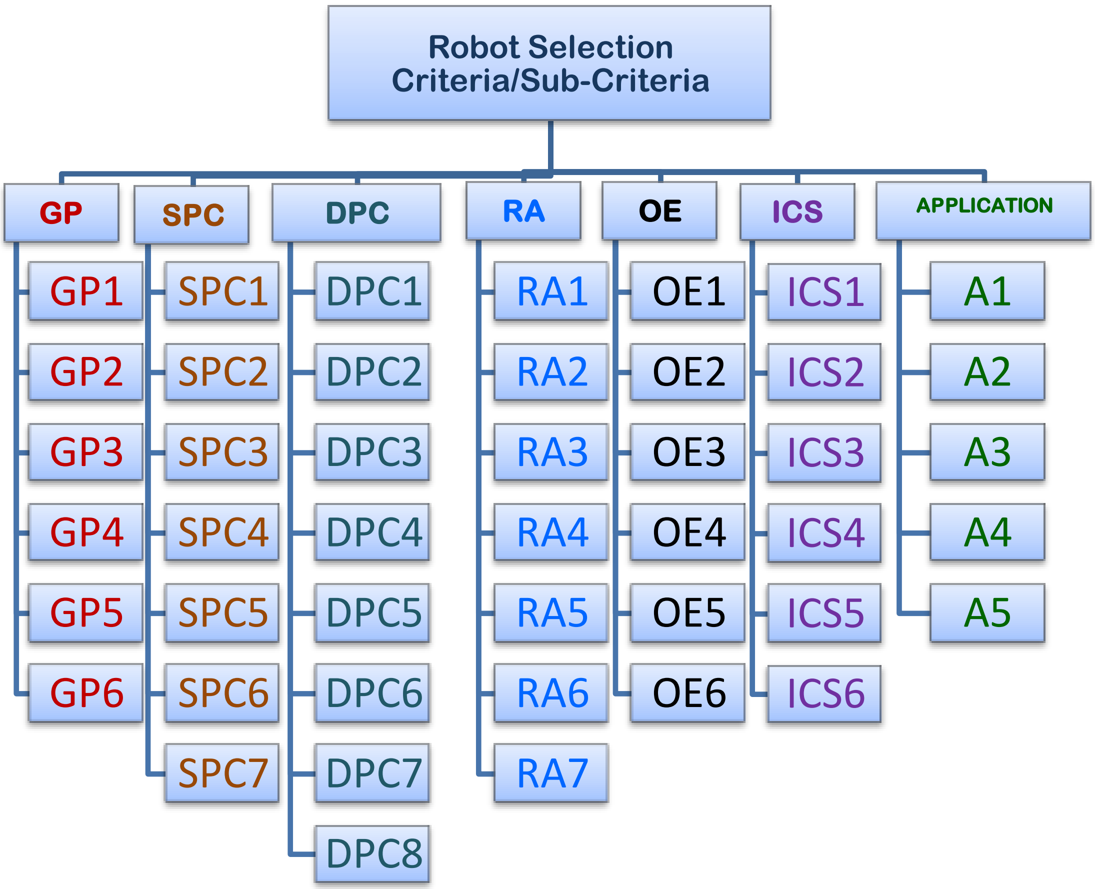


Fig. 1.2 Hierarchical Structure of a Robot Selection Criteria/Sub-Criteria

The abbreviations used in Fig. – 1.2 is detailed as under:

Abbreviations used for Selection Criteria

GP	General and Physical
SPC	Static Performance Characteristics
DPC	Dynamic Performance Characteristics
RA	Robotic Architecture
OE	Operating Environment

ICS	Instrumentation and Control Systems

Abbreviations used for Selection Sub-Criteria

GP1	Cost	RA3	Axis Motion Range (J2)
GP2	Robot Type	RA4	Axis Motion Range (J3)
GP3	Life Expectancy	RA5	Axis Motion Range (J4)
GP4	Warranty Period	RA6	Axis Motion Range (J5)
GP5	Reliability	RA7	Axis Motion Range (J6)
GP6	Vendor’s Service	OE1	Compliance
SPC1	Robot Mass(Kg)	OE2	Ambient Temperature
SPC2	Repeatability(±mm)	OE3	Ambient Humidity
SPC3	Load Capacity(Kg)	OE4	Vibration
SPC4	Memory Capacity	OE5	Protection Level
SPC5	Positioning Accuracy	OE6	Safety Features
SPC6	Degrees of Freedom	ICS1	Programming Methods
SPC7	Precision/Resolution	ICS2	Man Machine Interface
DPC1	Vertical Reach(mm)	ICS3	Type of Drive
DPC2	Horizontal Reach	ICS4	Control System
DPC3	Speed of Travel(JI))	ICS5	Path Control System
DPC4	Speed of Travel (J2)	ICS6	Sensors
DPC5	Speed of Travel (J3)	A1	Material Handling
DPC6	Speed of Travel (J4)	A2	Welding
DPC7	Speed of Travel (J5)	A3	Assembly
DPC8	Speed of Travel (J6)	A4	Dispensing
RA1	Arm Geometry	A5	Processing
RA2	Axis Motion Range (JI)		

$$
\begin{aligned}
VPF/Per(c) = {} & \prod_{i=1}^{6} A_i \\
& + \sum_{i=1}^{5}\sum_{j=i+1}^{6}\sum_{k=1}^{3}\sum_{l=k+1}^{4}\sum_{m=l+1}^{5}\times\sum_{n=m+1}^{6}(a_{ij}a_{ji})A_kA_lA_mA_n \\
& + \sum_{i=1}^{4}\sum_{j=i+1}^{5}\sum_{k=j+1}^{6}\sum_{l=1}^{4}\sum_{m=l+1}^{5}\times\sum_{n=m+1}^{6}(a_{ij}a_{jk}a_{ji})A_lA_mA_n \\
& + \Bigg(\sum_{i=1}^{3}\sum_{j=i+1}^{6}\sum_{k=i+1}^{5}\sum_{l=i+2}^{6}\sum_{m=1}^{5}\times\sum_{n=m+1}^{6}(a_{ij}a_{ij})(a_{kl}a_{lk})A_mA_n \\
& \quad + \sum_{i=1}^{3}\sum_{j=i+1}^{5}\sum_{k=i+1}^{6}\sum_{l=j+1}^{6}\sum_{m=1}^{5}\times\sum_{n=m+1}^{6}(a_{ij}a_{jk}a_{kl}a_{li}+a_{il}a_{lk}a_{kj}a_{ji})A_mA_n\Bigg) \\
& + \Bigg(\sum_{i=1}^{4}\sum_{j=i+1}^{5}\sum_{k=j+1}^{6}\sum_{l=1}^{5}\sum_{m=l+1}^{6}\times\sum_{n=1}^{6}(a_{ij}a_{jk}a_{ki}+a_{ik}a_{kj}a_{ji})(a_{lm}a_{lm})A_n \\
& \quad + \sum_{i=1}^{2}\sum_{j=i+1}^{5}\sum_{k=i+1}^{6}\sum_{l=i+1}^{6}\sum_{m=j+1}^{6}\times\sum_{n=1}^{6}(a_{ij}a_{jk}a_{kl}a_{lm}a_{mi}+a_{im}a_{ml}a_{lk}a_{kj}a_{ji})A_n\Bigg) \\
& + \Bigg(\sum_{i=1}^{3}\sum_{j=i+1}^{5}\sum_{k=i+1}^{6}\sum_{l=j+1}^{6}\sum_{m=1}^{5}\times\sum_{n=m+1}^{6}(a_{ij}a_{jk}a_{kl}a_{li}+a_{il}a_{lk}a_{kj}a_{ji})(a_{mn}a_{nm}) \\
& \quad + \sum_{i=1}^{1}\sum_{j=i+1}^{5}\sum_{k=j+1}^{6}\sum_{l=1}^{4}\sum_{m=l+1}^{5}\times\sum_{n=1}^{6}(a_{ij}a_{jk}a_{ki}+a_{ik}a_{kj}a_{ji})(a_{lm}a_{mn}a_{nl}+a_{ln}a_{nm}a_{ml}) \\
& \quad + \sum_{i=1}^{1}\sum_{j=i+1}^{6}\sum_{k=i+1}^{3}\sum_{l=i+2}^{6}\sum_{m=k+1}^{5}\times\sum_{n=k+2}^{6}(a_{ij}a_{ji})(a_{kl}a_{lk})(a_{nm}a_{mn}) \\
& \quad + \sum_{i=1}^{1}\sum_{j=i+1}^{5}\sum_{k=i+1}^{6}\sum_{l=j+1}^{6}\sum_{m=i+1}^{6}\times\sum_{n=j+1}^{6}(a_{ij}a_{jk}a_{kl}a_{lm}a_{mn}a_{ni}+a_{in}a_{nm}a_{ml}a_{lk}a_{kj}a_{ji})\Bigg)
\end{aligned}
\tag{1.4}
$$

The structural digraph of the robot selection system for its first level i.e. considering the selection criteria only is drawn and given in Fig. - 1.3. The variable permanent function for this structural digraph can be written in a concise form as given in Eq. - 1.4.

Equation 1.4 is the complete expression for the considered robot selection system, as it considers the presence of all criteria and all of the possible relative importance between the criteria. The terms are the sets of distinct diagonal elements and loops of off-diagonal elements of different sizes (E_{ij} E_{ji}; E_{ij} E_{jk} E_{ki}; E_{ij} E_{jk} E_{kl} E_{li}; etc.). As already explained this expression is nothing but the determinant of 6×6 matrix but considering all the terms as positive terms. A general expression of Variable Permanent Function for 'n' number of nodes is written as given in Eq. – 1.3.

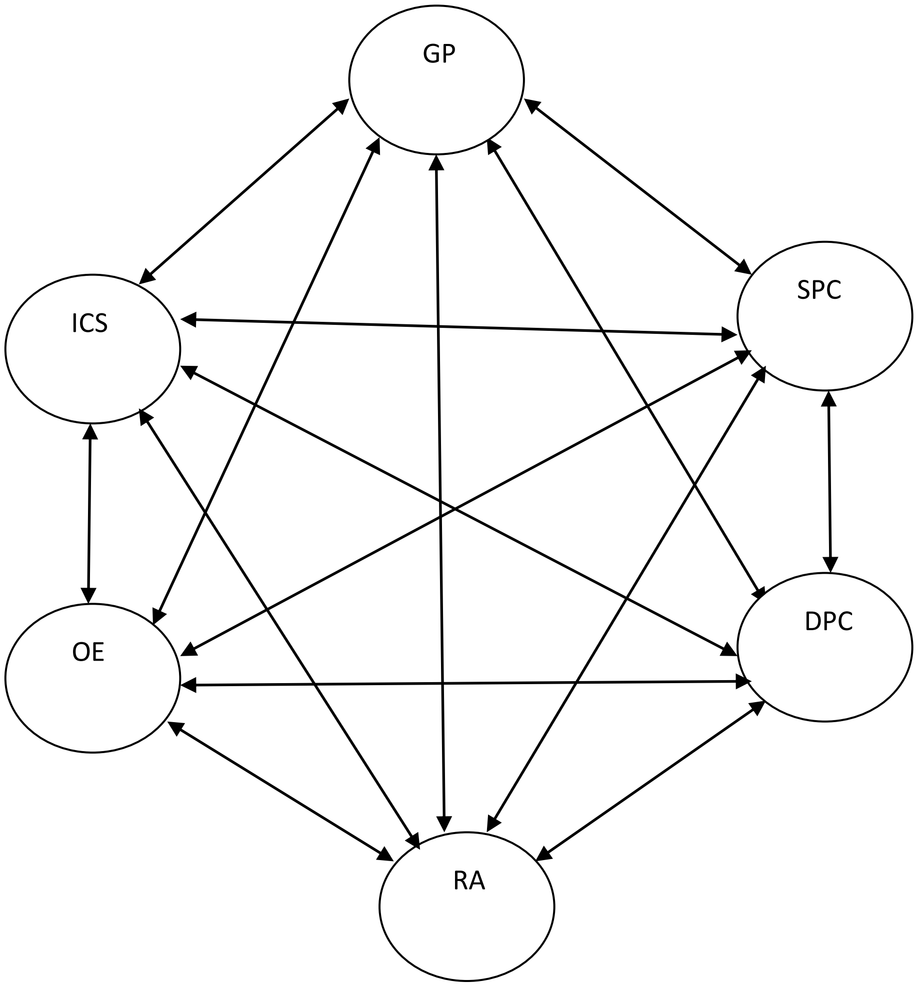


Fig. 1.3 Criteria Based Structural Digraph of a Robot Selection System

4.1 STRUCTURAL ANALYSIS

As explained earlier, the variable permanent function (VPF) represents the characteristics of the robot selection system and thus becomes a powerful tool for carrying out the structural analysis of a robot selection system. The terms in the polynomial function contain all possible structural information. Further, each of these terms yields useful information, if a term is interpreted as a set but not the product of structural components. This means that the system is analyzed in all possible ways in terms of its structural components. The physical meaning of the terms appearing in variable permanent function is interpreted as under:

Group - 1

The first group represents a set of structural features of the criteria and may be expressed as:

/ V_1 / V_2 / . . . . . . / V_N /

Group - 2

The second group shall be absent because the loops in the structure digraph for a criterion is not possible to be formed.

Group - 3

The third group represents a set of dyad of two criteria (E_{ij}^2) and characteristic structural features of the remaining criteria.

$/E_{12}^2/ V_3/ V_4/ V_5/ V_6/............/ V_N/$

Group - 4

The fourth group represents a set of structural loops of three criteria ($E_{ij}\ E_{jk}\ E_{ki}$), and characteristic structural features of the remaining criteria.

$/E_{12}\ E_{23}\ E_{31}\ / V_4/ V_5/ V_6/ ..../V_N/$

Group - 5

i. The first sub-group of the fifth grouping is a set of structural loops of four criteria ($E_{ij}\ E_{jk}\ E_{kl}\ E_{li}$), and characteristic structural features of the remaining criteria.
   $/E_{12}\ E_{23}\ E_{34}\ E_{41}\ / V_5/ V_6/ V_7/............/ V_N/$
ii. The second sub-group of the fifth group is a set of two structural dyads of two criteria (E_{ij}^2, E_{kl}^2), and characteristic structural features of the remaining criteria.
   $/E_{12}^2/ E_{34}^2\ / V_5/ V_6/ V_7/ ..../V_N/$

Group - 6

i. The first sub group of the sixth group is a set of structure loops of five criteria ($E_{ij}\ E_{jk}\ E_{kl}\ E_{lm}\ E_{mi}$), and characteristic structural features of the remaining criteria.
   $/E_{12}\ E_{23}\ E_{34}\ E_{45}\ E_{51}\ / V_6/ V_7/ ..../V_N/$
ii. The second sub group of the sixth group is a set of structure loops of three criteria ($E_{ij}\ E_{jk}\ E_{ki}$), a dyad of two criteria (E_{lm}^2), and characteristics structural features of the remaining criteria.
   $/E_{12}\ E_{23}\ E_{31}\ / E_{45}^2\ / V_6/ V_7/ ..../V_N/$

Group - 7

i. The first sub group of the seventh group is a set of structural loops of six criteria ($E_{ij}\ E_{jk}\ E_{kl}\ E_{lm}\ E_{mn}\ E_{ni}$), and characteristic structural features of the remaining criteria.
   $/E_{12}\ E_{23}\ E_{34}\ E_{45}\ E_{56}\ E_{61}\ / V_7/ V_8/............/V_N/$
ii. The second sub group of the seventh group is a set of structural loops of four criteria ($E_{ij}\ E_{jk}\ E_{kl}\ E_{li}$), a structural dyad of two criteria (E_{mn}^2), and characteristic structural features of the remaining criteria.
   $/E_{12}\ E_{23}\ E_{34}\ E_{41}\ / E_{56}^2\ / V_7/ V_8/............/V_N/$
iii. The third sub group of the seventh group is a set of three structural dyads, each of two criteria (E_{ij}^2, E_{kl}^2, E_{mn}^2), and characteristic structural features of the remaining criteria.
   $/E_{12}^2/E_{34}^2/E_{56}^2/V_7/V_8/............/V_n/$
iv. The fourth sub group of the seventh group is a set of two structural loops of three criteria ($E_{ij}\ E_{jk}\ E_{kl}\ E_{lm}\ E_{mn}\ E_{ni}$), and characteristic structural features of the remaining criteria.
   $/E_{12}\ E_{23}\ E_{31}\ /E_{45}\ E_{56}\ E_{64}/ V_7/ V_8/............/V_N/$ **(1.5)**

Here, slash notation is a separation mark between two criteria (entities). From the above, it is obvious that, in general, an i^{th} group contains the V_i's equal to (N+1-i). The number of remaining structural components (e.g., E_{ij}'s) shall be {N – (N+1-i)}. The terms of the expression are arranged in decreasing number of V_i's. The equation when expanded will contain N! terms means taking into account the maximum complexity of the robot selection system. The terms appearing in this expression when expanded can be arranged in (N+1) groups i.e. 7 groups for the present case. The physical meaning associated with each group can be interpreted on the similar lines as described above. Fig. - 1.4 present the structural digraphs of one term in each group. However, when there is a loop among four or more criteria, the loop shall be further divided in a number of possible sub-loops.

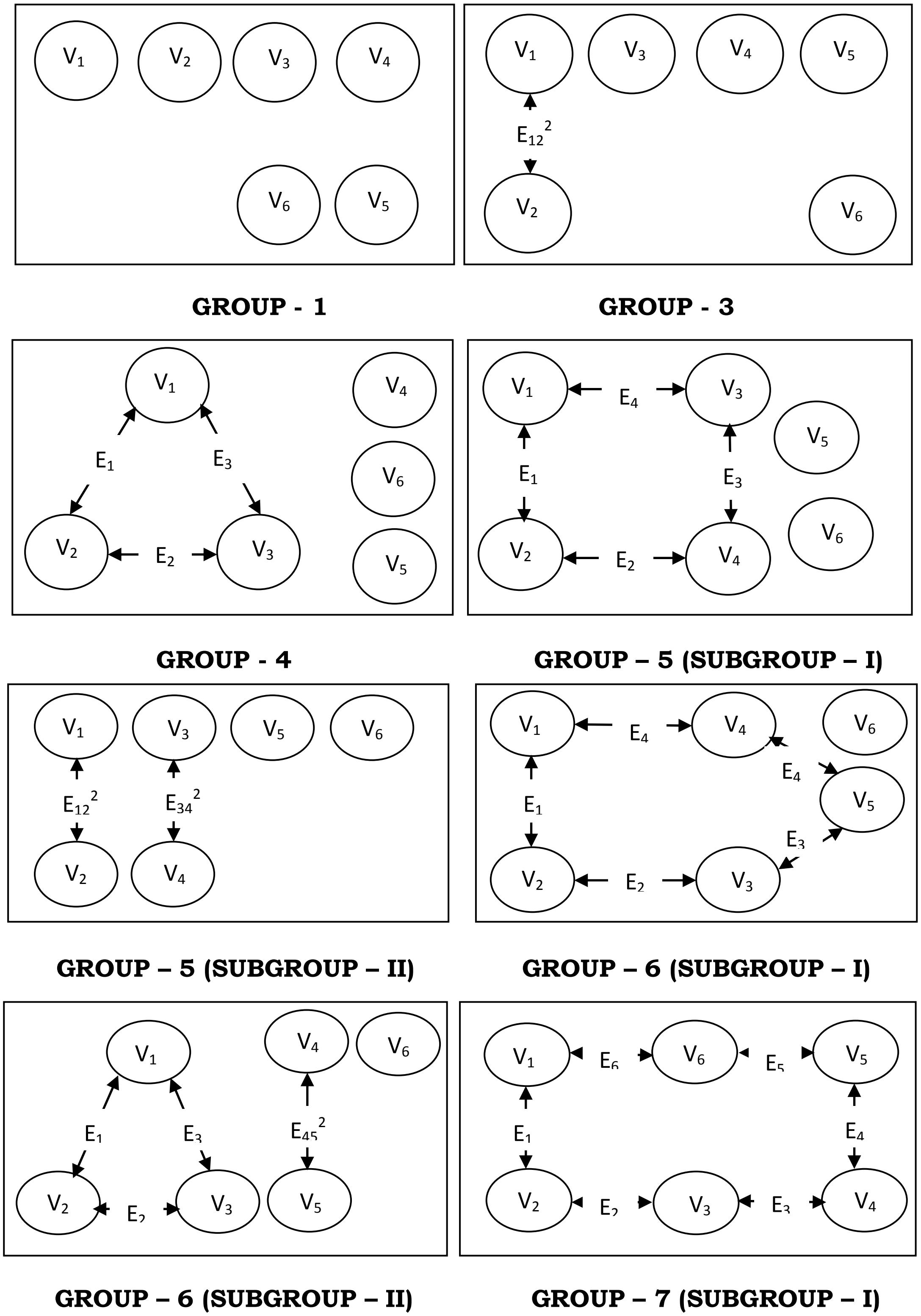
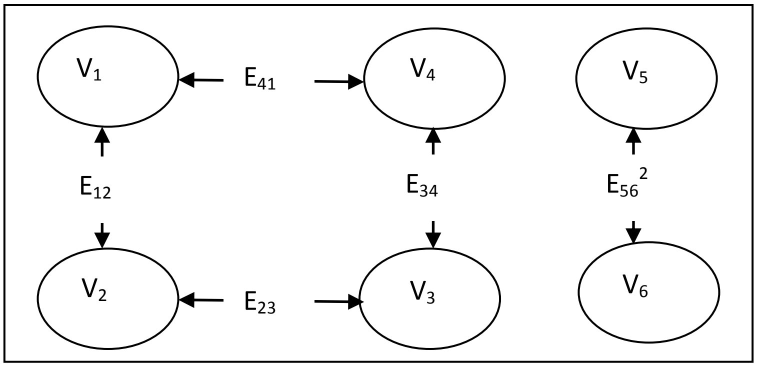
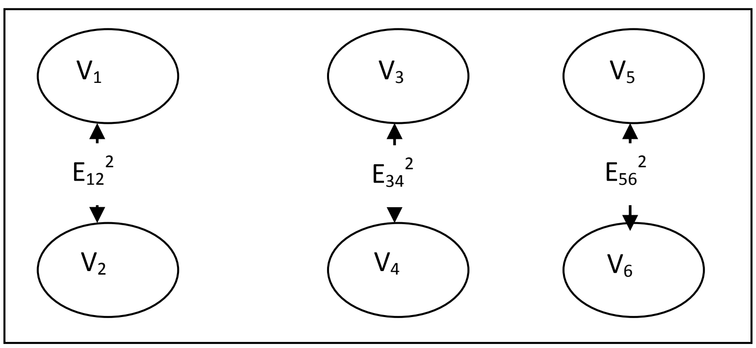


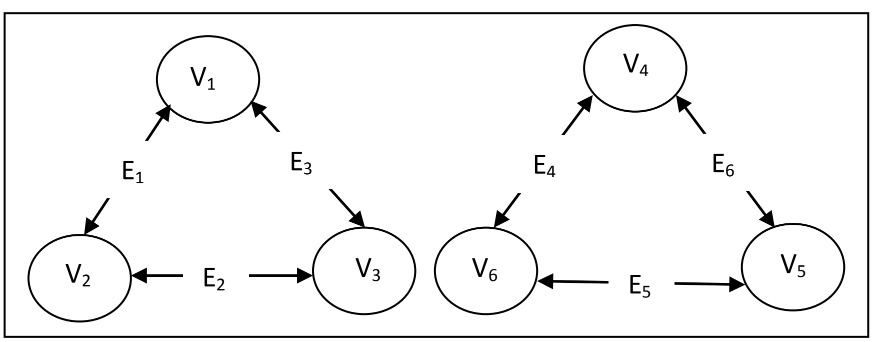
Fig. 1.4 Structural Digraph of Robot Selection System with 6-Criteria



GROUP – 7 (SUBGROUP – II)



GROUP – 7 (SUBGROUP – III)



GROUP – 7 (SUBGROUP – IV)

Fig. 1.4 Structural Digraph of Robot Selection System with 6-Criteria *(continued….)*

5.1 STRUCTURAL IDENTIFICATION AND COMPARISON

The structure identification of the robot selection system for an industry using robots and its comparison with other robot selection system is carried out by considering various terms appearing in the variable permanent function. Let j_{ij}^s represent the total number of terms of in j^{th} sub group of i^{th} group of VPF. In case, there is no sub group, then j_{ij}^s shall be same as that the total number of terms of i^{th} group. The sub-groups are arranged in decreasing order of the size of structural terms (e.g., E_{ij}'s) and so on. Based on this, structural identification set for robot selection system is given as:

$/J_1^s/J_2^s/J_3^s/J_4^s/J_{51}^s+J_{52}^s/J_{61}^s+J_{62}^s/J_{71}^s+J_{72}^s+J_{73}^s+J_{74}^s/$ (1.6)

This characterizes the complete structure of the robot selection system. Eq. – 1.6 may be used for comparison of two systems or a family of systems. Two systems are exactly similar (isomorphic) from structural point of view, if identification set for them are exactly the same. This means that the numbers of terms in each group/ sub-group are exactly the same. The values of j_{ij}^s and j_i^s are easily obtained either by visual inspection of the structure digraph or by simple calculations using closed form expression of variable permanent function (VPF).

Structural comparison of the robot selection system is carried out based on coefficient of similarity or dissimilarity. The coefficient is derived from VPF and provides a rational basis for comparison of structures of two robot selection systems or a family of robot selection systems. If a number of distinct terms in the j^{th} sub group of the i^{th} group of VPF of the two robot selection systems under consideration are denoted by J_{ij}^s and j_{ij}^s, then criterion 1 of coefficient of dissimilarity, Marcus and Minc [1965] is given as:

$$C_{d-1}^s = \frac{1}{y_1}\sum_i \sum_j \phi_{ij} \tag{1.7}$$

where, y_1 = maximum $\left[\sum_i\sum_j J_{ij}{}^s and \sum_i\sum_j J'{}_{ij}^s\right]$ (1.8)

When sub-groups are absents $J_{ij}^s = J_i^s$ and $J_{ij}^{'s} = J_i^{'s}$

Also $\varphi_{ij} = (J_{ij}^s - J_{ij}^{'s})$, when sub-groups exit and $\varphi_{ij} = (J_i^s - J_i^{'s})$, When sub-groups are absent.

Criterion 2 of coefficient of dissimilarity (C_{d-1}^s) is given as:

$$C_{d-2}^s = \left[\frac{1}{y_1}\sum_i \sum_j \phi^2{}_{ij}\right]^{1/2} \tag{1.9}$$

Where φ_{ij} is as described above, and

Y_2 maximum $\left[\sum_i\sum_j (J_{ij}{}^s)^2 and \sum_i\sum_j (J_{ij}{}^{'s})^2\right]$ (1.10)

When sub-groups do not exist, $J_{ij}^s = J_i^s$ and $J_{ij}^{'s} = J_i^{'s}$

Using Eqs. – 4.11 and 4.12, the coefficients of similarity ($C_{s-1}^s$and c_{s-2}^s) are given as:

$$C_{s-1}^s = 1 - C_{d-1}^s \tag{1.11}$$

$$C_{s-2}^s = 1 - C_{d-2}^s \tag{1.12}$$

From Eqs. - 1.7 to 1.12, it may be noted that coefficients of similarity and dissimilarity lie in the range of 0 to 1. If two systems have completely similar structure, their coefficient of similarity is one or coefficient of dissimilarity is zero. In case two systems are completely dissimilar, their coefficient of similarity is zero and coefficient of dissimilarity is one. These equations are also useful for comparison among family of systems and can be ranked based on the increasing or decreasing value of coefficient of similarity or dissimilarity. Using this approach, the optimum selection of a system with desired structure can be made among the possible alternatives.

6.1 ALGORITHM FOR STRUCTURAL MODELLING AND ANALYSIS

An algorithm for structural modeling and analysis of a robot selection system based on six criteria and forty sub-criteria has been prepared in accordance to the procedure developed using graph theory and as explained in previous section. The complete algorithm is presented in Fig. - 1.5.

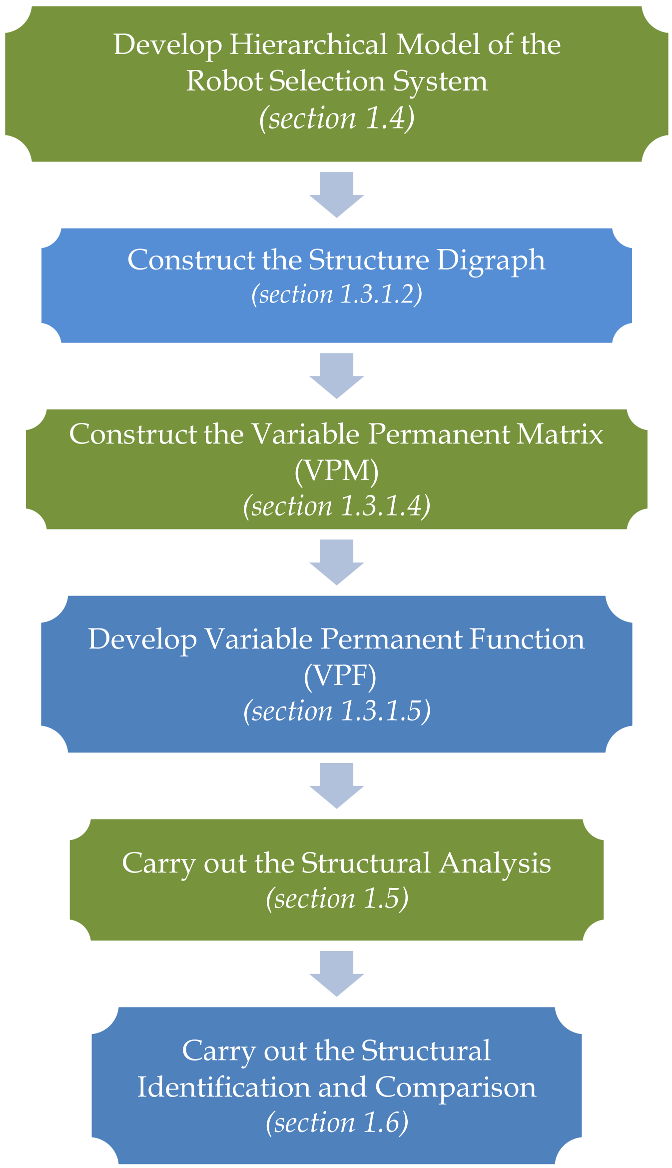


Fig. 1.5 Structural Modelling and Analysis Algorithm

7.1 CONCLUSION

The evaluation, selection and ranking of robots in general imply the identification and study of various selection criteria/ sub-criteria and their interactions considering in an integrated manner. The in-depth study of the structure of the robot is expected to lead to such a selection process that will be more reliable. Since, the criteria and sub-criteria are variable in nature; hence the evaluation and selection of robots may vary from one application to other application. The structural analysis of robot selection system is carried out using a structural approach called GTM (Graph Theoretical Methodology) by considering only the physical structure. Further where the abstract structure is necessary, the abstract structure with / without physical structure is considered. The methodology of arriving at an optimal selection is complex not only because of the arithmetic involved but also because of many qualitative judgments. The complexity also increases due to increase in number of the contributing selection criteria/sub-criteria. An algorithm for structural modeling and analysis of a robot selection system based on six criteria and forty sub-criteria has been prepared in accordance to the procedure developed using graph theory and is very helpful in development of software for evaluation and selection of industrial robots.

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