MODELING CAD PERFORMANCE WITH FUZZY COGNITIVE MAP

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ABSTRACT

This paper demonstrates how Fuzzy Cognitive Map (FCM) is used to model CAD performance in an engineering consultancy environment by simulating the effects of certain conditions and actions on CAD service quality. A knowledge base of CAD performance is built from expert knowledge that exists in the fuzzy linguistic domain. The knowledge is translated from a qualitative opinion scale to triangular fuzzy numbers ready for computation. It demonstrates that the knowledge captured and represented in a core CAD FCM can be stored and easily extended by the addition of sub-FCMs. Simulation of CAD performance using the FCM revealed its applicability in project management by providing the project manager with a tool to help her identify an optimal approach for dealing with CAD quality issues. It can thus, be an effective tool for engineering management and knowledge base building in an engineering environment.

Keywords : *CAD Performance, Engineering Management, Fuzzy Cognitive Map, Knowledge Engineering, Knowledge Representation*

INTRODUCTION

In the engineering consultancy industry, CAD*rafting* replaced manual drafting first, as a physical capital input to automate the drafting process and second, as a support to human capital. For cost-effective reasons, CAD has always comprised semi-skilled operators who perform the lower value-adding task (drafting) associated with design work. This manner of work decomposition is consistent with the method reviewed in [1]. As CAD operators are scarce resource, the situation has compelled those in CAD operations to optimise the utilisation of two different sets of skills, drafting and workstation techniques. Against the background of technological change, strong job segregation between CAD operators and design engineers continues to persist. Engineers will not draft for reasons of long learning duration against strict deadline pressure as cited in [2] and that drafting is intellectually less challenging than designing [1]. Thus, the line between designing and drafting continues to be drawn within the whole engineering design delivery process. The psychological separation between CAD operators and the design engineers as noted in [2] is further aggravated by the engineer's misconception of CAD arising from incomplete understanding of CAD's role in the design delivery process, and the capabilities and limitations of the CAD system for example, CAD's speed of delivery versus output quality. Experience has shown that the effectiveness of CAD operations is dependent on the manner of its resource deployment, assignment and the structuring of work tasks [1,3,4]. To resolve some of these management issues requires the project team to understand and to be familiar with CAD operations [1] and to make the needed adjustments, particularly in leading and in redefining the work relations between design engineers and CAD operators. Project managers should understand that developing social capital by teamwork could return huge benefits while accomplishing project goals simultaneously [2]. This social dimension [5] implemented by CAD-enabled communication methods [6] perhaps, will sustain the competitive advantage which companies have in the past, relied solely on the physical and human capital dimensions. To quote Robertson and Allen [6], *engineering is complex and communication-intensive work; communication is therefore central to an engineer's work.* There is a considerable body of evidence showing that technical communication leads to higher engineering performance [6].

The different perceptions of CAD pose some management problems that cannot be totally resolved within the CAD domain. From experience, many problems arose from other external causal factors in the domains of project management and project team perceptions and are psychological/attitudinal in nature. Project teams recognise that CAD drawings are a significant component in the service to their customers and they expect CAD drawings to be of high quality that consistently meet customers' requirements. However, they are less concerned about the problem that the CAD operators face in an environment where management just imposes tight quality control without contributing to effective CAD improvement strategies and without actively encouraging CAD-project team building. Any quality shortfall is promptly noticed in the drawings produced but the causes of such conditions are less apparent. For long-term CAD performance improvement, there is a need to identify the real causes, trace the propagation of their effects to CAD service quality and eliminate them at source. This can be done by presenting to the project teams, the impacts of their decisions and actions on CAD service quality through an understanding of the relationship between their causes and effects.

This paper describes an attempt to identify, in an engineering consultancy environment, the significant causes that affect CAD's quality of deliverables and their completion deadlines and to define their causal edges by constructing a fuzzy cognitive map (FCM) from the knowledge and experience of CAD operations. In recent years, FCM has found increasing use in the analysis of many ill-structured problems that involve cause-and-effect reasoning in a multi-dimensional mixture of subjective and objective causal discourse e.g. the modelling of organisational behaviour [7]. Here, the CAD FCM is a symbolic representation of the CAD operation knowledge base. An FCM of CAD performance can be used as a simulator for assessing how project team behaviour, decisions and organisation factors affect the quality of CAD service. The intention is to reveal through simulation the factors effecting CAD services so that managers become more aware of the consequences of their actions and hence, become more convinced to modify their management styles and techniques to suit particular situations. The FCM can also be used as part of the process of continuous improvement in the organisation's quality management system and in project manager/engineer training.

FUZZY COGNITIVE MAP (FCM)

An FCM as proposed by Kosko [8,9], is a weighted signed digraph with feedback that behaves as a one-layer associative neural network [10,12] and whose basis is the law of cause and effect. It employs the idea of fuzzy sets to represent vagueness in the concepts, which are connected by the strength of the edges. Using the idea of associative memories from neural networks, it stores information by virtue of the weights of the edges in a matrix and eliminates the indeterminacy problem [8] of signed graphs. A concept's value reflects the state or degree of activation of the concept in the system at a particular instant. An FCM symbolically represents structured knowledge in a way suited for qualitative inference by numerical matrix operation. Knowledge representation in an FCM is goal-directed and a solution obtained from it is as good as the knowledge stored in it.

FCMs are suited for ill-structured systems of high complexity that have many concepts (factors) connected by causal edges [8,9]. All the concepts in equilibrium represent the state of the system. The causal relations among them established by cause-to-effect edges, have signed directions of causality from a cause concept to an effect concept. Concept and edge numerical values represent their fuzzy/linguistic descriptions. A positive-signed edge value indicates (Figure 1) how much an increase (decrease) in a cause concept's degree of activation increases (decreases) an effect concept's degree of activation.

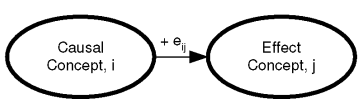


Figure 1: Simple FCM showing positive causality

A negative-signed edge value indicates (Figure 2) how much an increase (decrease) in a cause concept's degree of activation decreases (increases) an effect concept's degree of activation. After summing the activation levels to a concept node, a squashing function clamps its value to within a normalised range that represents its linguistic domain.

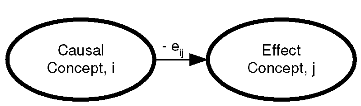


Figure 2: Simple FCM showing negative causality

Thus, FCMs combine the robust properties of fuzzy logic and neural networks to provide qualitative information about relationships. They have found applications in simulating dynamic systems in very diverse fields [26] using this powerful qualitative modelling technique, which is free from strict quantification of concept values and edge weights.

CAD FCM

The CAD FCM as depicted by a cause-effect digraph in Figure 3, shows the interrelationships of the perceptions of CAD as a physical asset, CAD as a support of human capital, CAD as a social capital enabler [6] and the managerial capabilities and attitudes of those involved in the use of CAD services, with the service quality factors of CAD. This core CAD FCM model is built from the operation knowledge acquired from an engineering consultancy environment. It can later be extended [11,12] with sub-FCMs built around it. Starting with core concepts eases knowledge acquisition in the initial stage and makes FCM building and extension flexible and easy without loss of knowledge. The policy nodes are identified as fixed-value cause concept nodes that initiate the propagation of their effects in the direction of their causal edges to other nodes by repeated excitation. The signs of all the edges are positive which ensures that all paths are also positive [7]. Thus, according to Kosko [8,9,10] and Tsadiras & Margaritis [13], this FCM is a balanced one, which does not increase its complexity nor decrease the clarity of relations. The description and definition of the variables associated with each core concept are given below to clarify their meanings and for developing sub-FCMs subsequently. The recent work of Miao et-al [23] has addressed the problems of robustness and false numeric inference by allowing every concept to have the linguistic term set expressed by either binary, fuzzy sets or continuous intervals. The CAD FCM model includes these ideas but the concept bounds are first defined.

Adequate CAD Stations (Concept Value ranging from –1 to 0)

This is the physical asset that replaced the drawing board and the T-square. This variable focuses on availability of hardware and software for production. The reliability of a CAD station is high due to timely replacement by new hardware and upgrading of software. A more significant shortage situation arises when the demand for drawing services exceeds the delivery capacity of CAD. Its severity is measured quantitatively by the number or percentage of stations short.

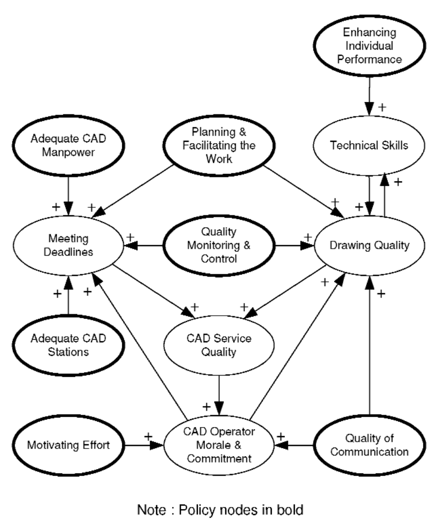


Figure 1: Simple FCM showing positive causality

Adequate CAD manpower (Concept Value ranging from –1 to 0)

The scarcity of CAD resource can create manpower shortage. Temporary shortage is experienced from time to time but serious shortage can also be created if there is excessive demand arising from over-commitment by project teams on deliverables that are to be produced at short notices i.e. compression of deadlines. Proper assignments and resource redistribution may help to even out workload if CAD operators are multi-skilled. If over-loading persists, the variable is measured quantitatively by the percentage of man-hours short or needed to meet demand.

Quality Monitoring and Control (Concept Value ranging from -1 to +1)

The quality control system imposes a demand for proper drawing reviews to be done and records to be kept. If quality control is cumbersome and attitudes towards quality are outmoded, then it is more of a burden than an asset. The quality system should address issues pertaining to problem prevention, problem solving and error reduction [17]. This variable also assesses qualitatively the attitude and actions of managers in quality monitoring and control and their (as well as CAD operators') compliance with the quality procedures.

Planning and Facilitating the Work (Concept Value ranging from 0 to +1)

This qualitative variable measures productivity enhancement from managerial actions taken by a combination of skills, right attitude, understanding of CAD operations and the appreciation of CADs capability and limitations [2]. It assesses the actions [18] of a manager to plan, coordinate and remove obstacles in the design-drafting process, to find alternative CAD strategies for optimum performance.

Enhancing Individual Performance (Concept Value ranging from 0 to +1)

Through managerial actions this qualitative variable adds value to the product by enhancing project knowledge and improves and maintains skills through project-specific operator training [14] and coaching [17,18]. It measures the contribution to the individual's accumulated technical skills, which is also being continually renewed by project work.

Quality of Communication (Concept Value ranging from -1 to +1

Communication must move beyond the mere exchange of information and data. This qualitative variable is an assessment of the quality and frequency of communication between design engineers and CAD operators in the design delivery process, on how CAD has been used as a medium to review designs together [6], as a clearinghouse of design information [16] and on the inter-person communication in times of crisis, e.g. handling of complaints on drawing quality and delivery. It reflects the quality and frequency of information and data exchanged and the efforts put in to reduce the social distance between design engineers and CAD operators.

Motivating Effort (Concept Value ranging from -1 to +1)

This qualitative variable is an assessment of the quality of long-term team building efforts [17] and the quality of leadership skills employed to motivate CAD operators for strong commitment to the project. It assesses how negative attitudes are eliminated, confidence and conviction are built through empowerment, how excitement is generated by meaningful and reputable work, how a shared team purpose is created by clear goals and directions and how good performance is acknowledged by recognition, job satisfaction [18] and career progress.

CAD Operator Morale and Commitment (Concept Value from -1 to +1)

This is an effect variable whose qualitative value is determined by the level of motivation and communication [18,19] and is feedback-enhanced by the sense of job satisfaction [18,20] from achieving a high standard of service quality.

Technical Skills (Concept Value from 0 to +1)

This other human capital factor is a combined qualitative assessment of CAD operator's application of skills, knowledge and experience. They are demonstrated in the practice of acquired CAD techniques and drafting skills to produce error-free drawings. It is sustained by an effective CAD strategy [15] that aims to transform and enrich the job [1] through continuous project learning and feedback, and by managerial actions to enhance the individual's performance through specific job-related training.

Meeting Deadlines (Concept Value from -1 to +1)

This qualitative factor depends on adequate CAD stations, manpower support, quality control and schedule planning as part of the managerial actions [17].

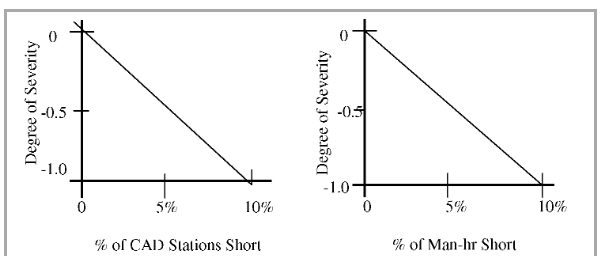
Drawing Quality (Concept Value from -1 to +1)

Drawing quality is driven by morale & commitment to the project and is dependent on the operators' practice of their technical skills and of their implementation of the quality system. It is further enhanced by their technical communications [6] in the design-drafting process.

CAD Service Quality (Concept Value from -1 to +1)

This ultimate effect variable is a measure of the qualitative assessment of the overall performance of CAD from the combined performance of how well deadlines and drawing quality are achieved in the whole process. Good service quality feedback improves morale and brings a fresh sense of commitment.

Adequate CAD stations and Adequate CAD manpower use the continuous intervals [–1,0] to represent their severity functions as shown in Figure 4. A numerical value is estimated



a) Adequacy of CAD Stations b) Adequacy of CAD Manpower

Figure 4: Membership functions of quantitative concepts

using its severity function that measures the degree a situation meets the concept's definition. Any shortage outside their limits is assigned a value of –1 while any excess (no shortage) is assigned a zero value.

THE FUZZY VALUES OF LINGUISTIC TERMS

Much of expert knowledge exists in the fuzzy domain. In most cases, FCM concepts and edges are expressed qualitatively in linguistic terms. Getting an expert to express her belief of a concept or an edge numerically does not seem to be consistent with how knowledge exists in her mind. The values obtained cannot be precise [12]. Furthermore, experts can have different degrees of belief, hence different strengths of the edges and produces fuzziness when their knowledge is aggregated. If knowledge is to be extracted, it is more consistent with the human cognitive process to use a scale that describes the strength of an edge by ordered linguistic terms. Their meanings may be context-dependent but they give stability to the qualitative assessment and their use is justified in [21]. The value set is a conversion of the linguistic terms into a numerical value range.

Table 1 suggests an expert's qualitative opinion scale for the FCM edge weights. After knowledge extraction, each of the qualitative opinion description is represented by a triangular fuzzy number denoted by $\boldsymbol{A = (a,b,c)}$ where a and c are the left and right hand-side vertices respectively at the base of the triangle representing zero membership and $\boldsymbol{b}$ is the vertex representing unity membership. A partial membership is determined from the x coordinates on the real line:

$$MF_{triangle}(x;\, a,\, b,\, c) = max\left[min\left(\frac{x-a}{b-a}, \frac{c-x}{c-b}\right), 0\right] \qquad (1)$$

Because the signs of the causal strength have been determined, the value of the edges is confined to the range 0 to +1. Figure 5 depicts the linguistic definition of the qualitative opinion scale corresponding to the numerical fuzzy causal strengths by repeated fuzzy partitioning of the scale [22]. With the exception of the extremes (centre values = 0 and = 1), each symmetrical triangular fuzzy number (TFN) is represented by its centre value, b while its $a = b - 0.1$ and its $c = b + 0.1$. Thus, 11 vertices (b's) represent the 11 linguistic terms with their a's and c's defining their range.

It is seen that neighbouring membership functions of the ordered linguistic variables overlap each other at $MF_{triangle}(x;\, \boldsymbol{a}, \boldsymbol{b}, \boldsymbol{c}) = 0.5$. The same overlap is maintained for other scales using symmetrical TFNs having the same width. Following Miao et al. [23], the linguistic variables are defined by their vertex functions, V_L as follows:

$$V_L(\boldsymbol{b}_L + 0.05) \geq x \geq V_L(\boldsymbol{b}_L - 0.05)) = \boldsymbol{b}_L \qquad (2)$$

where the subscript, $_L = \{1,2,3,\ldots,11\}$ indicate the linguistic variables of Figure 5 from left to right. They convert the numerical values obtained to linguistic terms and vice-versa.

For the CAD FCM, the causal strengths of the edges are converted from the qualitative opinion scale of context-dependent linguistic descriptions. The result is listed in Table 2 and is also shown in Figure 3 in the form of their vertex function. Taber & Siegel [11] and Taber [12] have suggested methods of obtaining numerical value from a group of experts who may have partial or different levels of knowledge of the problem. The method of averages was used to aggregate them numerically.

The development of the fuzzy value sets for the concept nodes is given in Appendix A.

AGGREGATION OF ACTIVATION LEVELS

The next stage performs a node function composition procedure by first aggregating the incoming activations directed at each effect concept node and then through a parameterised function to generate a single value output. Similar to neural networks [24], it starts with an iterative vector-matrix multiplication procedure to obtain the linear combination of their individual effects of perturbation on the state of the concept nodes. Before any perturbation, the FCM is in an equilibrium state, s_0, where $C_{j\,s0}$ denotes an effect concept's value whose activation level, $Ac_{j\,s0}$ remains unchanged.

In equilibrium at t-1, $Ac_{js0} = \sum_{i=1}^{N} e_{ij} C_{i\,s0}$ (3)

In moving to a new state, s, a perturbation in a cause concept, C_i brings about a change $\Delta C_{i\,s}$, which gives an effect concept, C_j a change in its activation level at t, $\Delta Ac_{ij\,s} = e_{ij}\, \Delta C_{i\,s}$. Summing all the activation changes to Cj by perturbations from connections with N causal concepts

$$\Delta Ac_{js} = \sum_{i=1}^{N} e_{ij} \Delta C_{i\,s} \qquad (4)$$

The procedure calculates the total force of activation to a concept node j, [25] by

Table 1: Qualitative opinion scale

Numerical Centre Value	Qualitative Opinion Scale	Triangular Fuzzy Number
0.0	No Causal Relationship	(0.0,0.0,0.1)
0.1	Very, very Weak	(0.0,0.1,0.2)
0.2	Very Weak	(0.1,0.2,0.3)
0.3	Weak	(0.2,0.3,0.4)
0.4	Slightly Weak	(0.3,0.4,0.5)
0.5	Moderate	(0.4,0.5,0.6)
0.6	Slightly Strong	(0.5,0.6,0.7)
0.7	Strong	(0.6,0.7,0.8)
0.8	Very Strong	(0.7,0.8,0.9)
0.9	Very, very Strong	(0.8,0.9,1.0)
1.0	Extremely Strong	(0.9,1.0,1.0)

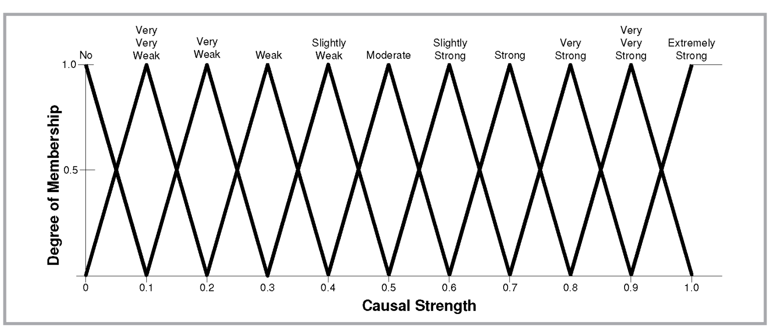


Figure 5: Qualitative opinion scale in terms of triangular fuzzy numbers

$$Ac_{j\,s} = \Delta Ac_{j\,s} + Ac_{j\,s0} = \sum_{i=1}^{N} e_{ij}\Delta C_{i\,s} + \sum_{i=1}^{N} e_{ij}C_{i\,s0}$$

$$= \sum_{i=1}^{N} e_{ij}(C_{i\,s0} + \Delta C_{i\,s}) = \sum_{i=1}^{N} e_{ij}C_{i\,s} \qquad (5)$$

where N is the number of causal connections to the concept node $\mathbf{C}_j$,

$C_{i\,s}$ is the causal strength of the concept node $\mathbf{C}_i$ at state, s.
e_{ij} is the edge weight or causality strength with direction pointing from $\mathbf{C}_i$ to $\mathbf{C}_j$.

Table 2: Casual strength of the edges

From Concept Node	To Concept Node	Qualitative Strength	Vertex Value
Adequate CAD Manpower	Meeting Deadline	VERY,VERY STRONG	0.9
Adequate CAD Stations	Meeting Deadline	VERY, VERY STRONG	0.9
CAD Operator Morale & Commitment	Meeting Deadline	MODERATE	0.5
Planning & Facilitating the Work	Meeting Deadline	SLIGHTLY STRONG	0.6
Quality Monitoring & Control	Meeting Deadline	VERY WEAK	0.2
Motivating Effort	CAD Operator Commitment	STRONG	0.7
Quality of Communication	CAD Operator Commitment	SLIGHTLY WEAK	0.4
Quality Monitoring & Control	Drawing Quality	WEAK	0.3
Planning & Facilitating the Work	Drawing Quality	MODERATE	0.5
Technical Skills	Drawing Quality	VERY STRONG	0.8
Quality of Communication	Drawing Quality	STRONG	0.7
CAD Operator Morale & Commitment	Drawing Quality	MODERATE	0.5
Enhancing Individual Performance	Technical Skills	STRONG	0.7
Drawing Quality	Technical Skills	SLIGHTLY WEAK	0.4
Meeting Deadline	CAD Service Quality	WEAK	0.3
Drawing Quality	CAD Service Quality	STRONG	0.7
CAD Service Quality	CAD Operator Morale and Commitment	VERY WEAK	0.2

Equation 5 can be written in matrix form by first defining $[C]_s$ as a row matrix of N causal nodes at iteration, s and [E] is a constant square matrix containing the elements e_{ij}, the knowledge base of the system. The resultant effect at state, s due to aggregation of N activation levels is the inner product

$$[Ac]_s = [C]_s\,[E] \qquad (6)$$

NON-LINEARITY AND SQUASHING FUNCTIONS

This paper adds to Miao et al's [23] procedure, a squashing operation on the effect node activation level, similar to the processing function in [24] to obtain an output value prior to vertex function operation. Given in matrix form, it has similar form as neural transfer functions [27,28] and is given as follows:

$$[C]_s{*} = S([Ac]_s) = S([C];[E]) \qquad (7)$$

where S is a non-linear squashing function that limits the effect node value, C_j to the appropriate bounds. Some of the non-linear squashing functions used in neural networks [24,27,28] are used here in either unipolar or bipolar form. In the binary (unipolar) case with interval [0,1], zero activation gives a zero value to Cj and maximum activation gives a value of 1 to C_j. In the bipolar case with interval [-1,1], minimum activation gives a -1 value to C_j and maximum activation gives a value of 1 to C_j. The following 3 types of squashing functions are used with the CAD FCM and are shown in Figure 6.

The Bipolar Step Function

$$S(x) = -1 \;\; \text{for} \;\; x < 0$$
$$S(x) = 1 \;\; \text{for} \;\; x \geq 0 \qquad (8)$$

The Linear Function (Unipolar and Bipolar)

$$S(x) = 0 \text{ (or -1)} \quad \text{for} \quad m(x\text{-}k) \leq 0 \text{ (or -1)}$$
$$S(x) = m(x\text{-}k) \quad \text{for} \quad 0 \text{ (or -1)} < m(x\text{-}k) < 1 \qquad (9)$$
$$S(x) = 1 \quad \text{for } m(x\text{-}k) \geq 1$$

where the bipolar values are contained in brackets. $\sqrt{m = \dfrac{a}{x_u - x_l}}$

where a = 1 for the unipolar linear and a = 2 for the bipolar linear. k the crossover point. If the upper and lower control limits of the function are defined as x_u and x_l respectively, then to preserve the symmetry within the control limits and about the crossover point, $k = {}^1\!/_2(x_u + x_l)$.

The Bipolar Step Function

There are many families of the sigmoid function. The two functions given below are used to ensure that linearity can be maintained further from the crossover point by allowing saturation to take effect only near the bounds.

For unipolar, $S(z) = \dfrac{c^z}{1 + c^z}$ (10)

where $z = f(x) = \alpha \sinh \left[\beta \left(\dfrac{x - k}{1/2(x_u - x_l)} \right) \right]$ and empirically,

$\alpha = 1.732,\ \beta = 1.642.$

And for bipolar, $S(z) = 2\,\dfrac{c^z}{1 + c^z} - 1$ (11)

where $z = f(x) = \alpha \sinh \left[\beta \left(\dfrac{x - k}{1/2(x_u - x_l)} \right) \right]$ and empirically,

$\alpha = 2.2,\ \beta = 1.643.$

c = 2 determines the slope of the function. When c approaches infinity, the function is steep and it approximates the step function with the occurrence of early saturation. When c is small, it approximates a linear function near the crossover point. All sigmoid functions exhibit these features. $k = \frac{1}{2}(x_u + x_l)$.

The MIN Function

The MIN function [22] is given by $f_{MIN}(x,y) = MIN\{x,y\}$ (12)

In the CAD FCM, *Meeting Deadline* assumes a bipolar step function because deadlines are either met or not. *CAD Operator Morale and Commitment* assumes a linear function. *CAD Service Quality* being an assessment result must satisfy the objectives of *Meeting Deadlines* and *Drawing Quality* in a non-compensatory manner. The MIN. function fulfils this requirement. Other than *Adequate CAD stations and Adequate CAD manpower*, the other concept nodes assume the sigmoid function in the interval [-1,1] with the exception of *Planning and Facilitating the Work, Enhancing Individual Performance* and *Technical Skills* working in the interval [0,1]. When managerial action to enhance productivity is lacking, there is no productivity increase in the system; hence its value set resides in the interval [0,1]. Technical skills can only be upgraded; hence the interval [0,1].

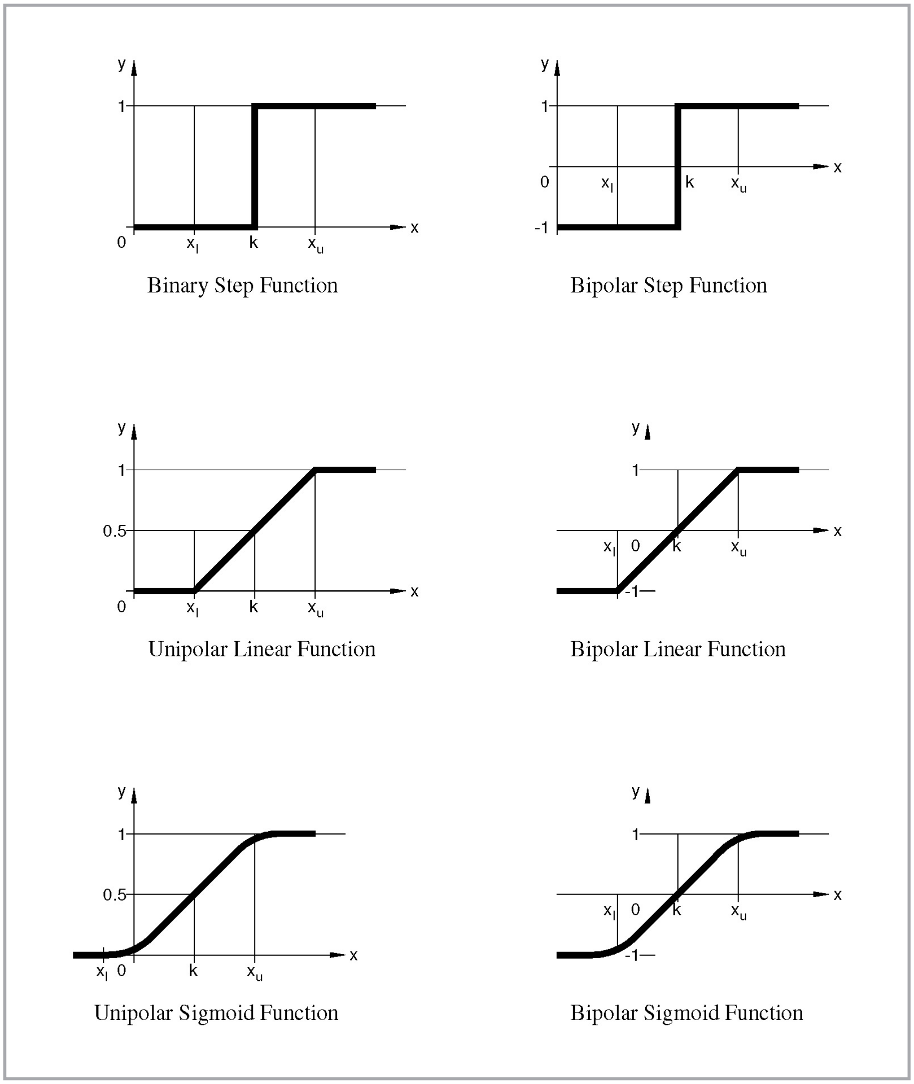


Figure 6: Squashing functions (above)

Table 3: Squashing functions selected for core CAD FCM effect concepts

Effect Concept Node	Squashing Function	Parameters
Meeting Deadlines	Bipolar Step	-
Drawing Quality	Bipolar Sigmoid	$c = 2, k = 0.65, \alpha = 2.2, \beta = 1.643$
Technical Skills	Unipolar Sigmoid	$c = 2, k = 0.35, \alpha = 1.732, \beta = 1.642$
CAD Operator Commitment	Bipolar linear	$m = 0.7692, k = 0$
CAD Service Quality	MIN	-

The parameters *m*, k and c of the squashing functions are assigned to each effect concept node such that the degree of saturation from the concept's total activation level according to expert opinion gives a valid concept behaviour and output. As a result, a heterogeneous FCM with mixed transfer functions is derived. The effect node functions are summarised in Table 3.

After squashing function operation, the value of C_j is only then fitted into one of the vertex functions [23] defined by Equation 2. C_j then assumes the centre/vertex value of that vertex function corresponding to its linguistic variable for the next iteration. This method allows non-linear linguistic expressions of cause and effect to be converted for a numerical procedure. The change in the state of the concept nodes comes from the iterative process involving the cyclical calculations between Equations 6 and 7, each with new values of $[C]_{s+1}$ converted to $[C]^*_{s+1}$. The linguistic form of [C] is obtained after the operation of $[C]^*_{s+1}$ is given by

$$[C]^L_{s+1} = f_v([C]^*_{s+1}) \quad (13)$$

The new values of C_j when used in their next iterations will reveal a sequence of C_j patterns [8,9]. When $[C]^L_{s+k} = [C]^L_{s+k+1}$ $(k > 0)$ is reached, the result has converged to an equilibrium point, which is a global stability point at which the linguistic values of all the C_j's remain constant.

CORE CAD FCM SIMULATION

At the end of the CAD knowledge acquisition exercise, an equilibrium scenario is established with numerical values for all nodes in the digraph of Figure 3. The core CAD FCM scenario is described as follows. There is *adequate CAD manpower* to complete the project with *no shortage of CAD stations*. The company depended greatly on its quality control system to deliver its designs and as such *Quality Monitoring and Control* is very highly activated. However, less emphasis is given to *enhancing technical skills* as there are only few occasions that training is considered needed. The pressure to meet deadlines has compelled the project manager to *facilitate and plan the work*. But join design reviews between engineers and CAD operators are rare and there are design gaps resulting from errors in received design data. As such, the project manager has on repeated occasions required the CAD operators to arrest error propagation at source but without a proper and effective channel of communication with the data source. Driven by deadlines, there is a loss of empowerment of the operators to seek solutions outside CAD in times of crisis. This problem has persisted and has brought the vital *communication* between engineer and operator to a low level. *Motivation* is only slightly on the upside and is sustained by the teamwork among the CAD operators and supported by an incentive scheme. There is neither strong nor weak *Morale and Commitment. Drawing Quality* and *CAD Service Quality* are neither good nor poor. The nodes values translated from this description are given below.

<u>Policy Nodes (Initial Equilibrium Condition)</u>

Adequate CAD Manpower = 0
Adequate CAD Stations = 0
Quality Monitoring & Control = 0.9
Enhancing Performance = 0.3
Planning & Facilitating the Work = 0.8
Quality of Communication = -0.4
Motivating Effort = 0.2

<u>Effect Nodes (Initial Equilibrium Condition)</u>

Meeting Deadlines = 1
Technical Skills = 0.4
CAD Operator Commitment = 0
Drawing Quality = 0
CAD Service Quality = 0

Apart from the knowledge extracted, two extremum conditions exist. A concept node should experience maximum output if all other concept nodes that point directly to it are at maximum activation. Conversely, a concept node should experience minimum output if all other concept nodes that point directly to it are at minimum activation. It is generally expected that all the effect node values should respond correspondingly. The core CAD FCM satisfies both the maximum and minimum activation conditions.

The initial equilibrium situation can be improved by taking positive actions in a number of ways to increase the policy node values. The FCM reaches a new state with changes in the effect nodes as shown in Table 4. Using linguistically defined vertex functions, the numerical results are translated to linguistic terms. Improving *Quality of Communications* to *Moderately Good* (0.4), improves *Technical Skills to Moderate* (0.5) and *Commitment* to *Slightly Good* (0.3) so that *Meeting Deadlines* is achieved (1). *Drawing Quality* improves to *Moderately Good* (0.5) and in turn causes *CAD Service Quality* to improve to *Moderately Good* (0.5).

If the CAD operators are motivated to a *High (0.6)* level, then *Commitment* improves to a *Moderately High* (0.5) level. *Technical Skills*, *Drawing Quality* and *CAD Service Quality*, each continue to improve to *Good/High (0.6)*.

Table 4: The effects of policy node change in the core CAD FCM

Policy Node Changes from Initial Equilibrium Condition	Effect Node Changes				
	Technical Skills	**CAD Operator Morale & Commitment**	**Meeting Deadlines**	**Drawing Quality**	**CAD Service Quality**
1. Improve Communication (-0.4 → 0.4)	0.4 → 0.5	0 → 0.3	1	0.1→0.5	0.1→0.5
2. Communication (-0.4 → 0.4) & Improve Motivating Effort (0.2 → 0.6)	0.5 → 0.6	0.3 → 0.5	1	0.5 → 0.6	0.5 → 0.6
3. Inadequate CAD Manpower and CAD Stations (0 → -0.8,0 → -0.8)	0.6 → 0.5	0.5 →0.3	-1	0.6 → 0.5	-1

Given the improvements achieved, the occurrence of a shortage of both manpower (-0.8) and workstation (-0.8) will cause reductions in *Commitment* to *Slightly High* (0.3) and *Technical Skills to Moderate* (0.5). Although *Drawing Quality* drops only to *Moderately High* (0.5), *CAD Service Quality* drops to *Extremely Poor* (–1) because *Deadlines* are not met (-1).

The simulations reveal how improvements in core areas of management from the physical assets, human capital and social dimensions, are required to bring CAD service quality to a higher level of performance. But what specific actions would contribute to improvement of CAD service quality? If there are a number of approaches, which one is the most effective to adopt?

THE EXTENDED CAD FCM

To answer the preceding questions, the core FCM is extended by expanding some core concepts with their own sub-FCMs. These are generally easy to construct if the initial identification of the core concepts is made such that they represent the direct aggregations of a number of specific causal components that are relevant to the respective policy nodes in the core FCM. Figure 7 of the extended FCM shows the core concepts of *Quality of Communication and Motivating Effort* expanded with their action components. They represent the actions that have to be taken to improve these two core concepts of CAD performance. Both these nodes are converted to effect nodes with the squashing functions shown in Table 5. The causal connection weights are given below.

<u>New Edge Weights (Causal Connection Weights)</u>

- *Frequency of Join Design Reviews to Quality of Communication = 0.5.*
- *Quality of Shared Design Information/Data to Quality of Communication = 0.8.*

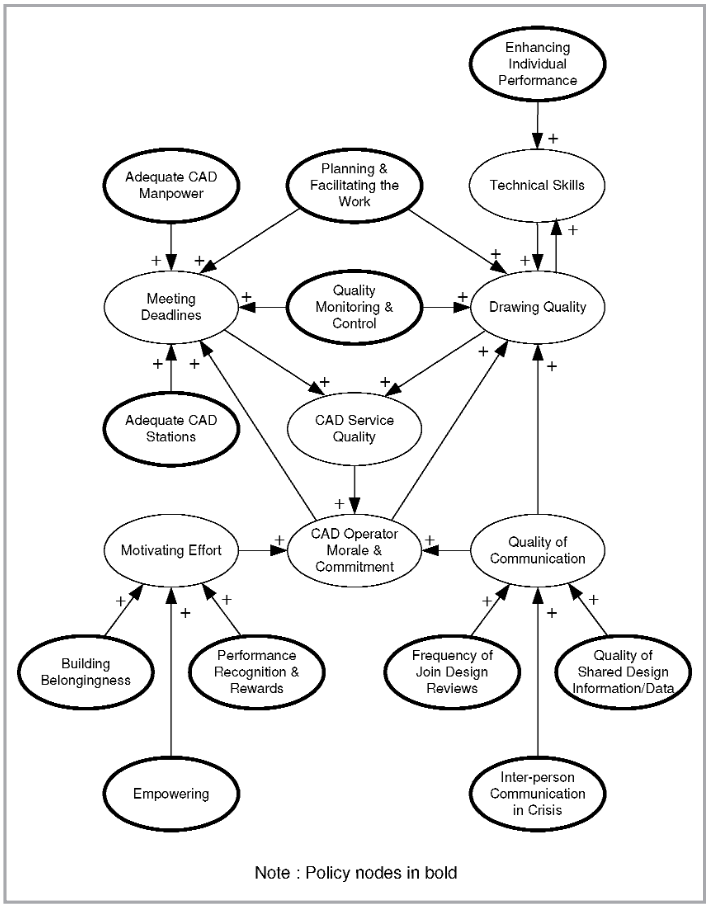


Figure 7: The extended CAD FCM (above)

Table 5: Squashing functions of new effect concept nodes

Effect Concept Node	Squashing Function	Parameters
Motivating Effort	Bipolar Sigmoid	c = 2, k = 0.65, α = 2.2, β = 1.643
Quality of Communication	Bipolar Sigmoid	c = 2, k = 0.25, α = 2.2, β = 1.643

- *Inter-person Communication in Crisis to Quality of Communication = 0.5*

- *Building Belongingness to Motivating effort = 0.7*
- *Empowering to Motivating effort = 0.5*
- *Performance Recognition and Rewards to Motivating effort = 0.8*

The simulation runs start with a similar equilibrium state as the core CAD FCM. The initial equilibrium values of the new policy nodes required to achieve 0.2 for Slightly High Motivation Effort and –0.4 for Moderately Poor Quality of Communication with the above squashing functions are given below.

Policy Nodes (Initial Equilibrium Condition)
Inter-person Communications in Crisis = -0.4
Frequency of Joint Design Reviews = 0.1
Empowering People = 0
Quality of Shared Info/data = -0.2
Building Belongingness = 0.5
Performance Recognition & Rewards = 0.6

Tests were performed on the 2 extreme conditions and they gave the same result as those of the core CAD FCM.

The following simulation runs demonstrate how specific decisions and actions taken will affect CAD service quality. The FCM can be used as an inference system to answer "what-if" questions pertaining to CAD service quality and then select the best approach in managing the CAD team.

The obvious improvement required as a first step in Approach 1 is in *Inter-person Communications in Crisis*. If it improves from *Moderately Poor* (-0.4) to *Moderately Good* (0.4), then the *Quality of Communication* will improve from *Moderately Poor* (–0.4) to *Slightly Poor* (-0.1). The effects on the other nodes are shown in Table 6. *Motivation* remains unchanged but there are improvements in *Technical Skills* to *Moderately Good* (0.5) and *Commitment* moving away from *Neutral* (0.1). *Drawing Quality* and *CAD Service Quality* both achieve *Slightly High* (0.2). The next step 1b is to *improve the Quality of Design Information* to *Moderately Good* (0.4) with *Quality of Communication* improving to 0.3. *Morale & Commitment* (0.3), *Drawing Quality* (0.4) and CAD *Service Quality* (0.4) all increase by 0.2 points. In the next step 1c, the *Frequency of Design Reviews* is increased to *Moderately High* (0.4). *Quality of Communication* improves from 0.3 to 0.4. *Technical Skills* and *Morale and Commitment* remain unchanged. *Drawing Quality* and *CAD Service Quality* are *Moderately High*, each achieving 0.5.

If as an alternative in Approach 2 *Empowering* is encouraged to a *Moderately High* level (0.4), then it will lead to improvement in *Motivating Effort* from 0.2 to 0.3. It is insufficient to improve *Morale and Commitment, Drawing Quality* and *CAD Service Quality*. If a little effort is then put into *Building Belongingness* from *Moderately High* (0.5) to *High* (0.6), then together with the achievement in *Empowering* the staff, there are improvements in *Morale and Commitment* from *Motivating Effort*. Both *Drawing Quality* and CAD Service Quality reach slightly higher than *Neutral* (0.1) levels.

A comparison between the two approaches suggests that improvement in the *Quality of Communications* and *Quality of Design Information/Data* is a more effective route to improvement in *CAD Service Quality*. The model points to the effectiveness of project team communication in the achievement of higher quality output as compared to dependence on motivation efforts alone. By combining the 2 approaches as in Approach 3, *Drawing Quality* and *CAD Service Quality* are improved to *Moderately High* (0.5) levels. The result is similar to Approach 1 but with improvements in *Morale and Commitment* from *Motivating Effort*, which can contribute intangible benefits that are not modelled in this FCM.

CONCLUSION

It has been demonstrated that a comprehensive CAD FCM helps managers to understand the relationships between causes and effects in CAD operations in qualitative terms. It gives them an opportunity to test and to simulate by numerical calculation how their decisions and actions have on CAD service quality and to select the optimum approach to improve quality.

Table 6: The effects of policy node change in the extended CAD FCM

Policy Node Changes from Initial Equilibrium Condition	Effect Node Changes						
	Quality of Com.	**Motivation**	**Technical Skills**	**CAD Operator Morale & Commitment**	**Meeting Deadlines**	**Drawing Quality**	**CAD Service Quality**
1a. Improving Inter-person Communication (-0.2 → 0.4)	-0.4 → -0.1	0.2	0.4 → 0.5	0 → 0.1	1	0.1→0.2	0.1→0.2
1b. Improve Quality of Shared Info/data (0.1→0.4)	-0.1 → 0.3	0.2	0.5	0.1 → 0.3	1	0.2→0.4	0.2→0.4
1c. Increasing Frequency of Joint Design reviews (0.1→ 0.4)	0.3 → 0.4	0.2	0.5	0.3	1	0.4→0.5	0.4→0.5
2a. Empowering (0→0.4)	-0.4	0.2 → 0.3	0.4	0	1	0	0
2b. Building Belongingness (0.4→0.6)	-0.4	0.3 → 0.4	0.4	0 → 0.1	1	0→0.1	0→0.1
3. Combining Approaches 1 & 2.	-0.4 → 0.4	0.2 → 0.4	0.4 → 0.5	0 → 0.4	1	0 → 0.5	0 → 0.5

However, FCM models are context dependent. They vary with different situations, organisations and among project managers. They do not necessary have the same concepts and causal connections. The results of simulation runs of one particular CAD FCM show that for CAD to perform well, all aspects pertaining to the perceived physical capital, human capital, communication, motivational and managerial and attitudinal dimensions must be given their optimal proportion of effort to achieve the desired results. The simulation of CAD performance revealed its applicability in project management by providing the project manager with a tool to help her identify an optimal approach for dealing with CAD quality issues. Indeed, it demonstrated the effectiveness of technical communications as the other crucial dimension in CAD service quality and reinforces Robertson and Allen's statement [6] that communication is central to engineering work.

The method of FCM modelling applied to CAD performance has demonstrated its applicability in engineering management knowledge base building. Knowledge of causal relationships is stored in the edge/connection matrix. The squashing functions determine the effect node behaviour and outputs in the presence of activation. Because an FCM can be extended as the knowledge base increases, it provides a means of capturing, storing and extending knowledge thus, improving the knowledge base. The use of the qualitative opinion scale allows qualitative knowledge that is expressed linguistically, to be translated to numerical values for computer calculation and the results to be converted to linguistic terms that represent the qualitative outputs. Thus, FCM makes knowledge processing possible and easy. It can be used as an effective tool for understanding engineering management and for knowledge building in an engineering environment. ■

APPENDIX A: FUZZY VALUE SETS FOR CONCEPT NODES

The qualitative scale for the concept – *Planning and Facilitating the Work* is shown in Table A1. Each linguistic term in the scale is represented by a triangular fuzzy number (TFN) denoted by $\boldsymbol{A} = (\boldsymbol{a},\boldsymbol{b},\boldsymbol{c})$ where $\boldsymbol{a}$ and $\boldsymbol{c}$ are the left and right hand-side vertices respectively at the base of the triangle representing zero membership and $\boldsymbol{b}$ is the vertex representing unity membership. The concept value range, [0 to 1] is partitioned into 11 TFNs with centre vertices (b's), each corresponding to the 11 linguistic terms on the qualitative scale. With the exception of the extremes (centre values = 0.0 and = 1.0), each triangular fuzzy number is represented by its centre value, b while its $a = b - 0.1$ and its $c = b + 0.1$. The fuzzy activation strengths are depicted in Figure A1.

Table A1: Qualitative scale for planning and facilitating the work and enhancing individual performance

Numerical Centre Value	Qualitative/Linguistic Scale	Triangular Fuzzy Number
0.0	Nil	(0.0,0.0,0.1)
0.1	Very, Very Few	(0.0,0.1,0.2)
0.2	Very Few	(0.1,0.2,0.3)
0.3	Few	(0.2,0.3,0.4)
0.4	Slightly Less Than Moderate	(0.3,0.4,0.5)
0.5	Moderate	(0.4,0.5,0.6)
0.6	Slightly More Than Moderate	(0.5,0.6,0.7)
0.7	More	(0.6,0.7,0.8)
0.8	Much More	(0.7,0.8,0.9)
0.9	Very Much More	(0.8,0.9,1.0)
1.0	Full	(0.9,1.0,1.0)

For the other concepts, their value range is –1 to +1 and they are partitioned into 21 TFNs. Table A2 and Figure A2 only show 11 linguistic terms over the range. Intermediate ones are indicated but not named. The positive fuzzy numbers represent positive impacts to the FCM while the negative fuzzy numbers represent negative impacts.

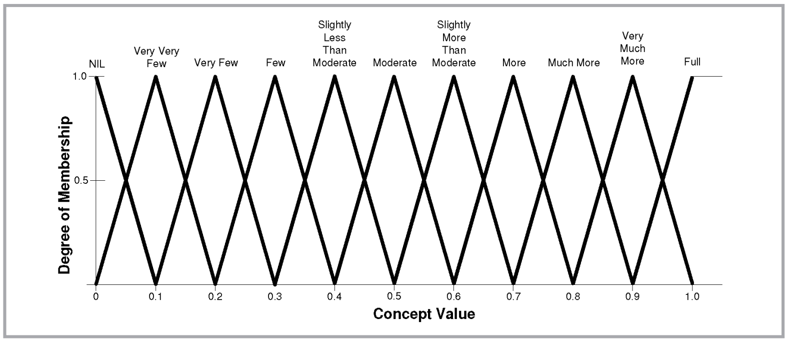


Figure A1: Qualitative scale [0, 1] for planning and facilitating the work and enhancing individual performance

Table A2: Qualitative scale for the other concepts

Numerical Centre Value	Qualitative/Linguistic Scale	Triangular Fuzzy Number
-1.0	Extremely Poor/Low	(-1.0,-1.0,-0.9)
-0.8	Very Poor/Low	(-0.9,-0.8,-0.7)
-0.6	Poor/Low	(-0.7,-0.6,-0.5)
-0.4	Moderately Poor/Low	(-0.5,-0.4,-0.3)
-0.2	Slightly Poor/Low	(-0.3,-0.2,-0.1)
0.0	Neutral	(-0.1,0.0,0.1)
0.2	Slightly Good/High	(0.1,0.2,0.3)
0.4	Moderately Good/High	(0.3,0.4,0.5)
0.6	Good/High	(0.5,0.6,0.7)
0.8	Very Good/High	(0.7,0.8,0.9)
1.0	Excellent	(0.9,1.0,1.0)
Intermediate (odd) Centre Values	NOT NAMED	EXIST AND DEFINED

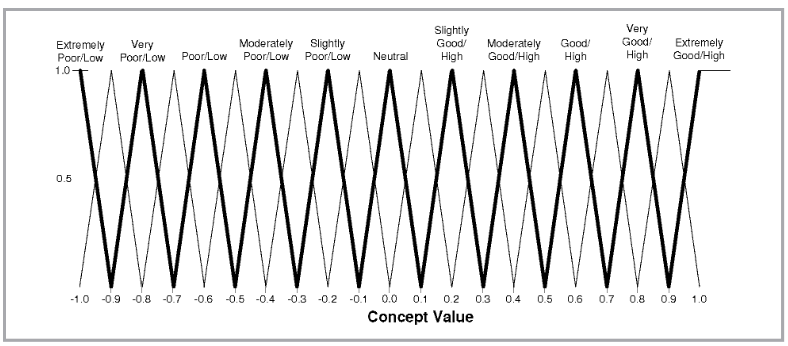


Figure A2: Qualitative scale [-1, 1] for other concepts

In all scales the neighbouring membership functions of the ordered linguistic variables overlap each other at $MF_{triangle}(x; \mathbf{a}, \mathbf{b}, \mathbf{c}) = 0.5$. Following Miao et al. [23], the linguistic variables are defined by their vertex functions, V_L as follows:

$$V_L(b_L + 0.05) > x > V_L(\mathbf{b}_L - 0.05)) = \mathbf{b}_L \quad \text{(A1)}$$

where the subscript, $_L$ = {1,2,3,….,21} indicate for example, the linguistic variables of Table A1. Along the same lines, similar linguistic terms and their corresponding vertex functions can be derived for Table A2. ■

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He joined Universiti Sains Malaysia, Penang as an Electrical Engineer after graduating with a First Class (Hons.) degree in Electrical Engineering from the University of Malaya in 1975. In 1977, he returned to University of Malaya, Kuala Lumpur as a Tutor in electrical Engineering and concurrently worked for his Master of Engineering Science Degree, which he obtained in 1980 for research in Lightning Protection.

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