HSIUPING JOURNAL. VOL.2. PP.93～112 (MARCH 2001) 93

The Analysis and Prediction of Dynamic Decision Outcomes by DBE and Causality

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Abstract

Because of substantial advances of automatic tchnology in human-machine systems, the operator has changed to a 'decision maker' in a control room. Modeling operator's decision behavior has attracted a major interest in research fields uch as human factors and reliability engineering. Considering the requirements of engineering applications, an event-driven approach, called the Dynamic Boolean Expression (DBE), is developed to model dynamic reasoning. Based on the deterministic nature of human decision-making, a quantitative 'causality' is derived to describe the drgree to which the decision outcome and its driving events. An experiment was performed to verify the validity of the DBE. The results show that the DBE accomplished with the 'causality' are useful tools in analyzing and predicting the dynamic decision outcomes.

Key Words : Deterministic decision process, Dynamic Boolean Expression (DBE), Causality[1]

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1. Introduction

Although automation of human-machine systems has not completely substituted for human involvement in machine operation, it has changed the traditional 'machine-manipulator' to a 'decision maker' whose role is to supervise and execute well-established automatic control procedures (Sheridan, 1986). Thus, modeling operator's decision behavior has attracted the attenton of researchers who are concerned with human-machine systems and industrial ergonomics (e.g., Helander, 1988; Broadbent, Baddeley & Reason, 1990; Poucet, 1990; Lee & Moray, 1992; Millot & Debernard, 1993; Gilmore, Gertman & Blackman, 1989; Ivergard, 1989; Cacciabue, Decortis, Drozowicz, Masson & Nordvick, 1992.)

In considering the needs of engineering applications, we propose in this paper the Dynamic Boolean Expression (DBE) method as a tool for modeling the dynamic decision process in this paper. A quantitative quantity called the "causality" is also developed to give numerical prediction of the dynamic decision outcomes. In order to verify the validity of the DBE and the "causality", an experiment based on the popular tic-tac-toe game was performed. The results show that the analysis performed by the DBE is consistent with that predicted by the "causality". It is thus concluded that the DBE and the causality are useful tools in modeling and analyzing the dynamic decision process.

2. Conceptual Framework of Decision Making

In this paper, the framework of decision making is defined on the concepts that

1) A decision making task is usually accomplished by one or more decision processes.

2) A decision process may include many decision stages.

3) The dominant mental activity carried out in each decision stage is reasoning.

Most researchers accepted the information-processing model as a common framework of decision-making (Wickens, 1992, pp.258-261; Mancini, 1990; Legren, Girotto & Johnson-Laird, 1993). According to this model, four decision stages are involved in the decision process:

Stage I Collection of information:

Sampling a number of cues or information sources from the environment.

Stage II Confirmation of state:

Formulating a hypothesis about the true state of th world.

Stage III Selection of alternatives or actions:

To evaluate and choose one from the alternatives or actions.

Stage IV Evaluation of consequence:

Feed back of consequences for the next round of decision-making.

The most important mental activity involved in these stages is reasoning.

2.1 The characteristics of deterministic dynamic reasoning

As the reasoning is the vital mental activity involved in the decision stages, the decision-maker will adopt suitable reasoning strategy to meet the requirement of the task (Edward & Lee, 1974; Edwards, 1987; Evans, Over & Manktelow, 1993). In other words, reasoning is a task-specific activity. In considering the dynamic interaction involved in procedure control, it is practical to regard the reasoning process is deterministic and characterized by the followings:

1) It is an event-driven process.

The term 'event-driven' is used to cover the concept that people prefer to make inference based on the deterministic states of events, and to address the phenomenon that decision maker will direct attention to the most perceptually important events of the external environment. Also, "driving events" are the events of which the information is used for reasoning.

2) The reasoning process is based on a discrete-state variation of driving events.

Considering human mental capacity it is reasonable to conceive that people sample event by finite states in order to fit the limited memory. As a result, reasoning is based on discrete-state variation of events. Although this is not always the case, the most simple way for the decision-maker to sampe events is by dichotomy. When dichotomy is taken, either one of the two opposite states is assigned to the event. Thses binary states are supposed to be 'true' or 'false', 'present' or 'absent', 'happened' or 'not happened', and so forth.

2.2 The requirements of engineering applications

Aside from human factors and applied ergonomics, practitioners from other engineering-oriented disciplines, such as system reliability and artificial intelligence, also need cognitive models of human control procedures. The requirements suggested to human reliability assessment (HRA) for modeling operator's reasoning behavior are worth noting in constructing dynamic reasoning models (Swain, 1990; Sprugin, 1990; Kantowitz & Fujita, 1990; Cacciabue, 1992; Caccibue & Cojassi, 1994; Cacciabue, 1997). They are summarized as follows:

1) To resemble true cognitive behavior of the operator, a cognitive model should account for biases of cognition.
2) To capture the interaction between the operator and the system, a model must be dynamic.
3) The model must be simple enough for practical allication which covering a variety of human-machine systems.
4) Due to substantial advances in computer technology, the model should be programmable so that the human-machine interaction may be simulated and

analyzed by computer.

2.3 Mathematical representations of dynamic reasoning models

Before closing this section, the requirements for any mathematical models using to represent dynamic reasoning are summarized as below:

1) The mathematical model should be event-driven and discrete-stated so as to account for the cognitive biases induced by limited memory and attention.
2) It should express the causal relationship of events explicitly so that the reasoning process can be simulated and analyzed on a computer platform.
3) The mathematical expressions or value accounting for the states of events should be easily updated whenever there is an interaction between the decision-maker and the externalenvironment so as to capture the dynamic nature of decision making.
4) The mathematics used for building the model should have practical validity and rigorous theoretic basis.

One can see that Boolean algebra is one of the candidates that may satisfy these requirements, however, the qualitative Boolean expression is restricted to static causal relationship between events. In order to meet the need of "dynamic", a new representation method called the Dynamic Boolean Expression (DBE) is developed (Yang & Hwang, 1998).

3. The Operations of Dynamic Boolean Expression (DBE)

Detailed explanations and illustrations on how the DBE is operated is given in this section. Quantities such as 'driving vector' and 'causality' are also defined so that the degree to which decision outcome is driven by the happened events can be caalculated numerically.

3.1 Notations used in DBE

Since deterministic reasoning is an event'driven process based on a discrete-state variation of driving events, the states of driving event are dichotomous and supposed to either have happened or not have happened.

1) If the driving event has 'happened', then it is denoted by capital letter E; otherwise it is denoted by small letter e.

2) If more than one event are considered, then subscripts 1, 2, 3…n are added to the notations.

For example, assume a decision with five driving events. If the first three have 'happened' and the last two have 'not happened', the notation is E_1, E_2, E_3, e_4 and e_5. The same principles apply to outcomes of decision or reasoning. Suppose that four decision outcomes can be selected. If the first two are 'selected' and last two are 'not selected', then they should be denoted: D_1, D_2, d_3 and d_4.

3.2 Causal relationship between driving events and their outcomes

The relationship between driving events and decision outcomes is regulated by the 'it…then' statement. If the state of driving event has changed, then the state of its consequent outcome should also be changed correspondingly. This relationshiprepresents a linkage. Four kinds of linkage can be identified: 'one-to-one', 'many-to-one', 'one-to'many' and 'many-to-many'.

1) One-to-one linkage

The decision outcome d is driven or activated by one specific event e only. "If e then d", the corresponding DBE is written as

$$d = e \tag{1}$$

The sign '=' is used to mean 'to be driven by'.

2) Many-to-one linkage

There are two kinds: 'either' type and 'all' type. The 'either' linkage is defined by the relationship that 'if either one of the mutually independent events has happened, then the consequent outcome will be selected.' If we assume the selection of decision outcome d is activated by n mutuallyindependent events in 'either' linkage, then the DBE is written as

$$d = e_1 + e_2 + \ldots + e_i + \ldots + e_n \qquad (2)$$

The '+' sign denotes 'either' operation. If one of the driving events, say e_i, has happened, then the decision outcome d is selected. The DBE is modified as

$$D = e_1 + e_2 + \ldots + E_i + \ldots + e_n \qquad (3)$$

The 'all' linkage is defined by the relationship that 'only if all of the driving events have happened, then the consequent outcome will be selected'. If we assume the selection of decision outcome d will be activated by n mutually independent events in an 'all' linkage, then the DBE is written as

$$d = e_1 \bullet e_2 \bullet \ldots \bullet e_i \bullet \ldots \bullet e_n \qquad (4)$$

The ' • ' sign denots 'all' operation. For simplicity, the expression can be rewritten as

$$d = (e_1)(e_2)(e_3)\ldots(e_i)\ldots(e_n)$$

3) One-to-many linkage

In some situations, one driving event may activate more than one decision outcome. This relationship is called the 'one-to-many linkage'. Assume that the decision outcomes d_1, d_2, d_3 are activated simultaneously by the driving event e, then:

$$d_1 = e;\ d_2 = e;\ d_3 = e \qquad (5)$$

4) Many-to-many linkage

In the real world, there are many-to-many linkages in which the number of driving events and possible choices are usually more than one. The actual way of how they are linked should reflect on the actual decision situation. Assume that there are five driving events linked with three possible decision outcomes, such that

$$d_1 = e_1e_2;\ d_2 = e_2e_3;\ d_3 = e_4 + e_5 \qquad (6)$$

3.3 Logical operations in DBE

All logical operations follow ordinary Boolean algebra. However, one special logical operation, the distributive law, is especially useful in expressing DBE in a standard form that is important to the causal analysis of reasoning. According to the distributive law in Boolean algebra, p(q+r) is equivalent to pq+pr. Assume that the relationship between decision outcome d and driving events e_1, e_2, e_3 and e_4 is given by the DBE as:

$$d = (e1 + e2)(e3 + e4) \qquad (7) \quad \text{or}$$

$$d = e1e3 + e2e3 + e1e4 + e2e4 \qquad (8)$$

We refer to (7) as the 'all of either' form of DBE since the 'either' terms, $(e_1 + e_2)$ and $(e_3 + e_4)$, are linked to outcome d by 'all' operation. Similarly, (8) is the 'either of all' form of DBE sincethe 'all' terms, e_1e_3, e_2e_3, e_1e_4, e_2e_4, are linked to outcome d by 'either' operation. We use the 'either of all' as the standard form of DBE in causal analysis developed in the following section.

4. Driving Vector and Causality

Suppose a decision outcome d is driven by N mutually independent events and their relationship can be expressed into a standard 'either of all' form similar to (8). Assume the total number of 'all' terms forming the DBE is m, and the number of driving events contained in the ith term is denoted by n_i. It follows that $1 \le i \le m$ and $1 \le n_i \le N$. We then define the following quantities accordingly:

1) The numerof happened events in the ith 'all' term is ki and $N \ge K_i \ge 0$.

2) The attendance of happened events in the ith 'all' term, denoted a_i, is defined as

$$a_i = \begin{cases} 0, & \text{if } k_i = 0 \\ 1, & \text{if } k_i \ge 1 \end{cases}$$

3) Partitions of the ith 'all' term by happened events. If there are k_i happened events in the ith 'all' term, then the number of not-happened events is n_i-k_i. One has to wait for the comings of n_i-k_i driving events in order to activate d. Therefore, the 'all' term is formed by n_i-k_i not-happened driving events and ONE part of happened events. We then define the partitions of the ith 'all' term by happened events, denoted p_i, as

$$p_i = n_i - k_i + a_i$$

4) Driving strength of happened events in the ith 'all' term is denoted by s_i. It describes the contribution of these happened events to the activation of the outcome d and we define the driving strength as:

$$s_i = a_i / p_i$$

5) Driving vector

m 'all' terms in the DBE will produce m entities of driving strength. To normalize these driving strength, the entities are ranked into a non-increasing order so that a 'driving vector' is formed. The driving vector of happened events with respect to the decision outcome d, denoted V_d, is defined as

$$Vd = [s1, s2 \ldots si \ldots sm]$$

where $s_1 \geq s_2 \geq s_3 \ldots \geq s_i \geq \ldots \geq s_m$.

6) Causality

Causality C_d is a scalar quantity derived from the driving vector. It describes the degree to which the decision outcome d is driven by the happened events.

$$C_d = \begin{cases} 1, & \text{if } s_1 = 1 \\ s_1 + s_1 s_2 + s_1 s_2 s_3 + \ldots + s_1 s_2 \ldots s_m, & \text{if } s_1 < 1 \end{cases}$$

Where $s_1, s_2, \ldots, s_m$ are elements of the driving vector V_d.

Since the possible states that s_i may attain are discrete and confined to 1, 1/2, 1/3, 1/4…0, it is easy to verify that the series $s_1 + s_1s_2 + s_1s_2s_3 + \ldots + s_1s_2 \ldots s_m$ is bounded by $s_1/(1-s_1)$. With $0 \leq s_i \leq 1/2$, the series is also bounded by the interval [0, 1]. For $C_d = 1$, all events required driving the outcome d to be activated have happened. Accordingly, d is changed to D. For $C_d = 0$, the happened events have no causal relationship with the outcome d.

7) Examples

To give a detailed explanation on how driving vector and causality is found, we illustrate by the DBE: $d = e_1 + e_2 (e_3 + e_4e_5)$, an suppose that events e_2, e_4 and e_5 happen successively in three decision cycles. The DBE is first expressed into the standard 'either of all' form

$$d = e_1 + e_2e_3 + e_2e_4e_5$$

Since E2 has happened in the first decision cycle, the DBE is rewritten as

$$d = e_1 + E_2e_3 + E_2e_4e_5$$

A tabulate method is used to identify the driving strength of the happened event as follow:

$d = e_1 + E_2e_3 + E_2e_4e_5$

n_i	1	2	3
k_i	0	1	1
a_i	0	1	1
$p_i = n_i - k_i + a_i$	1	2	3
$s_i = a_i / p_i$	0	1/2	1/3

The driving strength s_i is then ranked to form the driving vector $V_d(E_2) = [1/2, 1/3, 0]$. The causality is $C_d(e_2) = 1/2 + (1/2)(1/3) = 2/3$

To account for the coming of E_4 in the second decision cycle, the table is updated as follows:

$d = e_1 + E_2e_3 + E_2E_4e_5$

n_i	1	2	3
k_i	0	1	2
a_i	0	1	1
$p_i = n_i - k_i + a_i$	1	2	2
$s_i = a_i / p_i$	0	1/2	1/2

The driving vector becomes $V_d(E_2E_4) = [1/2, 1/2, 0]$. The causality is also updated as $C_d(e_2E_4) = 1/2 + (1/2)(1/2) = 3/4$. The causality increases as more driven events happened. Finally, the effect of the event E_5 is considered:

$$D = e_1 + E_2e_3 + E_2E_4E_5$$

n_i	1	2	3
k_i	0	1	3
a_i	0	1	1
$p_i = n_i - k_i + a_i$	1	2	1
$s_i = a_i / p_i$	0	1/2	1

The driving vector changes to $V_d(E_2E_4E_5) = [1, 1/2, 0]$. Since $s_1 = 1$, then $C_d(E_2E_4E_5) = 1$. This is consistent with the fact that outcome d is activated and replaced by D according to the basic operations of DBE.

5. Experimental validation of DBE

In this section, we use the result pattern of a 'tic-tac-toe' game as an illustration to show how the DBE can be used to analyze and model dynamic decision process. The validation is based on the experimental performed by Yang & Hwang (1998). Because tic-tac-toe is a game played by two players, the interaction between the two players can be regard as an interaction between the decision-maker and external environment. Obviously, playing tic-tac-toe is a dynamic decision task since there is strong interaction between the decision outcomes given in each step.

In this experiment, 70 subjects were grouped into 35 pairs of players. Each pair played the game twice. The game board was a 3 × 3 square drawn on a paper. The positions within the square are identified by letters a to I as shown in Figure 1. Since the 3 × 3 square is symmetric, positions a, c, g and I are called the 'corner positions'. Positions b, d, f, h are called the 'side positions' and position e is the 'central position'.

A	B	c
D	E	f
G	H	i

Figure 1. The nine positions labeled from letters a to i.

In the first run, one of the players within each pair acted as the offender and put the first X mark to occupy one of the nine opsitions of the 3×3 square. The opponent then acted as the defender and used the O mark. The game continued until all the positions are occupied by X and O in turn.

In the second run, the defender and the offender exchange their roles and played the game again. The players were required to write down description about their reasons, the strategies or the rules used for making decision as clear as possible after each step on a sheet of paper. The result patterns of 70 games are summarized in Figure 2.

As shown in Figure 2(a) the tie pattern E5 is the most dominant pattern played by the subjects because 41 out of 70 players, shortly written as 41/70, selected central position E in the 1st step. The proportion of games ended is E5 pattern is equal to $41/70 \times 33/41 \times 14/33 = 14/70$, which can be used as a typical result for illustration.

The game consists of 5 decision cycles for the offender and 4 decision cycles for the dfender. A stepwise analysis by DBE is summarized in Figure 3. The result shows that the DBE is useful in providing qualitative analysis of the dynamic decision process implicitly.

In order to verify that the "causality" can be used to give a quantitative prediction on the decision outcomes of the experiment, we define the "criticality" for the decision outcomes as

$$CR = \begin{cases} 1, & \text{if } c(W) - 1 \text{ or } C(L) = -1 \\ [C(W) - C(L)]/2, & \text{otherwise} \end{cases}$$

where C(W) is the "criticality" of the position that leads the player to win the game if it is occupied by the player at this decision step. Similarly, C(L) is the "criticality" of the position that makes the player to lose the game if it is occupied by the opponent at this decision step. The value of C(L) is negative since this represents the "loss" of the player.

The prediction of decision outcome in each step is calculated and depicted in Figure 4. One can see that the predication is consistent with the experimental results and the analysis by DBE.

6. Conclusions

The DBE method and "causality" developed in this paper is experimentally verified that can be used to analyze and predict the dynamic decision outcomes. The DBE accomplished with the "causality" is thus a new kind of valid tool that can be used in handling and understanding the dynamic decision process. Further researches and applications using DBE and causality may include:

1) Development of "Dynamic Fault Tree Analysis (DFTA)".
2) Design of human-machine interface.
3) Development of decision support system (DSS).

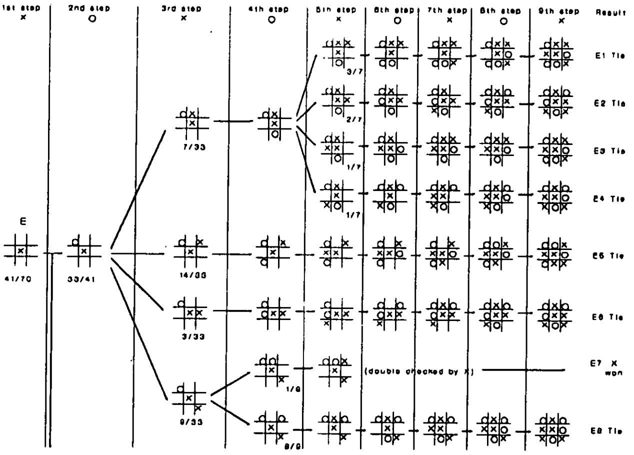

Figure 2(a). Summarized result patterns of E1 to E8.

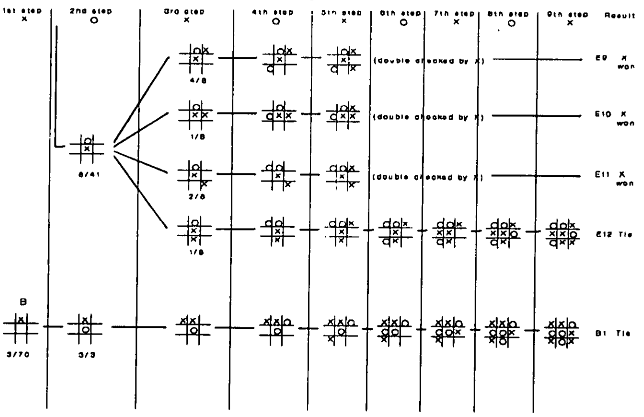

Figure 2(b). Summarized result patterns of E9 to E12 and B1.

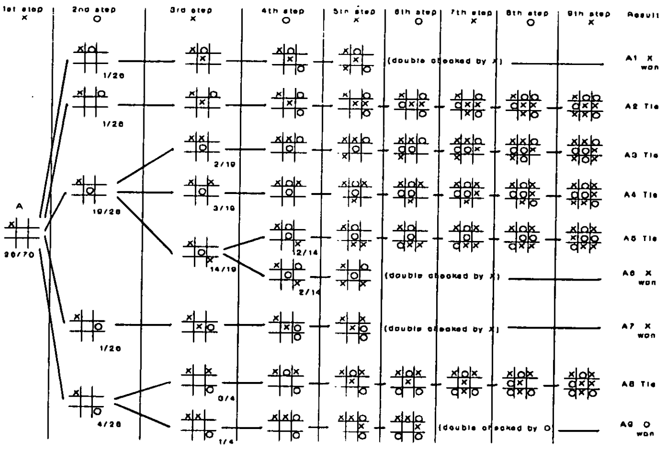

Figure 2(c). Summarized result patterns of A1 to A9.

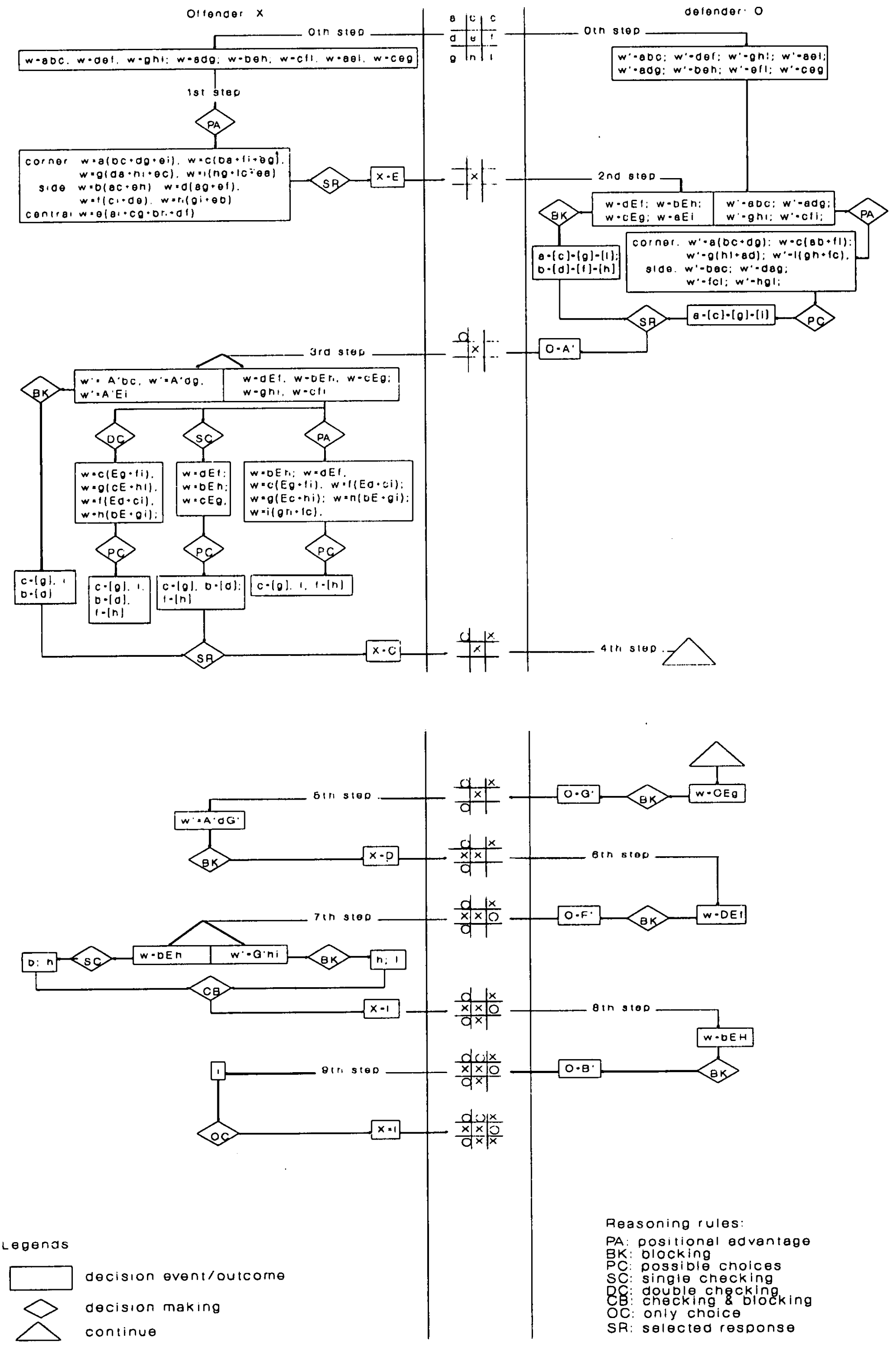

Figure 3. Stepwise analysis of E5 pattern by DBE.

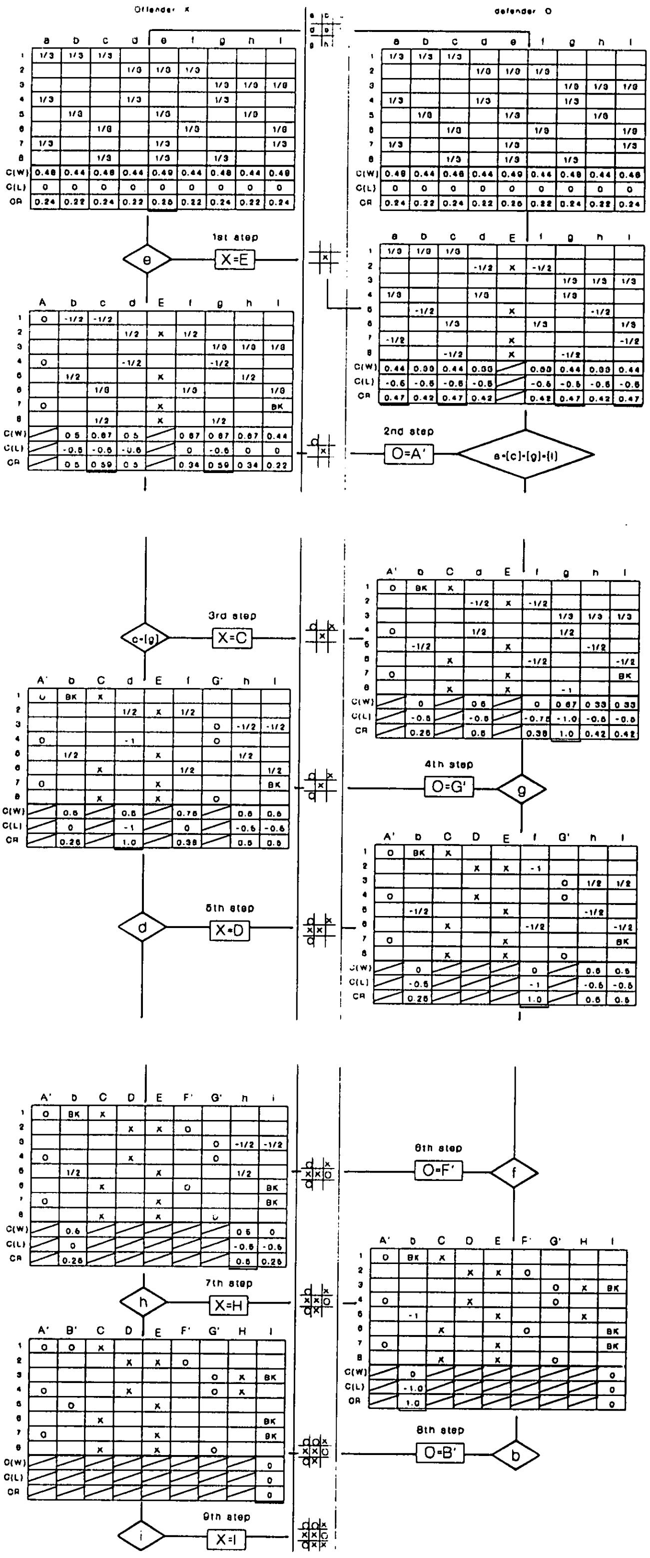

Figure 4. The prediction of decision outcomes by "criticality"

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利用 DBE 及因果性對動態決策結果之分析及預測

楊 昌 裔

摘 要

由於近代電子及電腦科技的不斷創新與突破，使得現代化系統（如運輸系統、生產系統及武器系統等）的功能設計日趨精巧複雜。爲了使這些系統能發揮最大的功能效率，以及基於系統可靠性的考量，因此這些系統的操作主要是透過事先建好的電腦控制程式依指定的程序進行。而操作人員的工作性質也從傳統上非常注重手動技巧的「機件操縱」，演變爲只需對電腦控制系統進行「監督」，並且「決定」該執行那些程序以維持整體系統運作正常的心智性工作。換言之，現代化系統操作人員已成了控制室內的「決策者」；而且在操控過程中，操作員所需執行的是一種與系統狀態有密切互動關係的「動態決策工作」。雖然心理學家曾提出多種理論與模式來解釋人類的決策行爲，但其研究通常只著重於靜態推理模式的建構，因而忽略了對動態決策過程的通盤考量。有鑑於此，本研究針對「動態決策過程」發展出一套稱爲「動態布林表示式」(DBE) 的分析法，同時也提出「因果性」的量化計算來預測其決策結果；並且藉由實驗驗證了 DBE 與因果性是一套適用於分析及預測動態決測結果的數學工具。

關鍵字：動態布林表示式、因果性、確定性動態決策

楊昌裔：工業工程與管理科講師