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EVALUATION OF THE AVAILABILITY BENEFITS OF UPGRADED DIAGNOSTICS ON PRODUCTION SYSTEMS

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ABSTRACT

Modern electronic and computer systems are impacting the availability performance of production systems. Automated fault indication equipment has not always given the expected availability benefits, and there is strong evidence in some cases that productivity might have improved if less complex diagnostic support systems were employed. Clearly diagnostic support is both a management and technical problem. Some availability modelling structurers which account for diagnostic support system performance are reviewed. An availability model which conforms to a consistent outage data classification policy is proposed. An example is given to show how availability returns can be calculated to compare the relative benefits of managerial and technical diagnostic support actions. The optimal deployment of diagnostic support throughout the life cycle of large scale or complex production systems can be achieved with the help of the proposed decision support model.

OPSOMMING

Moderne elektroniese en rekenaarstelsels beïnvloed die beskikbaarheidsprestasie van produksiesisteme. Outomatiese foutdiagnosetoerusting lewer nie altyd die verwagte beskikbaarheidsvoordele nie en daar is in sekere gevalle sterk aanduidings dat produktiwiteit benadeel word deur die kompleksiteit van diagnostiese steunstelsels. Dit is duidelik dat diagnostiese steun beide 'n bestuursprobleem en 'n tegniese probleem is. Sekere beskikbaarheidsmodelleringstrukture wat vir die prestasie van diagnostiese steunstelsels voorsiening maak, word bespreek. 'n Beskikbaarheidsmodel wat verenigbaar is met 'n spesifieke stilstand-dataklassifikasiebeleid word voorgestel. 'n Voorbeeldberekening word gegee om aan te toon hoe die relatiewe voordele van bestuursaksies en tegniese aksies ten opsigte van diagnostiese steun vergelyk kan word. Die optimale diagnostiese steunstelselontplooiing gedurende die lewenssiklus van grootskaalse of komplekse produksiesisteme kan behaal word met die hulp van die voorgestelde besluitsteunmodel.

1. INTRODUCTION

Modern production systems are becoming progressively more complex. The need to meet fine tolerances and exacting specifications on produced items is partially responsible for this trend. Complexity is encountered regularly when electronic controls and computers are integrated into the production process.

Diagnostic support systems are often integrated into the design of complex production systems in an attempt to reduce the effect of unavailability problems. These diagnostic support systems include built-in test equipment (BITE) and technicians with portable test equipment. Diagnostic support system performance influences availability most directly by impacting unplanned outage time. Unfortunately false alarms or incorrect fault indications tend to prolong unplanned outage time. Dependability problems with allocated fault detectors can lead to unexpected unavailability.

Moore and Damper [1] have reviewed the application of BITE within large systems, and have concluded that BITE deployment is as much a management problem as a technical one. This is because BITE has often failed in practice in its aim of easy maintainability with low skilled labour. Management can not expect low skilled artisans to easily locate faults or identify false alarms or incorrect fault indications on complex systems. There have been strong indications that lost production time on some systems might have been avoided if less sophisticated BITE was employed.

It is difficult to predict an optimum level of BITE, and it is suggested that the BITE specification be developed in an interactive way throughout design, development, implementation and field operation. This paper discusses an availability evaluation tool which was developed to facilitate reliability/maintainability trade-off studies throughout the life cycle of a complex production system. Special attention is paid to diagnostic support capabilities.

2. DEFINITIONS

$\tilde{A}$ = estimated availability (before change)

$\hat{A}$ = predicted availability (after change)

$A(\infty)|_{\Sigma_i \Sigma_j}$ = limiting state availability given all combinations of outage modes i and sub-system levels j

ΔA = availability returns

α = probability of system insecurity, given unavailable support from automatic fault indicators

c = probability of system insecurity, given automatic fault indication

D = diagnostic outage state

i = outage event classification

J_{ij} = availability functional related to individual outage mode i and sub-system level j

J_u = availability functional not requiring estimation

j = malfunction level classification

k = probability of system insecurity, given manual fault identification, i.e. the false alarm ratio = $1-k$

m = probability of incorrect fault indication, given available but undependable automatic fault indicators

$\bar{m}$ = $1-m$ = conditional false alarm probability

N = normally functioning state

R = repair outage state

r = probability that an automatic fault indicator will perform its function dependably

W = wait-for-reset (administrative) outage state

α = reset rate

ε = automatic fault indicator allocation $\varepsilon = 1$ (not allocated $\varepsilon = 0$)

θ = identification rate, i.e. identification of cause of outage

λ = outage rate

μ = repair rate

3. ACCOUNTING FOR DIAGNOSTICS IN THE AVAILABILITY MODEL

Availability modelling structures which have been reported in the literature vary widely in context. Availability models accounting for the effects of diagnostic support systems are rarely encountered in the literature. A very basic model accounting for the probability of fault detection and the fault identification rate was reported by Pau [2]. A model to optimise the allocation of fault detectors to various system levels, and which also accounts for fault detector dependability, was developed by Takami et al [3].

The model shown in figure 1 was developed by Lane [4] to extend the resolution of the model by Takami et al into the realm of outage modes i per system level j. In addition the model in figure 1 accounts for false alarm ratios $(1 - k)$ and system insecurity probabilities (c). The system is defined as insecure if it will not function successfully again unless repair or replacement tasks are performed.

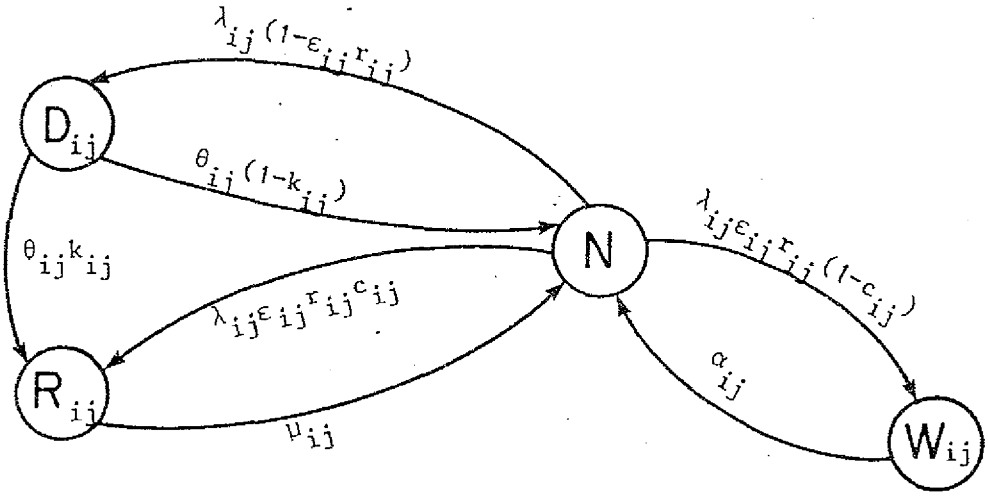

FIGURE 1: LANE'S GENERAL AVAILABILITY MODEL FOR COMPLEX SYSTEMS WITH DIAGNOSTICS

Lane's availability model makes the normal assumptions of lack of memory, statistical independence of transition mechanisms and mutually exclusive outage states. A limiting state availability equation for the model in figure 1, as derived in [4], gives

$$A(\infty) = \cfrac{1}{1 + \Sigma_i\Sigma_j \cfrac{\lambda_{ij}(1-\varepsilon_{ij}r_{ij})}{\theta_{ij}} + \Sigma_i\Sigma_j \cfrac{\lambda_{ij}k_{ij}}{\mu_{ij}} + \Sigma_i\Sigma_j \cfrac{\lambda_{ij}\varepsilon_{ij}r_{ij}(c_{ij}-k_{ij})}{\mu_{ij}} + \Sigma_i\Sigma_j \cfrac{\lambda_{ij}\varepsilon_{ij}r_{ij}(1-c_{ij})}{\alpha_{ij}}} \qquad (1)$$

This equation can be adapted to suit the particular logic of a system through adaptation of equation (1) to describe a specific system model. This is done by recognising each type of outage event as an embedded set in Lane's general model, simply by setting unencountered transition paths to zero. Lane's model also confirms that if each mutually exclusive outage event leads to an individual limiting state availability

$$A(\infty)\big|_{ij} = \frac{1}{1 + J_{ij}} \qquad (2)$$

then the limiting state availability which accounts for all of the possible types of mutually exclusive outage events will be

$$A(\infty)\big|_{\Sigma_i\Sigma_j} = \frac{1}{1 + \Sigma_i\Sigma_j J_{ij}} \qquad (3)$$

4. AVAILABILITY OF A PRODUCTION SYSTEM WITH CONSISTENT DIAGNOSTIC SUPPORT

With the help of (2) and (3) each of the consistent outage modes i can be accounted for individually, and then combined into a limiting state availability function for all consistent outage modes. By enforcing consistent outage mode classification the production engineer is creating a communication baseline so that all decisionmakers can distinguish between technical and management problems effectively. An example of a practical classification policy is given in figure 2.

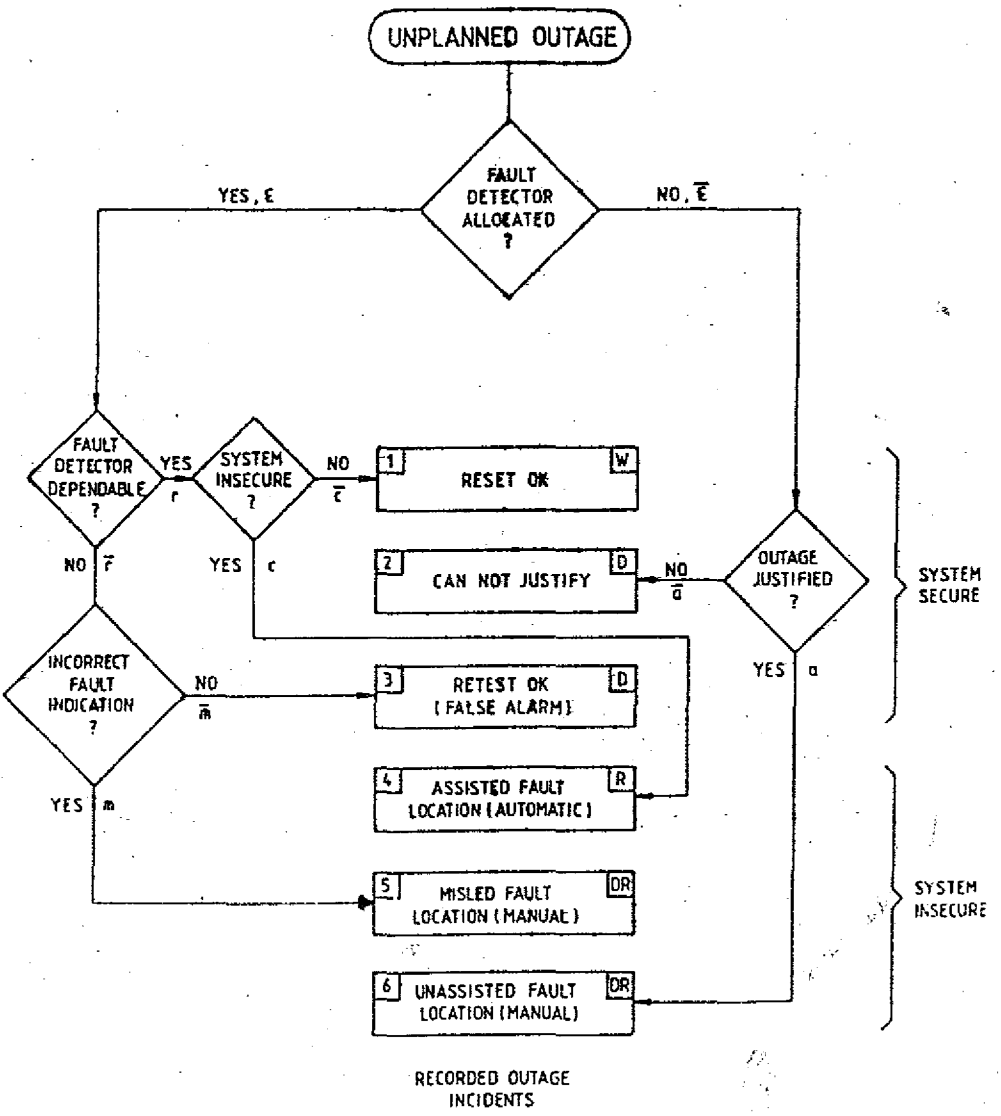

FIGURE 2: CLASSIFICATION OF EVENTS FOLLOWING AN OUTAGE

The outage state transition model associated with this classification policy is given in figure 3. Note that the subscripts j which indicate the sub-systems or functional levels which are unavailable have been omitted from figure 3 for convenience.

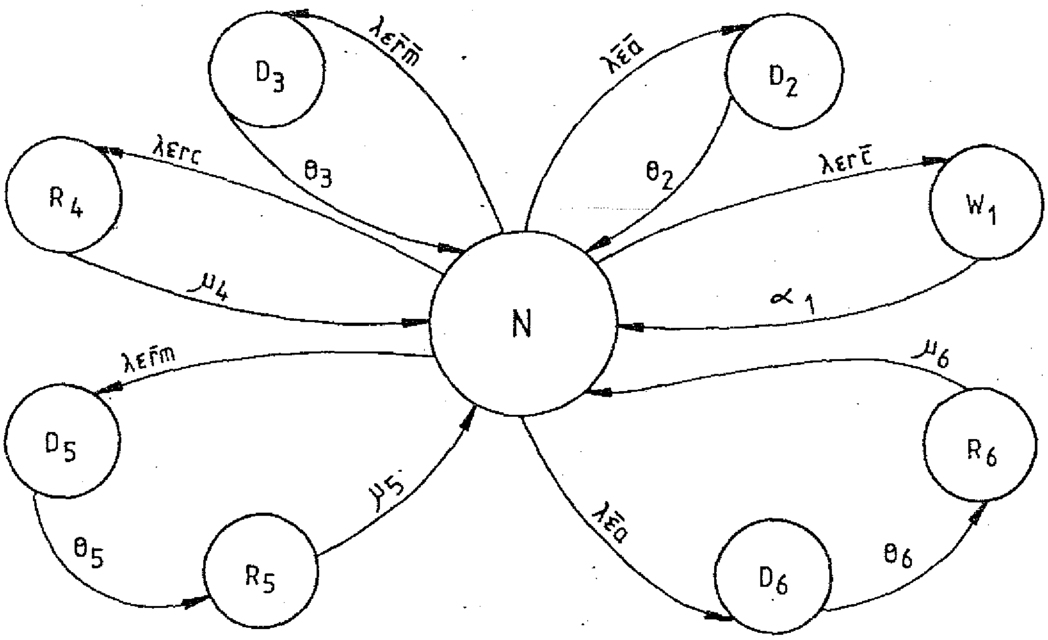

FIGURE 3: AVAILABILITY MODEL FOR A SYSTEM WITH CONSISTENT DIAGNOSTIC SUPPORT

The outage mode 1 associated with "reset okays" would then have

$$J_{1j} = \frac{\lambda_j \varepsilon_j r_j \bar{c}_j}{\alpha_{1j}} \tag{4}$$

Similarly for "can not justify" incidents (sometimes called "can not duplicates")

$$J_{2j} = \frac{\lambda_j \bar{\varepsilon}_j \bar{a}_j}{\theta_{2j}} \tag{5}$$

For "reset okays" or false alarms

$$J_{3j} = \frac{\lambda_j \varepsilon_j \bar{r}_j \bar{m}_j}{\theta_{3j}} \tag{6}$$

For incidents of automatically assisted repairable fault location

$$J_{4j} = \frac{\lambda_j \varepsilon_j r_j c_j}{\mu_{4j}} \tag{7}$$

For incidents of incorrect fault indication and therefore misled manual fault location

$$J_{5j} = \frac{\lambda_j \varepsilon_j \bar{r}_j m_j}{\theta_{5j}} + \frac{\lambda_j \varepsilon_j \bar{r}_j m_j}{\mu_{5j}} \tag{8}$$

For incidents of unassisted manual fault location

$$J_{6j} = \frac{\lambda_j \bar{\varepsilon}_j a_j}{\theta_{6j}} + \frac{\lambda_j \bar{\varepsilon}_j a_j}{\mu_{6j}} \tag{9}$$

The limiting state availability function for the system is then found by combining (4) to (9) into (10) as follows

$$A(\infty)\Big|_{\Sigma_i \Sigma_j} = \frac{1}{1 + \Sigma_j \lambda_j \left(\frac{\varepsilon_j r_j \bar{c}_j}{\alpha_{1j}} + \frac{\bar{\varepsilon}_j a_j}{\theta_{2j}} + \frac{\varepsilon_j r_j \bar{m}_j}{\theta_{3j}} + \frac{\varepsilon_j r_j c_j}{\mu_{4j}} + \frac{\varepsilon_j \bar{r}_j m_j}{\theta_{5j}} + \frac{\varepsilon_j \bar{r}_j m_j}{\mu_{5j}} + \frac{\bar{\varepsilon}_j a_j}{\theta_{6j}} + \frac{\bar{\varepsilon}_j a_j}{\mu_{6j}} \right)} \tag{10}$$

5. AVAILABILITY RETURNS EVALUATION

To illustrate the use of (10) during evaluation of the availability returns to be expected from allocation of more sophisticated diagnostic support, an example will be discussed.

EXAMPLE

Consider the problem of quantifying availability returns to be expected from the allocation of vibration fault indicators to boiler feed pump drives in a thermal power station. It is practical only to consider the availability returns on a single boiler feed pump drive, and then to quantify availability returns in terms of electricity production of the turbogenerator unit later with the use of combinatorial methods, since there are normally redundant boiler feed pumps and various system states to be considered. For simplicity this example does not go beyond the availability returns calculation for a single hypothetical boiler feed pump unit.

Firstly, we are only concerned with malfunction level y, defined as "system out of vibration design tolerance". So it is necessary to separate this malfunction from the set of possible malfunction classifications j as follows

$$\tilde{A} = \frac{1}{1 + \Sigma_i \Sigma_{j \neq y} J_{ij} + \Sigma_i \tilde{J}_{iy}} \qquad (11)$$

The term $\Sigma_i \tilde{J}_{iy}$ represents that part of system behaviour related to vibration exceedance prior to additional allocation of vibration sensors. This means that $\tilde{\tilde{\varepsilon}} = 1$, and

$$\Sigma_i \ \tilde{J}_{iy} = \tilde{\lambda}_y \left(\frac{a_y}{\tilde{\theta}_{2y}} + \frac{a_y}{\tilde{\theta}_{6y}} + \frac{a_y}{\tilde{\mu}_{6y}} \right) \qquad (12)$$

Table 1 gives estimates of the relevant system parameters prior to change.

TABLE 1: VIBRATION RELATED PARAMETERS PRIOR TO VIBRATION DETECTOR ALLOCATION (ESTIMATES)

DESCRIPTION	SYMBOL	ESTIMATE
Outage rate	$\tilde{\lambda}_y$	1×10^{-4}/hour
Insecure probability	$\tilde{a}_y$	0,8
Identification of unjustified outage	$\tilde{\theta}_{2y}$	0,04/hour
Identification of justified outage	$\tilde{\theta}_{6y}$	0,04/hour
Repair of vibration related outage	$\tilde{\mu}_{6y}$	0,015/hour
Availability	$\tilde{A}$	0,96

Relating table 1 to the hypothetical (but practical) situation, the values in table 1 suggest that a manual vibration detection procedure is followed, that manual measurements give 80 % successful indication of system insecurity, that troubleshooting takes typically 25 hours, and that repairs take about 67 hours. Also, using this procedure it has been estimated that boiler feed pump outages due to suspected vibration problems occur once per 10 000 operating hours.

Now the estimated availability functional related to vibration can be calculated to be

$$\Sigma_i \ \tilde{J}_{iy} = 7{,}833 \times 10^{-3}$$

The term

$$J_u = \Sigma_i \ \Sigma_{j \neq y} \ J_{ij} \qquad (13)$$

need not be estimated, because the boiler feed pump availability using the maintenance scenario prior to change is estimated (with reasonable confidence) to be 0,95. From (11) and (13) it is evident that

$$J_u = \frac{1}{\tilde{A}} + 1 - \Sigma_i \tilde{J}_{iy} \qquad (14)$$

$$\therefore J_u = 0{,}0447986$$

Now it is necessary to quantify the advantage (or disadvantage) of allocating permanent vibration sensors to the boiler feed pump drive systems. In this case $\varepsilon = 1$, and the availability functional related to vibration must be predicted as follows (using (4), (6), (7) and (8))

$$\Sigma_i \hat{J}_{iy} = \hat{\lambda}_y \left(\frac{\hat{r}_y \hat{\bar{c}}_y}{\hat{\alpha}_{1y}} \quad \frac{\hat{\bar{r}}_y \hat{\bar{m}}_y}{\hat{\theta}_{3y}} \quad \frac{\hat{r}_y \hat{c}_y}{\hat{\mu}_{4y}} \quad \frac{\hat{\bar{r}}_y \hat{m}_y}{\hat{\theta}_{5y}} \quad \frac{\hat{\bar{r}}_y \hat{m}_y}{\hat{\mu}_{5y}} \right) \qquad (15)$$

The predictions can be based on experience with similar installations elsewhere, or in the case of new technology they might have to be based on the allocated performance targets of the designer. Whatever the case (15) gives a good idea of the information that must be solicited to support a decision to improve availability by the addition of vibration indicators, as required for our example. These predicted parameters are given in table 2, using realistic values for example calculations.

TABLE 2: VIBRATION RELATED PARAMETERS AFTER VIBRATION DETECTOR ALLOCATION (PREDICTIONS)

DESCRIPTION	SYMBOL	PREDICTION
Outage rate	$\hat{\lambda}_y$	$1{,}1 \times 10^{-4}$/hour
Vibration detector dependability	$\hat{r}_y$	0,9
Insecure probability	$\hat{\bar{c}}_y$	0,9
False alarm probability	$\hat{\bar{m}}_y$	0,95
Reset rate	$\hat{\alpha}_{1y}$	0,2/hour
Reset rate	$\hat{\theta}_{3y}$	0,8/hour
Repair rate	$\hat{\mu}_{4y}$	0,02/hour
Illegitimate maintenance identification rate	$\hat{\theta}_{5y}$	0,02/hour
Illegitimate maintenance recovery rate	$\hat{\mu}_{5y}$	0,2/hour

It is evident from (15) and table 2, that additional diagnostic capability adds sygnificant complexity to the problem of soliciting adequate information to base predictions on. The practical implications of table 2 will be discussed briefly to relate theory to practice.

The outage rate with dedicated vibration detectors is likely to increase because sensing is done continuously and not on a sampling basis (as by hand). Automated detection equipment will not necessarily filter out spurious vibration signals coming from external sources. Due to design sophistication vibration sensor dependability could be an improvement on hand-held measurements, mainly because human error degrades the performance of hand-held methods. Therefore both $\hat{r}_y$ and $\hat{c}_y$ represent relatively higher probabilities of success. Reset, retest and repair rates are improved because these actions can be implemented with greater ease due to enhanced diagnostic capability. However, the illegitimate maintenance burden caused by detection of non-existent faults, or incorrect fault indications (failure of test equipment itself serves as an example), can be a disadvantage of more sophisticated diagnostic capability. Much time could be spent seeking a fault in the wrong functional area, hence the low illegitimate maintenance identification rate.

To determine whether the advantages of greater diagnostic sophistication outweigh the possible disadvantages, the availability returns evaluation must be completed.

From (15) and the predictions in table 2

$\Sigma_i \hat{J}_{iy} = 5{,}052 \times 10^{-3}$

The availability prediction for the modified system becomes

$$\hat{A} = \frac{1}{1 + J_u + \Sigma_i \hat{J}_{iy}} \qquad (16)$$

$\therefore \hat{A} = 0{,}952516$

And the availability returns are

$$\Delta A = \hat{A} - \tilde{A} \qquad (17)$$

$\therefore \Delta A = 0{,}002516$

Thus, in the case of the case of the given example, a 5 % reduction in unavailability of each boiler feed pump seems to be possible.

6. CONCLUSION

The proposed availability modelling structure is an extention of previous work by Takami [3] and Lane [4]. The main advantage of this model is that it provides insight into the amount of information that meeds to be solicited to make realistic evaluations of the effect that changes in diagnostic subsystems will have on availability. Another advantage is that the model makes it possible to quantify the disadvantages of diagnostic sophistication in a consistent manner.

From the given example it is evident that added diagnostic sophistication could easily degrade availability performance, and that the designer should take care to allocate revised performance criteria realistically and consistently.

Although the proposed model creates insight, it suffers from the disadvantage that data capturing and analysis would have to be highly disciplined. Such highly disciplined data capturing programmes are rarely encountered in practice, so the decision to add diagnostic sophistication rests more heavily on the trade-off capabilities of the model, rather than its ability to produce highly credible predictions.

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