INCA: A RETROSPECTIVE PERFORMANCE TOOL FOR PROJECT MANAGEMENT

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During an investigation of catastrophic paint failures on a major international building a method of determining the cross links between trade activities during the building process was developed as a post-construction analytical technique. The specially written software was recognised immediately as a possible generic performance tool, and of considerable use to facilities managers where major maintenance and construction problems were evident in buildings under their care.

INCA, the name of the software, aptly refers to 'Incompatible Construction Activities' during construction. The first case study that gave rise to this method is described. Data from the project documentation was processed together with the results of other on-site investigations, and confirmed a significant number of *unfavourable conjunctions of trades.* These effects were found to be associated with the evidence of paint failures found both on site and determined in the laboratory. A multi-million pound litigation case was involved.

This paper discusses the application of INCA, which was written by the author, and shows how, combined with traditional investigations, it assisted in a speedy final settlement. The software is equally applicable to similar construction management problems.

Keywords: building failure, computer analysis, critical path.

INTRODUCTION

The writer was invited by a firm of British architects to investigate widespread failures in a recently completed major international airport. The building owners were involved in multi-million dollar claims for paintwork failures which had occurred in all parts of the building. About 100,000 m^2 of substrate was involved, chiefly on the metal underside of composite reinforced concrete flooring and roofs. The floor area of the building was approximately 10.1 hectares, divided over 3 storeys. Three previous investigations by likely litigants had failed to pin-point the cause of failure, and agree on the apportionment of blame. It was necessary to organise an investigation and clear the mystery within a deadline of 12 weeks, including a technical report, which if possible would mitigate against court proceedings taking place, and by its definitive nature allow an out of court settlement. These objectives were achieved and the resulting weight of unbiased evidence that was gathered was sufficient to prevent further argument. The problem with the earlier investigations was that they were carried out by interested parties, and lacked sufficient scope in sensitive areas of debate. INCA was only one of the tools used in a multi-pronged approach to the problem of apportioning blame after the event.

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CONSTRUCTION MANAGEMENT

The project did not have a Clerk of Works, nor any form of normal client inspection arrangements. The architect's responsibility stopped short at the design and specification stage. In retrospect the arrangement was seen as an early form of novation contract. The main contractor utilised a site agent's office which produced weekly progress reports in the form of a brief log of trade activities. These were forwarded to the architects and others. Even before the building had been completed paint was hanging and falling from the underside of the galvanised ribbed sheeting which formed part of the composite floors and roof. The CPM included very little or no float time of any significance, and having obtained the contract the contractor was continually under pressure to complete each stage on time. This alone prompted our consideration of the sequencing of trades.

The building was well exposed on all sides, particularly to winds sweeping in from the south-west. During construction the site suffered two very bad winters. In cases where this type of construction management prevails and is followed by problems, it can prove illuminating to read the site agent's reports after a building is handed over, and the sequence of site activities are re-examined in reverse order to determine what actually took place on site at particular trade levels.

Such an approach we call *the inverse critical path method*. (ICPM) If only one trade is involved in a failure then a trace back is simpler than examining the whole CPM network. It is an illusion to assume that the CPM that is offered actually resembles what took place on site (Whitten, 1986). At any specific time during construction one trade involves correct operational timing relative to other trades - which is normal CPM sequencing. If this sequencing becomes out of phase, problems can arise in the durability or quality of the finished construction. These activities we call *unfavourable coincident trade activities* (UCTA's).

For example, if internal painting is carried out using internal quality paint, but with no outside wall cladding in position for two years (Jose, 1989), or if painting is attempted over fire resistant spray coatings, or in compartments that are simultaneously having wet floor screeds laid, or brickwork and blockwork constructed; then we could expect future problems. Heavy condensation was found to be endemic on the paint substrates of this building - visible stains were in evidence before and after the paint was applied.

Additionally, if the paint specification is altered to accelerate a lagging construction schedule and, for example, allows spraying rather than brush application; or, if the wrong type of etch primer is used on chromated zinc; or if a non-specified formulae paint is used; or if the substrate is left greasy from profiling oil; if any of these conditions apply then exposure to inclement weather will accelerate the failure rate in those areas, and this will be evident. If, for example, a different formulation of top coat with a different shrinkage rate is applied over a non-matching undercoat, then paint curling may arise firstly due to differential embrittlement, and secondly because the substrate primer has little or no attachment.

In the case of the paint failures described as a case study in this paper, the investigative approach on site was to determine the part played by any of these anomalies, and others, in the final extent of failure. The factors were categorised as those arising from construction management, specification, workmanship, application sequencing and formulation. Who is liable for what, and for how much? The leading question usually asked at litigation level is 'whether all reasonable avenues of investigation have been explored sufficient to force a settlement.' Anything less will allow one or other party to blame the failures that might be involved on one or more unexplored avenues of investigation, some of which can be quite fanciful.

From inception the building under investigation took over three years to complete. The main contractor, with an international reputation to protect, had undertaken contracts throughout the world and was generally well respected in the industry. The architects were of similar standing. No logbooks or weekly progress reports were available initially, but a batch of contractors reports were found just before they were due to be thrown out. To these were added other odd copies that were missing, until a set was assembled. Thus a history of construction on site was obtained.

All the relevant activity correspondence was gathered, together with weather reports, previous investigation reports, specifications, and other miscellaneous documents. Several cans of unopened original paint samples were discovered. An investigation of material properties of curd and failed paint samples was carried out at forensic levels using spectroscopic and analytical chemical methods.

Samples of paint were taken from the site, substrate and coating surfaces were examined using toluene and water swabs. A standard cross-cut adhesion test was carried out, and several other tests as required. Several hundred samples were taken, photographed, labelled and sent to the laboratory. Heating ventilation and air conditioning monitoring checks were carried out to judge the stability of internal temperatures.

INCA AND THE ICPM

Most construction managers are familiar with CPM methods when applied to large scale projects. The network can become extremely complex (Boesch, 1971). It will be of interest to outline the general principles of the inverse CPM or retrospective examination of trade activities which we have called ICPM (Weist and Levy, 1977)

For the purposes of the investigation the building geometry was divided into *levels (3),* and plan *zones (18)* which were linked with associated *activities* (trades) and an applied *time frame* (week number, or report number (1-46). Figure 1 indicates the notation. Four dimensions were thus perceived which suggested that a suitable computer algorithm might be devised for analytical purposes. The building shown in figure 1 is not the same layout as the building under consideration for reasons of anonymity.

The formal representation of the method chosen is indicated in figure 1 (top), which shows a matrix represented by four *imaginary* orthogonal axes OW, OX, OY and OZ. The matrix is strictly a chart as distinct from a graph since the axes OZ, OY, and OW represent *entity* labels. Only the OX axis representing discrete 28 day *time intervals* over the period of site construction is a value axis. The OZ axis represents the trade *activities* associated with the particular failure investigated; these can be in any order. The choice of associated trade activities is a matter of professional judgement. They include all trades that might have a bearing on the particular problem. Every trade could be included if necessary, but this would result in extra processing time, and in our case simply produce more blank output. Any relevant activity can be used providing it can be located geometrically using a zone, level, and time of occurrence. The matrix used was essentially a sparse matrix, holding nearly 900 triple binary flags as character strings which described the current trade state, within a total number of around 16,000 cells.

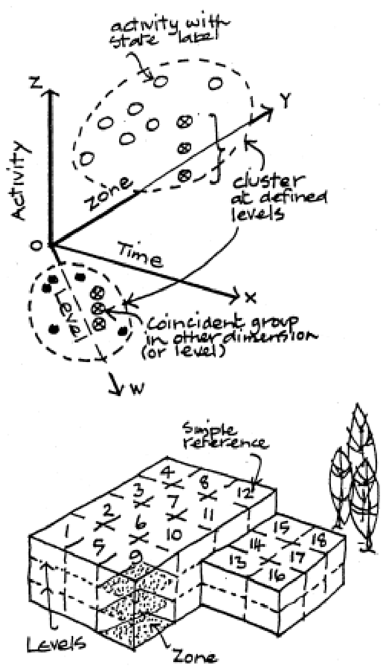

Figure 1: INCA nomenclature and matrix arrangement

The axes OZ and OX bound the familiar Gantt chart. It can be seen in figure 1, how successive vertical parallel planes along the OY axis represent Gantt charts for each physically contiguous zone at each level. These zones and levels can be designated using the same code as that used in the contractors CPM. With ICPM concepts in mind, they could perhaps be more specific zones delineated in terms of the contract. The zones delineated in the building under consideration were those used by the contractor in the 28 day progress reports. The three dimensional location of an activity, trade or otherwise, is defined by the OW axis, which represents *levels* in conjunction with the OY zonal axis.

Each cell of the four dimensional matrix, located as above, can be allocated a *state code* which can take several forms, but is designed to indicate the current state of the activity - usually *present* or *absent*. The simplest form of computer code for this is the *binary on/off flag (0 or 1),* which can define whether the activity or trade, or its stages are being undertaken in that zone. Alternatively, a single alphanumeric character could allow 36 states to be defined for a single activity which would allow a whole range of trades stages to be included. For this reason character string coding is more efficient than integer value coding was adopted. Binary character flags were used for INCA.

A segment of the program automatically encodes the input file in the manner described above, buffering the user from most of the complexities (figure 2). The zero (0) character (not integer) represents *no* activity in progress, and one (1) represents a *positive* activity. A character string of length 3 distinguishes which *level* is active at any given time, and is entered as the matrix cell value proper. The use of this type of stringing effectively reduces the matrix by one dimension, and increases the processing speed.

```
831
62
13 22 16 3
 FILE DESCRIPTIONS AS FOLLOWS:
 MATRIX ROWS--
 ROW     1: CONC. FLOORS & ROOF
         2: FLOOR SCREEDS
            ARD FLOORS TERRAZZO
 ROW             & BLOCKWORK
 ROW     6: RUC
 ROW     7: EXTERNAL
 ROW     8:       ENTRANCE L
 ROW     9: METAL TRUSSES:
 ROW    10: PAINTING
 ROW    11: SPECIALIST FIRE PROT. (PYROK)
 ROW    12: GENERAL FIRE PROTECTION
 ROW    13: SOFT FLOORS
 MATRIX COLUMNS--
 COL     1:  7/ 8/83  (REP.26)
         2:  4/ 9/83  (REP.27)
             2/10/83  (REP.28)
 COL                  (REP.29)
 COL    19:
 COL    20: 10/ 2/85
 COL    21: 10/ 3/85  (REP.46)
 COL    22: 21/ 4/85  (REP.47)
 MATRIX ZONES:
 ZONE    1: AREA  1
         2: AREA  2
            AREA  3
 ZONE
 ZONE   13:
 ZONE   14: AREA 14
 ZONE   15: AREA 15
 ZONE   16: AREA 16
 LEVELS--
 LEVEL  1:
 LEVEL  2:
 LEVEL  3:
  2  1   1 110
  3  4   1 010
  3  5   1 010
  3  6   1 010
  3  7   1 010
  3  8   1 010
  3  9   1 010
  3 10   1 010
  3 11   1 010
  3 12   1 010
  3 13   1 010
  3 14   1 010
  4  3   1 010
```

Figure 2: Input file prepared for INCA

It is also possible to encode the influences of activities in adjacent zones, including those above and below, and at the corners of the zone under scrutiny. This feature could be useful in open plan designs. However each zone is surround by 26 adjacent zones which creates a higher order of complexity, and results in much longer input file preparation time. The input file for INCA took the simpler form shown in figure 2 (approx. 1000 lines for this case study), and had to be prepared quite carefully from plans and documentation. The first part of the file contains descriptions of activities, zones, and levels. The rest of the file lists all those levels that are active due to trade or subcontractor work at a specific date. The remainder of the matrix is initialised with character blanks.

Much of the *state* matrix is empty, implying that the chosen activities are confined only to a relatively few cells. Unlike a computer CPM analysis INCA is much less complex and surprisingly efficient. Unless two or more activities are present in a zone INCA does not flag an event (prints a blank output). Sparse matrix techniques using cell addresses reduce processing times. Each active zone was allocated a location address, and the encoded *level states* were packed, as indicated above, as a character string. The estimated processing time was reduced by a factor of about 10 using this simple algorithm.

The output from INCA shown in figure 3 is basically a zone list which indicates all those parts of the building, at all time intervals, where non-compatible activities coincided, and problems might have arisen. It gave the dates, activities involved, and document reference where this was available and provided a quick pointer in terms of where to look for failure concentrations in the paintwork greatly. Part of the output list is shown in Figure 3. It offered leads to unsuspected problems due to exposure to weather for example, that had arisen during construction, and which, because of a clash of trades could exacerbate failures either as premature, immediate or latent defects.

```
PERIOD NO:  8-  4/ 3/84 (REF.33)                LEVEL
----------
Check: ROOF COVERING                       /    1
Check: EXTERNAL CLADDING                   /    1

Check: BRICKWORK & BLOCKWORK               /    2
Check: EXTERNAL CLADDING                   /    2
Check: SPECIALIST FIRE PROT. (PYROK)       /    2

Check: BRICKWORK & BLOCKWORK               /    3
Check: EXTERNAL CLADDING                   /    3
Check: SPECIALIST FIRE PROT. (PYROK)       /    3

PERIOD NO:  9-  1/ 4/84 (REF.34)
----------
Check: ROOF COVERING                       /    1
Check: EXTERNAL CLADDING                   /    1

Check: EXTERNAL CLADDING                   /    2
Check: SPECIALIST FIRE PROT. (PYROK)       /    2

Check: FLOOR SCREEDS                       /    3
Check: BRICKWORK & BLOCKWORK               /    3
Check: EXTERNAL CLADDING                   /    3
Check: SPECIALIST FIRE PROT. (PYROK)       /    3

PERIOD NO: 10- 29/ 4/84 (REF.35)
----------


PERIOD NO: 11- 27/ 5/84 (REF.36)
----------


PERIOD NO: 12- 24/ 6/84 (REF.37)
----------

Check: EXTERNAL CLADDING                   /    1
Check: PAINTING                            /    1
```

Figure 3: Output from INCA

For the case study under consideration, 219 positive prompts were generated, much greater than the few that were expected. The bottom of figure 3 shows a positive response for painting and external cladding being carried out at the same level, and in the same zone. The contractor's report and date is also listed which provides written proof of the discovery. Two blank entries are shown above in figure 3 which indicates no coincident trades (UCTA's); and two entries above this, show where concurrent wet trade work was in progress (not positive relative to painting). Some investigative leads involved pairs of trades, whereas others involved groups. The results allowed a perception of contractual responsibility, and the time related pressures that had been in force, as well as indicating latent fault prone zones that had not been revealed by three previous investigations. The contract fell behind schedule gradually, and this was reflected in the positive results discovered by INCA.

In summary therefore INCA indicated directly or indirectly the exact periods of time that individual zones were exposed to the weather, the type of weather, aspect, and internal trade activity. It was one tool in the investigation armoury. The output was cross-checked with the forensic work on site and the patterns and stages of failure in the paintwork and indicated good correlation with the INCA output. The lynch-pin of using the technique is of course the careful preparation of an input file from the available documents fortunately available for this case study. The synthesis of the various inputs in this kind of exercise is in turn very much dependant on the skills of the investigation team.

ASSOCIATED INVESTIGATIONS

It is instructive to briefly note the nature of the associated on site investigations. As a general procedure and companion to the use of INCA these would clearly vary depending on the kind of failure involved. For this site tests were carried out on the paint films to determine adhesion using a multi-blade cross-cut instrument. Paint film thickness was also determined using an elcometer (magnetic induction) instrument. In the laboratory, film thickness, coat types and numbers, overspray debris detection and incidence, pollution deposits, debris inclusions and solubility were determined from random samples taken from each zone. Spectrographic tests were carried out on the liquid and flake samples to determine the paint formulation.

It was the latter test that provided the common factor throughout the wide range of paint failures that were found. The oil length of the alkyd resin was below the acceptable level for the specification requested reducing the film elasticity. The embrittling effect that ensued, combined with lack of pre-cleaning and the wrong type of primer exacerbated the problem of paint failure. Over 70% of samples failed the adhesion test. The conjunction of incompatible trade activities and inadequate protection from exposure to the weather compounded the problem in clearly determined zones found by using INCA.

Following the presentation of the conclusions of the investigation, the contractor retracted former innocence and emphasised their obligation to accelerate progress in construction because of unanticipated delays in delivery and other contingencies. The paint, for example, was sprayed contrary to specification rather than brush applied. Evidence taken from areas where trade activities clashed indicated the reason for severe condensation problems under the composite floors (23% of samples) which also affected the interior paint durability. Early faults were found in those areas which showed up in the INCA output. For example, delays in the supply of cladding indicated that some zones were exposed for up to two winters of severe weather, and could not be heated. Despite this, painting continued.

INCA also revealed that soft flooring laying (carpets) had taken place in areas where wet floor finishes were under way, or had just been laid, or had not sufficiently dried. In some areas overspray from the application of fire resistant coatings rendered the simultaneous painting of nearby smooth decorative finishes impossible. This was nevertheless attempted over debris in the interests of expediency. Considerable pressure was on the contractors to make some gains on the stretched network plan.

CONCLUSIONS

The use of INCA, which is a computer method designed to determine retrospectively the unfavourable coincidence of trade activities, has been described. The software was used in conjunction with an on-site investigation of paint failures on a very large internationally recognised building. It was designed to provide evidence of possible causes of failure, and for this reason is seen as an additional performance tool very much needed in the current climate of building litigation.

The particular problem presented to the writer by the clients was solved on schedule, and a settlement achieved without recourse to the courts.

The importance of retaining site contract management documents, particularly those related to a log of on-site activities throughout the construction process, and particularly where novation type contracts are involved, is seen as vital whatever form this takes. Equally, the importance of signing watertight contracts by all parties is essential. The separation of design from design and full supervision increases the difficulties in apportioning blame when major construction problems arise.

In the current climate of performance specifications the professionals involved need little reminding that major failures are no longer isolated events. It is our current experience in trouble-shooting that at the time of a major failure, when performance experts are most needed, they are hard to find. Prior to the event, the industry is oversupplied with such experts, many offering cheaper performance design solutions based on unsubstantiated claims. The case study discussed in this paper was solved with mutually agreed results. This is not always the case. More performance tools are needed for the wide variations in performance designs that are now offered to the regulators, some hopefully rather than a factual basis.

The notion of an ICPM investigation using tools such as INCA has been offered as a contract management performance tool and is quite different from its companion CPM. It has been used successfully in a recent terrazzo failure for example, to chase specific leads about failure mechanisms *after*, rather than *before* the completion and hand-over of a building. For some contract and project managers this may not be so popular.

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