INDUSTRIAL CASE STUDY OF INNOVATIVE MANAGERIAL CONTROL SYSTEM APPLIED TO SITE CONTROL PROCESS (IMCS-CON)

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ABSTRACT: Construction projects are complex, fragmented and highly risk business, due to the nature of construction operations. Therefore project managers require more efficient techniques and tools to plan and monitor the construction project. In recent years many research studies have been carried out in order to make construction industry more efficient, profitable and attractive business. The IMCS-CON developed as decision support system for project mangers to assist project-controlling processes using a holistic approach. The IMCS-CON provide a framework to measure, analyse, review, and report performance data and enabling project management team to make corrective decision and keep project on track. The IMCS-CON system was evaluated using a case study of £2.3 million, three-story residential apartment building project in UK. The IMCS-CON system utilises multivariate statistical process control techniques to monitor the construction site variables. The MSPC combines a large number of variables into few independent variables, which then can be monitored and any process deviations from the normal operating conditions can be identified with corrective actions suggested. The IMCS-CON models on-site information as quantitative variables and uses historical data and establishes patterns of correlated variables and assists project management in making future decisions. The outputs can also be visualised in multi-dimensional graphs. Statistics of external variables and internal variables influencing construction site operations were identified using a real life case study. The results of modelling the variables and conducting experiments with IMCS-CON are analysed and discussed in this paper.

KEYWORDS: performance measurement, construction process variables, statistical process control, construction process benchmarking, construction process improvement, construction productivity.

1 INTRODUCTION

In complex and fast track construction projects, project analysis is very complicated. It is understood that the development of dynamic tools to monitor and control on-site construction performance by implementing modern construction management theories and techniques are appreciated, which enable to practice modern research techniques and theories into current practice. The automating control of on-site construction performance enables management to take corrective measures in real-time. As there are large numbers of variables that influence a performance on construction sites, it is very essential to take a holistic approach to study the variability and impact of the variable on the process. In today's competitive market, the success of construction projects depends largely on project managers' capabilities to make corrective decisions during construction planning and control stages [16]. The IMCS-CON developed to monitor and control key construction processes variables on site. The system will be able to analyse historical and current information and visualise the result in multidimensional graphs, establish patterns and report to project managers on weekly basis. Therefore project managers able make effective decisions and corrective action to keep project on track using advance statistical tools integrated with information visualisation techniques. The results of modelling the variables and conducting experiments with IMCS-CON are analysed and discussed in this paper.

2 IMCS-CON FRAMEWORK

The aim of IMCS-CON is to develop a decision support system that can be utilised by project managers to control construction processes using a holistic approach. The IMCS-CON provides a framework to measure, analyse, review, and report construction site information and enabling project management team to make corrective decision and keep project on track. The IMCS-CON has three main components, which includes 1) Electronic site diary; 2) Database; and 3) Data analysis and visualisation using MSPC (Multivariate Statistical Process Control) technique. The electronic site diary provides facilities to enter the site information and output of the site diary provides summary of weekly site performance in terms of values of the construction process variables. Database is used to record all the weekly variable values as historic and current information. Marasini and Dawood [12] developed innovative managerial control system (IMCS) to monitor and control business processes of a precast building products industry. The IMCS utilises Multivariate Statistical Process Control (MSPC) techniques combined with information visualisation model. The IMCS able to analyse data and visualise information of large number of variables. In order to analyse and graphically visualise construction variables, IMCS system has been utilised as a key component in IMCS-CON system. Figure 1 shows an outline structure of the IMCS-CON control process.

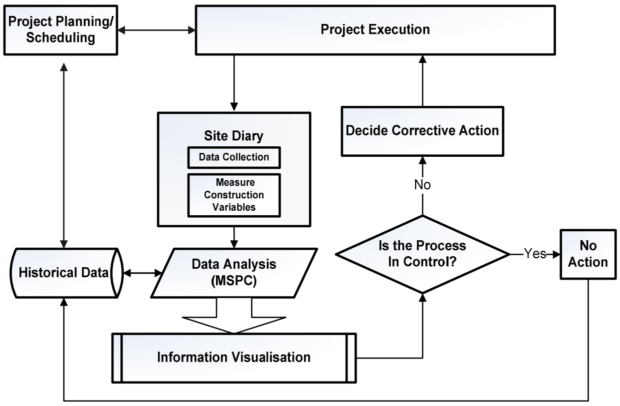


Figure 1. IMCS-CON model.

The IMCS-CON consists of three main components (figure 2) which are:

1. Electronic Site diary: Input site records and measure site performance variables
2. Data base: Store weekly data of site performance variables
3. IMCS: analyse current construction site performance variable with historical data and report project managers to assist decision-making process.

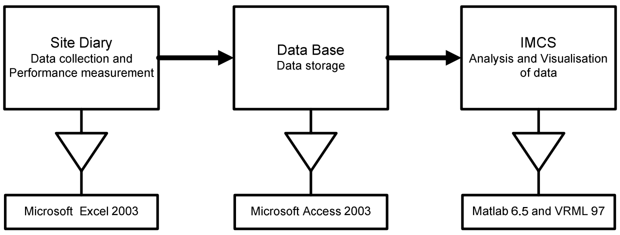


Figure 2. Components of IMCS-CON and the development environment.

By identifying and modelling key construction process variables the methodology for measuring construction site performance is developed. Therefore the construction site performance can be assessed effectively by measuring in term of key construction process variables. Construction site information's are collected and recorded using site diary and then convert collected site data in to useful construction variables, analyse them and report to project management team in weekly basis. In order to analyse and report site performances IMCS prototype is used. The IMCS system has two main applications first: analyse the current variable with historical data and highlight whether the variables in control limit or not. Second: graphically visualise input and out put variables in 3D-VRML graphs. Overall, IMCS-CON will act as a hub of project control and as a platform that allows integration of different modern project planning and controlling techniques to implement it; such as Earned Value technique, Last Planner System, 4D planning etc.

2.1 *Innovative managerial control system (IMCS)*

Marasini and Dawood [12] developed an innovative managerial control system (IMCS) to monitor and control business process of with precast concrete building products industry. The system introduce a methodology and tools that will be able to analyse historical and current information about business processes, establish relationships between internal and external variables and advise senior management on possible future decisions. The IMCS-CON, which utilise and extends this concept to develop a monitoring and controlling of construction process variables.

The IMCS utilises multivariate statistical process control techniques (mainly Principal Component Analysis- PCA and Partial Least Squares-PLS) combined with information visualisation to model large number of variables and processing of their data values. The system enables the visualisation of variables using database queries and the results obtained from multivariate statistical process control analysis (MSPC) results. In process variables visualisation the data are imported from databases and the number of variables to plot can be selected interactively and axis labels are assigned. As the variables have different data values and ranges, the variables are scaled with zero mean and unit standard deviation to convert them into standard units i.e. independent of measurement units. The actual values can be seen by holding mouse on the data object. This has added advantage that the users can see the variations on data about mean and hence the trend. The information visualisation model is to facilitate simulation of data so that how the variables are behaving with respect to time. In MSPC, large number of variables are transformed to fewer variables by transforming the actual variables into linear combinations, which are monitored to control the business performance.

The IMCS prototype mainly got two type of functionality:

1. Multivariate Statistical Process Control (MSPC)
2. VR Visualisation

2.2 *Multivariate statistical process control (MSPC)*

PCA is a multivariate technique in which a number of related variables are transformed to a smaller set of uncorrelated variables [8-12]. According to [8], the procedure for monitoring a multivariate process using PCA can be summarized as follows: For each observation vector, obtain the z-scores of the principal components and from these compute T^2. If this is in control, continue processing. If it is out-of-control, examine the z-scores. As the principal components are uncorrelated, they may provide some insight into the nature of the out-of-control condition and may then lead to the examination of particular original observations [2]. Marasini and Dawood [12] has described that PCA identifies principal components, which are linear combinations of the measured variables in the data set. All principal components are orthogonal. Non-linear instead of linear relations between the process variable will lead to a higher number of principal components. In such situation, one PC will represent one process variable, there will be no reduction in the number of variables to be analysed.

PCA can be used to assess the following aspects (14-12].

- Identification of process variables, which are associated with the bulk variability in the data set.
- Identification of data subsets with a different correlation structure from the bulk of the data.
- Identification of the number of independent phenomena leading to data set variability.
- The objective of the principal components is to determine a set of new variables that are linear combinations of the original variables and are orthogonal to each other.

The results of the PC and PLS analyses can be displayed graphically, including multivariate control charts, MSPC, (e.g., Hotelling's T2 and PC components scores and loading charts). These charts based on the model residuals, provide tools for early fault detection, the detection of drift, mean shifts etc. These indicate which variables those are likely to be related to process problems, upsets, and other process events.

The rational of the MSPC is to identify the combined relationship among the different variables, establish the control limits of the process variables and identify any significant deviations in the processes. Multivariate control charts usually generate one common statistics from the values of many variables that can be plotted on a control chart.

In order implement MSPC technique Marasini and Dawood [12] described two step processes.

Step 1: Establishment of base line model

The first step is the establishment of base line model, which utilises large historical data of process variables. The faulty measurements and disturbances are removed from the historical data so that an in-control set of process data is obtained representing normal operating conditions of the process. The screened (cleaned for errors) data are used for monitoring, control and optimization operations. The screened historical data set is referred, in the MSPC literature, as historical data set (HDS), calibration data set, base line or reference. The relationships between the variables and their control limits are established to develop a base model of the business process.

Step 2: Monitoring of new operational data to ascertain if control is maintained.

The second step is monitoring of new operational data to ascertain if control is maintained i.e. the new data are projected into the base model and are analysed whether new values are within the limits specified in the base model. If any significant deviations are detected, the cause of it is diagnosed and corrective actions are decided.

This paper introduces the methodology of modelling the construction variables using MSPC techniques mainly PCA techniques and the following section will demonstrate experiments using real life project data obtained from a one of local UK Construction Company.

2.3 *VR visualisation*

The data visualization is one powerful form of descriptive data mining [6, 24]. It helps accentuate the relationship among data points in extremely large amounts of data, and allows the visualization of multiple metrics based on multiple data sources on a single screen or dashboard [7]. In order to develop a VR visualisation component in IMCS prototype several functions were written in MATLAB6.5 to create VRML97 information visualisation models reading process variable values directly from the database and the output variables of the MSPC analysis. Utilising IMCS prototype the site information can be percent in clear and effective form through multidimensional graphical information visualisation of in put and out put variables.

3 APPLICATION OF IMCS-CON SYSTEM: A CASE STUDY

This section describes experimentation of the IMCS-CON system through a case study. A case study is used to evaluate functionality of IMCS-CON components which includes electronic site diary, database, utilisation of IMCS. An appraisal of the developed IMCS-CON regarding its validity, its benefits, and its limitations to the construction industry is lastly reported. A £2.3 million, three storey residential apartment construction project in UK was selected as a case study for the system evaluation.

3.1 *Selection of construction variables*

The key variables which have impact on construction site performance were identified through industrial and literature review. The IMCS-CON system design to monitor and control construction site operation through measuring and analysing these selected variables. The selection of variables should represent complete picture of construction site process. The key construction process variables were selected from ten main construction variable categories. Table 1 illustrates list of selected variables and their measurement units.

Table 1. Selected key construction variables.

Variables Category	Key variables	Unit
Time		
	Schedule Performance Index (SPI)	Index
	Time Lost	Hrs/week
Productivity		
	Percentage of Milestones achieved	%age
	Percentage Plan complete (PPC)	%age
Cost		
	Cost Performance Index (CPI)	CPI
Quality		
	Quality performance	Score
Client satisfaction		
	Client satisfaction	Score
Health and safety		Score
	Health and safety performance	Score
Communication		
	Communication Performance	Score
Architectural/Design Engineer performance		
	Architectural/Design Engineer performance	Score
Resource utilisation		
	Labour productivity rating	Rate
	Labour availability	%age
	Space utilisation	Score
	Subcontractor performance	Score
	Supplier performance	Score
Weather		
	Temperature	^0C
	Rainfall	Mm
	Sunshine Hours	Hours

These variables can be classified as internal variables and external variables. The external variables that are beyond the control of the managers; that are external to the company (example: Rain fall, Temperature) and the internal variables that can be controlled by the managers; that are internal to the company (example quality, site safety etc). The comprehensive approach identifies these variables and establishes method to measure and analyse them and taking action to ensure desired results. Developing a methodology to assess the above key performance variables for above ten categories provide an integrated construction operational level performance measurement system. These construction process variables can be subsequently used by construction executives and project managers both to monitor and to evaluate site performances. The two type of construction processes variables considered in this research are:

1. Quantitative variables: these variable values can quantify. The commonly used quantitative construction performance variables or indicators are deriving from literature review.
2. Qualitative variables: for those variables which can not be quantify, score based approach is used to measure them.

In the score based measurement system for each qualitative variables, the project managers are asked to rank 1 to 5 in a point scale the extent to which they believe each variable was performing (for example: quality, site safety, client satisfaction etc). In order to assist the project managers in ranking each variable the relevant performance criteria has been provided, so that they can correlate with other relevant values and rank particular variables appropriately where, the performance variables are ranked using 1 to 5 scale based on their level of performance during their operation. The 1 to 5 scores are defined as:

1 = very poor
2 = poor
3 = fair
4 = good
5 = excellent

The score 3 is considered as average performance level of the variable. The application of this score system will be illustrated in following sections.

3.2 *The electronic site diary*

In construction project, to record site information in regular bases site diaries are widely used. In order to input and retrieve site records effectively, an electronic site diary is developed. The electronic site diary provides project managers with an enormous data to improve the results of project. Here MS excel software is selected for development site diary in electronic format due to its simplicity and it is wide functionality. The following sub-sections illustrate the developed system interfaces. The site diary is organised in 3 layers in Micro soft excel.

- Layer 1: Site data collection sheet
- Layer 2: Site diary
- Layer 3: Weekly site variables values

Layer 1: Weekly site report

The weekly site report includes categorise records of site information which are; the main site occurrences, the detail of plan and actual tasks for particular week, information about labour input and their rating, site weather condition, records of quality control, site health and safety, site space utilisation, client satisfaction, sub contractors, suppliers and architect/design engineers performances etc. It is clear that the searching process would be simplified if the activities recorded in the electronic diary were kept with categorise format. The figure 3 shows an example of weekly site report.

WEEKLY SITE REPORT

CONTRACT NO: 757002 SITE NAME: HOMES APARTMENT WEEKLY ID: 42 CONTRACT COMMENCE: 08/01/2006

PROGRESS (Give position in relation to programme, detail any delays):
the NHBC inspectors has confirmed that none of the metal stud partition walls comply with their standards, considerable remedy work may be required, the extent or waigh is to be decided on Wednesday.
The GRP dormer windows were supplied for one Pitch only (Architectural drawing shows all window domer same size) during fixing two pitch roof structure had been noticed.The wrong dormer units had to be returned and new units manufactured.

	Mon	Tues	Wed	Thurs	Fri	Sat	Sun	Total	Avg
Actual Hours	8	8	8	8	7				
Working hours lost	8	4	6	6	6			30	
Weather									
Temperature (Max/Min)	10	8	3	4	2				5
Rain Fall (mm)									95.1
Snow									
Sunshine hours									66.2
Labour (Direct/SC)									
Site Agent									
General Foreman	1	1	1	1	1				
Engineer	1	1	1	1	1				
Trainees									
Carpenters	2	2	2	3	3				
Bricklayers									
Labourers	24	27	24	16	16				
Labour availability	100	100	95	100	100				99
Avg-Labour Rating									50

Weekly Work Assinment

Operations Commenced		Operation Completed		Milestone achieved	
Plan		**Plan**		**Plan**	
Tasks	**Dates**	**Tasks**	**Dates**	**Tasks**	**Dates**
Int.wall (N.E-L3)	13/11/2005	Int.wall (N.E-L3)	20/11/2005		
Roof truss (S-L3)	14/11/2005	Roof truss (S-L3)	17/11/2005		
Drainage (N.E-L1)	13/11/2005	Drainage (N.E-L1)	20.11/2005		
GRP doomer (W-L1)	15/11/2005	GRP doom(W-L1)	20/11/2005		
		Total No	4	Total No	0
Actual		**Actual**		**Actual**	
Tasks	**Dates**	**ID**	**Dates**	**Tasks**	**Dates**
Int.wall (N.E-L3)	13/11/2005				
Roof truss (S-L3)	14/11/2005	Roof truss (S-L3)	19/11/2005		
Drainage (N.E-L1)	14.11/2005				
		Total No	1	Total No	0
% of Plan Completed (PPC):			25%	%Milestone Achieved	

Tasks	Actual Duration (Hrs)	Plan Duration (Hrs)
Roof truss (S-L3)	40	24
Total	40	24
Planning Efficiency	0.6	

Quality control Report	
No of Inspection (Self)	1
No of Inspection (NHBC)	1
No of Non-Complains Record Received	1
No of Rework	1
No of Man-hrs lost	86
Project Manager Scoring:(1 - 5)	1

Health and Safety	
No of accident reported per 1000 labour hrs	0
No of Compliance received	0
No of Man-hrs lost	0
Project Manager/Safety Officer Scoring: (1 - 5)	3

Communication	
No of Request for Information(RFI) Raise	0
No of RFI Responds on time	0
% working hrs lost	0
Project Manager Score: (1 - 5)	3

Client Satisfaction	
Quality of Finished Product	1
Ability to Identify and resolve problems	2
Speed and reliability of service	2
Attention to detail	1
Overall value for money	1
Overall Performance Score: (1 - 5)	1

Sub Contractors	
Speed and Reliability of Service	3
Ability to Keep Promise	3
Ability to Complete Work on Time	3
Resolution of Defects	3
Project Manager (Score): (1 - 5)	3

Supplier	
No of Late Deliveries	0
%age of work hrs lost	0
Project Manager (Score):(1 - 5)	3

Architect/Structural Engineer	
No of drawing/design error	1
No of man-hrs lost(rework)	45
Project Manager (Score): (1 - 5)	1

Space Utilisation	
No of space congestion identified	0
%age of work hrs lost	0
Space utilisation Score: (1 - 5)	3

Figure 3. An example of weekly site report (Layer 1).

Layer 2: Daily job diary

The daily job diary is used to record site information on a daily basis and for specific events to record exactly when they occurred such as activities under operation, inspection, impact of rain fall on site etc. Figure 4 shows an example of daily job diary.

Day	Visitors	Daily Job Diary
		Rain all day No ground work has been done
Mon	P.Grant	Fixing framing domer windows
	P.Praklin	Quality and site health and safety checks(Inspection)
		2nd side bording and skur on 1 st floor south end
		Core driling flue holes
		Strip scaffold on east elevation
		Stuff insulation at tops or party walls
		Rain part of the day
Tues	D. Thompson	Line out velux dry dormer windows with ply wood
	J.Horin	2nd side board and skin on 1st floor south end.
	P.Grant	The fixing of metal stud partion wall work is now stoped due which does not fulfill NHBC stadards
	P.Praklin	Excavation with 360 degree dider to check drawn invert levels.
		Excavate and construct Manholes
		Insulation to tops or party walls.
		Fix balustrade to curved balcony
		Framming dormer windows
		2nd side board and skin on 1st floor south end
Wed		Excavate and lay pipe on foul outfal
		Excavate two Manholes and place rings
		Fasten cables bundles on ground floor staircase
		Place up brickwork under balcony support beams
		Fixing roof trusses northe end
Thurs		Skin workson 1st floor south end
		Finshed ceilings
		Complete scarefold strip
		Fix balustrade to curved balcony
		Pofresses to noth side rooms
Fri		Cleaning after plasters
		Concreting the manholes surrounds and backfiling
		Fix flats 15and 20 windows
Sat		

Figure 4. An example of daily job diary (Layer 2).

Layer 3: Weekly site variables

When weekly site records are fed into the layer 1 and layer 2, based on this information summery of weekly site variables are calculated and displayed in layer 3 as shown in figure 5.

WEEKLY SITE VARIABLES

Cost	
Cost performance Index	0.6
Time	
Schedule Performance Index	0.63
Working Hours Lost/Idle Time	30
% of Plan Completed (PPC):	0.25
%Milestone Achieved	0
Productivity	
Planning Efficiency	0.6
Weather	
Temperature	5.4
Rain Fall (mm)	95.1
Sunshine hours	66.2
Resources Management	
Labour Availability	99
Labour Productivity Rating	50
Space Utilisation	3
Quality (Score)	1
Health Safety (Score)	3
Client Satisfaction (Score)	1
Sub Contractor Performance (Score)	3
Supplier (Score)	3
Communication (Score)	3
Architect/Structural Engineer Performance	1

Figure 5. An example of weekly site variables (Layer 3).

The MSPC technique utilises to monitor and control construction process variables. The MSPC technique utilises for process monitoring, control and knowledge management. The selected 15 construction process variables are modelled and analysed using IMCS.

3.3 *Multivariate statistical processes control (MSPC)*

In IMCS-CON, Principle Component Analysis (PCA)-multivariate statistical technique used to monitor and control processes variables in which a number of related variables are transformed to a smaller set of un-correlated variables [8]. PCA identifies principal components (PC), which are linear combinations of the measured variables in the data set. The monitoring process consists of two steps: development of a base model and testing of new data.

3.3.1 Development of base model

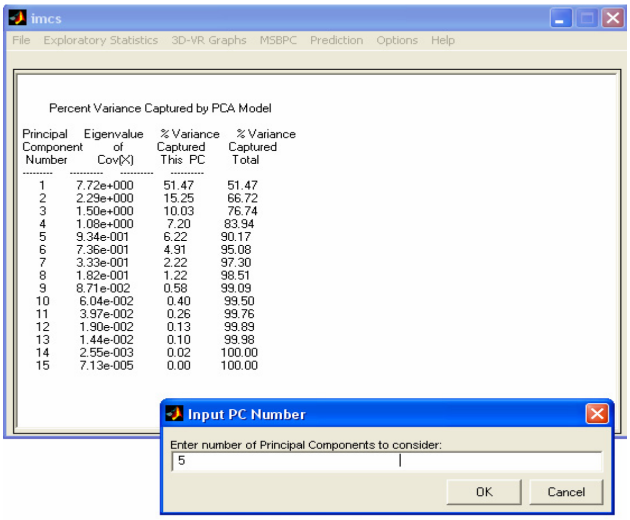
The first step is the establishment of base-line model, which utilises large historical data of process variables. The erroneous measurements and disturbances are removed from the historical data so that an in-control set of process data is obtained representing normal operating conditions of the process. The correlation and regression analysis between the variables was carried out to identify the relationship between the variables. This was essential to identify the variables that formed the core of the control process. The selected fifteen variables, 100 weeks historical data samples used in pre-screening, the variables considered include Sunshine, Temperature, Rainfall, Total time lost, Architect/Design engineers performance, Communication, Labour availability, Site productivity, Supplier performance, Quality, Site safety, Space utilisation, Labour productivity, Schedule performance index (SPI) and Cost performance index (CPI). Table 2 shows correlation coefficients between the variables, the shaded cells in the table show significant correlation coefficients. As an example, Time lost has significant positive correlation with Rainfall and negative correlation with Architect/design engineer’s performance, Communication, Site productivity, Supplier performance, Quality, Site safety, Space utilisation, SPI, CPI and Labour productivity rating. Similarly, Cost performance index (CPI) and Schedule performance index (SPI) have significant positive correlation Architect/design engineer’s performance, Communication, Site productivity, Supplier performance, Quality, Site safety, Space utilisation, and Labour productivity rating.

Table 2. Correlation analysis on original data.

Correlation Coefficients															
Variables	Sunshine	Temp	Rainfall	Time Lost	A/DPerforma-nce	Communication	Labour Availability	Site productivity	Supplier Performance	Quality	Site_Safety	Space_Utils	Labour Rating	CPI	SPI
SunshineHrs	1.00														
Temperature	0.73	1.00													
Rainfall	-0.30	-0.43	1.00												
Total_Time_Lost	0.14	0.09	0.43	1.00											
AD_performance	0.06	0.11	-0.64	-0.59	1.00										
Commmuinication	-0.18	-0.18	-0.20	-0.52	0.41	1.00									
Labour_Availability	-0.28	-0.33	-0.01	-0.33	0.07	0.03	1.00								
Site productivity	-0.07	-0.05	-0.33	-0.84	0.55	0.67	0.26	1.00							
Supplier_Performance	-0.28	-0.27	0.04	-0.51	0.13	0.26	0.11	0.54	1.00						
Quality	-0.14	-0.14	-0.07	-0.49	0.59	0.56	0.09	0.45	0.06	1.00					
Site_Safety	0.02	0.06	-0.61	-0.52	0.57	0.55	0.20	0.46	0.05	0.58	1.00				
Space_Utilisation	-0.13	-0.17	-0.24	-0.75	0.62	0.72	0.33	0.86	0.41	0.68	0.64	1.00			
Labour_Rating	-0.04	0.04	-0.47	-0.79	0.44	0.54	0.31	0.83	0.36	0.38	0.52	0.74	1.00		
CPI	-0.21	-0.26	-0.28	-0.79	0.63	0.63	0.20	0.74	0.63	0.50	0.57	0.50	0.62	1.00	
SPI	-0.17	-0.17	-0.38	-0.82	0.67	0.68	0.25	0.71	0.46	0.75	0.71	0.79	0.20	0.50	1.00

Significant Correlations have been highlighted with 95 percent confidence limits.

Utilising IMCS, PCA base model was developed. For the purpose of monitoring, certain (minimum but sufficient) number of principal components in the raw model is considered to establish a base PCA model. Figure 6 shows percent variation captures in PCA model.



Principal Component Number	Eigenvalue of Cov(X)	% Variance Captured This PC	% Variance Captured Total
1	7.72e+000	51.47	51.47
2	2.29e+000	15.25	66.72
3	1.50e+000	10.03	76.74
4	1.08e+000	7.20	83.94
5	9.34e-001	6.22	90.17
6	7.36e-001	4.91	95.08
7	3.33e-001	2.22	97.30
8	1.82e-001	1.22	98.51
9	8.71e-002	0.58	99.09
10	6.04e-002	0.40	99.50
11	3.97e-002	0.26	99.76
12	1.90e-002	0.13	99.89
13	1.44e-002	0.10	99.98
14	2.55e-003	0.02	100.00
15	7.13e-005	0.00	100.00

Figure 6. Variance Captured by Principal Components.

The raw model consists of all PCs that will describe 100 % variations in the data set. The first PC captures highest variance in the data; the successive PC's contribute to lower percentage of data variance. The first PC describes the systematic data variation and the last PC describes the stochastic data variation. For the purpose of monitoring, certain (minimum but sufficient) number of principal components in the raw model is considered to establish a base PCA model. Modelling higher percentage of variations leads to fitting noise while a much lower percentage variation makes the PCA model less accurate [14]. PC's that describe more than 90% of the data variation [3] is considered and 5 principal components were selected (Figure 6) to develop a PCA base model. The developed base model describes 90.17% of data variation in the data set.

The base model consists of data about PC's loading and scores; and Hotelling's T^2 statistics. The graphs shown in figure 7 are available for all principle components considered for modelling. The loading vectors are the link between measured variables and principal components. The score vectors represent the co-ordinates of the data points projected on the principal components. The base model consists of data about PC's scores and PC's loadings with 95% and 99% confidence limits. The 95% confidence limit is considered as 'Warning Limit' and 99% limit is considered as 'Action Limit'. The figures: 7 shows loading and scores of Hotelling's $T^{2,}$ PC1, PC2, PC3, PC4 and PC5 respectively. The loadings are the link between measured variables and principal components. A common statistics, Hotellings T^2 value, from the values of many variables (PCs) can be plotted in a control chart as shown in figure 7. The score plots of Hotellings T^2 and PC reflect all the observations are within the normal operating range. As an example: Bivariate plots between the scores of PC1- PC2, PC1-PC3, PC1-PC4 shows that all the observations are with the limits (Figure 8). This model is used to monitor new observations, which is described in the following section.

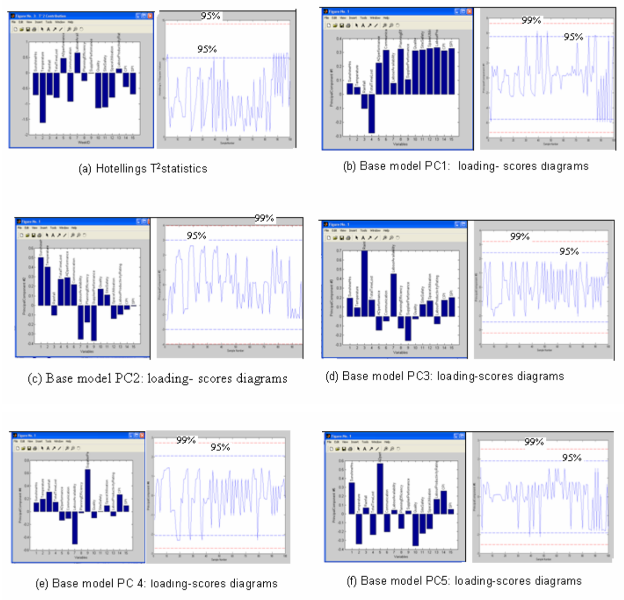


Figure 7. PCA – base line model.

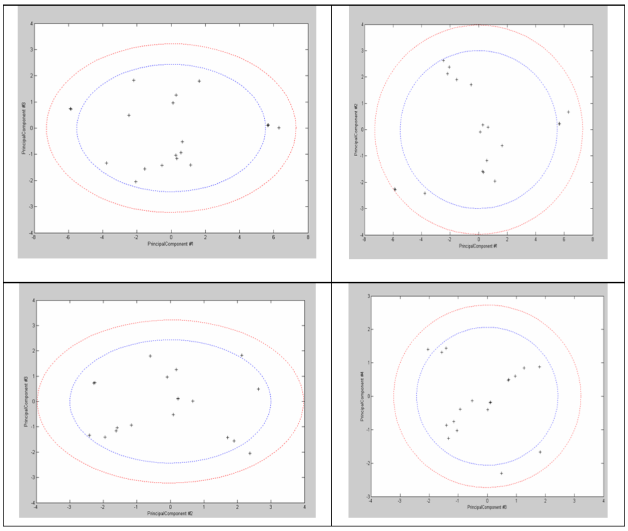


Figure 8. An examples of bivariate plot between Principal Components for base model.

3.3.2 Monitoring of new operational data to ascertain if control is maintained

When a PCA model was established based upon historical data collected (when only common cause of variation was present) future behaviour can be referenced against this nominal or 'in-control' representation of the process. The contribution plots are the tools to identify components of the processes making a significant contribution to the observed variances in the process. The loadings indicate that which variables are important. The purpose of the contribution plots is to suggest the investigator where to begin investigation and the contributions help interpret the events that are identified as special causes by querying the underlying data. The following section percents brief description about experimentation's and it is results.

Table 3 shows 41 to 47 weeks data's. Where 41^{st}, 42^{nd}, 43^{rd} and 44^{th} data's obtained from project record and 45^{th}, 46^{th}, 47^{th} records are made upon assumption for the purpose of testing. This data sets are tested using the above base model (PC scores, loadings, T2 chart).

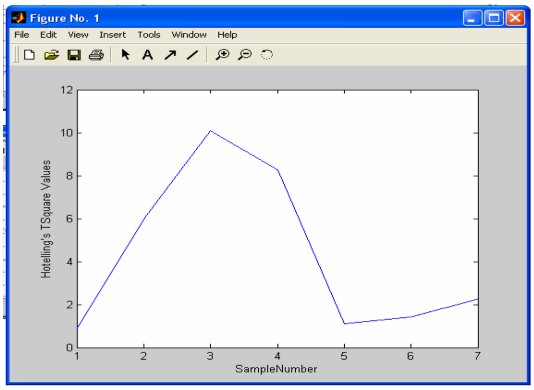
Table 3. Test data table.

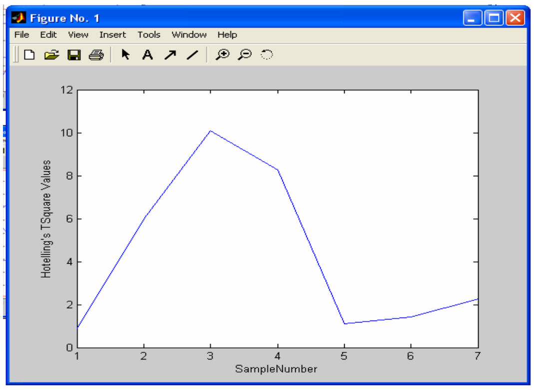
Sample #	Week ID	Sunshine (Hrs)	Temperature (°C)	Rainfall (mm)	Time Lost (Day)	AD performance (Score)	Communication (Score)
1	41	66.2	7	48	2	3	3
2	42	66.2	7	63.1	4.75	1	3
3	43	66.2	7	95.1	4.75	1	3
4	44	66.2	7	95.1	3.75	1	3
5	45	61.8	14	50.1	1.3	2	3
6	46	157.4	15	48	0	3	4
7	47	157.4	15	40	0	3	5

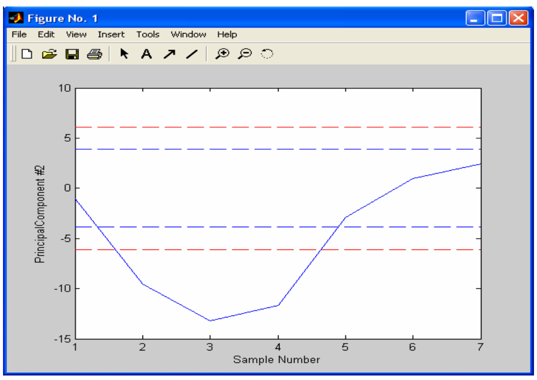
Labour Availability (%)	Productivity (PPC) (%)	Supplier Performance (Score)	Quality (Score)	Site Safety (Score)	Space Utilisation (Score)	Labour Productivity (Rating)	CPI (Index)	SPI (Index)
100	82	2	3	3	2	125	0.75	0.77
100	50	3	1	3	3	50	0.6	0.63
100	53	3	1	3	3	50	0.6	0.6
99	53	3	2	3	3	50	0.6	0.63
98	75	3	3	3	3	50	0.78	0.75
99	100	3	5	5	5	125	1	1.19
100	1	3	5	5	5	125	1.6	1.5

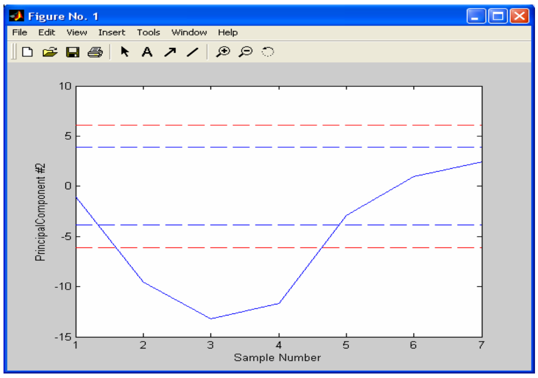
T^2 Statistics (T^2 control chart)

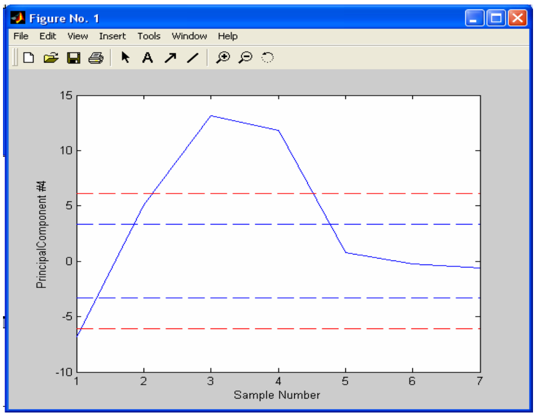
The T^2 statistics for the test data is shown in Figure 9. The chart shows that the observations are with in the 95% limit.











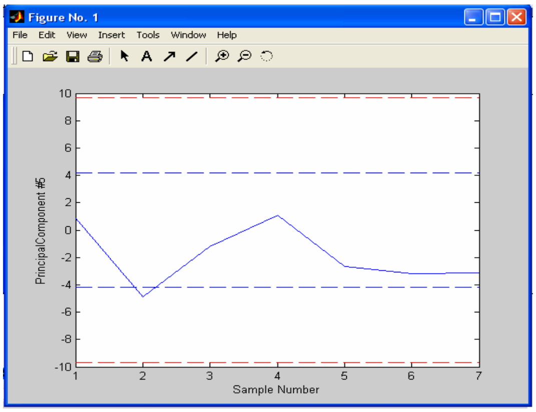


Figure 9. Hotellings T^2 and Principal components (1, 2, 3 , 4 and 5) scores on test data.

PC's Score plots

As explained in the section above, the score plots of PC reflect whether the observations are within the normal operating range or out of control. Out-of-control situation occur, due to the different loadings of variables on each principal components, some PC's will be in the operating range and some will be outside the limit. Looking at the PC scores, the observations that are out-of-control can be identified. In Figure 11 shows that, PC5 within the 95% limit, PC1, PC2, PC3 and PC4 are outside the 99% limit (action limit). Bivariate plots between the scores of PC1 and PC2 shows the observations that are outside the limits (Figure 9). The next step is to investigate why the process is outside the warning limit, which can be carried out in the ways described in the subsequent sections.

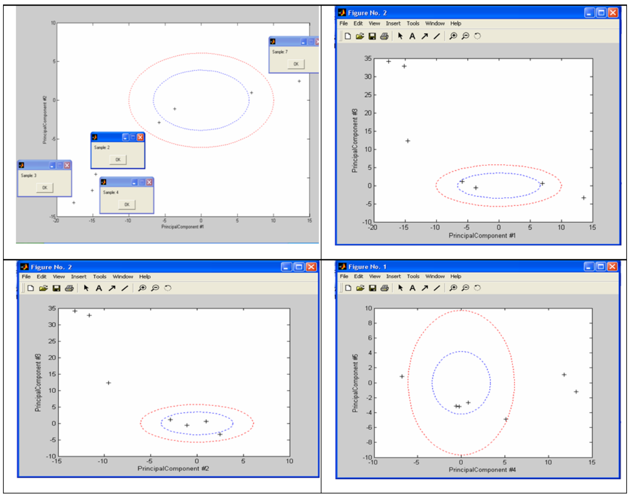


Figure 10. an examples of bivariate plot between Principal Components for test model.

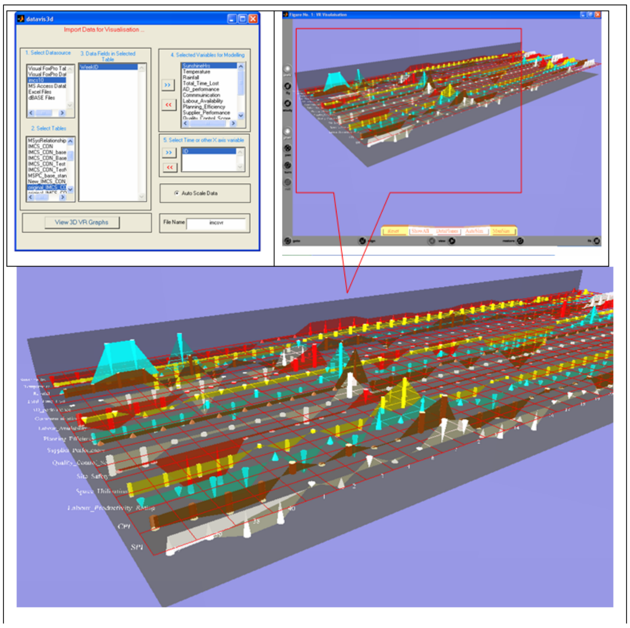


Figure 11. Visualisation of process variables.

Investigations of the loading (Contribution plot)

The next step was to identify the causes of the process moving away from desired state. Using principal components score plot we can see if samples differ from each other but we cannot explain why they are different. The loading plots are the link between the measured variables and the principal components and the loadings indicates that which variables are important. The loading plots are the coefficients of the variables in the principal components and thereby indicate the contributions of each measured variable to that PC. The loading analysis offers the possibility to link an observed residue increase to the variable(s) associated with it. The contribution plots identify components of the processes making significant contribution to the observed variances in the process. In Figure 9 PC1 scores show that the observation #7 is outlier and PC1, PC2, PC3 and PC4 scores shows that the observations #2, #3, #4 are outliers. The purpose of contribution plots is to suggest the investigator where to begin investigation and the contributions help interpret events that are identified as special causes by querying the underlying data.

- In PC1 most influential variables are labour rating, SPI, CPI, Time lost and quality. While investigating sample #7 with other base line samples it is clear that variables SPI, CPI, Time lost and quality are main factors (showing higher performance) causing the out of control. Similarly investigating samples #2, #3 and #4 the base line samples it is clear that SPI, CPI, Total time lost, quality and labour rating are main factors (showing lower performance) causing the out of control situation.
- In PC2 most influential variables are sunshine hrs, temperature, AD performance and supplier performance and Total time lost. When investigating samples #2, #3 and #4 with other baseline samples, it is clear that sunshine hrs, temperature, AD performance, and Total time lost are main factors (show low performance) causing the out of control situation.
- In PC3 most influential variables are rainfall, labour availability, supplier performance and SPI. When investigating samples #2, #3 and #4 the baseline samples, it is clear that rainfall and SPI are main factors (showing low performance) causing the out of control situation.
- In PC4 most influential variables are supplier performance, labour availability, rainfall and CPI. When investigating samples #2, #3 and #4 the baseline samples, it is clear that rainfall and CPI are main factors (showing lower performance) causing the out of control situation.

As described above in 41st, 42nd , 43rd , 44th weeks out-of-control signals were obtained. Through investigation of PC loading plots it has been identified that adverse weather condition, AD(Architect/Design Engineer) performance, total time lost, CPI and SPI are the main factors (showing low performance) causing the out of control situation. Therefore the project managers were able to understand the root causes for out of control signal and make corrective action to bring out of control variables into control. The variables having highest values should be reduced or increased to bring the process in-control state. As illustrated in PC score plots (figure 5.16) in the following weeks (45th and 46th), due to improvement in weather condition, AD performance, communication and labour productivity rating, the site performances were brought back to the control limit. This also resulted, improvements in other variables such as SPI, CPI and quality.

3.4 *Information visualisation*

Visualisation, in the context of this study, means a graphical representation of data or concepts. The IMCS visualisation component provides facilities to visualise data in 3D Virtual Reality environment dynamically. In IMCS the VR visualisation component able to reads data from the relational database dynamically and creates a VRML model (Figure 13 and 14) that can be viewed using 3D-VR viewers. These VRML models enable project managers to identify construction site performance and relationship between the variables. The other facilities include the interactive display of data attributes in the graph and simulation of information based on certain attributes such as time or variation of values against other variables.

3.5 *System evaluation*

In order to test and validate the system evaluation session were contacted with the project managers of the collaborating company. The tests were indicated that performance results measured by the developed performance measurement are significant suggesting that new performance measurement system able to produce complete picture about site performance. The development of current level of the electronic site diary provides template for record site information measure site performance on weekly basis. Through evaluation, it was concluded that the IMCS-CON can provide an insight into the effect of internal and external performance variables on the construction process and how any deviation from the 'controlled state' of construction performance variables should be explored and tackled. Implementing of the MSPC technique to a monitoring and control construction process: In the MSPC, PCA was used to model construction performance variables and establishes a base line. The new data can be monitored against normal condition (base line), when the process is found to be out of control the system can provide dynamic feedback for managers therefore managers can decide corrective actions. Through a real case study project, fifteen variables for ten categories were modelled using MSPC approach. Utilising historical data about fifteen construction process variables PCA baseline model has been established with the five PCs. The PCA base line model was experimented with new data and it has been identified that the model was significant, when the process is out of control, the model indicates with a signal and the managers able to identify the root causes for "out of control" through investigating contribution plots (PCs and Hoteling T2 charts). The contribution plots are the tools to identify components of the processes making a significant contribution to the observed variances in the process. The loadings indicate that which variables are important. The purpose of the contribution plots is to suggest the investigator where to begin investigation and the contributions help interpret the events that are identified as special causes by querying the underlying data. The system can be utilised to confirm that MSPC technique can provide an insight into the effect of internal and external variables on the construction process and how any deviation from the 'controlled state' of construction process should be explored and tackled. In order to evaluate the system data from a single project were used to model the variable using PCA. The more accurate PCA model can be achieved by considering more number of data. Further more, as the proposed technique required many variables to be analysed, data of many internal process variables could be analysed.

The 3D graphical visualisation of variables values were tested with project managers in the collaborative company. It was identified that the visualisation assisted managers in understanding the relationship between variables and therefore more quality decisions can be made. Also, the visualiser helped managers in deviation detection i.e. for the discovery of anomaly and changes; identification of relationship between variables; summarisation i.e. viewing of the information provided in large databases can be summarised and viewed in one user friendly and interactive environment and viewing data variations according to time.

Further, through evaluation it has been highlighted that IMCS-CON concept is useful for company project performance benchmarking and continues improvement. The IMCS-CON system enable to monitors and control wide area of construction performances. The IMCS-CON statistically analyses current variables with historical data and highlights root cause of variables which originate system out of control. If the root cause variable out of control is external to the company it can be brought to the client attention. Therefore IMCS-CON can also be used as a tool to prove to the client the real problem on site and request for time extension or claim.

4 CONCLUSION

The IMCS-CON developed and tested a conceptual system for monitoring and controlling construction processes. It is envisaged that the IMCS-CON provides a tool and methodology to monitor and control construction process variables, thereby ensuring effective and closer construction project monitoring and control with improve on-site productivity. However, successful implementation of the developed technique and tool will largely depend on advancement of future research and development, proven business cases, as well as human resource development and transformation of working culture in the industry.

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