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IMAQCS: Design and implementation of an intelligent multi-agent system for monitoring and controlling quality of cement production processes

Iraj Mahdavi [a,*], Babak Shirazi [a], Narges Ghorbani [a], Navid Sahebjamnia [b]

[a] Mazandaran University of Science and Technology, Babol, Iran
[b] Department of Industrial Engineering, College of Engineering, University of Tehran, Tehran, Iran

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ABSTRACT

In cement plant, since all processes are chemical and irreversible, monitoring and control is a critical factor. If the process is not controlled at any stage, the final product can be damaged or lost. Thus, in such environments, considering the quality of the product at each state is essential. Also, to control the process, communication among different parts of production line is essential. The wasted time in production line has a direct effect on process correction time and cement production performance. Here, a model of a new intelligent multi-agent quality control system (IMAQCS) for controlling the quality of cement production processes is suggested. This model, using of rule-based artificial intelligence technique, concentrates on relationship between departments in cement production line to monitor multi-attribute quality factors. With the presence of agents for controlling the quality of cement processes, real-time analyzing and decision making in a fault condition will be provided. In order to validate the proposed model, IMAQCS is deployed in real plants of a cement industries complex in Iran. The ability of the system in the process production environment is assessed. The effectiveness and efficiency of the system are demonstrated by reducing the process correction time and increasing the cement production performance. Finally, this system can effectively impact on factory resources and cost saving.

1. Introduction

The importance of process control in quality products is clear. Most manufacturing process such as chemical and industries process have automated process control systems. The majority of automated quality control systems are used to detect out-of-control conditions [1]. Also they focused on the process output and control actions. Tsung to detect changes in a process, provided functions of the process output and control actions [1]. Wu in [2] with the help of probabilistic neural network (PNN) proposed a method for pattern recognition of control chart in cellular manufacturing. Yu et al. used a genetic algorithm based rule extraction approach to recognize the relationship between manufacturing parameters and product quality. They integrated a knowledge-based artificial neural network and a genetic algorithm rule extraction to improve the product quality in a japanning-line [3]. Moreover, intelligent systems for monitoring, control, and diagnosis of industries process are based on three main approaches: knowledge-base, analytical and data-driven as mentioned in [4]. Uraikul et al. provided an overview on intelligent systems for control and diagnosis of process [4].

Among several systems for process control and fault detection have been proposed, depending on the type of process, the quality control is different. The process control is more difficult in chemical process because of their irreversible nature. The product is completely wasted, if the process is out of control. Many technological methods in cement process quality control automation have been proposed in recent years. Most of these methods are about X-ray analysis at the different departments of cement production line. They focused on the control of the chemistry of cement production [5–7]. Apart from chemistry of the cement, Tsamatsoulis provided a reliable model of the dynamics among the chemical modules in the outlet of raw meal grinding systems in [8]. Also, he has developed a dynamical model of cement milling process in [9]. In these two works, each department is assessed separately. The whole plant has not been considered. In cement process, an integrated system for controlling the quality of process has received less attention. Along with the nature of the cement process, monitoring and interaction among departments are important too. A quality control system that monitors the process, controls the input and output of different departments, and detects fault conditions in cement industries complex is an issue.

* Corresponding author.
E-mail address: irajarash@rediffmail.com (I. Mahdavi).

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The control of plants that are spatially distributed has been considered recently. Chan presented a system that monitors operations at the plant based on the input data. Then it detected abnormalities in the data and suggested some actions to the operator. It was an expert decision support system for monitoring, control and diagnosis of a petroleum production and separation plant [10]. Mahdavi et al. suggested a real-time quality control information system that improves control of the quality of products through an integrated monitoring of distributed shops [11]. Van Brussel et al. presented the architecture consists of three types of basic holons: order holons, product holons, and resource holons to reduce the complexity of the system and enable easy reconfiguration [12]. However, multi-agent systems (MASs) can be used to control the plant, and especially the control of process in distributed manufacturing. Seilonen et al. utilized MAS to design a process automation system. They applied agents to run supervisory control and make decisions [13]. A large number of researches on distributed manufacturing and MAS in industries focus on scheduling and planning tasks among different machines for optimizing their throughput [14–18]. Some other works on MAS are done in the area of supply chain management (SCM) systems [19]. A review of all related work to agent-based systems in manufacturing is provided in [20]. In addition, some other researchers have proposed different models of MAS and deployed them in manufacturing [18,21–24]. Finally, Behdani et al. in [25] proposed an agent-based system for modeling a complex network of a chemical manufacturing enterprise which can capture the interactions among the various constituents including the plants, functional departments, and external entities. Among the researches that have been referred to, the use of MAS to cope with the control of chemical process quality among different parts of plants has been less noticed.

In this paper, we proposed an automated process quality control system for cement process that is designed based on multi-agent system. In our proposed model, we try to concentrate on the communication between sampling station, laboratory and different departments of the cement production process which are not extensively described in previous researches. Also, we transform statistical quality control into a new communication method for cement production. We found MAS technology to cope with sophisticated interaction among departments. Besides, we compare a manual system with our system in a part of cement plant to evaluate the model. With this method, we were able to reduce the time of correcting the process. This reduction in process correction time is lead to reduce wasted raw materials and has the financial impact for the factory.

The other parts of this paper are organized as follows: Section 2 gives an overview of problem domain. Our proposed model is presented in Section 3. In this section, agents in the system, their interaction and coordination approach, analysis and design method and implementation technique are explained. Next, in Section 4 the proposed system has been tested and evaluated. Finally, conclusions and future work are provided in Section 5.

2. Problem statement

The quality of processes and products has become a major decision factor in most businesses, because consumers expect quality to be considered of equal importance as cost and schedule. Online statistical process control is a powerful tool for achieving process stability and improving quality. Monitoring the conditions of the processes and investigating their capability in the shortest time, can result in optimal use of resources. Therefore, for inspecting process quality in shortest time, an intelligent distributed quality control system, which is deployed at the whole factory, is an essential necessity.

In this research, we focused on chemical process control, because of its nature and special properties. These kinds of processes are chemical, and in such environments, the monitoring and control are important issues. Similarly, in a cement industries complex, the control of cement processes is a critical factor. Our studies on the problem show that in cement production, there should be quick ways of communication among various departments and continuous monitoring on output of each state.

As shown in Fig. 1, cement production has several inner departments. At the end of each department, there is a sampling station. Conveyor transports samples, which are taken from sampling stations, to the laboratory. These samples are analyzed to test process quality. Then, tests on samples determine the values of quality indicators. Afterwards, quality control engineers

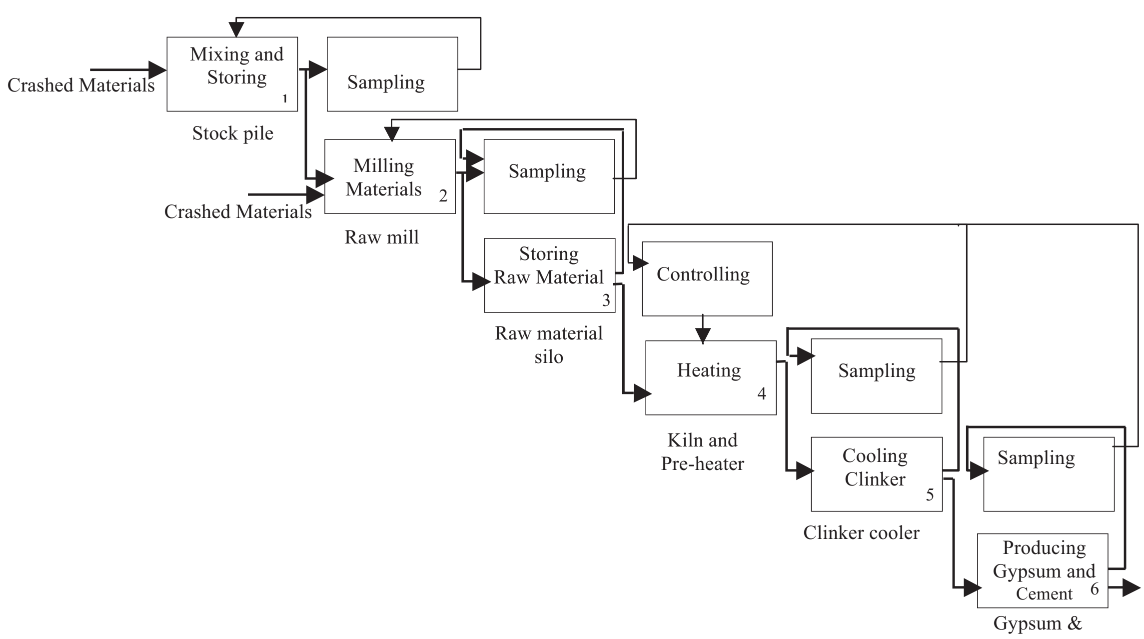

Fig. 1. Cement production process.

investigate these values and send them to the production experts. Next, the production experts decide on the acceptability of the output of the phases. Later, if necessary, the production experts dispatch essential instructions to the departments. Finally, according to instruction and conditions of each department, crashed materials are put into the stock pile or raw mill department or kiln settings are changed in controlling room. Thus, the next iteration of cement production process is improved as possible.

By reviewing all stages in controlling cement processes, we realize that there is a delay in the communication among quality control unit (laboratory and engineers) and departments. Consequently, in emergency conditions there will be a delay in process correction of departments. This delay may lead to some problems such as sever fluctuations in production process, unstable state of production conditions, and finally an increase in the rate of undesirable products.

Three important measures including lime saturation factor (LSF), silica modulus (SIM), and alumina modulus (ALM) are considered to control the quality of cement process. The larger value of SIM, LSF and ALM in the clinker indicates that cement production has insufficient quality. These measures would be obtained by Eqs. (1)–(3).

$$\mathrm{SIM} = \frac{\mathrm{SiO_2}}{\mathrm{Al_2O_3} + \mathrm{Fe_2O_3}} \quad (1)$$

$$\mathrm{ALM} = \frac{\mathrm{Al_2O_3}}{\mathrm{Fe_2O_3}} \quad (2)$$

$$\mathrm{LSF} = \frac{100\mathrm{CaO}}{2.8\mathrm{SiO_2} + 1.1\mathrm{Al_2O_3} + 0.7\mathrm{Fe_2O_3}} \quad (3)$$

3. The proposed IMAQCS architecture

The proposed model of the current study is based on three-layer architecture. As shown in Fig. 2, in the presentation layer, users, with little knowledge about the mechanism of the system, can access application via the designed user interfaces. In fact, this layer is an interface for executing quality tools that are designed by experts. In addition, in the presentation layer all subsystems in the plant are covered by designing interfaces to execute quality control tools and receive essential instructions. This is the outer layer that is used by workers in the production line.

In the business logic layer, analysis of quality test results and decision-makings are done. This layer, receives the result of quality tests from presentation layer via messages, and then analyzes them for control processes. In this layer, the control of raw data and quality of process, quality analysis and decision making for improving process are done.

Finally, in database access layer, there are database and knowledgebase. In database some data such as raw data (values of measurements that are sampled from stations); messages information, test and analysis result, and other information are stored. In knowledgebase quality control rules, domain ontology, data acceptance rules and decision rules are stored.

3.1. Agents in IMAQCS

Agents used in this system are software agents, which are developed as software applications. In this architecture, we define six types of agents: Quality Control Tools Executor Agent (QCTEA), Process Quality Control Analyzer Agent (PQCA), Internal Decision Maker Agent (IDMA), External Decision Maker Agent (EDMA), Data Base Manager Agent (DBMA) and Knowledge Base Manager Agent (KBMA). The duties of each agent are expressed in details in the following:

- Quality Control Tools Executor Agent (QCTEA): this agent can be deployed in different departments of a plant. QCTEA, including its departments, is responsible for executing quality control tools such as capability six-pack, capability analysis, control charts (X-bar and R, X-bar chart, S-bar chart and etc.) and symmetry plot. Quality experts determine quality control tools suitable for each department according to the condition of departments, input data type, and importance of checking quality. These tools are used in the design of QCTEAs.

Table 1
Some data acceptance rules.

Rule #	Data acceptance rule	Rule #	Data acceptance rule
1	$(88.6 \leq \mathrm{LSF} \leq 92.6)$	5	$(\sigma(\mathrm{LSF}) \leq 0.1)$
2	$(2.5 \leq \mathrm{SIM} \leq 2.75)$	6	$(\sigma(\mathrm{SIM}) \leq 0.1)$
3	$(1.3 \leq \mathrm{ALM} \leq 2.\ 5)$	7	$(\sigma(\mathrm{ALM}) \leq 0.1)$
4	$(\sigma(\mathrm{CaCo_3}) \leq 0.2)$	8	$(\sigma(\mathrm{CaO}) \leq 0.1)$

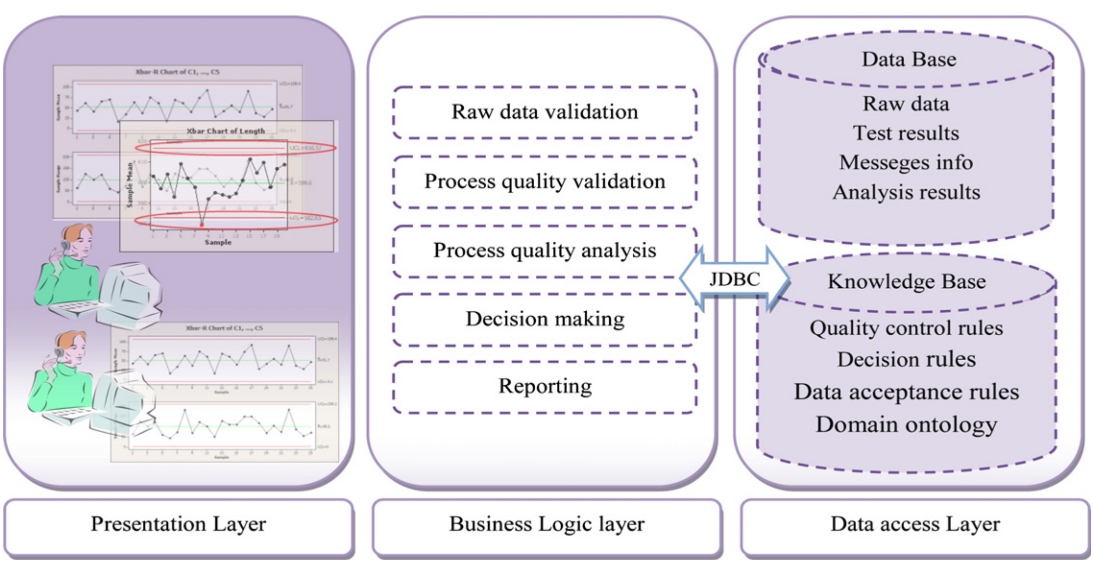

Fig. 2. Architecture of IMAQCS based on three layer architecture.

Table 2
Examples of quality control rules.

Rule #	Quality control rules
1	If there are K points more than 3 standard deviations from center line then data is not valid
2	If K points out of $k+1$ points greater than 2 standard deviations from center line then data is not valid

Table 3
Some decision rules.

Rule #	Decision rules
1	IF NOT between(LSF,88.6,92.6) AND greater than(LSF,92.6) THEN DecCaO
2	IF NOT between (SigLSF,0,0.1) AND greater than (SigLSF,0.1) THEN SamplesNotOk, resample
3	IF greater than (BrnFct,120) THEN IncKilnTemperature

- Process Quality Control Analyzer Agent (PQCA): these agents have a one to one relation with QCTEAs. Each PQCA receives quality results from the related QCTEA. At first, experts define some available rules of control conditions. PQCA receives required rules and knowledge from KBMA. Then PQCA analyzes data according to its knowledge. This data comes from two main categories: the first group of data is raw data, and the second group is results of running quality tools. In the first step, PQCA evaluates all raw data limitations. This way, it checks some data acceptance rules that are actually constraints. Some samples of these rules are shown in Table 1. After that, if raw data is correct, PQCA allows QCTEA to run the required quality control graphs such as capability six-pack and X-bar and R charts. Otherwise PQCA informs IDMA. The second task of PQCA is assessing the results of running charts. Rules that have been received from KBMA here are used. For instance Table 2 shows some quality control rules. In both situations, if the rules or constraints are been violated, PQCA informs IDMA.

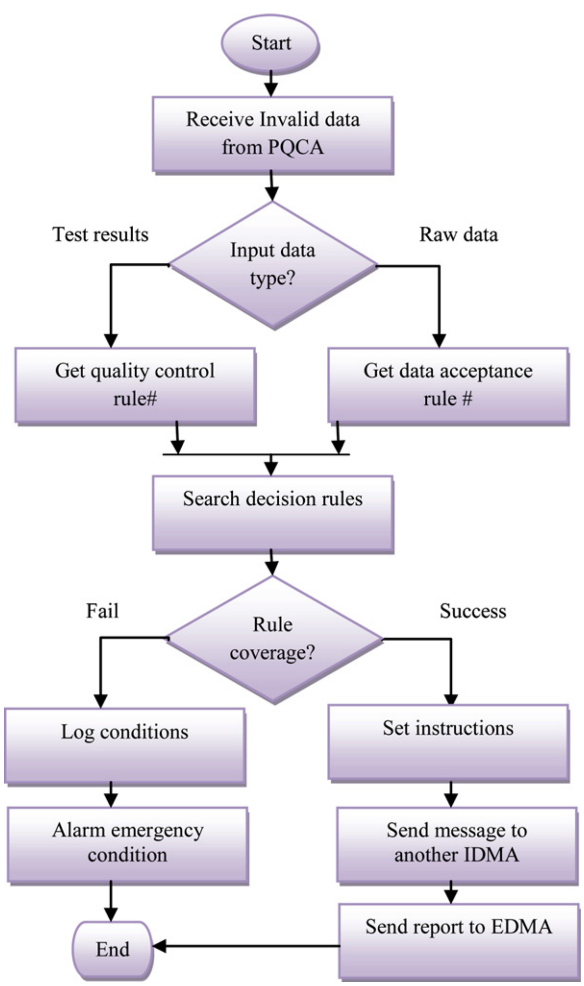

Fig. 3. The internal activity of IDMA.

- Internal Decision Maker Agent (IDMA): for each department, there is one IDMA. At first PQCAs check the control conditions or quality rules of the processes and send results to IDMA if they are not valid. Then, IDMA searches decision rules according to results received from PQCAs, quality standards priorities, input data types, rules that are used by PQCA and other conditions. IDMA completes its knowledge of decision rules with the help of KBMA. After that, if the decision rule is covered, IDMA sets instructions based on the rule. Finally, IDMA sends the instructions as messages to IDMA, which is deployed in the previous department. We show the internal activity of IDMA in Fig. 3. As we show in this figure, if IDMA does not find associated rule, the system will declare state of emergency. In such a case, the experts will decide then add this circumstance to the knowledge base. We generate 42 decision rules that are related to stock pile, raw mill, raw material silo and clinker cooler departments. Examples of these rules are expressed in Table 3.
- External Decision Maker Agent (EDMA): there is one EDMA for all departments in a plant. This agent receives all decisions of IDMAs and certain conditions in which the decision has been taken. In addition EDMA considers the functionality of each department. Then according to the conditions and control limitations, which are determined for each department, EDMA analyzes these measurements and plans a long term solution. To do this, EDMA gets help from KBMA. After that, EDMA sends required instructions to the departments. EDMA uses TOPSIS algorithm as a base of making a long term plan for departments. Each department also has a technical characteristic matrix. These matrices and the attributes of the output of each department are used in TOPSIS algorithm [26] for making decision.
- Data Base Manager Agent (DBMA): in the proposed IMAQCS, there is one DBMA for each department. To maintain the security of access to the database, we define DBMA. Only DBMA has direct access to the database. In fact, this agent is a mediator between database and other agents. This agent is responsible to manage the database and serves other agents' requests. In the database, there are tables that store raw data, test results, messages and some other information; DBMAs manage these tables. Other agents in IMAQCS access these data through DBMAs.
- Knowledge Base Manager Agent (KBMA): in our proposed IMAQCS, there is one KBMA in a department. At first experts, define required rules, knowledge, and standards in knowledgebase. KBMAs manage tables that exist in the knowledgebase. Other agents in IMAQCS access knowledgebase through KBMAs.

Table 4
Value rules elements.

Elements	Value
P	$\{p_1, \ldots, p_n\}$ is a set of value rules
S	$\{s_1, \ldots, s_n\}$ is a set of states
A	$\{a_1, \ldots, a_k\}$ is a set of joint actions of k agents

Table 5
Value rules elements.

	Value
Roles	M = {executor, analyzer, decision maker, data manager}
Actions	A = {run-charts, check-limitations, check-result, get-data, get-constraint, analyze-data, run-decision-algorithm, set-instructions}
States	S = {stable, invalid data, unstable, emergency}

Table 6
Some value rules.

#	Value rules
1	$\langle (P_1)^{\text{analyzer}}$; stable $\wedge\ a_1$ = check-limitations(raw-data) $\wedge\ a_2$ = get-data(data-id):$v_1\rangle$
2	$\langle (P_2)^{\text{analyzer}}$; stable $\wedge\ a_1$ = check-result(results) $\wedge\ a_3$ = get-constraint():$v_2\rangle$
3	$\langle (P_3)^{\text{analyzer}}$; stable $\wedge\ a_1$ = analyze-data() $\wedge\ a_4$ = run-charts():$v_3\rangle$
4	$\langle (P_4)^{\text{executor}}$; stable $\wedge\ a_4$ = run-charts():$v_4\rangle$
5	$\langle (P_5)^{\text{decision maker}}$; unstable $\wedge\ a_3$ = get-constraint() $\wedge\ a_5$ = run-decision-algorithm():$v_5\rangle$
6	$\langle (P_6)^{\text{decision maker}}$; emergency $\wedge\ a_5$ = set-instructions():$v_6\rangle$

3.2. Agents coordination

According to cement production process, IMAQCS should monitor and control production processes quality through different departments. Thereby, agents need to interact with each other among department. To control the interactions between departments and perform the optimal action, it should be considered a coordination mechanism. We use a context-specific coordination graph to represent the coordination and dependencies among agents [27]. We define set of value rules. Each value rule has a current state and some joint actions which have value. In fact a value rule $p = \langle s \wedge a\text{: } v\rangle$ shows that rule value is equal to v when the current state is s and the agents perform the joint action a. We define value rule elements that are shown in Table 4.

In addition we use role-based context-specific Q-learning method according to [28] to learn the optimal policy. A role is a tuple $\langle m, P_{\mathrm{m}}, r_{i,m}\rangle$, where $m \in$M is the identity of a rule; P_{m} is a set of value rules associated with the role m and $r_{i,m}$ is a potential function which determines how appropriate the agent i is for the role m in the current state. Based on this method we first define

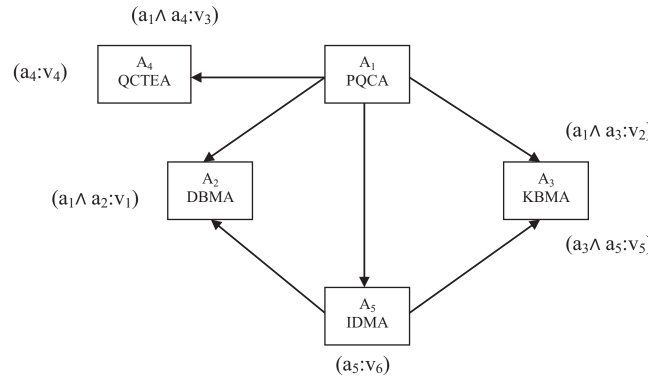

Fig. 4. A part of the coordination graph for five agents in IMAQCS.

value rules for each role then we assign roles to the agents [28]. In IMAQCS we define roles, actions and states as reported in Table 5.

We generate value rules in the coordination graph. Table 6 shows our generated value rules. Fig. 4 shows a part of the coordination graph in IMAQCS.

Some of rules that are expressed above are shown on the coordination graph. The coordination algorithm is applied for each iteration or run. The coordination structure between agents depends on the current state of the system and a set of actions that is defined. So in each iteration, agents use predefined actions to interact with others.

More, when the number of agents increases, the joint action space grows exponentially. We use Role-based context-specific Q-learning (RQ-learning) algorithm that is introduced in [28] to reduce the joint action space. With the help of this algorithm role assignment is performed first, and then variable elimination (VE) is used to determine the optimal joint action. In this way, we could run IMAQCS in the shortest possible time without doing any extra action.

3.3. Analysis and design IMAQCS

There are some methodologies for the development of multi-agent systems including [29–34]. Also, methodologies that are mentioned above are based on agent oriented methodologies and their analysis phase is generic in nature, they attempt to adapt object-oriented analysis and design methodologies to agent-based

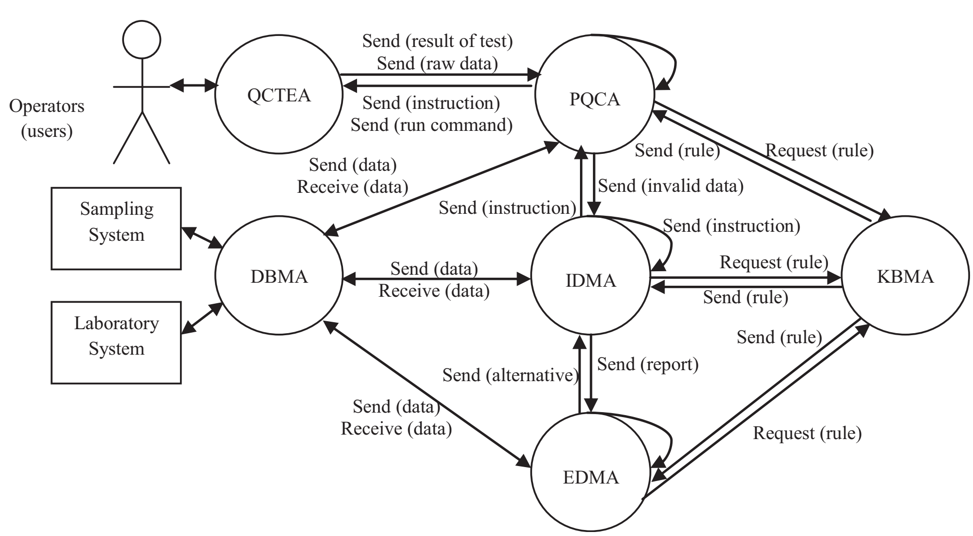

Fig. 5. Agent diagram.

Table 7
The responsibility table for PQCA.

Agent type	#	Responsibilities
PQCA	1	Receives notification of fetching raw data from QCTEA.
	2	Requests data from DBMA.
	3	Tests the control limitation of data associated with its embedded knowledge.
	4	Orders QCTEA to execute charts if the raw data is within an acceptable region.
	5	Receives notification of executing quality control charts from QCTEA.
	6	Evaluates results of quality control charts based on its embedded knowledge.
	7	Requests additional rules from KBMA if are required.
	8	Receives notification of instructions from IDMA.
	9	Orders QCTEA to do new instruction.

design [34]. So, we use the methodology that proposed in [34]. The selected methodology is formalized for the analysis and design phases of the agent-based software development life cycle using JADE platform. This methodology focuses on agents specifically and the abstractions provided by the agent paradigm. It combines a top-down and bottom-up approach so that both existing system capabilities and the applications overall needs can be accounted for [34].

We model agent diagram for IMAQCS as shown in Fig. 5. In this diagram the actual agent types are represented by circles. People that must interact with the system are represented by the UML actor symbol. External systems that must interact with the system under development are represented by rectangles. It can be observed that in this model there are two external systems associated with the IMAQCS; sampling system that samples the output of each department and laboratory system which identifies the chemical compositions of materials.

In order to clarify the responsibilities of each agent, we provide the responsibility table for all agents in IMAQCS. Table 7 shows the responsibility table for PQCA as an example.

3.4. Agent communication

Agent communication is a form of interaction which expresses relationship among agents. Here we consider the role of communication as sending messages from sender to receiver. The content of message is encoded by sender with the help of languages which will be decoded by receiver. In this paper we use FIPA Agent Communication specifications[1] that deal with Agent Communication Language (ACL) messages,[2] message exchange interaction protocols and content language representations. We use FIPA SL content language[3] which is a human-readable string-encoded content language.

To continue our design, we determine the interaction protocols for all responsibilities of each agent that are related to another agent. Table 8 shows how the interaction table might look for the PQCA. AS we have mentioned above, we use FIPA interaction protocols[4] for the relation among agents in the IMAQCS.

3.5. Agents implementation

In this paper we use JADE (Java Agent Development frame work) as an agent design platform. JADE is a software framework that simplifies the implementation of multi-agent systems. In

Table 8
The interaction protocols for PQCA.

Responsibility #	IP (interaction protocol)	Role (responder/initiator)	With
1	FIPA Request IP	R	QCTEA
2	FIPA Query IP(Query-ref)	I	DBMA
4	FIPA Request IP	I	QCTEA
7	FIPA Query IP(Query-ref)	I	KBMA
8	FIPA Request IP	R	IDMA
9	FIPA Request IP	I	QCTEA

addition to the design of ontology, we use Protégé [35]. This tool is suitable for constructing ontology. Moreover, we use Jess Tab which is a rule engine for the Java platform to produce our rules in the knowledge base. Fig. 6 is a sample of rule in the Protégé with the help of Jess Tab. To create and use ontology, we use Bean Generator on Protégé environment. With this plug-in, domain ontology is exported to Java Class.

As mentioned previously, in this research, we use ACL message format and FIPA SL content language. Fig. 7 is a sample of our message content. In this example, PQCA sends a message to QCTEA using "CEMENT_ONTOLOGY" that run process capability chart and set the results into variables.

4. Experiment and validation IMAQCS

In this study, an agent-based model for controlling quality of process is proposed. We generate 42 rules for the stock pile, raw mill, raw material silo and clinker cooler departments. These rules are produced according to DAG (Directed Acyclic Graph). In these departments, the product has not yet formed in cement. The quality rules for the cement are different from the quality rules of cement process and it is not the scope of our work. The rule-base coverage measures [36] were applied to check that defined rules are covered any situation. So, we have not observed any uncovered condition during tests.

To evaluate the performance of IMAQCS, we have deployed IMAQCS in real plants and assessed the effectiveness and efficiency of our model on the cement process. Experimentally, IMAQCS has

```
(Defrule CHECK_BURNING_TEMPERATURE
(Object (is-a CLINKER)(BURNING_FACTOR_VALUE? BF& :(< =? BF 120)| (>=? BF 126)))
?f<-(object (is-a CEMENT_EMERGENCY_CONDITION))
=> (slot-set? f EMERGENCY_TYPE_NAME "burning factor"))
```

Fig. 6. Rule definition in the Jess Tab.

```
(request :sender (agent-identifier :name PQCA@192.168.1.2:1099)
:receiver (set (agent-identifier :name QCTEA@192.168.1.3:1099))
:communicative act request
:content "" ((action
(agent-identifier :name QCTEA@192.168.1.2:1099)
( (run_charts(data_id));
(set-result(PROCESS-CAPABILITY_TEST_REQ : LSL ?lsl
: SAMPLE_MEAN ?sample_mean:STDEV ?stdev)) ))""
:language FIPA-SL
:ontology CEMENT_ONTOLOGY
:protocol FIPA Request
:reply-with query2)
```

Fig. 7. An example of message exchange between PQCA and QCTEA.

[1] Foundation for Intelligent Physical Agents.
[2] FIPA ACL message structure specification, Document number: XC00061D.
[3] FIPA SL content language specification, Document number: XC00008G.
[4] FIPA modeling, interaction diagrams, Document number: TBA.

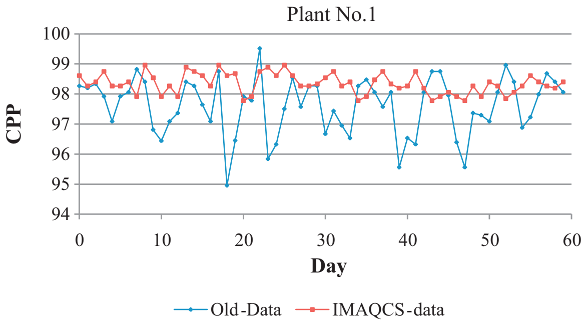

Fig. 8. Comparison cement production performance in plant No. 1.

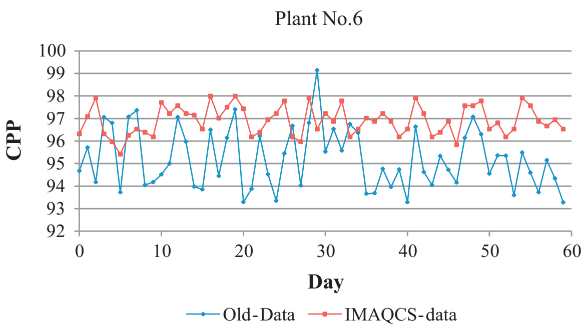

Fig. 9. Comparison cement production performance in plant No. 6.

Table 9
Comparison values of average of CPP in two plants.

Average of CPP	Plant No. 1	Plant No. 6
Old approach	97.60%	95.20%
IMAQCS approach	98.34%	96.90%

been run in two plants with the production line of Portland cement type 1-325 and 1-425(plant No. 1 and No. 6) for 60 sequential days. Due to reduce effects of other factors on our measurements, we consider a short period of time (60 days) to test the system. Therefore, there will be fewer fluctuations and more similar conditions for the production units.

In plant No. 1, and plant No. 6, respectively, 3000 and 4000 tons of cement are produced per day. Therefore, the time is wasted in the production line by doing process correction has directly affected the production of high quality cement. In this research, we compare the current condition of the cement plant to the condition that IMAQCS is deployed. This method enables us to examine cement production process in two approaches, the production line with employing IMAQCS and without it. First, we measure the amount of low-quality cement, produced during a day in the old approach to the two production lines. Next, we measure the amount of low-quality cement by deploying IMAQCS in the production lines. Then, we define Cement Production Performance (CPP) in order to determine how our system is effective. In addition, besides recording these data, we measure the process correction time (PCT) for each fault that was occurred per day. Finally, by the use of values of low-quality cement, we calculate the cost saving. The following shows the value of CPP in a day where i specifies the number of days

$$\mathrm{CPP}_i = \frac{\mathrm{CPC(cement\ production\ capacity)} - \mathrm{LQC}_i\mathrm{(low\ quality\ cement)}}{\mathrm{CPC}} \times 100$$

In addition, values of CPP during 60 days for both approaches in the two plants are shown in Figs. 8 and 9. It is clear that the values of CPP have increased generally in the production line with using IMAQCS.

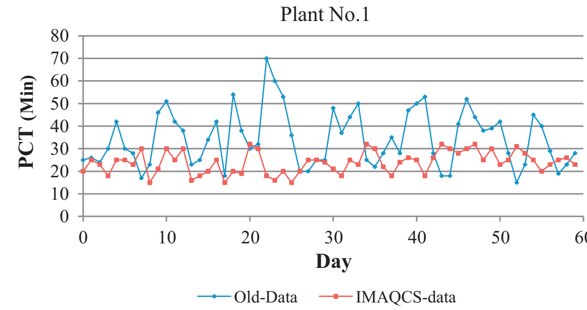

Fig. 10. Comparison process correction time in plant No. 1.

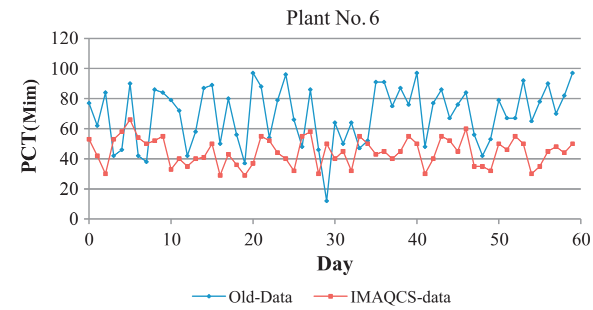

Fig. 11. Comparison process correction time in plant No. 6.

The values of the average CPP for 60 days in these two cases are shown in Table 9.

These results show that in average, we can increase cement production performance by utilizing IMAQCS. Also, we calculate the sum of PCT per day for the two approaches mentioned above (with deployment of IMAQCS and without it). Figs. 10 and 11 show data of PCT per day.

These experiments show the values of PCT have decreased by using IMAQCS in the production line. Table 10 shows averages of PCT for 60 days in two plants.

Depends on the number of faults that occur in each plant, the average value of PCT is different. But in general, the correction time will be shortened surely.

To prove our claim, we use paired samples t-test. In this test, we assume that there is no any significant difference between the average value of PCT in old approach and IMAQCS approach. The values of PCT for both approaches during 60 sequential days are tested. The results are shown in Table 11. We can infer that at $\alpha = 0.05$ level of significance, there is a difference in the mean PCT

Table 10
Comparison values of average of PCT in two plants.

Average of PCT (min)	Plant No. 1	Plant No. 6
Old approach	34.4	69.0
IMAQCS approach	23.8	44.6

Table 11
t-Test for PCT.

Plant no.	t	Degree of freedom	Sig. (2-tailed)	Mean difference	95% difference confidence interval	
					Lower	Upper
1	−5.796	59	.000	−10.53	−14.169	−6.896
6	−9.618	59	.000	−24.40	−29.483	−19.328

Table 12
t-Test for CPP.

Plant no.	t	Degree of freedom	Sig. (2-tailed)	Mean difference	95% difference confidence interval	
					Lower	Upper
1	5.57	59	.000	0.74	0.47	1.00
6	9.61	59	.000	1.69	1.34	2.04

Table 13
Cost of low-quality cement for 60 days in the two plants.

LQC	Plant No. 1	Plant No. 6
Old approach	4315.28	11504.7
IMAQCS approach	2983.33	7438.7
Total cost saving	(4315.28–2983.33) × 39.9$ = 531445$	(11504.7–7438.7) × 41.5$ = 168739$

index for the two approaches. This statistical test also has been done for CPP in both plants. Table 12 shows the result of the test. We can conclude that at α = 0.05, there is a significant difference in the mean CPP for the two approaches, too.

In addition, we have calculated cost saving to demonstrate the economical justification of our model. Based on the low-quality cement values produced in two approaches in plant No. 1 and No. 6, we could estimate financial impact of IMAQCS. This calculation is shown in Table 13.

Because cement production process during the correction operation cannot be stopped, usually cement that is produced at this time is undesirable. Therefore, low-quality cement is rarely used in the market. In result, the reduction of amount of low-quality cement has direct effect on cost saving. Also, it leads to save other resources of factory such as fuel of kiln and electricity that are not mentioned in this research.

5. Conclusion

In this study we use the agent-oriented design to cope with the problems in cement production processes. We focus on improving the quality of cement processes by controlling the process correction. Also, the effectiveness and efficiency of IMAQCS is assessed. To evaluate the effectiveness of the system, we use CPP and demonstrate how IMAQCS improves CPP. For illustrating the efficiency, we use PCT and financial impact of the system. In addition, using low-quality cement data and the price of cement, we estimate the cost saving in the plants. So, we demonstrate that IMAQCS can increase the performance of the cement plant. It should be noted that the IMAQCS contains specific rules for inner departments of cement process. Indeed, to deploy such system in other industry, the rules should be redefined. The main contributions of this paper can be summarized as follows:

- IMAQCS with the help of the agent-oriented framework can control the complex structure of the cement plant to cope with monitoring and correcting the processes.
- IMAQCS uses a rule-based quality control mechanism that serves as an online quality control method acting after the faults occurs.
- The effectiveness and efficiency measurements prove our system capabilities.

There are other issues raised from this paper. One of these issues is that data mining techniques such as clustering method allows decreasing the run time of the system. Fuzzy rules can be applied to alternative crisp rules. This type of rule could tackle the uncertain conditions of the factory.

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Iraj Mahdavi is the professor of Industrial Engineering at Mazandaran University of Science and Technology and Vice President of Graduate Studies and Research. He received his PhD from India in Production Engineering and Post-Doctorate professor from Hanyang University, Korea. He is also the editorial board of four and referee of eight international journals. He has published over 70 research papers. His research interest includes Digital management of industrial enterprises, intelligent operation management and industrial strategy setting.

Babak Shirazi is the professor of Information System Design in Industrial Engineering at Mazandaran University of Science and Technology. He studied Computer Engineering in Tehran University. His research interest includes intelligent knowledge-based system, Enterprise Architecture, e-Based architectures. Now, he is working on ultra large scale information system projects. He has published over 40 research papers.

Narges Ghorbani received her B.S degree in Software Engineering from Iran University of Science and Technology, Tehran, Iran, in 2008. She received her M.S in Industrial Engineering from Mazandaran University of Science and Technology, Babol, Iran, in 2011. Her research interest includes intelligent monitoring and control, multi-agent learning and intelligent knowledge-based system.

Navid Sahebjamnia is a Ph.D student of Industrial Engineering at faculty Engineering of Tehran University. He received his master in Industrial Engineering from Mazandaran University of Science and Technology in 2009. His research interest includes Assembly shop management, e-Based architectures and Information systems. He has published over 25 research papers.