INTEGRATED MANAGEMENT AND OPTIMIZATION OF THE SANITATION CYCLE BY THE COMBINED USE OF EXPERT SYSTEMS AND SUPERVISORY SYSTEMS IN REAL TIME OPERATION

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ABSTRACT

The society's acknowledgement of the importance of Earth's water resources has been significantly enhanced over the last decades, in the 1990s and 2000s. The populational growth and the environmental degradation make the efficient management of water resources even more vital for humanity. This article presents a new systematic proposal comprising the use of automation technology in order to allow significant efficiency gains in harnessing, treatment, reservation, distribution, collection and management of water resources and thus to contribute towards a sustainable development. The proposed system is nominated Automated Management Integrated System of Intelligent Sanitation (*Sistema Integrado da Gestão Automatizada de Saneamento Inteligente* - SIGASI). Consists of a hardware and software architecture that integrate the Expert Systems (Artificial Intelligence) and the Supervisory Systems, in actual operation time. The system was virtually validated with tests based on parameters of an actual Water Pumping Station (WPS). The test methodology, the virtual treatment station simulation system and the automation system, the hardware and software architecture and the gains obtained in the tests are also shown in this article.

Keywords: Automation, Management, Water Resources, Sustainability, Expert System, Artificial Intelligence

1. INTRODUCTION

Water is not only an essential element for life, but a factor of major importance in the processes of social and economic development, increasingly taking an essential role in humanity's sustainable development. It is notorious and evident that the concern with water or its shortage has brought, to an increasing extent, challenges to different societies and Government bodies. However, the issue includes more than the existence of water resources, it embraces their use and supply systems, which are required to meet the needs related to people's general health and the economic and sustainable development (Tsutiya 2004).

1.1. Need of a Better Management of Water Resources

The use of water for different purposes has been expanded due to the intensification of human and economic activities and populational growth (Brandão 2003; Tsutiya 2004). Thus, during times in which the development process rate runs faster, there is an increase of the basic resources demand, including water. This was noted in some regions of the world, during the second half of the last century. Therewith, the management of water resources also grew more important and complex, benefiting from systems analysis theories and practices and operational researches since the end of the Second World War (Brandão 2003). Afirming that the sanitation system in Brazil is the context for which this article is headed, it becomes necessary to show a few macrodeficiencies in this segment's infrastructure, which may aid sustainable growth if minimized and help a more efficient management style, for example:

a. The absence of a device establishing the monitoring and encouragement of performance enhancements in the losses reduction in Brazillian water supply systems. According to Tsutiya (2004), the losses measured through the ratio between invoiced volumes and the volumes available for distribution were 40.6% of the national average value. Also in 2001, the State companies recorded an average income loss of 40.4%. (IWA 2002) In 2007 and 2008, this value was respectively 39.1% and 37.4%, according to a National System for Information report about Sanitation (*Sistema Nacional de Informações sobre Saneamento* – SNIS). The physical losses, represented by leakages in the distribution networks, have had serious consequences in the company's business performance. Since the lost water is not billed, they represent greater production costs and greater expenses with electrical energy and chemical products for water treatment, which end up being incorporated into the rates. Internationally, on average, Asia shows an overall loss of about 42% in its water systems, compared with 39% in Africa, 15% in North America, and 42% in Latin America and the Caribbean (WHO-UNICEF 2000). For example, the city of Delhi, India, showed a water loss rate of 53%, while the city of Tokyo, Japan, a country whose cities have the lowest water loss rates in the world, had an average loss of only 4.5%. In case of New York City, in the United States, the water loss indicator in the system suggests a water loss of 30%.

b. Ineffective operationalization of sanitation systems, which must be optimized through the use of more rational techniques and scientific work, possibly through partnerships with Universities. One clear example of optimization would be paying close attention to the electric power consumption issue in the sanitation cycle and making it more efficient, as electric power is the most significant element of the sanitation cost in Brazil, usuallyusually second only to payroll. For example, by using the data released by São Paulo Sanitation Company (*Companhia de Saneamento Básico do Estado de São Paulo* – SABESP) (2010), one can notice that in 2010 the kilowatt-hours/m³ number indicator in the water production process was 0.613 kWh/m³, with a consumption of 1,810,291,074 kWh and a produced volume of 2,952,386,248 m^3, providing a unit cost per kilowatt-hour of 0.13 (US$/kWh). In the sewage treatment process, the indicator came to 0.411 kWh/m³, with a consumption of 320,942,186 kWh, a treated volume of 780,950,895 m³ and a unit cost of 0.14 (US$/kWh).

c. Need for optimization in the use of chemical products used in the water and sewage system, through efficient and automated control, as these products have a direct effect on the water bill.

d. Need for processes automation, using Automation Technology, associated to intelligent system, as a tool to improve the management of water resources – which is the main purpose of this article.

1.2. Justification and Purpose of this Article

Currently, there are three main weak points in the operational models for water resources management. These are:

a. In order to carry out the management and control of sanitation subsystems, most managers and supervisors, known as sanitation managers, use a conventional management model in which the data is treated in sequential manner, which means that they issue a final result and process a certain volume of data in a repetitive way to solve a problem. This model may not perform more efficient and optimized actions such as the automatic systematization of knowledge through rules and procedures, to allow better decision-making, as well as the systematic standardization of knowledge between the different sanitation managers;

b. The sanitation manager action occurs at the third level of the theoretical model in the automation pyramid (Durkin 1994; Webb, J.K 1992). This level operates the Supervisory System, which receives information from controlling devices such as Programmable Logic Controllers (PLC), frequency inverters, control valves, etc. This system executes several vital functions within an automated process and also operates as an interface between Human Machine Interface (HMI), with operators and managers, enabling them to analyze, diagnose, infer and make decisions during the process. The managers and operators spend a lot of their working time operating the Supervisory System. This operation is usually executed by several managers in many subsystems of the sanitation cycle. According to the general automation theory (Andrade 2001), the action of human beings in an automated process is considered a manual action, and it is thus subject to all kinds of occurrences arising from non-automated processes;

c. The procedures involved in the sanitation cycle are usually known to the people responsible, but as a rule, this knowledge tends not to be fully systematized. Hence, the use of knowledge of the managers of the subsystems is not always done in an assertive and efficient manner, in the automation systems. Other factors such as restructuring of the functional workforce and retirements have meant that the knowledge accumulated by operators and sanitation managers tends to be lost, leading to costs resulting from undue operation and new training for replacement labor. Even making an effort for training, this is usually not enough to make sure of the full transmission of knowledge as acquired by the managers over the years.

The shortcomings mentioned in management of Brazilian sanitation system show the need to develop an efficient methodology which is able to ensure the preservation of the knowledge held by those responsible for the function and operation of the sanitation subsystems and also to optimize the operation routines. For this, the use of Knowledge Engineering and Expert Systems at the third level of the theoretical model of the automation pyramid, more specifically at the base of supervisory systems, comes as an alternative to the methods currently used by the managers of the sanitation system in Brazil. Figure 1 shows the proposal made by this methodology.

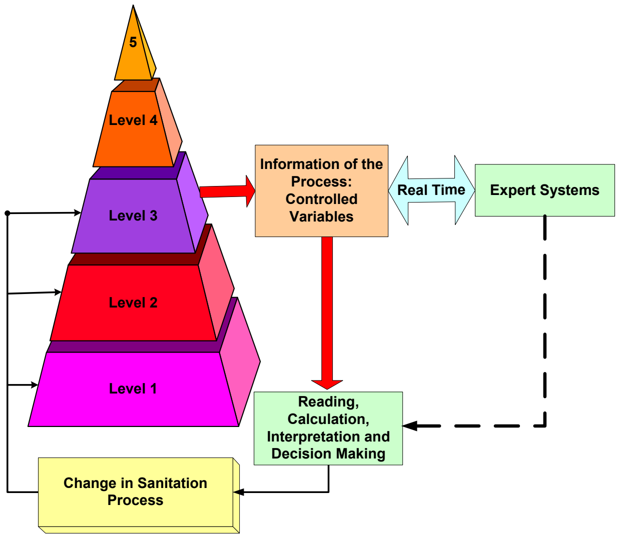

Figure 1. Proposal for Sanitation Cycle Management Methodology

Figure 1 shows the actions of the system operator, as well as the actions of the Expert System, working to promote the integrated management of the sanitation cycle. Here we see that this activity may occur mainly in the three lowest levels of automation period, according to the following cycle:

a. The operator perceives the process information in S.S. through his or her senses;

b. The operator then uses the capacities of his or her brain for data analysis and interpretation, making decisions or not;

c. After the decision, the operator changes the operating parameters, which can range from maintenance help and diagnosis (Level 1), verification of logic of operation (Level 2) or mainly direct operation of the S.S. (Level 3).

d. The Expert System operates in real time with the S.S. base to provide guidance to and/or automate the functions executed by the sanitation system operators, through rules and procedures stored on the Expert System database.

As proposed, this methodology allows two different methods of operation and management:

a. Operate as total or partial substitute, in the sanitation cycles in decisive processes;

b. Operate in real time, as a counselor to the managers and operators, in the sanitation process.

Thus, according to the operational skill of the Supervisory Systems and the capacity to deal with the knowledge of the Expert Systems, the union of architecture of hardware and the architecture of the software packages, in this article, makes it feasible to help or even automate the decision making in the sanitation cycle operation and management. Thus, the objective of this study is to develop an integrated management model, which uses an Expert System and which could give guidance automatically to the operator in the sanitation cycle management, if implemented. This proposed architecture, in this article is known as the Integrated System for the Automated Management of Intelligent Sanitation (*Sistema Integrado da Gestão Automatizada de Saneamento Inteligente* – "SIGASI").

2. AUTOMATION IN SANITATION SYSTEMS

The automation in systems for water supply and sanitary drains consists of collecting, concentrating and processing of the process information with the use of Information Technology (Souza 2011). Based on the obtained results, the automation systems act in an autonomous manner on the states and the variables in the process to obtain the results as desired. Figure 2 shows the process of data collection and activities in the Sanitation system.

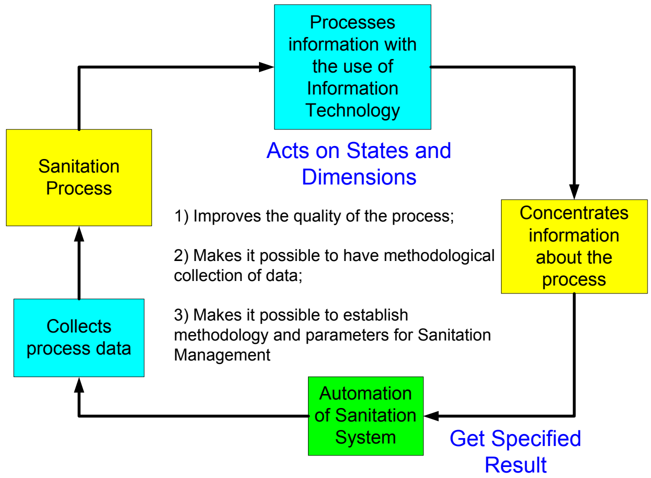

Figure 2. Automatic Process for Data Collection in the Sanitation System

Figure 3 shows the subprocesses of the sanitation cycle.

Figure 3. Sanitation Cycle - Source: Water Supply System Company from State of São Paulo – Sabesp (2005)

Figure 3 shows that the sanitation cycle involves all the water treatment stations, sewage treatment stations, water Pumping stations, reservoirs and all sources of water resources; thus, the number of communication points involved (data exchange between field signals and controllers – tags, as they are known in technical and commercial literature) is highly significant. This requires an enhancement of the automation systems to meet the need for the organizations to carry out a global management of their processes.

The greatest complexity of the automation process then requires that responsible parties have greater effort and skills to manage a high number of communication points. Exemplifying with data from the local water company (SABESP) which serves around 20 million people in São Paulo Metropolitan Area (*Região Metropolitana de São Paulo* - RMSP), including 27 municipalities, in an urban sprawl of over 8,500 km² and which uses an Operational Control Centre (*Centro de Controle Operacional* – CCO), consisting of a supervisory system to monitor and control the water transport system in the RMSP: currently, its set of communication points consists of about fifteen thousand (15,000) tags. To meet the current needs and demand for automation, the same supervisory system is being adapted to control one hundred and fifty thousand (150,000) tags.

The main reasons to justify the investments made in automation in the water supply system refer to the improvement of water treatment and distribution through real time monitoring and control, reduction of operational costs, through the management of electric power consumed and control of physical losses in the system.

F. Mário (2001) explains that the concept of automation in water supply systems is very similar to what happens in the case of electrical system. In the same way that this segment can be divided into generation, transmission and energy distribution, the sanitation segment has water production, transport to reservoirs, distribution to consumers, sewage collection and treatment.

The automation of sanitation in many Brazilian companies is still an one-off occurrence. This is a consequence of the lack of planning and resources of water companies, which has continued for several decades. One obstacle faced for the adoption of automation in this segment is the geographical aspects, which have an influence on communication means. Normally, the remote units of monitoring and control are installed in locations where there is poor infrastructure of telecommunications or electric power, implying the use of alternative structure such as mobile phones, transmission by radio waves, frame relay and others.

3. PROPOSAL OF HARDWARE AND SOFTWARE ARCHITECTURE

The proposal of the development methodology of hardware and software architecture, as well as the operational methodology of SIGASI, are presented in this item. SIGASI is a new proposal for an automated methodology, which proposes an integration between Supervisory Systems and Expert Systems, seeking advances in the sanitation cycle management. Its macroarchitecture is presented in details, as well as the stages of their implementation through simulations in virtual tests, with the due results as obtained.

Supervisory Systems (S.S) and Expert Systems (E.S) have capacities, which can be associated to promote the optimization of water resources management. The Supervisory Services offer easy interpretation, flexibility, process structure, generation of income, scripts, information trackability and easy operation, while the Expert Systems represent a powerful tool to deal with knowledge. Due to this fact, SIGASI, in its architecture, integrates E.S. and S.S, to make the most of the conditions offered by the two systems.

The methodology for development of SIGASI was based on the study by Andrade (2001), which drew up a software solution for operation, in real time (Laplante, P. A. 2004)., of Expert Systems with Supervisory Systems for industrial automation, known as the System for Integration Between Specialist and Supervisory Systems (*Sistema de Integração Sistemas Especialistas e Supervisórios* -(SISES). This new software became one of the models to be part of SIGASI. Figure 4 of this Article shows the macroarchitecture of SIGASI.

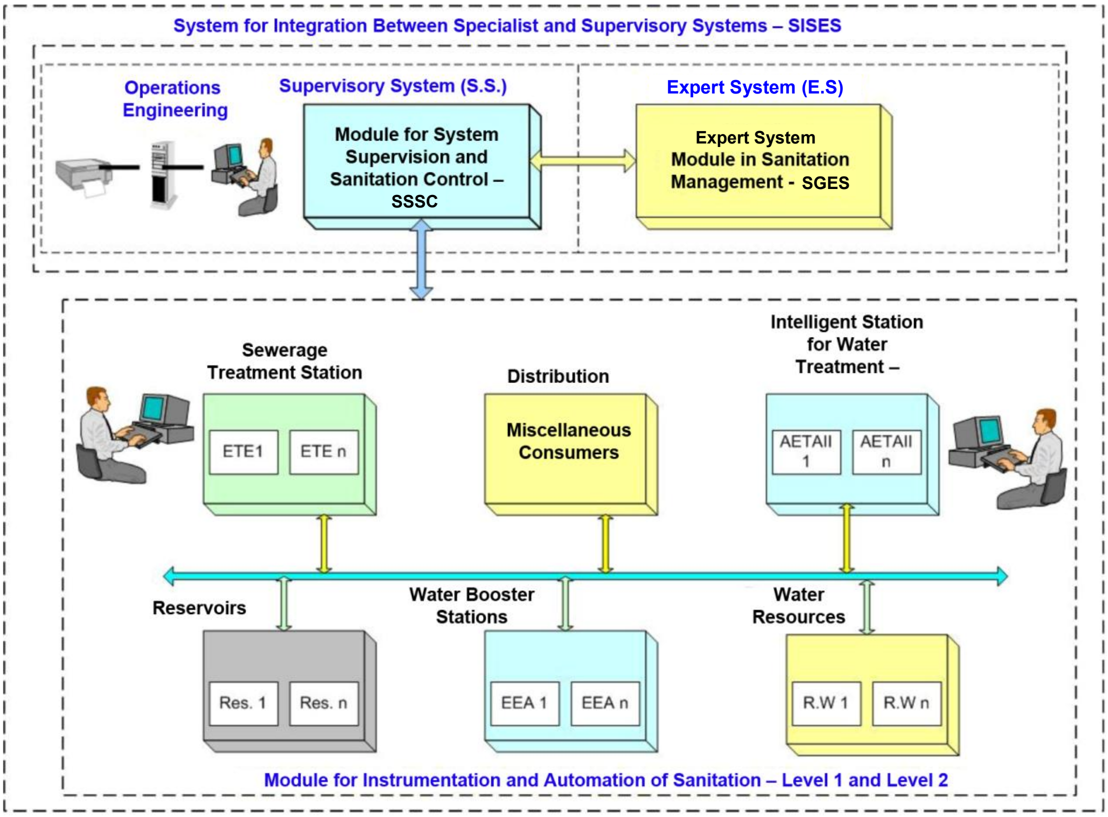

Figure 4 – Macroarchitecture of Hardware e Software of SIGASI

As shown in Figure 4, the SIGASI comprises the following modules:

a. Module for Instrumentation and Automation of Sanitation (*Módulo de Instrumentação e Automação do Saneamento* – MIAS) (levels 1 and 2);

b. System for Sanitation Supervision and Control (*Sistema de Supervisão e Controle do Saneamento* – SSSC) (level 3);

c. System for Integration Between Specialist and Supervisory Systems (*Sistema de Integração Sistema Especialista e Supervisório* – SISES);

d. Expert System of Sanitation Management (*Sistema Especialista e Gestão do Saneamento* – SGES).

The macroblock of the Sanitation Instrumentation and Automation Module (MIAS) conceptually comprises levels 1 and 2 of the automation pyramid module, which is part of Instrumentation and Controllers.
The System for Sanitation Supervision and Control (SSSC) uses electronic supervision and uses data communication technologies and computer systems to concentrate all the information of a system, installation or set of installations in one single operating point. Through electronic supervision, one or more operators operate much equipment, distributed throughout a large area. This module also operates the Supervisory System, which receives information from control devices such as Programmable Logical Controllers, frequency inverters, control valves etc. Supervisory Systems have a tool for storage of the variables of greater relevance, regarding the production system.
The System for Integration between Specialist and Supervisory Systems (SISES) is a computer tool or an environment for development of Expert Systems, which enables communication with the Supervisory Systems in real time. SISES consists of two macroblocks: Module of Interface with Supervisory Systems and the Module for Construction of Expert Systems.

The Expert System of Sanitation Management (SGES) is a Expert System dedicated to operation with S.S. in real time and with the aim of helping and/or automating the taking of decisions in the management of the sanitation cycle. Figure 5 shows the macroarchitecture of the SGES.

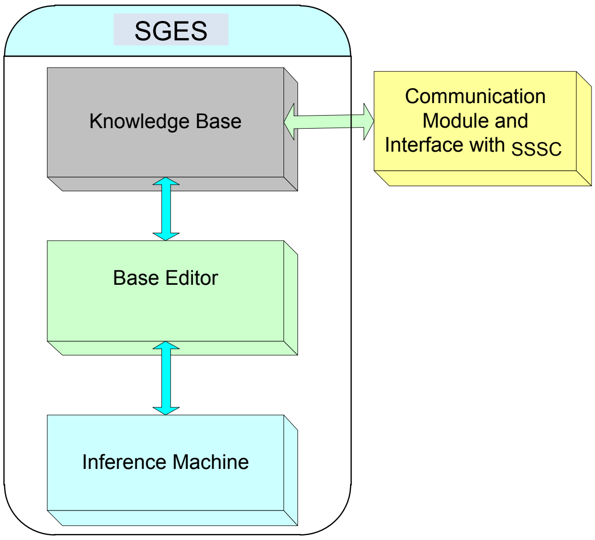

Figure 5. Basic Architecture of the Expert System Generated in the SGES

As shown in figure 5, SGES includes the following features:

a. Knowledge Base: this is the information (facts and rules) used by a specialist, represented in computer form;

b. Base Editor: this is how Shell (specific software packages for drawing up of E.S.) allows the implementation of the desired bases;

c. Inference Machine: this is the part of E.S. responsible for deductions on the knowledge base;

d. Communication Module: this is the part of E.S. that allows communication in real time with System for Sanitation Supervision and Control (SSSC).

3.1. Stages for the Implementation and Validation of SIGASI

As the first stage in a long and permanent project, the phases as defined for this article were the following:

a. Definition of Targets and Subprocesses to be monitored by SIGASI;

b. Development of Expert System:

 b.1. Knowledge Management activity;

 b,2. Preparation of Communication Base;

 b.3. Preparation of Inference Machine;

c. Development and Implementation of Virtual SIGASI;

d. Definition of the methodology to validate SIGASI;

3.2. Target and subprocess monitored by SIGASI

In this article, we present the macrotargets defined to be simulated and monitored with the SIGASI proposal. These are:

a. Reduction of expenses with electrical energy, through water pumping;

b. Reduction of electricity consumption with the pumping of water;

c. Reduction of water loss in the supply system, using intelligent systems;

d. Optimization of the quantifiers of supplies for water production;

e. Optimization and establishment of grounds for maintenance actions of Sanitation Cycle;

f. Generation of database in real time.

To simulate the rules and procedures used in a water supply system, first, a part of the subprocess was selected from a water supply system, where the water Pumping station (WPS) was monitored by SIGASI. According to Tsutiya (2004), Water Pumping Stations are defined as “sets of buildings, installations and equipment, intended to house, protect, operate, control and maintain the lifting sets (motorized pumps) which promote the pumping of the water”.

3.3. Development of the Expert System

For the implementation of the Expert System of Sanitation Management (SGES), there was the need to develop three basic phases:

a. Knowledge Management Activities: this stage involved the development of knowledge engineering activities. In this phase, information was collected specialists, end users and operators of the system. The main target here was to acquire relevant information about the sanitation system operation.

b. Knowledge Base Preparation: this stage was the systematization of the information (facts and rules) which had been collected in the previous phase. Such information was used by the sanitation subprocesses specialist to solve a certain process problem, and is computationally represented on the E.S. The information is systematized in this phase so the system may help with decision-making during the sanitation system operation, whether performed by the operator or automatically.

c. Inference Machine Preparation: this stage consisted of preparation of the inference machine, part of E.S. responsible for deductions on the knowledge base, as constructed in the previous stage of this article. Figure 6 shows the rule synthesis, which was prepared to reach the objectives of this article.

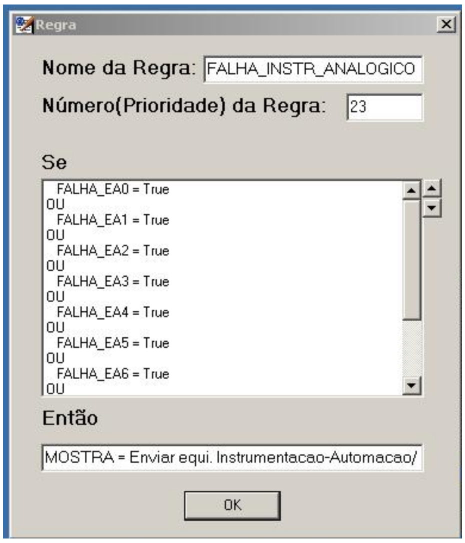

Figure 6. Example of the Preparation of Rules for the Sanitation Process

3.4. Development and Implementation of Virtual SIGASI

This item presents the development and implementation of the practical application of SIGASI for the real sanitation system. This part of the article shows the development as well as the tests executed, making use of SGES generation tools, an E.S. capable of observing the variation of S.S. parameters in the sanitation system, and have an influence thereon in real time. This E.S. provides messages about the inferences resulting from the interaction with S.S. The SGES Module also allows the inferences lead to actions in S.S., to allow the operationality of SIGASI. For the compliance with this stage, a strategy was prepared, as shown in Figure 7 that follows.

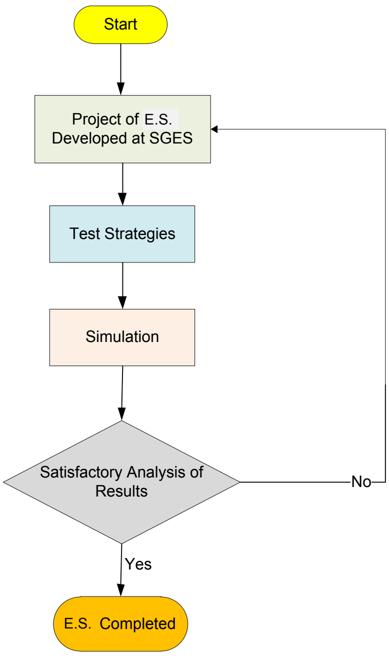

Figure 7. Strategies for the Preparation of E.S. in SGES

3.4.1. Methodology for Validation of Virtual SIGASI

SIGASI was validated through simulation. For this, there was the programming of the SGES module, which operated in a laboratory with a Supervisory System, where the variables of a sanitation process were then treated, according to the need to promote a simulated contingency. For the tests execution, a Programmable Logic Controllers - PLC, emulator was used, a supervisory system developed in a similar way to the current systems of a sanitation company. The main function of the PLC emulator is to feed the supervisory system data which, in turn, communicates with the E.S. in real time. Thus, by simulation, part of a sanitation system is virtually replicated. The macrostructure of this model's virtual hardware is shown in Figure 8.

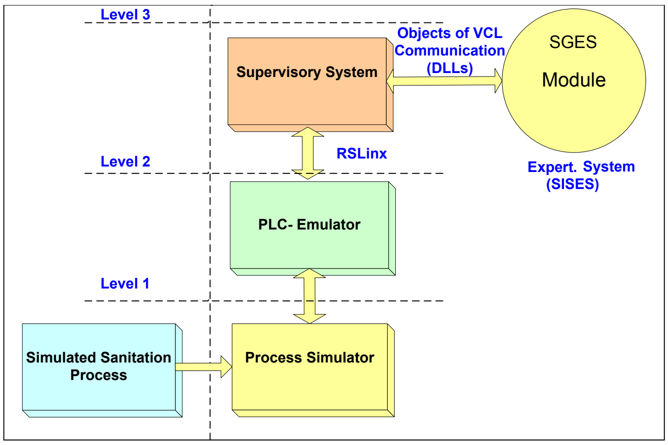

Figure 8. Macroarchitecture of the Virtual Hardware of SIGASI's Validation Model

In Figure 8, it should be noted that the field signals are virtual, which means they are generated by the process simulator. The emulator itself is not enough for simulation because it cannot reproduce the field responses; it needs the process simulator. The software used for the PLC emulator simulation and the process software was the RSLogix Emulate 500 software package made by Rockwell Software (2004), due to its technical features, which allow a simulation of complex processes, truthful to the reality of a process to be simulated. This software makes it possible to emulate PLCs from Allen Bradley, from SLC (Small Logic Controller) family, based on the programs that shall be run on the real PLCs; in other words, it processes the ladder lines (Michel 1990) or the blocks of an SFC (Sequential Flow Chart) (Michel 1990). This emulator, just like the PLCs used by Allen Bradley, uses as data exchange mechanism the RSLinx communication software made by Rockwell (Rockwell 2004), which manages all data exchange, also being responsible for the exchange that occurs between PLCs and S.S. Between SISES and S.S. (RSView), the communication is made through two DLLs known as VCL objects; they are small programs typical of Windows package.

3.4.2. SIGASI Validation Criteria

To validate the SIGASI simulation tests, the following criteria have been adopted:

a. Global performance of the system: the system as a whole shall operate in a satisfactory way;
b. S.S. Performance: the S.S. shall not suffer a significant drop in performance;
c. Execution time: the time for E.S. to reach a conclusion cannot be dimensionally higher than the standardized times that human operators take to reach the same conclusions;
d. Compatibility: the E.S. cannot request such a volume of resources from the operational system (Windows) that has a negative effect on performance;
e. Assertiveness: E.S. has to reach the correct results.

3.4.3. Tests and Performance Analysis of SIGASI

During the tests phase, the correct results, as well as clear and objective messages that were supplied by SGES showed compliance with the objective of this study. SGES presented the conclusions about the actions that the operators should take in seconds, making them much faster than the usual times taken to make decisions, which are often considered in terms of minutes. The performance of the SGES was satisfactory in all testing criteria. Figure 9 shows an example of the message screens generated by SGES, during the tests on the hardware and on the software packages of SIGASI.

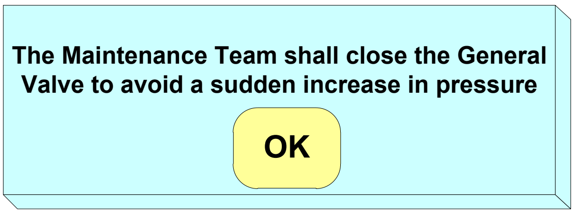

Figure 9. Example of a message screen generated by SGES in the process of automation test of water Pumping station (WPS)

Note that the messages generated by SGES are obtained through heuristics, supplied by specialists in the sanitation process, which have been turned into rules in the SGES (see item 3.3). The message sent to the S.S. shall be recognized by the operator of the subprocess, through the "OK" button, to allow recognition of the contingency informed by SGES, as also for the operationality of E.S. itself. Another relevant confirmation to be stressed during SIGASI tests was the capacity of SGES to map, through a decision tree diagram, the sequence of how the operator came to a solution for a certain contingency of the sanitation process. Figure 10 shows an example of a decision tree, obtained during SIGASI simulation.

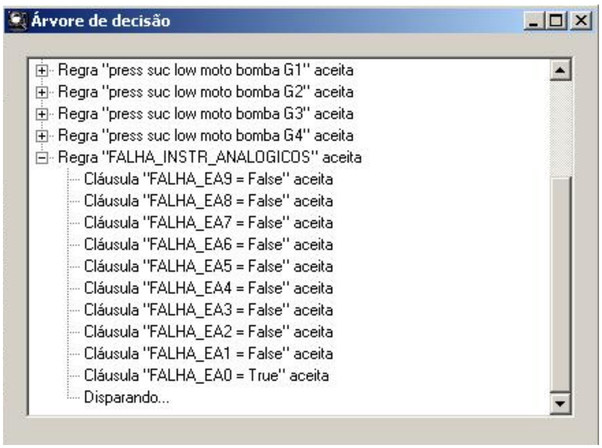

Figure 10. Details of the decision tree as generated by SGES

Notice that in Figure 10 the decision tree supplies the sequence of events (rules) and shows the way in which SGES came to the solution of a certain contingency in the sanitation process. This function of the SGES is very useful and important in the system operation, especially in processes with a significant number of tags, such as the sanitation cycle (see item 2). Surely, the human specialist would have great difficulty to describe, in systematic form, how he or she reached the solution of a certain problem. Thus, we can conclude that through this function of the SGES it is possible to systematize, over time, the taking of decisions in a certain contingency situation within the sanitation process, through procedures and rules. Thus, it is able to transfer the knowledge systematically to different operators, some of whom have even less information about sanitation subprocesses, as well as the register itself, of what was stored in theory and in practice by experienced professionals who are now close to retirement.

4. CONCLUSIONS AND FUTURE RESEARCH

This article presents the operational integration of a sanitation automation Supervisory System with the Expert System, thus bringing together the dynamic reality of the sanitation automation process and the knowledge acquired in E.S., in order to prepare the resulting system to make inferences on the sanitation cycle set and also execute actions in this set as mentioned.

This methodology, using E.S., has a relative advantage when compared to conventional automation systems: the fact of allowing deliberate actions on decision-making, in real time, about occurrences involving equipment of the sanitation program, which still, for some reason, are not inserted in the automation process. Through programmed rules and messages on E.S, screen, it is possible, for example, for the operator to receive guidance through E.S. method: "close the entrance valve of a certain water supply system, due to excess pressure, caused by power outages in the region. If this valve is not closed, then there can be significant damage to the tubing". Even though the valve is not part of the automation system, it is still possible to establish actions through E.S.

In short, the conclusion is that SIGASI brings significant technical and economic benefits compared to the management system currently used by managers of sanitation companies. This enables, for example, greater grounds in taking maintenance actions, as well as greater response speed to the disturbances of the process, systematization of procedures used for decision-making, greater knowledge of specialists who are active in leading the subprocesses of the sanitation cycle and the automatic taking of decisions, in real time, including sectors as yet not automated. As this is a new methodology, this study can be easily replicated for other sanitation subprocesses. This new management methodology, as proposed for the sanitation segment, helps to improve automation and, thus, the management of water resources.

As for the macrotargets defined (item 3.2), SIGASI has shown that they comply, in qualitative fashion, with all the six points as raised, mainly due to the fast identification of operational problems, which avoids significant waste in the productive sanitation process, both for water and supplies used in the production thereof, as also in the electricity consumption and respective expenses, incurred with the water pumping process.

The SIGASI proposal is an opening for new lines of investigation in the field of sanitation management, water resources and environment, with the use of automation technology associated to intelligent systems. This article, on seeking a more efficient and optimized style of the sanitation cycle management, intends to expand the contribution so that the availability and use of water, one of the most important natural resources on the planet, may be done in a more rational manner, thereby improving the conditions for sustainability of human development.

As possibilities of future enhancements of this work, we could mention:

a. Continuity of research and implementation of SIGASI for the accurate quantification of the indicators as well as the relations mentioned in item 3.2 of this article;

b. Improvement of H.M.I., making the operation even easier for the users;

c. Research in new techniques of software packages to enhance the SISES;

d. Implementation of the proposal of this research work in a sanitation unit, during a test period for validation, before managers and sanitation operators.

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