CERAMIC Industry 4.0, A CASE STUDY

G. Mallol[1], J. Boix[1], D. Llorens[1], J.J. Clausell[1], J.I. Cantero[1],

R. Debón[2], J.A. Ureña[2], C. Vallejo[2]

S. Herrando[3], P. Alcoriza[3]

[1] **Instituto de Tecnología Cerámica (ITC). Asociación de Investigación de las Industrias Cerámicas (AICE). Universitat Jaume I. Castellón. Spain.**

[2] **COLORKER, S.A**

[3] **Core Digital Industry**

1. ABSTRACT

In the coming years, all industrial sectors must necessarily adapt their production environments to the digitalization, interconnectivity and automation required by the implementation of Industry 4.0 standards. This paper describes the advances carried out in this sense at the COLORKER ceramic tile manufacturing plant in Xilxes.

The digital transformation process of the plant was initiated by enabling and/or adapting the communications of the different machinery and production equipment in order to acquire the corresponding process information. All information generated in the plant was integrated by means of an industrial communications network with specially developed optical fibre. Through this network, the data necessary to calculate batch manufacturing costs, efficiencies of the different production stages, energy consumption and CO_2 emissions were centralised in real time. To guarantee continuity of information within the manufacturing process, it was necessary to develop and fine-tune the internal traceability system of the manufactured tiles ensuring individual identification.

Finally, implementation of a MOM (Manufacturing Operations Management) platform adapted to the requirements of Ceramic Industry 4.0 was started. The

platform integrates all operations within the same system, ensuring correct consolidation of all relevant data, regarding both the production process as well as business management, enabling integrated and optimised management of company operations.

2. INTRODUCTION

The concept of Industry 4.0, a term first coined in 2011 during the industrial technologies trade fair in Hannover, refers to a new way of organising means of production, enabling development of agile and flexible systems that respond quickly to constant changes and alterations in the production environment. Process industries in general must be able to respond to the increasing demands of current markets and supply chains. The trend towards customisation of mass production, expectation of quick response times, increasingly short product life cycles and efficient use of energy and resources are forcing companies to rethink certain such important aspects as flexibility of their plants, capacity to reconfigure production flows or decentralisation and integration of suppliers [1].

The emergence of new technologies based on the Internet of Things (IoT) and Internet of Services (IoS) has facilitated integration of new types of devices into production chains. These technologies allow devices such as sensors, actuators or smartphones, to interact and cooperate with each other to achieve common goals. The sets of these devices are known as Cyber-Physical Systems (CPS) because they act as links between the real (physical) world and the virtual (cyber)world. In fact, integration of these technologies into manufacturing processes, together with hyperconnectivity and Big Data, among others, has marked the beginning of what is known as the fourth industrial revolution, described by the concept Industry 4.0 [2]. The new industrial revolution is based on the so-called Smart Factory, characterized by interconnection of machines and systems at the production sites themselves, and also by fluid exchanges of information at all levels of plant production and management.

Industries embracing Industry 4.0 are characterized by interoperability, modularity, integration capacity, security, digitalisation, decentralisation and real-time capacity of their systems. Implementation of these measures into production processes is key toindustry future, since they will increase productivity as well as the quality of the products, resulting in increased competitiveness and, therefore, enhanced company profitability.

A clear example of the importance of the technological changes advocated by Industry 4.0 for industrial sectors is the initiatives that many countries have adopted in recent years. Thus, Industry 4.0 is a key project in the German government's technology strategy, which promotes the digital revolution of industry. The United States, through initiatives such as the Smart Manufacturing Leadership Coalition project, is focusing on industrial manufacturing of the future. Even the EU itself, in the Horizon 2020 plan, considers these aspects in priority lines of action such as Factories of the Future (FoF) or "Sustainable Process Industry (SPIRE)". The Spanish government presented the Connected Industry 4.0 plan in 2015, to be developed in the coming years through the Ministry of Industry.

Currently, the ceramic tile manufacturing process may be considered a technologically mature process, from the point of view of the degree of automation

[3]. Throughout the process, products arehandled automatically without human intervention of any kind. However, from the point of view of process control and plant operations management, the ceramic process requires significant adaptation to achieve Industry 4.0 standards. Currently, information is not only managed manually, it is discontinuous, poorly processed, delayed in relation to actual production time and oftendoes not allow reliable operations analysis. Moreover, at process controllevel, the different manufacturing stages constitute islands of isolated control between which information does not flow automatically.

This low degree of maturity at control level, compared to other much more advanced industries in this field, such as the chemical or petrochemical industries, diminishes the competitiveness of ceramic companies. In fact, lack of information on the production process prevents correct traceability of production in continuous and real time, which would facilitate knowledge of such significant aspects, for example, as the real cost of ceramic tile manufacturing, of a production process system or energy consumption resulting from a batch production, among others. It may also be noted that appropriate exploitation of the information generated in the production process enables use of advanced business models to improve company competitiveness.

Currently, the main equipment and machinery manufacturers for the ceramic industry are proposing, through newly created production plants, solutions and tools that guarantee a certain degree of hyperconnectivity and integration of tile manufacturing processes. However, there is a large industrial machinery park, still in perfect operating condition, which requires adaptation to ensure digitalisation of the ceramic industry. The work described here focuses precisely on the adaptations required in a standard ceramic plant, in order to achieve appropriate hybridisation between the world of information technologies and plant operations themselves.

3. OBJECTIVE

The main objective of this paper is to describe the transformation process that a ceramic tile manufacturing plant needs to undergo to adapt operations management to Industry 4.0 standards. For this, implementation of a pilot project for industrial integration was proposed, assisted by a new traceability system for the process based on tile coding, to optimise company operations while improving competitiveness.

4. STARTING SITUATION

For implementation of the pilot demonstration project it was considered necessary to select a typical production unit that guaranteed demonstration of the transformation process in a real production environment. Implementation of this pilot project is being carried out at the Colorker company production facilities in Xilxes, in which single-fired porcelain stoneware tile and white-bodyearthenware tileare manufactured.

4.1. DESCRIPTION OF THE PILOT PROJECT

The pilot project consisted of two lines forunfired ceramic tile preparation, each using a hydraulic press with capacity to manufacture tile sizes from 20 cm x 40 cm to 120 cm x 60 cm, a horizontal dryer with five decks and a glazing line with different types of decorative applications, notably including an inkjet printing machine.

The unfired product manufactured in these two lines was stored on cars in an intermediate stockpile pending subsequent firing in a single-layer roller kiln. Also included in the pilot project equipment were two machines for sorting the finished product along with a cutting and edge-grinding machine. After firing, the tiles were again stored in the intermediate stockpile and are then, depending on the characteristics of the final product, classified directly for packaging and shipment or rectification prior to sorting.

4.2. PREVIOUS CONTROL LEVELS

As in most companies dedicated to the manufacture of ceramic tiles, the level of prior automation existing in the facilities undergoing transformation was quite high. Manufacturing lines were completely automated, all tile handling and processing operations were controlled by means of PLCs.

Nevertheless, the degree of existing process control was relatively low. Critical manufacturing variable controls were carried out only at the level of each facility or, in some cases, at the level of specific manufacturing stages. Thus, for example, during the shaping operation, the hydraulic press automatically controlled the maximum pressing pressure in each cycle. However, another critical process variablesuch as bulk density was controlled intermittently by manual actions on the process to try to keep it constant. In addition, most control records were entered manually by annotations on control sheets, without an information flow between the different manufacturing stages or towards higher levels of management.

As the most outstanding point of the methodology used in the manufacturing plant, prior to the beginning of the transformation, of note was solely the existence of a continuous improvement system, based on the LEAN Manufacturing methodology.

5. TRANSFORMATION PROCESS

The different stages through which the digital transformation of the production process was being addressed in the implemented pilot demonstration project are described below.

5.1. HYPERCONNECTIVITY OF THE DIFFERENT PROCESS STAGES

The first tasks carried out in the transformation process consisted of evaluating the degree of connectivity of the different facilities making up the lines of the pilot project. Based on the diagnoses, three possible ways of guaranteeing hyperconnectivity were detected among all the elements in the production chain:

- For the main manufacturing line equipment, such as presses, dryers, kilns or sorting machines, the most appropriate solution, to guarantee hyperconnectivity at higher levels of control, was to contact the corresponding manufacturer in order to carry out the appropriate modifications and/or enable communication ports to facilitate acquisition of the process information generated in each stage.
- The second way of guaranteeing complete hyperconnectivity was through incorporation of external transducers that sent information to data storage elements. Such was the case, for example, of the incorporation of analogue/digital conversion modules in the natural gas meters of the kilns and dryers.
- Finally, the third way to ensure plant interoperability was replacement of the programmable PLCs of the different machines and equipment responsible for tile handling, such as transport lines and machines for loading/unloading tiles on the cars, among others. This was motivated by the low, or even null, degree of connectivity offered by the existing generation of PLCs in the industrial equipment of the pilot project. For this reason, PLCs with remote communication capability were incorporated, which could handle standardised industrial communication protocols. In addition, the system was equipped with a central controller with the ability to manage information from the entire PLC network of the pilot project and store it directly in the relevant databases, without the need to incorporate PCs or intermediate data acquisition systems.

To enable correct data transmission, a new industrial opticalfibre communications network was incorporated that connected the different production sections of the pilot project. In order to guarantee the cyber-security of the transformed industrial environment, this industrial network was designed such that there was only one access point from the external network, at which point information traffic was controlled by a specially dedicated firewall.

5.2. INCORPORATION OF A TRACEABILITY SYSTEM

The ceramic tile manufacturing process does not currently allow tracking of manufactured products by all the internal corporate processes. This is fundamentally due to the fact that, although it might seem otherwise, the process is not really a typical continuous manufacturing process. Indeed, the existence in most factories of an intermediate or buffer zone, in which both unfired tile prior to firing and fired tile prior to final sorting are stored, greatly hinders correct production tracking. This made it necessary to develop a specific system to assuremanufactured product traceability. Among the different possibilities evaluated to track production, the option most adapted to the needs of the ceramic process was identification using two-dimensional DataMatrix (DM) codes on the back of manufactured tiles.

As illustrated in the diagram of figure 1, the system as a whole consisted, on the one hand, of a printhead (1) located at the press exit, which marked the processed tiles with an individualidentifier (2) and, on the other, a series of detection cameras (3) located at points in the manufacturing lines where control of the passing tiles wasdesired.

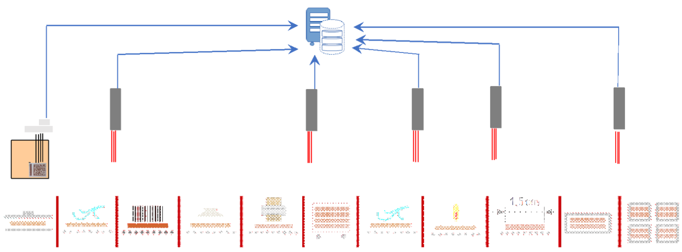

Figure 1. *Scheme of the operation of the developed traceability system.*

The system recorded, in a set of databases (4), the exact moment at which each tile crossed a certain point in the manufacturing line. It was thus subsequentlypossible to determine the process conditions as well as the rest of the operational events taking place at the exact moment at which thetile was processed. To guarantee the integrity of the codings during the thermal treatments to which the tiles were subjected, it was necessary to use ceramic pigment inks that remained fixed to the body during firing. The potentiality of the system was very high. Thus, for example, it would be possible to relate variables such as tile size at the kiln exit, with firing, and/or pressing conditions or tile defects recorded using automatic inspection systemsin real time, tile by tile, with operating conditions or line events.

5.3. INDUSTRIAL INTEGRATION OF INFORMATION

To achieve industrial integration of all data from the plant, a computer server was configured, used exclusively for industrial data management. The Nexus-Integra tool, developed and marketed by CORE Digital Industry, was integrated into this machine. This technological platform is able to integrate production processes in a unified way, on a common basis and in a controlled and secure manner.

The Nexus platform facilitates easy control over the three layers on which data flow is structured in the production area:

- Integration of equipment, sensors, production and field lines, as well as all industrial information sources.
- Optimised storage management and data consultation in real time, in a controlled manner on Big Data services.
- Presentation and business applications in continuous development for data processing, production control and/or process optimisation, offering a complete response to the digital transformation process.

While other possible solutions exist, the Nexus tool waschosen, mainly for three reasons:

- It guarantees excellent flexibility and scalability of the system, so that once deployed in the company environment, any additional element to be incorporated into the system has a common layer to all production assets and business resources, which is a significant saving in terms of development.
- It is an open platform fully manageable by the user, which provides complete independence for integrating desired resources, creatingcustomiseddisplays and consultations and controlling production, facilitating a capacity for continuous adaptation to changes in the industrial ecosystem in which it is implemented.
- It provides complete interoperability free of industrial proprietary exclusivity, which makes it compatible with all existing information systems in the plants (BBDD, ERP, MES, SAP, etc.).

Based on the initial data collected,in view of the hyperconnectivity achieved in the pilot, development of a series of specific modules on the Nexus platform was initiated to adapt its use to the requirements of the ceramic industry. These modules addressed the following issues:

- *Control of production and real time:* quick and easy way to display the reality of the production process in real time, based on the developed traceability system.
- *Energy efficiency:* detailed control of energy consumption, additionally offering a document management system to handle the information required by Standard ISO50001.
- *OEE (Overall Equipment Effectiveness):* detailed control over OEE metrics at each production point, offering detailed analysis regarding the causes of efficiency losses.
- *Alarms and events:* centralised alarm management of all production variables in an integrated manner with real-time and OEE modules.
- *Data Analytics:* use of standard system APIs; this management module enables linking with Machine Learning tools and advanced algorithms.
- *Reports*: simple practical tools to design customised reports based on MS Excel and Power Point, enabling any user to cross reference complex information using standard tools.
- *Business Intelligence and Dashboards:* agile and open system for the management of custom dashboards, enabling graphic display of relevant data and KPIs for the organization.

6. PRINCIPAL RESULTS

Although the transformation process has not yetended at the time of drafting this paper, a number of results may be noted.

6.1. PRODUCTION TRACKING

After a preliminary development stage in the laboratory and on a pilot scale, an industrial traceability system for ceramic tiles was developed, which enabled tile tracking through the different manufacturing stages. Markings on the backs of the tiles with DM codes was carried out using printheads specially adapted for vertical printing. The system, which works with a ceramic ink customarily used in tile decoration, detects the passage of newly pressed bodies, printing anindividual identification code on the rear of each tile (see figure 2).

Figure 2. *From left to right: printhead for tile marking, coded tile and detection camera.*

A first detection camera was located right at the marker exit. In addition to recording the passage of tiles between the pressing and drying stages, the camera enables evaluation of printed code integrity. The system has a retractable mechanism forregular, automatic cleaning of the printhead or when codes with a certain degree of deterioration are detected.

The detection cameras were locatedunder the manufacturing lines, with a compressed air cleaning system installed in zones with the greatest tendency to become dirty. Each camera was connected to the industrial network, so that management of the cameras and of the information generated was carried out from the central server.

6.2. EQUIPMENT INTEROPERABILITY

With the hyperconnectivity of all equipment of the pilot project lines, the ceramic production process was fully digitised, creating a virtual twin, thus having all process information integrated into a single tool for later processing (see figure 3). This integration, together with the information flow generated by the traceability tool, facilitated not only correct assignment of information to specific production batches, but also within the batches themselves.

In addition, a series of additional control devices were also deployed, which enabled generation of key information for process optimisation (see figure 4). Specifically, a non-destructive system for controlling bulk density by X-ray absorption [4] was implemented in the pressing section with automatic control of the pressing operation [5] based on moisture content measurements, and a dimensional control system was set at the kiln exit. The information generated by these devices will be of great help when it comes to incorporating, in the future, Algorithmic Machine Learning into process management.

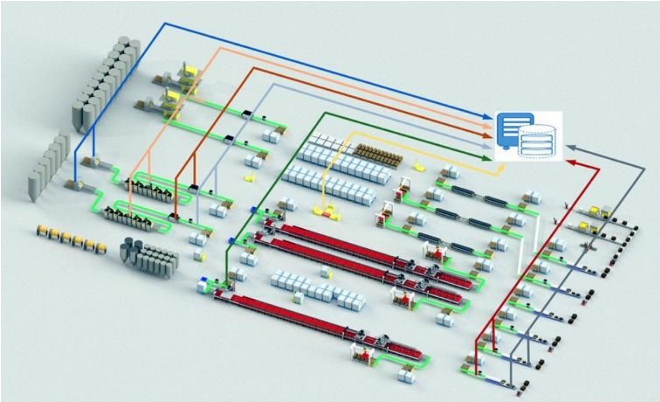

Figure 3. *Diagram showing the degree of interoperability achieved in the demonstration pilot.*

Use of such Big Data analysis is expected to detect situations such as that plotted in figure **5**. Using a unified time scale thanks to the traceability system, these graphsshowthe evolution of average bulk density of the newly pressed bodies of a complete batch (figure **5** left), estimated with the control parameters acquired from the press itself and the constitutive relations of the compacted material. They also show the evolution of tile size at the kiln exit for the same batch (figure **5** right).

Figure 4. *Incorporated control devices. From left to right: Densexplorer® bulk density control, automatic pressing control and dimensional control at the kiln exit.*

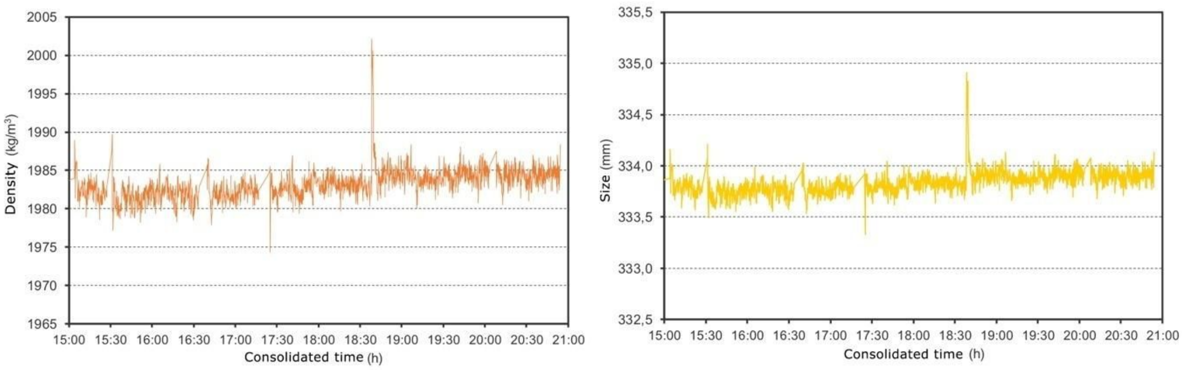

Figure 5. *Left: evolution of bulk density in press. Right: evolution of fired tile size.*

As can be seen, during the 6 hours recorded, bulk density displayed an upward trend that was subsequently reflected in a progressive increase in the final size of the fired tiles. Similarly, the sudden fluctuation of bulk density detected between 18:30 and 19:00 h translated, after firing, into a significant change in fired tile size. The idea is to progressively acquire large amounts of data from the process, once these have been consolidated thanks to the traceability system, establish process analysis models that enable prediction of future situations and act to correct them in real time. The prediction of firedtile size is paradigmatic, given the special incidence of "calibre" defects in the final product; however, these same tools may be used to evaluate the effect of processing conditions on other relevant parameters such as defects detected by inspection machines, product curvatures at the kiln exit, energy consumption or product manufacturing costs.

6.3. DEVELOPMENT OF MANAGEMENT MODULES ADAPTED TO THE CERAMIC ENVIRONMENT

Finally, to adapt the modules of the Nexus integration system to the needs of the ceramic process, identification of all variables and parameters requiring measurement and/or controlled in each process stage was carried out. By way of example, the analysis performed for the shaping and drying of tile bodies is described below.

Table 1 shows the minimum information considered necessary to carry out correct management of these operations in a tile manufacturing plant. The information is grouped in terms of four fields: productionefficiencies, process variables, consumption of resources and variable costs.

Information	PRESS	DRYER
PRODUCTION EFFICIENCY	Availability (D) = Production time / Available time (%)	
	Efficiency (R) = Actual production / Theoretical production (%)	
	Quality (C) = Good tiles / Tiles produced (%)	
	OEE = D x R x C (%)	
PRODUCTION VARIABLES	Moisture content (%)	Exit temperature (ºC)
	Bulk density (kg/m^3)	Maximum temperature (ºC)
RESOURCE CONSUMPTION	Powder consumption (kg)	Gas consumption (kcal/m^2)
		Electricity consumption (kw h/m^2)
	Electricity consumption (kw h/m^2)	CO_2 emissions (kg/m^2)
VARIABLE COSTS	Cost of spray-dried powder (€/m^2)	Cost of thermal energy (€/m^2)
	Cost of electrical energy (€/m^2)	Cost of electrical energy (€/m^2)

Table 1.*Minimum information required for pressing and drying operationsmanagement.*

To obtain this information, it is essential to have the directly measurable variables indicated in table 2 and the non-measurable variables reflected in table 3. In both tables, together with the variables, it is shown how they can be obtained. Combining these variables with, on the one hand, real-time knowledge of the start/stop and/or alarm conditions of the facilities and, on the other hand, with the information generated by the traceability system, allows precise determination in real-time of the management information reflected in table 1.

Stage	Variable measured	Sensor used
Pressing	Rows pressed	Provided by press
	Moisture content	Infrared sensors
	Electricity consumption	Electricity meter
	Good tiles	Traceability system
Drying	Good tiles	Traceability system
	Electricity consumption	Electricity meter
	Natural gas volume consumed	Natural gasflow rate meter

Table 2. *Required measurable variables for shaping and drying operationsmanagement.*

Correct storage in databases used by the Nexus system of all management information indicated in table 1 will enable a posteriori analysis of specific production batches, thanks to the traceability achieved with the system developed. Indeed, from the first moment in which tiles assigned to a specific production order are manufactured, thanks to the traceability achieved with the coding system, the information generated will be perfectly indexed and referenced to this production order. This will enable perfect real-time monitoring of the production process as well as easy segmentation of information for subsequent processing using Big Data analysis tools.

Further Information	Ref.	Information associated with additional information	Location non-measurable information	Calculated variable
Dieoutput	N	-	Press	Efficiency Quality OEE
				Powder consumption
Press speed	G	-	Press / Moisture content sensor	Efficiency Quality OEE
				Powder consumption
Article reference or Manufacturing Order	S	Size (mm x mm)	Article database	Efficiency Quality OEE
	M	Specific weight (kg/tile)	Article database	Powder consumption
Cost of powder (€/kg)	C_{at}	-	ERP	Cost of powder
Lower heating value (J/Nm^3)	PCI	-	ERP	Cost of thermal energy
Higher heating value (J/Nm^3)	PCS	-	ERP	Cost of thermal energy
Cost of thermal energy (€/J)	C_{et}	-	ERP	Cost of thermal energy
Cost of electrical energy (€/Kw h)	C_{ee}	-	ERP	Cost of electrical energy
Natural gas emission factor (kg CO_2/J)	FE	-	ERP	CO_2 emissions

Table 3. *Required non-measurable variables for shaping and drying operationsmanagement.*

7. CONCLUSIONS

- The ceramic tile manufacturing industry has manufacturing processes with levels of automation mature enough to address digital transformation towards Industry 4.0. without excessive cost.
- It has been shown that it is possible to achieve hyperconnectivity of the different production elements in a ceramic tile manufacturing plant.
- A traceability system has been developed and validated under industrial conditions that assures the flow of information throughout the entire production process.
- Management modules specially adapted to the ceramic industry are being developed for complete integration of industrial information under the Nexus tool.

8. ACKNOWLEDGEMENTS

The authors of this work would like to thank the Instituto Valenciano de Competitividad Empresarial (IVACE) for the financial support provided, through the European Regional Development Fund (ERDF), to carry out this research through the grant program for Technology Centres of the Valencian Community for the development of R&D projects and the INNOVA i4.0-CV program.

9. REFERENCES

[1] Kagermann, H.; Wahlster; W.; Helberg, J. Recommendations for implementing the strategic initiative Industrie 4.0: Final report of the Industrie 4.0 working group, 2013.

[2] Hermann, M.; Pentek, T.; Otto, B., Design principles for Industrie 4.0 scenarios: a literature review, 2015.

[3] Mallol, G. Control y automatización en la industria cerámica. Evolución y perspectivas. *Cerámica Información,* 347, 63-80, 2007

[4] Amorós J.L.; Boix, J.; Llorens, D.; Mallol, G.; Fuentes, I.; Feliu, C. Non-destructive measurement of bulk density distribution in large-sized ceramic tiles, J. Eur. Ceram. Soc. 30 (2010) 2927-2936.

[5] Amorós, J.L.; Mallol, J.G.; Mezquita, A.; Llorens, D.; Castro-Lopes, F.; Cerisuelo, J.A.; Vargas, M. Mejora de la estabilidad dimensional de piezas de gres porcelánico a través de la medida en continuo de la humedad de los soportes prensados. *Cerámica Información,* 311, 117-126, 2004