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Asociación Española de Fabricantes de Maquinaria y Bienes de Equipo para la Industria Cerámica

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Asebec 4.0 Guide

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Business digitalisation is the foundation for growth of our industrial fabric and for interconnection between every stage in the value chain, from the production process to sales and users. It is a path that needs to be travelled and implemented as soon as possible in order not to fall behind in an increasingly complex and volatile global scenario, with growing uncertainties.

At the moment of writing these introductory lines to the ASEBEC 4.0 Guide, it is necessary to bear in mind the serious economic crisis that we are suffering as a result of the SARS-CoV-2 pandemic, which has changed our lives and made it necessary to speed up the development and implementation of certain processes and technologies that had not been sufficiently implemented.

The Regional Authority for Sustainable Economy, Production Sectors, Commerce and Labour of the Autonomous Government of Valencia (GVA) and, in particular, the Valencian Institute for Business Competitiveness (IVACE) are firmly and steadfastly committed to the development of a ceramic sector pioneering the implementation of strategy 4.0 and incorporation of the so-called 4th industrial revolution in its activity. We therefore congratulate the Spanish Association of Ceramic Machinery and Capital Goods Manufacturers (ASEBEC) and the Institute of Ceramic Technology (ITC) for this joint initiative, which will facilitate technology transfer of high added value to every one of the manufacturing process stages in ceramics plants, in addition to their interconnection, so that the machinery manufacturers themselves will assist tile manufacturing companies is making this essential leap.

It is time to do so and IVACE has not hesitated in responding to this vital need for the development of the ceramic industry, to enable it to continue to be a global benchmark in innovation also through the implementation of these new technologies, which lay the groundwork for the next industrial revolution.

Júlia Company Sanus
Director of the Valencian Institute for Business Competitiveness (IVACE).
Regional Authority for Sustainable Economy, Production Sectors, Commerce and Labour. GVA.

As president of the Spanish Association of Ceramic Machinery and Capital Goods Manufacturers (ASEBEC), it is incumbent upon me to introduce the reading of this ASEBEC 4.0 GUIDE we have developed thanks to the support of the Valencian Institute for Business Competitiveness (IVACE) through the European Regional Development Fund (ERDF) with the help of the Institute of Ceramic Technology (ITC), a pioneering centre in implementing the 4.0 strategy in the ceramic industry. With this Guide, the machinery manufacturers for the ceramic industry seek to place at the disposal of ceramic tile manufacturing companies an instrument that will help them digitalise their plants and interconnect the different manufacturing process stages.

We find ourselves before a fast-changing global outlook, which has more than ever evidenced the importance of implementing innovative technologies such as the Internet of Things (IoT), Artificial Intelligence, Big Data, the Digital Twin, and others, set out in this Guide that also explains how they can be implemented. We know time flies and we now need to move forward with this new stage that sets a milestone in ceramic industrialisation. We are already heading towards it and, in fact, the latest ITC market survey in which ASEBEC member companies were polled revealed that 38% of these companies were investing or intended to invest in driving and developing the adoption of Industry 4.0.

It remains for me to thank both IVACE and ITC for their support and work, while I invite the industry to join us as rapidly as possible in putting into practice everything this tool, the ASEBEC 4.0 GUIDE, is offering them.

Juan Vicente Bono
President of the Spanish Association of Ceramic Machinery and Capital Goods Manufacturers

Index

Chapter 4

Chapter 5

Chapter 6

References

Annex

Chapter 1.
Introduction

Industry 4.0 or Connected Industry, as it is also known in Spain, is a concept whose authorship is still being debated, even today. Certain authors state that it was first coined in 2011 at the Hannover Trade Fair, where the Communication Promoters Group of the Industry–Science Research Alliance presented its vision of the industry of the future, describing the increasingly widespread integration of information and communications technologies into industrial production [1]. Other authors claim that several economic study groups began to use the term in 2013 [2] in reference to the emerging change in industry. Some documents also assert that the German government itself [3] put forward the name while concurrently defining an ambitious back-up programme aimed at strengthening German industry, which felt its leading position in the field of industrial automation was beginning to be threatened by the power of emerging economies. In any event, it is clear that the term "4.0" signals the potentially revolutionary impact of current industrial trends, which will undoubtedly involve a sequel to the three previous industrial revolutions.

1.1 What is Industry 4.0?

Industry 4.0, in numerous contexts termed the fourth industrial revolution, has become possible owing to a series of actions or events that have lately been developing in industry, enabling it to move towards the present configuration. Unlike the three previous industrial revolutions, the fourth industrial revolution is not being described from a historical viewpoint but is being interpreted as it unfolds (**see Figure 1.1**).

A look back shows that, starting with the first industrial revolution, stemming from the mechanisation of production equipment by the introduction of the steam machine, numerous advances have enabled improvement of production capacities and operating conditions in industrial manufacturing. The second industrial revolution, marked by electrification of production means, involved the appearance of assembly lines and thereby the beginning of mass production and development of new materials and forms of transport. Finally, the third industrial revolution took place in the 1970s with the incorporation of computer systems and control electronics, which enabled operations and repetitive tasks to be automated.

At present, manufacturers, particularly in Europe and the U.S.A., face increasingly competitive markets. In a highly complex, globalised and dynamic environment, decisions must be made correctly and as quickly as possible to maintain long-term competitiveness. Unfortunately, current corporate operations management is unable to address this challenge successfully, which can sometimes put at risk control of a company's core business. Indeed, decision making can often involve latencies of weeks or months and decisions are practically always based on intuitive feelings, rather than analysis of detailed information.

Thus, for example, product development processes often establish product specifications without prior detailed analysis of a client's requirements. On other occasions, when a company has mastered a new procedure or technique, it is very difficult to make great changes in development or manufacturing processes, such changes also being very costly in resources and time. And many employees and managers typically devote much of their time looking and/or waiting for the right information for decision making. These are just some examples that illustrate the greatest current shortcomings in industry and the potential for wide-ranging transformation, such as that being sparked by the fourth industrial revolution.

Industry 4.0 is also known as Connected Industry in Spain, owing to the strategic initiative under the same name, promoted by the Ministry of Economy, Industry, and Competitiveness in line with the Agenda for Strengthening the Industrial Sector in Spain (2014) [4]. Industry 4.0's economic potential stems from its ability to accelerate corporate decision making and to adapt organisation internal processes to changes in the environment. This applies both to efficiency enhancement processes in different corporate areas (engineering, manufacturing operations, services, sales and marketing) and to business models in general.

Thus, Industry 4.0 may be defined as "a digital transformation process of industry, which will enable multilateral communication and interconnectivity between cyber-physical systems and individuals by handling large volumes of data in real time". The availability of large amounts of data and information, at accessible prices and in real time, facilitates better understanding of the relationships between different events that could affect the processes, laying the groundwork for faster decision making.

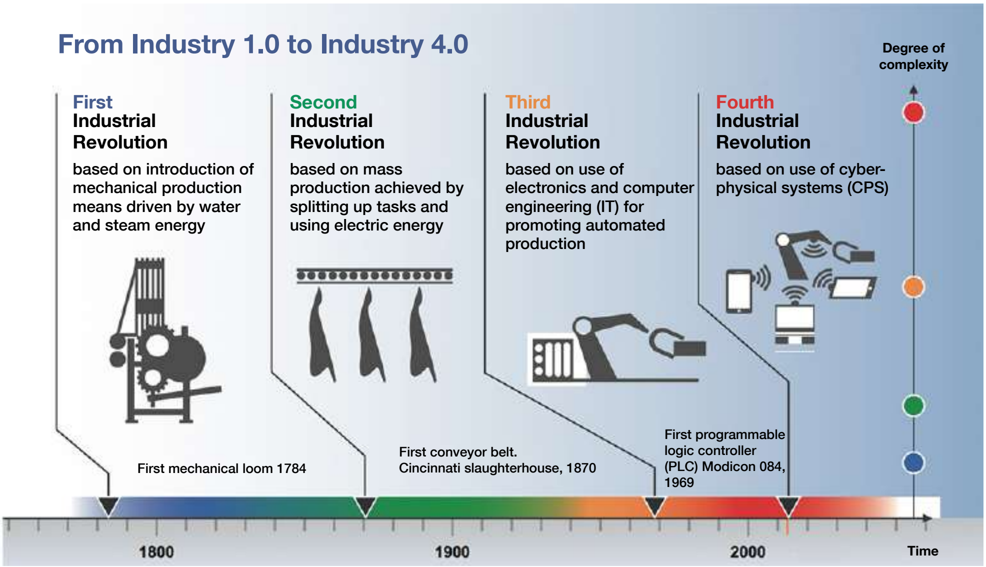


Figure 1.1. Industrial revolutions throughout history (source: http:/nctech.com.mx).

Backed by an appropriate organisational structure, Industry 4.0 allows companies to react with greater agility in increasingly dynamic markets, reducing development times of products more closely matching customer needs and putting these products on the markets in an exponentially faster way. The interconnection of the technological components, but above all of their organisational structure, enables companies to acquire key agility for the transformation associated with Industry 4.0.

Agility is a strategic characteristic, which has become increasingly important to business success. In the current context, company agility refers to its ability to implement changes in real time in its internal processes, including systematic changes in its business models.

Faced with events that can lead to changes in their operations or business models, companies must adapt to maintain their competitiveness (**see Figure 1.2**). The faster an organisation adapts to such events, the greater the resulting benefit from that required adaptation and, hence, the greater the organisation's competitive edge. These events may be of multiple natures and have different impacts on company business. Thus, for example, a short-term event would be involved in the case of a breakdown in a manufacturing line. In contrast, modifications in the requirements of the products made and hence in their design, manufacturing process, and related supply processes, quality, and services, would involve mid- to long-term events.

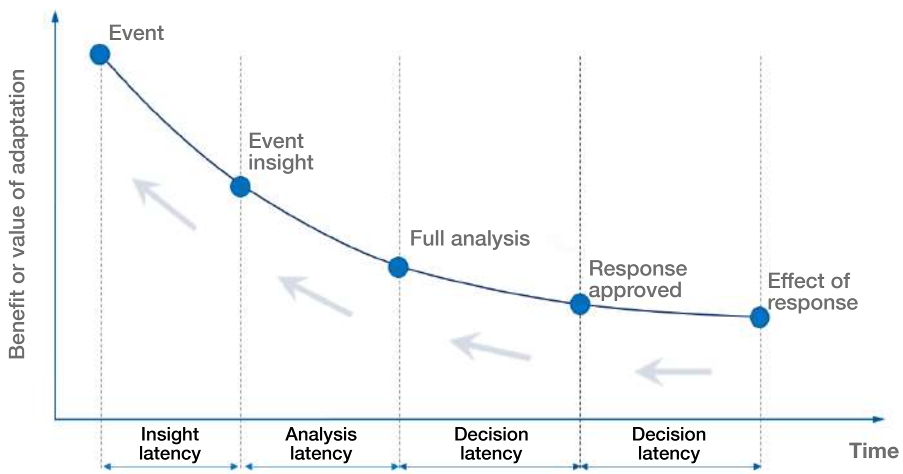


Figure 1.2 Adaptation process versus changes in the environment (source: based on Hackathom 2002; Muehlen/ Shapiro 2010)

Today, when an event occurs, from the moment it happens there are inevitably a series of delays in event detection, analysis, and the application of the relevant adaptation measures. The main reason for such delays is that the relevant information is not sufficiently integrated to allow full processing from beginning to end, from data collection to data analysis.

The capabilities of Industry 4.0 can help manufacturers drastically reduce the time elapsing from the occurrence of an event to the implementation of the corresponding corrective measures (**see Figure 1.3**). To do so, a series of enabling technologies must be deployed and the relevant information must be made accessible, eliminating so-called "information islands". New approaches must concurrently be incorporated into the corporate structure and organisational culture in order to prepare for the continuous changes associated with transformation.

All these apparently distant concepts are at present already being designed and tested in different industrial sectors. For example, there are standalone machines that report information in real time on their states of operation, information that can be processed and analysed to pre-empt failures or breakdowns and to anticipate them, reducing response times and improving the efficiency of facilities. It is also possible accurately to determine production profitability of a given product and which stages are most critical in its manufacturing process.

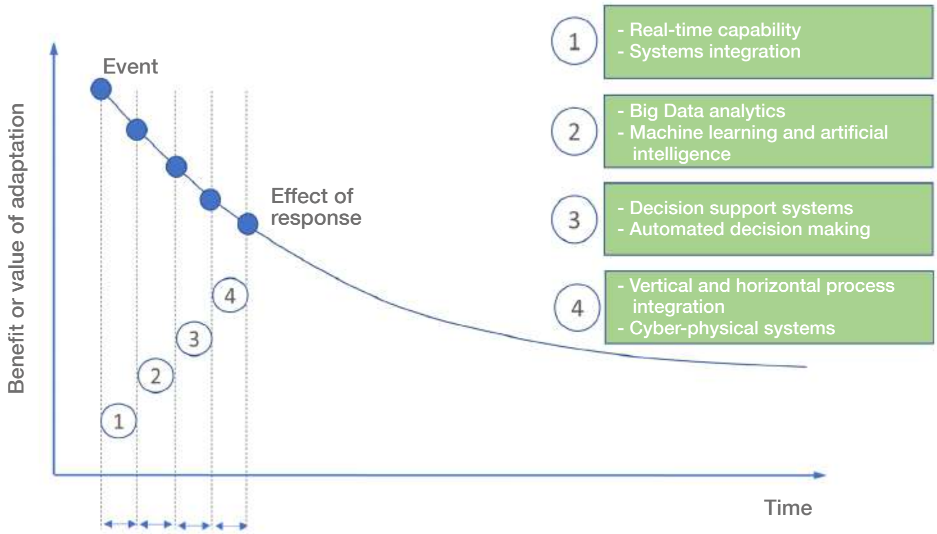


Figure 1.3. Increased benefit associated with an adaptation thanks to organisational learning provided by Industry 4.0. (source: based on FIR e.V. at RWTH Aachen University).

Or similarly, it can be ascertained, in a simple fashion, whether the organisation of production resources is suitably adapted to the production needs of a given article or whether a given energy cost is justified or could be optimised. Although these simple examples illustrate the possibilities that the ongoing transformation is at present providing, the measures implemented in many companies are limited to pilot projects that often only entail technological validation actions. In fact, according to Henning Kagermann, president of Acatech, *"the hesitant implementation of Industry 4.0 is due to rigid organisational structures that have developed organically and to a conservative culture in which people lack the courage to do things differently."* [5] This is why the technological transformation process related to Industry 4.0 must be accompanied by a cultural change in organisations to assure adaptation to the new paradigm.

The ultimate aim of the transformation towards Industry 4.0 is the creation of agile, knowledge-based companies that are able to adapt to the changing conditions of their environment thanks to the use of enabling technologies, the learning capability of the organisation itself, and the use of rapid decision-making processes that can use available quality data.

1.2 Transformation Process towards Ceramic Industry 4.0

As set out above, the current trend in industrial production processes is to have agile and flexible systems that quickly respond to the constant changes and alterations in production environments. Process industries in general need to be able to respond to the demands of current markets and supply chains, so that the trends towards customisation, rapid response times, shorter product life cycles, and efficient use of energy and resources are obliging them to consider aspects such as flexibility, agility in reconfiguration, decentralisation, and supplier integration.

As in other manufacturing sectors, the ceramic industry also faces this type of challenge in order to achieve a degree of control of production, supervision and management of systems that enables the need for flexibility and rapid response of manufacturing processes to be addressed. In today's ceramic plant, it is almost impossible to find advanced control systems such as continuous measurement systems that provide information on the development of the operation in real time, or alarm systems that warn of any deviation from the fixed settings variables. Although the ceramic manufacturing process appears to be automated, only product handling and some isolated stages are actually automated, moreover without information flowing in a reasonable and agile way between them. The information managed is manual, discontinuous, relatively unprocessed, delayed in time relative to actual production, and often not analysed owing to distrust of its validity.

Indeed, this lack of information on the production process prevents proper, continuous production traceability in real time, which would allow accurate determination of such important aspects, for example, as a ceramic tile's real manufacturing cost, the efficiency of a system in the production process, or energy consumption in producing a tile batch. All this, without forgetting that appropriate use of the information generated in the production process would allow advanced business models to be implemented to enhance business competitiveness.

The latest process control models focus on the concept of hierarchic control introduced by the Max Planck Institute. According to this theory, in any conventional industry, six hierarchised levels of control may be defined. In a current ceramic plant, the levels determined are machine safety (level 0), part of levels 1, 2, and 3, corresponding to the use of sensors and actuators (level 1), basic control (level 2), and development of operator interfaces and control supervision (level 3). Levels 4 and 5, corresponding to comprehensive plant management, advanced control, business planning and logistics in connection with the process often have yet to be developed.

Corporate digital transformation is currently being addressed by different approaches, often structured on the basis of each country's own initiatives. In Spain, the Connected Industry 4.0 initiative establishes a conceptual framework for Industry 4.0, whose application allows a series of challenges involved in the digitalisation of society and industry to be addressed. The purpose is to generate opportunities for industrial sectors that will enable them to adapt their business models, processes, infrastructures, and organisation to the new socio-economic circumstances.

Companies that successfully address the challenges at issue (**see Figure 1.4**) contribute to generating an industrial model in which innovation is collaborative, productive means are connected and completely flexible, supply chains are integrated, and distribution channels and customer service are digital. At the same time, this model facilitates smart, customised product management, and allows generation of new business models.

The conceptual framework promoted by the Connected Industry 4.0 initiative (**see Figure 1.5**) reflects what an SME that has been transformed into an Industry 4.0 organisation will look like and how it will operate in a time horizon of 5 years, envisaging five specific dimensions:

- Business and market strategy
- Processes
- Organisation and People
- Infrastructures
- Products and services

		From…	To…
1	Using collaborative methods for fostering innovation	… individual and same-line innovation approach	… innovation involving several companies and customers and being disruptive
2	Combining flexibility and efficiency in production means	… not always efficient and not very flexible production means	… efficient, flexible, and smart production means
3	Managing shorter production runs and faster response times	… mass production with long response times	… ever shorter production runs and times
4	Adopting smart logistic models	… reactive logistics management	… integrated and smart logistics management
5	Adapting to canal transformation (digitalisation and omnichannel approach)	… traditional unconnected channels	… channel digitalisation and omnichannel management
6	Using information to anticipate customer needs	… reactivity to demand	… predictive analysis of customer needs
7	Adapting to customer hyperconnectivity	… limited and poorly disseminated information	… detailed value information
8	Managing end to end multidimensional traceability	… little or no monitoring and visibility of product processing	… transparency in multidimensional traceability of the entire production process
9	Managing specialisation by coordinating industrial value ecosystems	… linear value chains	… specialisation and value ecosystems
10	Assuring long-term sustainability	… little sensitivity to sustainability	… minimised environmental impact of production process and product
11	Offering personalised products	… standard products	… product mass personalisation
12	Adapting the product portfolio to the digital world	… traditional industrial product	… digital evolution of the product portfolio

Figure 1.4. Challenges stemming from the digitalisation of society and the industrial environment (source: The digital transformation of Spanish industry. Preliminary report).. [6]

Figure 1.5. Industry 4.0 conceptual framework according to the Connected Industry 4.0 initiative (source: Self-diagnosis tool HADA.).

Industry 4.0 tools and concepts, which duly applied allow development of agile companies aware of the change, are relatively simple to apply in implementing new business models, companies, or production processes. In contrast, in well-established companies with a consolidated business model and markets to attend to, the transformation towards Industry 4.0 needs to be gradual and well planned. Such is the case of most ceramic tile manufacturers and spray-dried powder and frit and glaze producers, both in the Spanish ceramic cluster and in other countries worldwide.

The conceptual framework defined by the Connected Industry 4.0 initiative focuses on comprehensive corporate transformation, particularly of SMES. However, in order to illustrate the transformation process towards Ceramic industry 4.0, particularly in the manufacturing process in which the members of the Spanish Association of Ceramic Machinery and Capital Goods Manufacturers (ASEBEC) are technology leaders, this Guide has preferred to follow the model set by the German Academy of Science and Engineering (Acatech) (**Figure 1.6**). The approach introduced by its conceptual model is based on a succession of different states of maturity, which define a series of development levels that may serve as a guide for companies during their transformation process, from Industry 4.0 basic requirements to full implementation.

As noted above, introducing Industry 4.0 in any industrial sector, generally, and in the ceramic tile manufacturing sector, in particular, requires significant adjustment of the competencies and digital capabilities of a company and the introduction of changes in its organisational structure.

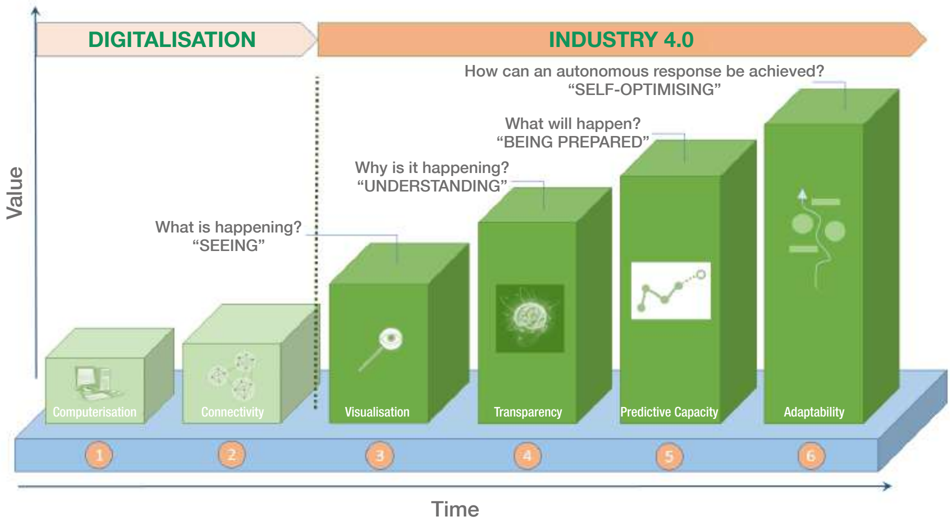


Figure 1.6. Industry 4.0 development and implementation stages (source: based on FIR e.V. at RWTH Aachen University).

As in-depth corporate transformation is involved, this needs to be carried out over several years. In addition, it is very useful to plan and implement the transformation so as to enable observation of the positive impacts on the organisation, regarding both improved efficiency and growth, in the different states of the transformation process. This approach enables the benefits of the transformation to become visible in the different stages, providing an indicator for monitoring the overall success of the actions.

The corporate transformation strategy needs to be carried out according to a progressive approach that begins with the basic requirements for Industry 4.0 and serves as a basis for an agile company with self-learning capability. This progressive approach is structured in 6 levels of development. Each stands on the preceding level and describes the capabilities that organisations need to have to achieve it and the benefits resulting from it.

At present, numerous businesses are still facing the challenge of creating the basic conditions to enable commencement of their transformation towards Industry 4.0. This means that they are still in a digitalisation state. Although digitalisation is not, of itself, part of Industry 4.0, computerisation and connectivity are basic stages or requirements for its implementation. These two initial stages are followed by four others, in which the actual transformation capabilities towards Industry 4.0. are developed (**Figure 1.6**)

1.2.1 First stage: Computerisation

Ceramic companies exhibit quite an advanced degree of computerisation, PCs being used to perform repetitive tasks, providing very important benefits for the companies. Thus, for example, computerisation of ceramic design and digital printing have enabled manufacture of relatively economic ceramic products with very high levels of quality and degrees of accuracy, which would have been unattainable with other technologies. However, it is also true that the manufacturing process still contains a significant amount of machinery with very limited or even no digital interfaces. Computerisation is thus urgently required in equipment with longer service life or in production elements only charged with handling and moving products.

An example of the need to raise the level of computerisation in the ceramic tile industry might be the line for forming, drying, and decorating ceramic tile bodies. Although repetitive operations are carried out with a high degree of accuracy and automation in each part of this line, in most cases thanks to the use of computer control systems, at present the information regarding the work “recipe” and/or manufacturing order needs to be transferred manually to the relevant facilities, i.e. the machines are not connected. Thus, a first step in the transformation process of the ceramic tile industry would involve elimination of paper work slips, replacing these with an information management system that processed the information currently recorded on those slips in a fully digitalised way.

Another more general example might be business and/or management applications not connected with a company's ERP systems. This could readily lead to situations in which the quality controls of a quality assurance system are generating data that are incorrectly related to manufacturing orders or to article references, which then make it difficult to obtain accurate business operation results.

1.2.2 Second stage: Connectivity

In the connectivity stage, isolated computer system deployments are replaced with or incorporated into connected components or systems. Most business applications used by ceramic firms are interconnected, thus mirroring in a centralised form the core of their business processes. In contrast, at production process level, this connectivity is much more restricted and the different manufacturing stages are information islands that do not share information with each other. Most operation technologies currently running at ceramic plants provide connectivity and a certain degree of interoperability, but integration of computer systems and operation technologies has yet to take place.

The Internet Protocol (IP) is being ever more widely used in ceramic companies, even at production plant level. As the current version of the IPv6 protocol allows a much large number of network addresses than its IPv4 predecessor, all production system components can be connected without requiring network address translations (NAT, Network Address Translation), critical for the so-called Internet of Things (IoT) [7].

Achieving the connectivity state in a ceramic plant would mean, for example, that when a design has been created and validated, the relevant data on the design would be sent to production so that, after these had been complemented with the data corresponding to the article and the needs, the production stages would be carried out to meet a certain manufacturing order. During the production process, upon completion of each stage, confirmation of conclusion would be generated and sent automatically in real time through a manufacturing execution system (MES). Similarly, connectivity would allow remote assistance service of the machines and equipment at customer facilities, thanks to the availability of high-bandwidth connections at reasonable prices (**see Figure 1.7**).

It may be noted that, just as in other industrial sectors, in the ceramic tile sector it is common to find industrial assets that remain in production as long as they are able to make products exhibiting the qualities demanded by the market. Thus, equipment that has been running for over 25 years can readily be found in the plants, this being equipment whose productivity remains high for certain products, but which has limited connectivity. At present, however, thanks to the connectivity provided by the IP and to sensorisation, production data from these industrial assets can be obtained quite simply.

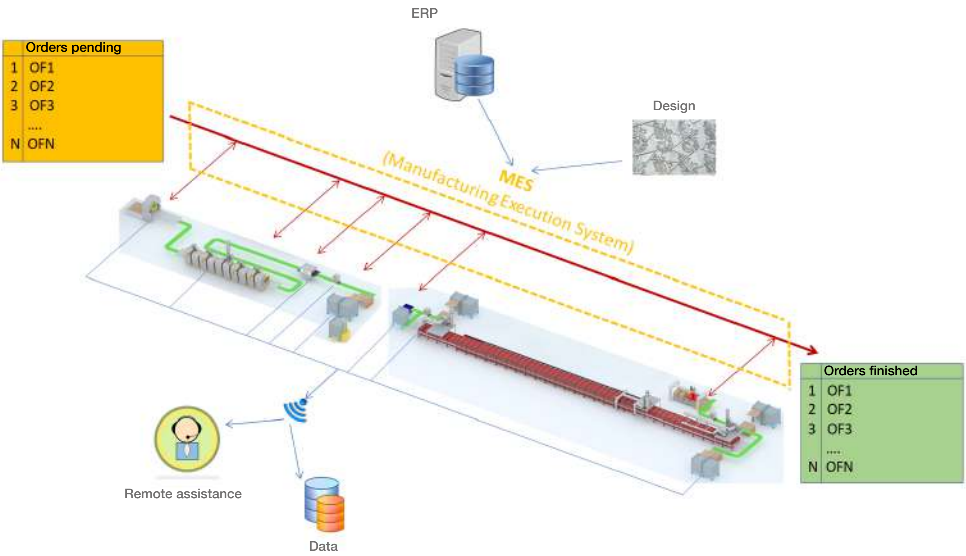


Figure 1.7. Plant-level connectivity in the ceramic tile manufacturing process.

1.2.3 Third stage: Visualisation

The current degree of sensorisation of industrial processes allows data to be collected from beginning to end with a great number of acquisition points. In addition, the available technologies enable real-time recording of all production process events and states, far beyond the collection of a few process variables in certain production stages, as done to date. This enables always having an updated digital model of the factory, customarily known as a digital twin or digital shadow (**Figure 1.8**). This digital twin helps determine what is happening in real time, either in the production process or in the company, if the digital twin reaches into all areas of the company. The interest in having a digital twin lies in being able to manage decisions based on information generated from real data.

The attainment of a digital twin[8] in a ceramic company is a great challenge, fundamentally because information is decentralised in different data islands, in many cases there not being just one valid source. In addition, particularly in manufacturing and logistics processes, the amount of information is often limited and visualisation is restricted to a certain number of employees that are allowed to access the information or understand the systems in which it is stored. Such would be the case, for example, of the process variables relating to the pressing operations, which lie inside the machine itself and can only be consulted at the machine by the operators and workers in the forming section. That is to say, in a certain sense, widespread use of the information in the companies is not possible owing to the system's own boundary constraints. However, to move towards becoming an agile company, it is essential for companies to comprehensively collect data, this being critical to generating significant information regarding plant and business operations.

For example, an appropriate degree of visualisation would allow more accurate definition of delivery times and determination of how these are affected by a particular problem thanks to the use of real-time indicators and reports. The use of this information would, in turn, enable production heads to adjust planning, and customers and suppliers could thus be informed of the arising changes.

The attainment of this third level, which involves the start of the transformation towards Industry 4.0, undoubtedly requires a change in corporate mentality [9]. Beyond simply collecting data for a certain analysis or for backing up performance of certain operations, data need to enable creation at all times of an updated model of the manufacturing process or, in the best of cases, of the entire business, which is not tied to the individual analysis of particular data.

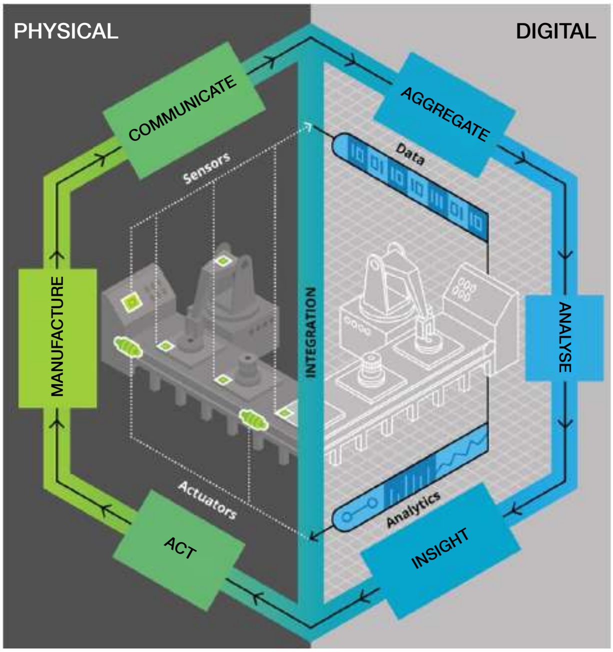


Figure 1.8. Integration of the digital twin and the physical world (source: Deloitte University Press).

For a ceramic company, the combination of current information sources, with the data provided by new sensors installed in plant and the integration of ERP and MES systems will provide a comprehensive image of the state of operations and make the company's situation visible. This integration, together with the use of modular applications and mobile applications, will contribute to the attainment of a single information source for operations management.

1.2.4 Fourth stage: Transparency

As set out above, attainment of the third stage in the transformation process involves having a digital twin that mirrors the state of the company at all times. The following stage entails using this twin to understand why given events occur and to use this process to generate insight based on casuistic analysis. With a view to identifying and interpreting interactions in the digital twin itself, the data collected needs to be analysed by applying process engineering tools and techniques. Data exploitation, aimed at adding information and the corresponding contextualisation in the industrial ecosystem, provides the required insight into the process for quick and effective decision making, including when such decisions exhibit a high degree of complexity.

In this sense, the new enabling technologies that allow analysis of large volumes of data can be of great help. In fact, Big Data is a very topical term, frequently used in these contexts, referring to large amounts of data that cannot be processed and analysed by conventional tools for analysing business processes. Thus, the term Big Data is also used to refer to the technologies and applications that allow exploitation of these large amounts of customarily heterogeneous data.

Generally, Big Data applications typically run parallel to business management applications such as ERPs or MES. They thus provide a common platform on which, for example, to carry out statistical analyses that reveal interactions between the events and incidents mirrored in the digital twin.

The transparency achieved in the fourth level of the transformation can be used for advanced monitoring of the operating conditions of the equipment and machines in a plant. The parameters collected of an apparatus can be continuously analysed in pursuit of relationships and dependencies, relative both to the parameters of other apparatuses and to resulting product quality. This is aimed at generating aggregate information that accurately reflects the operating conditions of the industrial assets and constitutes the basis for preventive maintenance actions (**see scheme in Figure 1.9**).

Given the special quality and aesthetic finish requirements demanded of ceramic products, at a tile manufacturer, the level of transparency of the manufacturing process will particularly focus on establishing and ascertaining the relationships between process variables and end-product properties. Although these relationships have been known for years, real time analysis of these relationships under industrial manufacturing conditions has never been carried out. Thus, for example, though bulk density of freshly pressed tile bodies is known to affect the end size of vitrified products, current transparency in the process does not allow a direct relationship between those two variables to be established upon completion of a production batch. Something similar occurs with other process variables. By way of example, one might mention the relationship between spray-dried powder moisture content and tile bulk density, the relationship between tile curvature at the kiln exit and firing conditions, or the influence of firing conditions and/or glaze application on product shade.

To achieve the transparency that assures accurate knowledge of the relationships between the critical variables of the ceramic manufacturing process, it is essential to have a suitably traced process. On assuring product traceability, unequivocal relationships can be established between product properties (shade, size, curvature, defects, etc.) and product travel through the different manufacturing stages. It is otherwise very difficult to establish causality relationships between the different events occurring in the various production stages on not knowing for sure, how these have affected the product made. By way of example of the attainable degree of transparency in the ceramic process it may be noted that, if a traceability per unit product is available, it is even possible to relate defects detected in particular tiles by the artificial vision units to tile processing conditions and/or the operational state of the equipment.

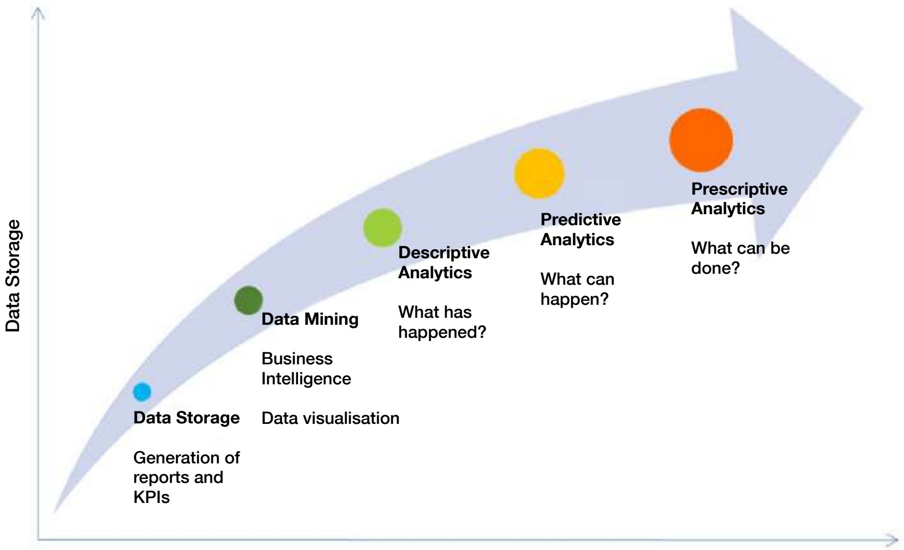


Figure 1.9. Usefulness of Big Data analysis techniques in the context of the transformation towards Industry 4.0.

1.2.5 Fifth stage: Predictive capability

The tools implemented in the introduction of the transparency stage enable development of the following level by providing the different company processes, particularly the production process, with predictive capability. On reaching the milestones relating to this fifth level, the company is able to simulate different future scenarios and to choose the most interesting ones. This involves projecting the digital twin into the future (see Figure 1.10), with a view to predicting a series of possible scenarios, which will be prioritised after evaluating their likelihood of occurrence. Such predictions enable companies to anticipate possible events, speeding up their decision-making processes and the implementation of corrective measures.

Although the action measures against events and unforeseen incidents are still carried out manually in this stage, the greater agility achieved in decision making provides a substantial improvement in execution times, ranging from the design and/or planning stages to dispatch of the end product. In addition, the anticipation contributed by predictive capability and the reduction in unexpected events, such as production stoppages or changes in planning, contribute enormously to improving the robustness of plant operations and hence of business in general. One example might be the case of prediction of a serious breakdown, such as the failure of a hydraulic press pressure multiplier, whose anticipated replacement or repair could be much less onerous for the company than the unexpected shutdown of a manufacturing line for several days.

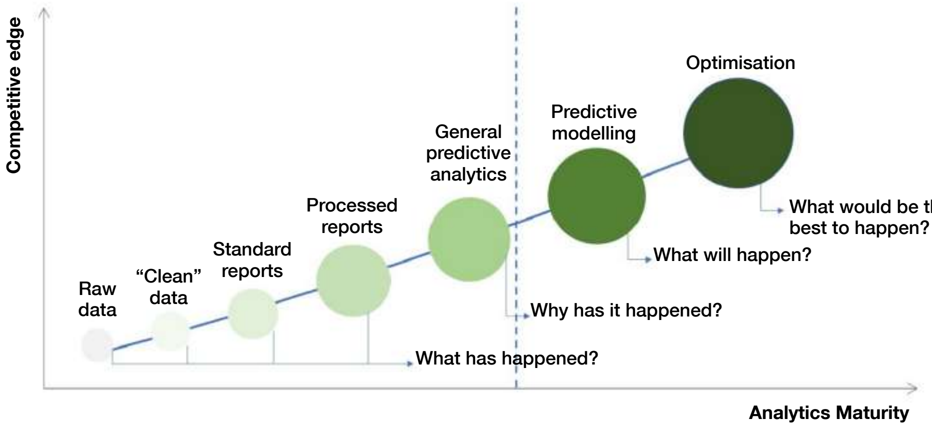


Figure 1.10. Connection between transparency (sensorisation and response) and predictive capability (prediction and action) stages by projecting the data acquired in the digital twin into the future.

The case of predictive maintenance (see Figure 1.11) is the most widely used example to refer to the predictive capability stage in the transformation process towards Industry 4.0. However, predictive capability needs to extend to every corporate context and, in the ceramic sector, particularly to manufacturing process areas. Indeed, multiple unexpected incidents currently occur in the usual course of in-plant operations, involving incidents which could have been detected or anticipated beforehand by implementing appropriate predictive capabilities. A case in point, for example, is the problem of small colour differences, which could be studied from the standpoint of predictive analytics, as real-time analysis of process data relating to product decoration and processing, based on models defined in the transparency stage, could anticipate the deviation of colour properties in the end product.

It may be noted that a company's degree of predictive capability depends enormously on the preceding groundwork done in the implementation of the previous levels of Industry 4.0. A properly implemented digital twin, as well as specific knowledge of possible company process interactions, is key to assuring that both the predictions and the recommendations stemming from these predictions are of the highest possible quality.

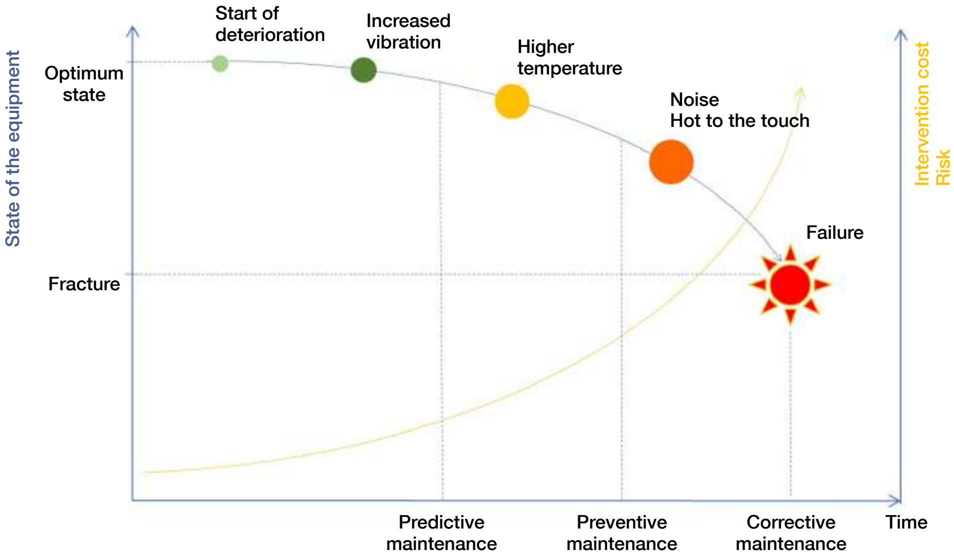


Figure 1.11. Cost reduction resulting from predictive maintenance of failures in production equipment.

1.2.6 Sixth stage: Adaptability

The predictive capability achieved in the previous level is key to enabling automation of corporate actions and decision-making processes. To assure ongoing corporate adaptation to a constantly changing environment requires delegating certain decisions to computer systems that, based on previous prediction of scenarios, are able to adapt business operations as rapidly as possible.

The degree of adaptability attained in the transformation process will depend on the complexity of the decisions to be taken and of the possible benefits that they can provide. Thus, it will often be preferable just to automate individual processes, such as production planning. In other cases, it might be worth evaluating the possibility of equipping more general operations that involve repetitive performance of certain actions with a certain autonomy. Whatever the case, it is very important always to assess the risk involved in automating approvals and notifications for clients and suppliers, as they could become counterproductive. For example, in certain cases it would be convenient to enable the sequence of planned manufacturing orders to change automatically, based on failure predictions, or to avoid delays in certain production orders. However, it might also not be advisable, in a particular case, to inform a given client of delay in supplying an order.

This sixth level of transformation towards Industry 4.0 might certainly be the most difficult to implement, particularly in the ceramic tile manufacturing sector. In any event, the main objective of this last adaptability stage will have been reached when the company is able to use the data mirrored in its digital twin to make decisions in the fastest possible way, decisions that, in turn, provide the best attainable results. This is all achieved by introducing corrective actions to be implemented automatically, as far as possible, without human intervention.

A simple example of such adaptability might be automatic adjustment of the vitrified tile firing process based on measurements of fired tile properties at the kiln exit and on the anticipation provided by analysis of tile body forming conditions. In a first approach, the data mirrored in the digital twin on the forming conditions could be used to predict different kiln exit scenarios and to provide recommendations for optimised firing of the material. At the same time, real-time monitoring of fired tile properties would enable these recommendations to be validated or adapted to ensure that in manufacturing successive batches of the same material, production would be carried out to the highest standards of quality. At a more advanced state, these recommendations could even be fed automatically into the kiln's own control system, hence not requiring, a priori, direct human action, so that the operators would thus only be playing a supervisory role. This relatively simple example could be made more complex by adding variables that might influence not only product properties, but also company operations.

1.3 General structure of the Guide for transformation towards Ceramic Industry 4.0

The ASEBEC 4.0 project seeks to start an Internet platform stemming from entrepreneurial collaboration among several bodies pertaining to ASEBEC (Spanish Association of Ceramic Machinery and Capital Goods Manufacturers). The platform is intended to structure and centralise the adaptations that ceramic tile manufacturing firms, as well as capital goods manufacturers, need to undergo to enable digital transformation of the ceramic tile manufacturing industry.

For decades, the ceramic tile manufacturing process has demonstrated its efficiency in manufacturing most products. However, today's new challenges require different ways of doing things. The need to fabricate new products while maintaining quality standards and reducing manufacturing costs, the globalisation of current technology with the appearance of new stakeholders, such as emerging countries, and the incorporation of new technologies that enable complete digitalisation of the plant currently require envisaging a new factory of the future for ceramic tile production.

Some of the challenges that the new factory of the future needs to address are, for example, the manufacture of large tile sizes, product differentiation with respect to competitors, incorporation of new decorating techniques, and new surface coatings, while maintaining end-product quality, at limited costs, with minimal environmental impact. The Spanish manufacturers of machinery and capital goods for the ceramic industry in ASEBEC intend to play a major role in this ceramic plant automation and digitalisation process, and the machines they supply must be fully equipped to address this challenge. ASEBEC 4.0 is a project that aims to start a collaborative platform to show ceramic tile manufacturers what changes they need to make in their machines and production environments, what control systems they need to implement, and what information they need to acquire in real time in order to convert their current factory into a smart factory, fully aligned with Industry 4.0 concepts.

To do so, first, it is essential to carry out a series of needs analyses to generate the information to feed the platform. The most important points to be dealt with in these needs analyses are as follows:

- Definition of critical operating and control variables
- Identification of the current state of the art in data collection technologies
- Identification of the interconnection and digitalisation needs of the different production elements.

Based on this information, the platform's most significant functionalities enable information to be provided, on the one hand, on already existing control systems and control systems that need to be developed in each manufacturing stage and, on the other, on information integration systems and automatic control systems of the manufacturing process.

Together with the development of the platform, which will entail the cooperation of different ceramic sector stakeholders, the project will also involve an important step forward in the understanding of Industry 4.0 for the ASEBEC environment. Indeed, the structuring itself of the information required for the fine-tuning of the platform, as well as the development of new information, control, and processing systems, either as already established solutions or as solutions generated upon defining the platform, will allow Industry 4.0 culture to be disseminated to the entire ceramic cluster.

Chapter 2:
Infrastructure

Following the introduction to the general features of Industry 4.0 and the conceptual framework on which ceramic companies can focus their transformation process, this chapter describes the different communication elements that allow attainment of the second level of digitalisation: connectivity (see Figure 1.6). The basic principles of communication networks, which constitute the infrastructures through which the different computer systems established in the first transformation stage are going to be able to intercommunicate, are therefore introduced first. The main types of fieldbuses used in industry, through which industrial equipment provides data, are then presented, briefly explaining their characteristics, advantages, and disadvantages. Finally, the most widely used communication protocols at industrial level and their basic related concepts are also introduced.

2.1 General fundamentals of industrial communications

The intercommunication of different elements in an industrial ecosystem is performed through data communication networks. To determine the state of any production system there are innumerable field devices (temperature sensors, pressure sensors, safety interlocks, counters, flow meters, photocells, etc.) that provide control systems and plant operators with information. This information enables industrial processes to be kept running under optimum operating conditions in order to maximise productivity, within appropriate levels of safety, both for the people working in the plants and for the surrounding environment.

Industrial processes, in general, and the ceramic tile manufacturing process in particular, are usually made up of different stages whose monitoring and control are automated, thus constituting a series of "automation islands" between which it is not essential for there to be any communication to carry out the process. A clear example of such a "standalone" stage occurs in the ceramic tile manufacturing process, in which the spray-drying stage is separated from the rest of the manufacturing process, the operation occurring to such a standalone extent that spray-dried powder production is often outsourced.

To carry out the transmission of information through the communication networks within a production process, a set of rules are used that enable data transfer and exchange in a structured and standardised way. These communication standards are known as communication protocols.

Two types of networks are customarily differentiated in industrial settings, even though, as will be set out below, the communication protocols used for data transmission through these networks may be common.

Thus, on the one hand, the terms networks or fieldbuses are usually used to refer to the network structures closest to the process. These networks are designed to carry data traffic consisting of a great number of small packets of information, generally working in real time, and are usually used to interconnect PLCs, PCs, sensors, and primary measurement elements. In addition, these networks need to resist a generally hostile environment containing a great amount of electromagnetic noise and harsh ambient conditions.

On the other hand, there are also information networks (LAN (Local Area Network)/ WAN (Wide Area Network)) that focus on transporting and exchanging large packets of information and hence require higher bandwidths for rapid information delivery. These networks are therefore used when a large volume of information with not necessarily critical response times needs to be interchanged, unlike what usually happen in field conditions. The elements that are typically connected by means of these networks are usually PCs and servers.

2.1.1 Levels of automation: CIM pyramid

The data communication networks in industrial processes are structured according to so-called levels of process automation. The definition of automation levels of the CIM (Computer Integrated Manufacturing) model, established by the US National Bureau of Standards 1981 [10], is currently recognised worldwide.

This model is one of the most widely used for structuring the distribution of communication networks, according to the purpose for which they were designed and implemented, considering the factory as a whole and dividing the control actions into different hierarchic levels depending on their function [11].

In the so-called CIM pyramid (**see Figure 2.1**), each level develops specific tasks, linking different types of data and information processing approaches. The hierarchy of a particular communication network is determined by the level of control to which it belongs, governing the functions of the lower level and acting as an interface for the higher level. This assures that the information flow is established both in a horizontal direction (at the same level) and in a vertical direction (towards a higher or lower level).

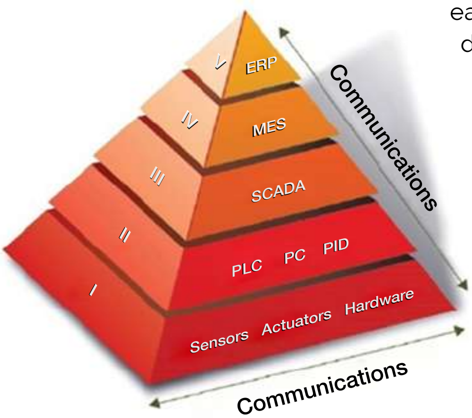


Figure 2.1. Levels of automation according to the CIM pyramid (Source: http://www.autracen.com/la-piramide-cim/).

The CIM structure defines the following levels in an industrial communication network. The definition of the CIM pyramid characteristics for a particular process needs to be performed in a top-down mode. In contrast, implementation needs to be bottom-up. That is why the levels are preferably introduced bottom-up:

Level 1: Process control

This is the level of instrument or field data logging and is, hence, closest to the manufacturing process. The sensors and actuators of the plant equipment and production lines, which allow the production process to run and the measurements to be made for proper automation and supervision, are to be found at this level. Customarily, at this level, communications take place by traditional wiring systems, though in certain industries, fieldbuses with simple performance features are beginning to be used. In a ceramic plant, this level contains primary measurement elements, such as thermocouples in firing kilns, pressure sensors in forming presses, and level sensors in storage silos, to mention only a few examples.

Level 2: Field control

All local controllers such as computers, programmable logic controllers (PLCs), and proportional-integral-derivative controllers (PIDs) are grouped at this second level. The equipment at this level uses process data provided by level 1 instruments and provides actuator settings. At the highest point in these networks there are usually one or more modular PLCs in charge of managing the corresponding "automation island". The use of fieldbuses is already quite consolidated at this level and the use of more advanced communication networks such as Industrial Ethernet is on the rise. Generally, in ceramic plants, the field control level is assured by the industrial equipment's own control systems. Thus, for example, the most recent presses have a PLC and/or an automation PC for operation control of the pressing stage. The machines for loading/unloading tiles between the different process stages are fitted with a PLC, which would be located within this hierarchy in the CIM pyramid.

Level 3: Cell control

This level contains the supervision equipment for coordinating the manufacturing sequences of the machines belonging to a manufacturing cell, the production process being subdivided into different interconnected areas or systems by high-performance PLCs or computers for control or programming. In the ceramic manufacturing process, this level would be made up of HMI (Human Machine Interface) systems, with which industrial equipment such as presses, dryers, kilns, and finished product sorting machines are often fitted. Further included in this hierarchy are SCADA systems, which graphically concentrate information stemming from different points of a manufacturing cell, such as raw materials storage and preparation systems before tile forming.

Level 4: Plant control

This level features systems that perform manufacturing operations management and planning functions in the factory as a whole. Execution orders are generated in these systems towards the cell level, based on indications of the immediately higher level. Production sequences and tasks are also generated, and plant resources are coordinated, with a view to optimising workflows and finished product quality. Systems that may be considered at plant level control are historians, computerised maintenance management systems (CMMS), and manufacturing execution systems (MES). In addition to the information historians themselves, which are essential for rapid, simple access to stored process data, MES have become a virtually indispensable tool for the development of in-plant operations. Unfortunately, in the ceramic sector, this level of the CIM pyramid has not yet become widespread, there being proposals both from industrial machinery manufacturers and from other stakeholders that ceramic companies are beginning to assess.

MES are computer systems used in manufacturing operations to monitor and document the transformations that raw materials and/or semi-processed products undergo in order to become finished products. MES provide information that help decision making in the manufacturing process on providing insight into how plant conditions could be optimised to improve production. MES run in real time to incorporate information from different elements, such as production data, operators, machinery, and assistance services, into the production chain. Combining the information drawn from all these sources, MES can operate in different operations spheres, such as resources planning, execution and monitoring of manufacturing orders, analysis of production variables, use of production metrics for management of equipment availability (OEE, Overall Equipment Effectiveness), product and semi-processed product quality management, and product traceability.

Level 5: Business control and management

The top level of the CIM pyramid is charged with integrating the production process into the company management area. This level features all business-related activities that enable maintenance of a given industrial organisation, communicating, if such be the case, several production centres and supporting different tools for the relationship with customers and suppliers. The top level thus allows the various company departments to supervise the evolution or state of the production process, drawing information from this, but never taking part in it. This is where ERP (Enterprise Resource Planning) systems or BI (Business Intelligence) tools operate, whose use is quite widespread in the ceramic sector. However, it should be noted that, in general, the level 5 systems customarily used by ceramic sector companies exhibit a lack of integration into the CIM pyramid precisely because of lack of appropriate implementation of level 4 systems, through which they would be fed with information from the manufacturing process.

Starting out from the general CIM pyramid structure, it is deemed of interest to define a CIM pyramid focusing in particular on the ceramic tile manufacturing industry. This pyramid is set out in the graph in Figure 2.2 and displays the different systems and tools that a ceramic company with an appropriately implemented CIM pyramid needs to include in each of its automation levels.

Each automation level exhibits some examples of systems that would be located at that level. Thus level 1, the level closest to the manufacturing processes, would contain the field devices charged with monitoring and controlling the transformation operations carried out in the factory. By way of example, the devices proper to the forming, drying, and firing stages have been included.

The second level, i.e. field control, would include the elements and devices proper to local control of the industrial equipment, such as press automation PLCs or dryer visualisation and interface elements.

Typical cell control elements would include SCADA systems, customarily used in laser-guided vehicle (LGV) stations for management of semi-processed product storage or, though not indicated in the scheme in Figure 2.2, visualisation and management systems at a cogeneration plant in a spray-drying facility.

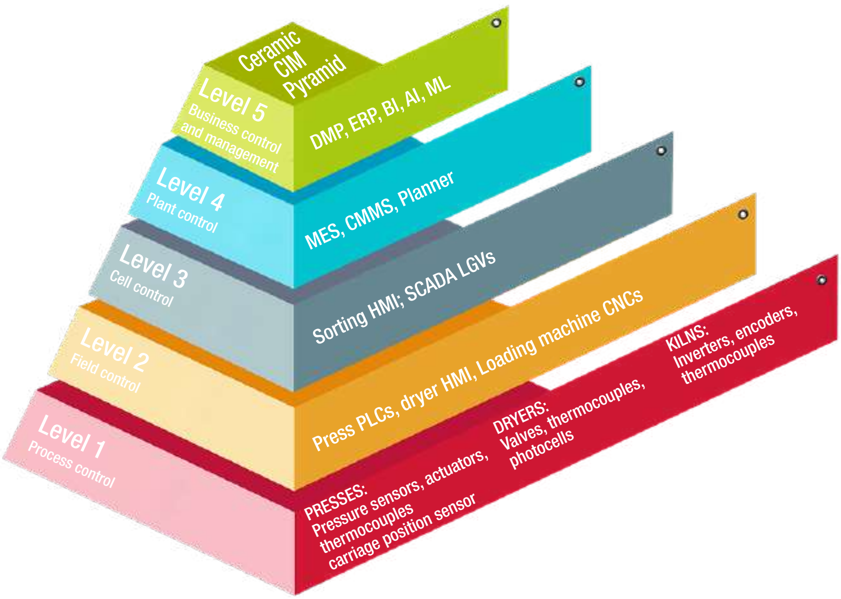


Figure 2.2. Automation levels according to the CIM pyramid in a general ceramic plant.

The fourth level, corresponding to plant control, would contain all tools that perform manufacturing operations planning and management functions in the factory as a whole. Unfortunately, in the ceramic industry, this fourth level of the CIM pyramid is generally poorly developed, the most advanced cases exhibiting manufacturing executing systems (MES), though a significant shortage of computerised maintenance management systems (CMMS) and of production planning/sequentialisation systems has been detected.

Finally, at level 5, despite the technology gap at level 4, ceramic companies usually have tools to assure business management and control, such as ERP or BI (Business Intelligence) systems. At the moment, other level 5 tools that could begin to be deployed, such as a digital manufacturing platforms (DMP) or specific Machine Learning (ML)/Artificial Intelligence (AI) modules, have as yet practically not been implemented.

2.1.2 Types of industrial networks

The different levels of the CIM model allow industrial networks to be broken down into at least 4 levels. By way of example, **Figure 2.3** schematically illustrates some of these types of networks.

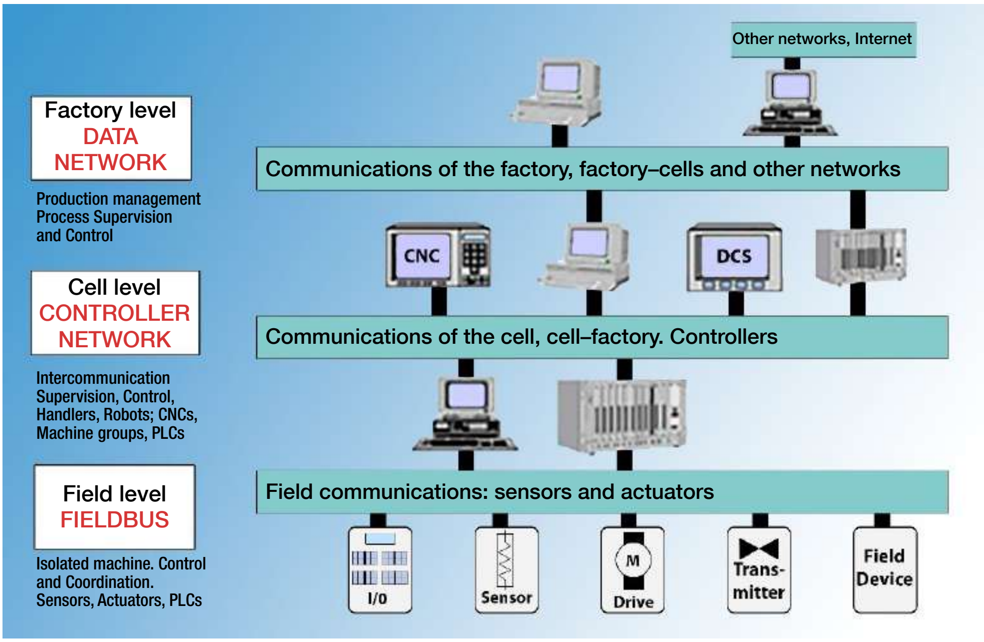


Figure 2.3. Communication networks deployed in an industrial environment.

a. Factory or plant network:

These are networks that link factory departments and services using computers or servers: plant, store, laboratory, design, general services, sales and marketing, etc. It is generally the network used for information exchange by the different systems in level 5 of the CIM pyramid.

b. Control or supervision network:

These networks are used to manage the data required to direct the plant production process or processes. Through these networks, control systems and plant operators transmit the necessary data for production monitoring and send the relevant setting changes to the process to keep it running under optimum conditions. In a ceramic plant, this network would mainly use the MES system to monitor production operations.

c. Cell network:

Cell networks are control networks restricted to "automation island" level, at which they connect together each cell's command and control equipment. According to the CIM hierarchical structuring, cell networks connect the functions defined at level 3.

d. Fieldbus or network:

Finally, the fieldbus is an industrial local network that links field devices such as actuators, sensors, transducers, and visualisation elements to devices that support application processes, such as PLCs, CPUs, Robots or other systems that need to access field devices to carry out their functions. This level of communications has traditionally been established through wired networks linking sensors, actuators, and control elements, in which data transmission occurs by 4–20 mA or 0–10 VDC power. Today, in the ceramic industry, equipment and devices can still be found that work like that.

2.1.3 Control typologies

After the above review of the general concepts of industrial communication systems and the hierarchical structuring of automation levels, the different control typologies customarily found in industry are set out below.

Three types of industrial control systems may be distinguished: centralised control, hybrid control, and distributed control. The criticality of the tasks to be performed by the control system or the possibility of subdividing the process control tasks will often determine choice of one type of control or another.

• Centralised control:

This is the type of control typically used in not very complex cases, where processes can be managed by a single control element charged with supervising and managing the tasks associated with the production process.

The main advantage of this control approach is that it is not necessary to plan a system interconnecting elements or processes, as they are all managed by the same system, which makes it less costly than other methods. The disadvantage of this type of control is that it requires incorporating a redundant system because otherwise, if the system fails, the entire facility shuts down.

• Distributed control:

Distributed control is based on the distribution of processes, groups of processes, or functional areas to specific control algorithms that can run in standalone form. Note that, owing to the interdependence of production stages, these control units need to be linked together by digital inputs and outputs or a communication network to share data and/or states.

The most important advantage of this control model stems from the fact that each functional unity is simpler than a single comprehensive control unit, enabling significant reduction of programming and management errors, as well as use of simpler control units. In addition, unlike what occurs in centralised control systems, in distributed control systems, failure in a unit does not lead to a complete system crash.

• Hybrid control:

Hybrid control systems exhibit the typical characteristics of the two foregoing control systems, with a combined structure. Their use is justified in industrial settings or processes in which it is convenient simultaneously to take advantage of the benefits of centralised and distributed systems. Or in those systems in which, owing to their complexity, the control system cannot be fully distributed.

A distributed control system generally consists of a communication network with several physically distributed nodes, fitted with a processing capability and connected to the sensors and action systems. In contrast, as mentioned above, a centralised control only has a single controller where all the sampled inputs come together. These are processed by applying the appropriate control algorithms, and the output signals are generated. Traditionally, control centralisation has been the common way to proceed, giving rise to expensive and heavy point-to-point wirings and the use of analog networks, both for connecting devoted sensors and for activating actuators.

The current trend in industrial systems is migration towards distributed systems, given the need to simplify and standardise the wirings, going from point-to-point wirings with analog links to smart node systems connected by a fieldbus or network through low-cross-section wirings.

In distributed systems, one of the most common examples is that used in automobiles. These require a great number of low-cost reliable components that can work in aggressive environments, which makes it necessary to use distributed systems embedded in the vehicle by a CAN (Controller Area Network) bus, discussed below[12].

2.2 Main buses and communication standards

The communications on a horizontal and a vertical level within the network structures deployed in a factory can be carried out by a great variety of communication protocols, physical means, fieldbuses or networks, whose applicability depends on the environment in which they are to be deployed and on system requirements.

The most widespread physical means are RS-485, Ethernet, Optic Fibre and more recently Wi-Fi support. The communication buses and protocols associated with these usually depend on the physical means for information transmission. Thus, for example, the most widespread buses running on an RS-485 are Canbus, Modbus, and Profibus. In networks of the Ethernet type, most traditional buses have evolved to enable use on these networks, exhibiting specifications based on this physical means. The market thus includes Profinet, Ethernet/IP, Ethercat, or Modbus/TCP buses, among others. Finally, communication protocols or standards have more recently appeared intended exclusively for supervision networks in which, in addition to the Modbus/TCP protocol, the DNP3 or OPC protocol is typically used. The most widely used fieldbuses in industrial environments, as well as their adaptations to Ethernet support are described below.

2.2.1 Fieldbuses

As noted previously, a fieldbus is a data transmission system that allows replacement of point-to-point connections by power links between field elements and the corresponding controlling equipment. Fieldbuses are digital, bi-directional, or multi-point networks that communicate devices such as PLCs, transducers, final control elements, or sensors. Historically, different industrial and/or academic groups have tried to develop and establish a standard that would allow integration of equipment from different suppliers. However, at present no fieldbus can be considered universal.

Although perhaps obvious, the main advantages afforded by fieldbuses for data interchange at the lowest levels of the CIM pyramid are detailed below:

- They allow replacement of analog signals, based on power loops, by much more accurate and reliable digital signals.
- They allow multi-variate access, component outputs not being limited to a single variable.
- They facilitate configuration and diagnostics of devices on allowing remote access to the devices, which simplifies, for example, calibration processes or detection of failures.
- They significantly reduce and simplify wiring of the facilities.
- They open the way to performing distributed process control.
- They assure interoperability of the devices by facilitating the replacement of elements by others that meet network specifications.
- They assure development of open systems as the specifications for producing compatible hardware and/or software with a given bus are available for device developers.

Given the great diversity of available fieldbuses on the market, it is of interest to classify these as a function of the data volume they can transmit and functionalities they provide. The speed of transmission and functionalities of the bus will indicate at what level it can be set in the CIM pyramid and, therefore, which type of industrial network can most appropriately be addressed by each type of bus. One possible classification thus distinguishes three types of fieldbuses:

- Buses with high speed and low functionality
- Buses with high speed and medium functionality
- High-performance buses

For simplicity's sake, the main specifications for each of these groups of fieldbuses is detailed below, with an example of the most widely used fieldbus in each group.

2.2.1.1 Fieldbuses with high speed and low functionality: the CAN bus

These fieldbuses enable industrial automation and communication to be addressed at levels 1 and 2 of the CIM pyramid at which, on the one hand, the communication networks of sensors and actuators and, on the other, the machine control networks are established. Their use is pre-eminently focused on the implementation and deployment of field networks. They transmit information at bit level by means of digital variables to interconnect switches, samplers, sensors, button-type interaction elements, etc. The following are the most widely used fieldbuses of this type in industry:

- AS-i (Actuator Sensor Interface)
- CAN (Controller Area Network)
- SDS (Smart Distributed System).

The most commonly used bus in this group is the Canbus which, though initially developed for use in the automotive industry, has been widely accepted at industrial level owing to its performance features, robustness, and low cost. The CAN protocol on which this fieldbus is based was developed by the German company Bosch in 1986 [13] to simplify wiring in automobiles of different brands, allowing a notable reduction in the existing number of wires for communication of the great amount of electronics associated with the elements installed in the engine and the rest of the vehicle (braking system, airbags, safety belts, thermal conditioning, etc.). Its use enables distributed access to all these elements of the network [14], and at present it has many more uses in industrial environments, such as connecting smart devices (robots, lifts, machinery, etc.).

The CAN protocol has been standardised since 1993 in the ISO 11898 [16] standard and other protocols have subsequently been developed from this standard, such as DeviceNet and CANOpen.

Their basic characteristics are as follows:

- CAN is a message-oriented protocol, i.e. the information that is going to be interchanged is broken down into messages, which are assigned an identifier and encapsulated sequentially for transmission. Each message has a single identifier in the network, with which the nodes decide whether or not to accept the message.

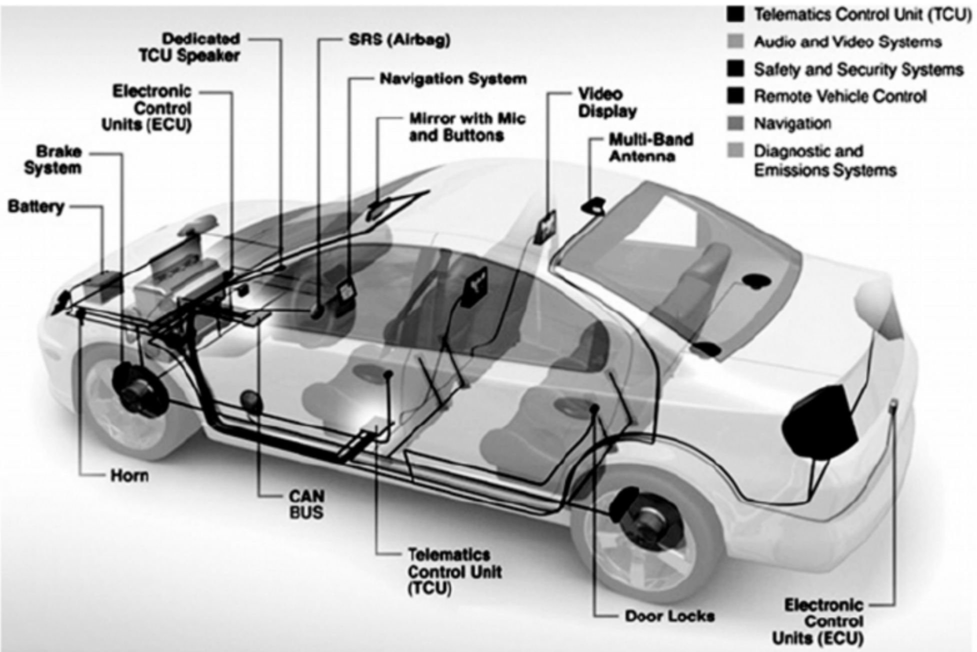


Figure 2.4. Example of a CAN communication network in an automobile [15]

- Message priority.
- Guaranteed latency times.
- Configuration flexibility.
- Multicast reception with time synchronisation.
- Robust system regarding data consistency.
- Multimaster system.
- Error detection and signalling.
- Automatic retransmission of erroneous segments
- Distinction between temporary errors and permanent failures of the network nodes, and autonomous switching off of defective nodes.

Advantages:

- Minimisation of the amount of wiring.
- Use of fewer sensors and fewer connections between control units.
- Better component performance.
- Integrated diagnostics and notification of failures.

Disadvantages:

- More complex and expensive to implement than other buses.

2.2.1.2 Fieldbuses with high speed and medium functionality: MODBUS

These buses transmit information in bytes, using both digital and analog variables. They are used to connect devices, controllers, PLCs, and PCs with a view to sharing field devices among several control units. In the CIM pyramid, these buses are used in communications at the cell control level and their use therefore focuses on the implementation of cell networks. The currently most widely used buses of this type in industry are as follows:

- DeviceNet	- COMPOBUS	- LONWorks
- MODBUS	- INTERBUS	-UNI-TELWAY
- BITBUS		

Among these, one of the most commonly used buses in the ceramic sector in particular, and in other process industries, in general, is the MODBUS. This is one of the most widely found industrial communication protocols at present as, given its simplicity and open character, its use is widespread among numerous device manufacturers.

Specifically, in the ceramic sector, there is a very illustrative example of the use of this protocol for interconnecting process control systems. This is the case of the communication established with the press by the pressing operation's automatic control system based on moisture measurement of the freshly pressed tile bodies, developed by the Instituto de Tecnología Cerámica (ITC) in 2007. This control system obtains the pressure values at which the processed tiles have been formed, communicating directly with the press control system through a MODBUS bus. From this pressure and the moisture measurements made with an infrared sensor, the system calculates the pressure at which the press needs to run to keep tile body density constant. This pressure is sent back to the press through the same MODBUS communication bus.

MODBUS is a protocol of the request/response type, so that, in the data transactions, the device that makes a request is identified as the client or master and the device that sends back the response is deemed the server or slave of the communication. In a MODBUS network, the master device can access several slave devices, identified by a single address. Data interchange can be performed in 3 different ways: RTU, ASCII, and TCP. The supporting physical layers on which MODBUS can be used are RS-232, RS-422, RS-485 or high-speed network based on HDLC (High-Level Data Link Control), in traditional transmission modes, and Ethernet in TCP mode, developed to run on networks with TCP/IP architecture.

MODBUS was originally developed by MODICON (now Schneider Electric) in 1979 [17]. As mentioned, there are several variants, with various numerical representations of the data and slightly differing protocol details. Modbus RTU is a compact binary representation of the data. Modbus ASCII is a legible representation of the protocol, albeit less efficient. Both protocol implementations are serial. The RTU format ends the sequence with a checksum of the cyclic redundancy check (CRC), whereas the ASCII format uses a checksum of the longitudinal redundancy check (LRC). The Modbus/TCP version is very similar to the RTU format, transmission being established by TCP/IP packets.

Advantages:

- Designed taking into account use for industrial applications.
- Public and free.
- Easy to implement and requires little development.
- Handles blocks of data without involving restrictions.
- Appropriate for small or medium amounts of data <= 255 bytes
- Data transfer with acknowledgment.

Disadvantages:

- Large binary objects are not compatible
- Modbus transmissions must be contiguous, which limits the types of remote communication devices to those that can store to data to avoid gaps in transmission.
- The Modbus protocol offers no security against unauthorised commands or data interception

2.2.1.3 High-performance buses: PROFIBUS

The information transmitted with these buses is structured as "words" or tables, allowing data exchange between devices and controllers or PCs. In the CIM pyramid, these buses would be located at plant level, as they enable execution commands to be generated towards cell level on processing the received information. They are used to create control or supervision networks that allows the necessary data to be transmitted to the operator to govern the process and to send setting changes to the elements in the cells. The most widely used bus in this group is currently the PROFIBUS, though there are also others, such as the following:

- ControlNet
- Fieldbus Foundation
- World FIP
- PROFIBUS

PROFIBUS was developed in the period 1987–1989 by a number of German companies (ABB, Bosch, Klöckner Möller, Siemens, among others) and five German research institutes, becoming the world's most widely used fieldbus with more than 20 million installed communication nodes. At present there is the PROFINET version, specially developed for use on Ethernet networks. Its operation is based on the use of master nodes and slave nodes, the masters and slaves also being designated active nodes and passive nodes, respectively. This bus has three formats: PROFIBUS-DP, PROFIBUS-PA, and PROFIBUS-FMS.

- *PROFIBUS DP (Distributed Peripherals).* It has high-speed transmission, is economical, and transfers small amounts of data. It exhibits a classic master–slave structure. It is the most widely used at field or cell level, acting at field level. The physical layer on which it is implemented is RS-485.

- *PROFIBUS PA (Process Automation).* It has similar characteristics to the DP but adapted to intrinsically safe areas, i.e. for hazardous environments with explosion risk. It also acts at field level.

- *PROFIBUS FMS (Fieldbus Message Specifications).* This is the general-purpose, supervision, and configuration format. It is a multimaster format (token step between masters, master–slave with other devices) and is used at plant or cell level. With the evolution of PROFIBUS towards its use with the TCP/IP protocol, this format is becoming less important for the link at cell or plant level.

The general characteristics of the PROFIBUS bus, regardless of the mode in which it is used, are set out below:

- Maximum length: 9 km with electrical means, 150 km with optical glass fibre, 150 m with infrared.
- Can support up to 126 nodes
- Transmission rate between 9.6 kbit/s and 12 Mbit/s.
- Can transfer a maximum of 244 bytes of information per node and cycle.
- Topology: star, tree, ring, and redundant ring

Advantages:

- It is the world's most widely accepted standard and is extensively used in Europe.
- The three available versions cover practically all automation applications.

Disadvantages:

- Not very effective in transmitting short messages as the message contains a lot of addressing information.
- Has no associated power supply and is slightly more expensive than other buses.

2.2.2 Industrial LAN networks

In 1984, under standard ISO 7498 [18], the ISO (International Standards Organization) approved the OSI (Open Systems Interconnection) model, which describes the rules governing communication equipment that exchanges information through a network infrastructure. The model specifies the rules in terms of their functional objective and classifies them in seven layers or levels: application, presentation, session, transport, network, data link, and physical.

In 1985, the IEEE (Institute of Electrical and Electronics Engineers) produced a set of standards for local area networks (LAN), designated IEEE 802.X [19]. One of the IEEE 802 standards is the so-called Ethernet standard (IEEE 802.3) [20], adopted by ISO as ISO 8802-3. The Ethernet is a network with a bus logical topology, whose standard specifies a transmission speed of 10 Mbit/s, though the Fast Ethernet version reached 100 Mbit/s and the current gigabit Ethernet reaches up to 10 Gbit/s.

Ethernet is an enormously popular communication network, among other reasons, because of the open scheme of its interconnection, its efficiency in the exchange of large volumes of information, the low cost of the interfaces required in its implementation, and its speed. Its spectacular spread has allowed it to achieve significant market share even at the communication pyramid level reserved for fieldbuses. In the support of numerous distributed control systems, it has emerged as a serious competitor to traditional networks. However, when the maximum delay that messages may face has to be assured, in real-time applications, choosing it has not been without risk, given its initially non-deterministic character. This non-deterministic behaviour of classic Ethernet networks did not allow assurance of sending and receiving a data packet in a certain period of time, an essential issue in industrial network design, particularly when these networks focus on supervising and/or controlling critical applications.

However, Ethernet has today developed to a level that allows control of the deterministic delivery of information, enabling checks distributed in real time to be carried out. This has been achieved by implementation of new protocols and transmission controls, which have enabled the standard Ethernet to evolve.

As already noted, the most advanced traditional buses have evolved for use on Ethernet networks, thanks to the development of specifications at transport level of the OSI standard and continued use of the original specifications in the lower layers. Thus, the following traditional buses with Ethernet-based specifications are currently in use in industry, particularly for deployment of networks located at the highest levels of the CIM pyramid:

- Modbus TCP
- Ethernet/IP
- EtherCAT
- PROFINET
- CYP Sync
- FieldBus HSE

A description follows of the main characteristics of the most commonly used protocols in industrial LAN networks: Modbus TCP, Ethernet/IP, EtherCAT, and PROFINET.

Modbus TCP

The development of the Modbus TCP/IP specification was based on the Modbus RTU standard in 1999, allowing encapsulation of the information packet in the Modbus sequence in the message structure of the TCP/IP protocol.

Modbus TCP may today be considered the most popular Industrial Ethernet protocol owing to the simplicity of its application using standard Ethernet hardware.

Ethernet/IP

An Ethernet-based protocol is also involved here for industrial automation applications under the set of standard Ethernet IP/UDP/TCP protocols. Unlike Modbus/TCP, the Ethernet/IP protocol has been developed to provide safety characteristics in real time.

EtherCAT

This could be considered a real-time fieldbus for use on an Industrial Ethernet network. It was developed by the Beckhoff company, seeking to solve the integration of the Ethernet protocol in an industrial environment, and later passed on to the EtherCAT open technology group for maintenance, supports, and development. It combines the functionalities and technologies of Ethernet with the simplicity of a fieldbus, specifically CANopen, this being its basis.

The bus system used by this protocol slightly modifies the standard hardware used in Ethernet, with a view to assuring communication efficiency by using a structure that allows repetitive data transfer between devices. This prevents star networks from being created; nor does it allow either the realisation of any type of tree structure unless I/O terminals with branch wiring are used. Finally, communication between Ethernet and EtherCAT components must always be made through a Virtual Switch in the PLC, direct communication not being possible.

ProfiNET

Its operation is based on the Profibus standard, but it is integrated, as noted above, on Ethernet. This means that, though keeping Profibus functionalities, it improves and optimises transmission at layer-2 level, allowing coexistence with protocol telegrams, such as TCP/IP, keeping the same connection.

ProfiNet's main advantage lies in providing users with a safe and reliable way of using industrial Ethernet, combining ease of use of a well-established standard, such as the PROFIBUS DP Fieldbus, with the high-performance effectiveness and capability that characterise the physical level of the Ethernet standard, it even being possible to share the network infrastructure with other Ethernet communications.

2.3 New communication standards for Industry 4.0

The CIM pyramid has been the design standard on which, over the last 20 years, any industrial control project aimed at connecting field systems (known as the shop floor) with management levels (the top floor) is based. The pyramid graphically structures the different technologies that connect the input/output devices in the field, with the control elements and the latter with the MES and business control systems. However, the emergence of concepts such as the Industrial Internet of Things [21] (IIoT) is driving a progressive transformation of the CIM model that industry had become familiar with.

The term IIoT refers to the different hardware devices that are able to work together through the Internet of Things (IoT) to help improve manufacturing and industrial processes. The IIoT therefore includes all sensors, devices, and machines that contribute to improving the physical processes of business in an industrial environment. In contrast, on referring to the Internet of Things (IoT) in a general way, any device is included that adapts to the IoT model, e.g. household devices that allow the end-consumer to connect directly with the supplier.

This change in the communication standards relating to the IIoT involves an implicit, necessary transformation of the CIM model structure. Indeed, as shown in the scheme in **Figure 2.5**, the structure of the automation levels is progressively converted from a pyramid into a true pillar of automation.

The reorientation that the CIM pyramid is undergoing is needed, basically, for two reasons. First, because of the need to more clearly differentiate the different control/management layers in industrial processes and, secondly, to reflect the fact that some technologies may cease to be located at company facilities and be housed in a cloud computing environment, either at local or external level.

The new IIoT applications, such as safe remote access for maintenance actions or the deployment of industrial applications of Big Data for continuous process optimisation and predictive maintenance, require having direct access to field data, which becomes difficult if they are supported by a strict pyramidal model. Hence the need for a new model or structure, the so-called automation pillar.

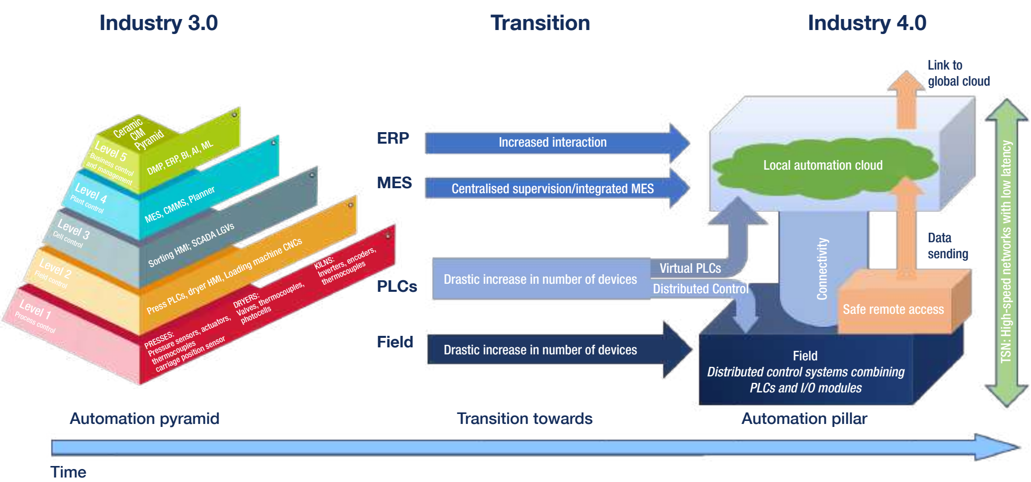


Figure 2.5. Transformation process of the CIM pyramid towards a structure based on a connectivity pillar (source: Belden).

The industry is currently moving towards ever more widespread use of networks based on Ethernet technology, not just in business areas, but also in the process itself, in which data logging and computing are really very important. In this sense, processes that require no thorough real-time control may at present be carried out virtually in the cloud, as depicted in **Figure 2.5**. The figure also shows how, thanks to the IoT, data may be shared in a simpler fashion among all levels without needing to travel sequentially from a lower to a higher layer.

The new proposed model is more open and flexible, and it is able to support new requirements relating to intense vertical communication. As a result, certain functionalities associated with PLCs and SCADA and ERP systems can be virtualised and relocated in a local or remote cloud. At the same time, the new model also considers the constant growth in the number of "smart" devices and sensors at field level, which facilitates shifting certain critical functions, such as safety, to field level.

In the current situation, in which industry is progressively about to abandon its dependence on fieldbuses in favour of massive use of Ethernet, it becomes necessary to distinguish more clearly the aspects relating to communication networks between devices as regards management systems. Hence, the two blocks joined through the connectivity pillar, depicted in **Figure 2.5**. The development of time-sensitive networking (TSN) technology, which provides the Ethernet standard with determinism, i.e. assurance of information reception in a set time, highlights the importance of the changes described here.

The following sections briefly describe some of the technologies and tools that are expected to contribute to the paradigm change in the coming years: OPC, TSN, cloud computing, 5G, and cyber safety. It may be noted that, despite the foreseen changes in production environments, the operational premises established by the CIM pyramid currently remain necessary to assure fluid transformation of the production processes. Indeed, to the extent that the massive exploitation of process data is going to generate real-time information for improving decision making, the ordering of the starting production structures must at least match CIM standards as the transformation process could otherwise be much more expensive than expected.

2.3.1 OPC: Open Platform Communications

OPC (Object Linking and Embedding (OLE) for Process Control or Open Platform Communications) is a set of specifications that provides a communication standard, simplifying the relationship between input/output (data source) devices and the network element(s) that act(s) as data clients. It was developed to solve the problem resulting from the existence of a multitude of data, drivers, and communication protocol formats in the industrial market.

In 1995, five automation technology development companies (Intellution, Opto 22, Fisher-Rosemount, Rockwell Software, and Intuitive Software) allied with Microsoft to create the non-profit industrial consortium OPC Foundation, for the development and implementation of an open system of communications that would remove those communication barriers. This led to the creation of OLE/COM (Object Linking and Embedding/Common Object Model), the basis of the current classic OPC [22].

On the one hand, OPC facilitates the work of automation solutions integrators by reducing the complexity associated with element interconnection. In addition, it allows cheaper and simpler trial environments to be developed with OPC-implementing simulators. On the other, the industries themselves may benefit from using OPC on having the possibility of choosing the best solutions from different providers, without any compatibility restrictions. This all results in cheaper control and automation technology, generating more flexible and dynamic industrial ecosystems. However, though classic OPC solves many interoperability problems, it has several disadvantages. These include:

1. Being based on Windows technology by using Distributed Component Object Model COM/DCOM. (Technology that allows development of distributed software components that communicate with each other).
2. An OPC cannot be mounted directly on a PLC. Computers are required that communicate with the machines.
3. Data are not encrypted, nor are there safety levels.
4. It is not easy to use if there is a Firewall in the middle. The number of ports and configuration elements make start-up tedious.
5. The data models differ as a function of the type of information. OPC DA for real time, OPC HDA for data historicisation, and OPC A&E for alarms and events.

In response to these problems, in 2008 the OPC Foundation launched a new version called OPC-UA (Unified Architecture) to replace all the specifications based on the COM standard without losing any of its characteristics or efficiency, as shown in **Figure 2.6**.

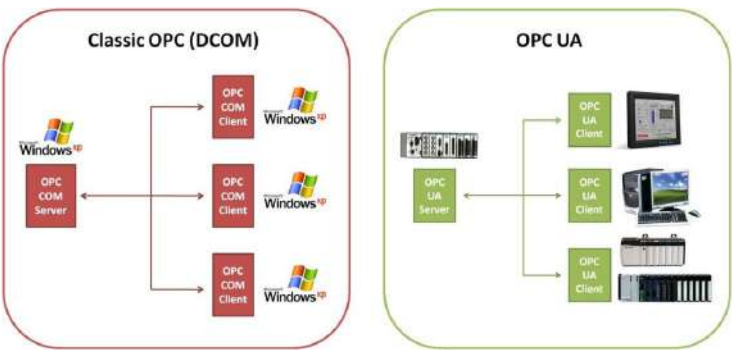


Figure 2.6. Main differences between OPC-DA and OPC-UA [23]

Table 2.1 Requirements for the development of OPC-UA. Source: https://larraioz.com

Communication between distributed systems	Data model
Reliability	Common model for all OPC data
Robustness and failure tolerance	Object-oriented
Redundancy	System of expandable types
Platform independence	Meta-information
Scalability	Complex methods and data
Internet communication and firewall	Model scalability from simple to complex
High efficiency	Abstract basic model
Safety and access control	Basis for another standard data model
Interoperability	

At present, the great variety of applications in which OPC is used requires scalability that ranges from the embedded systems themselves, on through SCADA systems, to MES and ERP tools. The necessary and most important requirements on which the OPC Foundation based the development of OPC-UA are detailed in **Table 2.1**.

2.3.2 TSN: Time-Sensitive Networking

TSN (Time-Sensitive Networking) is a standard defined by the IEEE that allows deterministic messages to be transmitted on the standard Ethernet. [24]

As mentioned in the introduction to Point 3, Ethernet is a very popular communication network standard, which is becoming increasingly widespread in the production process part of the factory. This expansion customarily faces serious limitations, particularly in regard to response times and failure tolerance.

With a view to resolving the disadvantages associated with use of Ethernet in industrial environments, TSN reformulates and optimises Ethernet, improving the quality of service (QoS) mechanisms and synchronisation time, reducing transmission latencies and redundancy without any interruptions to allow real-time communication.

TSN is defined in standards specified in IEEE 802.1Q-1CM-1CB [25]. These standards can be grouped in three main basic categories. Each can be used by itself, but their use together allows TSN's full potential to be really tapped. The three components are as follows:

1. Synchronisation time: All devices that participate in real-time communication need to have a common understanding of time. In other words, all must have the same format and the same time at the same moment.

2. Programming and configuration of traffic: The devices that participate in the network do so in real time with the same rules for processing and resending packets.

3. Selection of communication routes and failure tolerance: All devices stick to the same communication rules and bandwidth, using more than one route and therefore reducing the possibility of failures.

2.3.3 IIoT: Industrial Internet of Things

As has been remarked in the Guide, the equipment spread out over ceramic plants is usually isolated from the rest of the equipment and from the higher levels of control, forming information islands that are generally difficult to access from other points of the plant. The new Industry 4.0 paradigm seeks to eliminate these islands and to endow all elements involved in production with transparency, thus obliging the company to be fully connected.

Wiring has many advantages, particularly in regard to robustness, bandwidth, low latency, and scalability, but it cannot always be used, or the implementation cost may be too high for the criticality of the connection. In these cases, in which the connectivity in wired supports may be compromised, use of the IIoT may be a good option for assuring connection of industrial assets. However, it should be borne in mind that not every technology in the world of the IIoT is functional in every possible scenario. As **Figure 2.7** shows, the communication needs, environmental and situational conditions, and the particular element to be connected will tip the balance in favour of one technology over another.

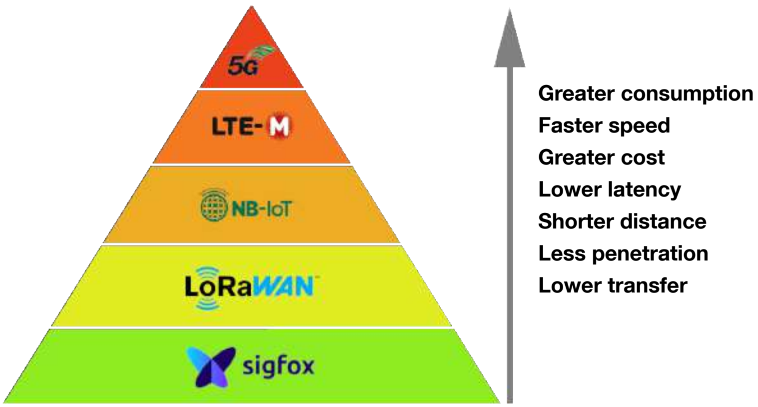


Figure 2.7. Comparative analysis of the functionalities of different IoT technologies.

The main technologies that can be used in deploying IIoT networks, as well as their respective advantages and disadvantages, are briefly described in the following points.

2.3.3.1 5G.

5G (5th Generation) is a standard defined by 3GPP (3rd Generation Partnership Project) [26] in response to the new communication needs in both the home and industrial market. It is the latest upgrade in the 4G wireless coverage network.

In principle, according to the specifications established by its developers, it needs to resolve some of the limitations existing in current wireless communications, such as stability, response times, and transfer speed.

Figure 2.8 shows the relationships between key features of current techniques and new 5G contributions

Its greater bandwidth, faster speed, lower energy consumption, and latencies below the millisecond can allow 5G to be a real alternative to wiring. Many of these benefits are achieved, as Figure 2.8 shows, thanks to the use of high-frequency radio waves and improvements in the physical layers (antennas and receivers).

Although it is true that higher frequency provides greater speed, it is no less true that high frequencies entail shorter transmission distances and lower penetration capability at walls and glass windows. This requires having a greater hardware infrastructure and hence also higher implementation cost or the coverage will be too poor to be able to connect to the network.

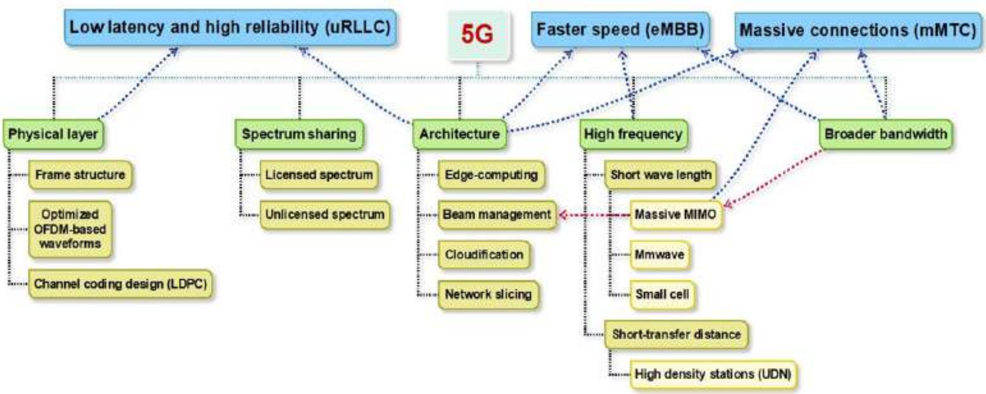


Figure 2.8. Relationship of essential 5G techniques (in yellow) and key characteristics (in blue). Blue arrows: direct links between the technique and resulting characteristic; red arrows: connections between the two technologies.

Source: IDTechEx Research [27]

Therefore, 5G provides new wireless communication possibilities for devices whose response times had made this unimaginable. But it should not be forgotten that thorough study and analysis of the requirements and costs are fundamental, before opting for this technology. The choice for or against needs to be based, primarily, on the necessary consumptions, latency, and coverage requirements.

2.3.3.2 LPWAN.

LPWAN (Low Power Wide Area Network) [28] is a type of wireless communication network designed to have a long reach with a low bit rate between battery-powered, connected objects. The technologies can be divided into those that use the private-use spectrum and solutions that use common-use bands. A number of these technologies are described below, beginning with the (licensed) private band technologies.

2.3.3.2.1 NB-IoT

NB-IoT (Narrowband IoT) is a standard developed by 3GPP [29] in LPWAN networks with bands for private use to enable connection to a wide range of devices and services by using LTE mobile networks. The low frequencies (180 kHz) allow its field of use to focus particularly on indoor or underground devices with low consumption, enabling long battery life and a low implementation cost.

Its main advantages are as follows:

- Great energy efficiency, allowing battery life of over 10 years.
- Low-cost modules (from 1€).
- Reliability and safety thanks to the coding of its connections.
- Simple deployment and scalability on using existing LTE mobile network architecture.
- Great number of connected devices, allowing up to 100,000 devices per antenna.
- Excellent penetration into buildings and below ground.

The maximum download and upload transfer rate is 200 kbit/s and 144 kbit/s, respectively.

2.3.3.2.2 LTE-M1

Another option in the commercial band spectrum, which has also been standardised by 3GPP, is LTE-M (Long Term Evolution, Category M1) [30].

It holds an intermediate position between NB-IoT and LTE. The bandwidth of its channels is of the order of 1.08 MHz. Its efficient energy use enables battery life of 5 to 10 years, depending on transfer speed. The maximum download as well as upload transfer rate is 1 Mbps.

Another improvement is the voice transmission and positioning support capability. Comparison of LTE-M1 and NB-IoT reveals the differences shown below.

2.3.3.2.3 SigFox

SigFox [32] is one of the bands of common use. It is defined both as a technology and as a French teleoperator that operates on its own technology.

It uses below sub-GHz frequencies, specifically at 868 MHz in Europe and 902 MHz in the U.S.A. It has its own network, which allows users to deploy their devices without needing a large investment or much knowledge of telecommunications. It is only necessary to buy a compatible radio module (from 20 cents) and subscribe to its network that currently covers 47 countries.

The main constraints or considerations to bear in mind before opting for this technology are the size and number of messages that it allows to be sent and received per day. At present, the maximum number of messages that can be sent per day is 140, while maximum message size is 12 bytes. This makes it a technology that is not designed for real-time applications or with great data sending needs.

Table 2.2 Comparative analysis of LTE-M1 and NB-IoT networks. (Source: accent systems [31])

	NB-IoT	LTE-M
Bandwidth	180 kHz	1.08 MHz
Download / upload rate	1 Mbps / 1 Mbps	160-250 kbps / 100-150 kbps
Latency	1.5–10 sec	10–100 ms
Battery life	+ 10 years	5–10 years
Transmission power	20 / 23 dBm	20 / 23 dBm
Cost per module	5–10 €	10–15 €
Positioning	No	Yes
Penetration	Extremely good	Good
Voice	No	Yes

2.3.3.2.4 LoRa and LoRaWAN

LoRa is the type of radio frequency modulation invented by Oliver Bernar Andre and patented by Semtech [33] for LPWAN communications with bands of common use. It uses frequencies below 868 MHz in Europe, 915 MHz in America, and 433 MHz in Asia. It has a reach of 10 to 20 km with data transfer up to 255 bytes.

On the other hand, LoRaWAN is a network protocol that uses LoRa technology to communicate. Its main characteristics are the ability to create both public and private low consumption networks, with AES-128 encryption support and point-to-point or star topology design.

LoRaWAN networks must always have at least one Gateway to act as bridge and handles communication between nodes. It can support up to 62,500 nodes and listen simultaneously to 8 nodes.

Its main disadvantage is its high cost and need for knowledge to implement it. While SigFox already has a network infrastructure into which it is only necessary to incorporate the device by paying the subscription, in Lo-Ra, it is necessary to create an infrastructure to use it.

2.3.4 MQTT, AMQP, and CoAP

To round off this chapter, the main communication protocols used in the IIoT are briefly discussed below. Note that these protocols, particularly MQTT and CocAp, were not designed with safety in mind so that there is consequently a serious cyber-safety risk [34].

MQTT (Message Queue Telemetry Transport Protocol) is a message protocol of the publish/subscribe type developed by Andy Stanford-Clark of IBM and Arlen Nipper of ARCOM in 1999. It has now been opened and has been converted into an ISO standard (ISO/IEC PRF 20922 [35]).

It is mainly designed for battery-powered devices in order to form sensor communication networks, though it can be used as a protocol for other types of applications, such as communication applications of the Facebook Messenger type.

MQTT architecture is simple. It has a server known as "Broker", which receives clients' communications. Communication is based on the publication of "topics". These are created by the client that publishes the message. The nodes that wish to receive them must subscribe to the client and will become part of "one-to-one" or "one-to-many" communications, depending on the number of nodes that subscribe to the "topic". This allows a hierarchy of clients that publish and receive data to be created. The "topic" is represented by a hierarchical chain separated by the symbol "/".

AMQP (Advanced Message Queuing Protocol) is another widely accepted standard in the IoT world. It was developed by John O'Hara at JP Morgan [36]. Its development was documented and then passed on to a work group (with companies such as Cisco, Red Hat, Microsoft, Bank of America, and Barclays) for improvement, implementation, and dissemination.

It is a protocol at the level of message-oriented wiring of the MOM (Message-oriented middleware) type. It was designed to support question/response as well as subscription messaging. AMQP stipulates server and client behaviour, allowing very high interoperability. This means that any program can create and interpret messages depending on the data format it establishes and, therefore, any other tool that meets this format can communicate regardless of the implementation language.

CoAP (Constrained Application Protocol) is an application level protocol in the OSI layer developed by the IETF (Internet Engineering Task Force) [37], designed to connect low-power devices to Internet.

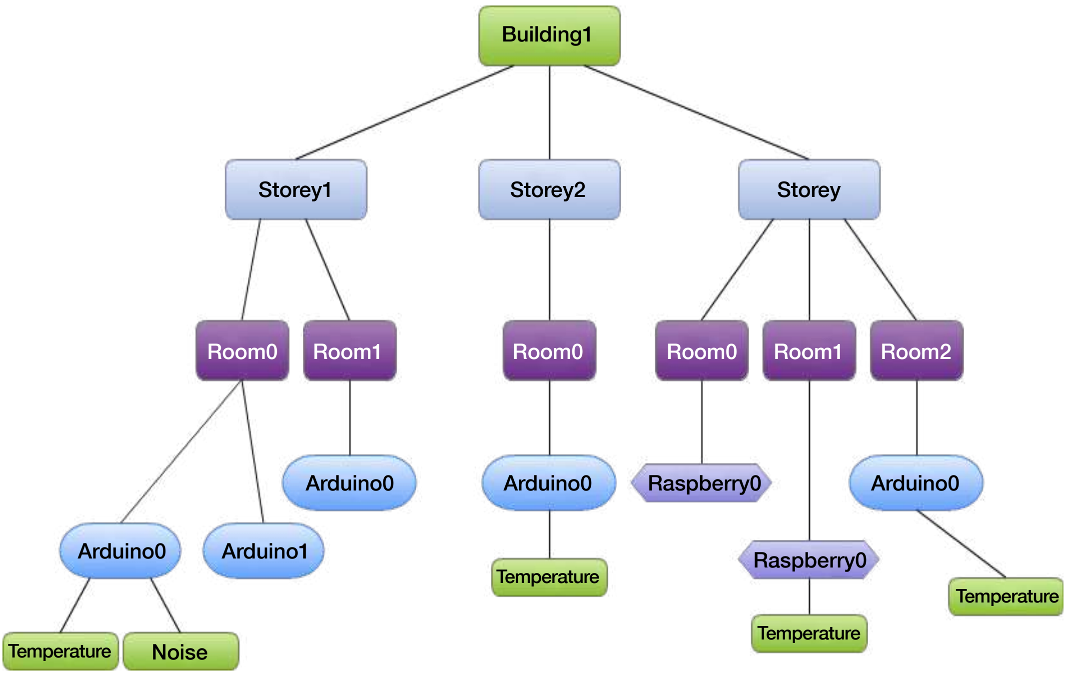


Figure 2.9 Scheme of MQTT "topic" operation with the ensuing sequence "building1/ storey5/room1/raspberry2/ temperature". (Source: https://geekytheory.com/que-es-mqtt)

Its design was originally inspired by HTTP. It was specified for use on UDP in networks with low bandwidth and low availability. To UDP the protocol added reliable delivery, congestion control, and flow control.

Subsequent updates allowed use of DTLS (Datagram Transport Layer Security) [38,39] on TCP, enabling it, in comparison to other protocols like MQTT, to provide safety thanks to DTLS and the possibility of continuing to operate even in networks with poor connectivity or with billions of simultaneously connected nodes thanks to TCP.

Chapter 3:

Sensorisation and control

The preceding chapter of the Guide reviewed industrial communications fundamentals and presented an overview of the most widely used communication protocols in the ceramic industry, in addition to some general aspects of the new Industry 4.0 standards. This chapter sets out the different types of sensors and their applications in the ceramics manufacturing process, while also indicating which manufacturing process variables need to be monitored to properly control production plants and lay the groundwork for subsequent deployment of actual Industry 4.0 tools. Finally, the different automatic control systems that can currently be used in the manufacturing process are reviewed, with a view to closing control loops to keep critical process variables constant that directly affect end-product quality and properties.

3.1 Levels of control in the ceramic industry

Generally speaking, sensors are devices that are able to detect changes in their environment, this capability being used to measure different types of physical magnitudes such as temperature, pressure, and distance. In addition, in most cases sensors are able to convert the measurement made into a signal that can be sent to and processed in other electronic devices. Nowadays, sensors are used in innumerable everyday objects.

The first references on the use of sensorial elements for measuring physical magnitudes date back to the Renaissance, when experiments began with devices that were able to provide information on air temperature. Thus, in 1592, Galileo proposed a system based on the displacement of a liquid in a sealed tube, in which the shrinkage–expansion undergone by air when subjected to temperature changes provided an indication of this magnitude. In 1612, the Italian Santorre Santorio added a numerical graduation to Galileo's invention and gave it a medical use.

During the 18th and 19th centuries, the eagerness to improve temperature measurement elements and the investigations carried out in the field of electricity led to the discovery of the Seebeck effect, on which current thermocouples are based, in 1821 and to the invention of the thermoresistance, at the beginning of the 20th century.

Since then, the unceasing development of sensors has led to today's sensors, which measure a great number of physical magnitudes in very wide and different ranges, enabling development of numerous technical applications. In recent years, developments in sensorics have focused on ameliorating the digital systems resulting from signal conversion, which allow communication over large distances while preserving measurement integrity.

There are numerous possible classifications for sensor typologies, depending on their measurement principle, magnitude to be measured, etc. One such classification follows:

- According to the type of signal received, sensors may be analog or digital.

- According to the type of variable parameter, sensors may be:

  Resistive
  Capacitive
  Inductive
  Magnetic
  Optic

- Depending on the magnitude or physical or chemical variable to be detected, sensors may be:

  Position
  Proximity
  Presence
  Touch
  Acoustic
  Displacement
  Temperature
  Humidity
  Speed
  Acceleration
  Force and torque
  Pressure
  Strain
  Light
  Flow rate

The incorporation of sensorics and control associated with the above magnitudes or variables in the ceramic industry has advanced in a series of phases, often evolving in parallel fashion, but without achieving the same degree of development in every production stage.

In the traditional chemical industry, process control is more highly developed than in the ceramic industry. This is partly because the ceramic sector works with solids, and the level of knowledge on solids unit operations is much lower than on fluids unit operations. The second feature that adversely affects automatic control stems from the structural nature of the ceramic product, which requires an array of end characteristics, unlike what occurs in most chemical processes in which there is usually a single major end characteristic, typically its chemical composition. In the case of ceramic tiles, the end product must meet a set of requirements that range from purely technical (low porosity, wear resistance, etc.) to aesthetic (gloss, design, etc.) requirements, often making it difficult to implement control systems. Finally, a further aspect that hampers automation of these types of industries is the wide variety of products (models) that a single company must make.

The fact that the ceramics manufacturing process requires consecutive performance of different unit operations (spray drying, pressing, etc) on the materials involved, in order to obtain the end product, has led to gradual introduction of automatic control, this being addressed in terms of process stages. The modular character of the process has led the characteristics of a material resulting from a series of operations that in themselves constitute a stage, even though they do not have a determining effect on the end product, to be of extraordinary importance, as they determine product behaviour in the following stage. The material resulting from a given stage, which is sometimes called a product, is in fact a semi-processed raw material that will be used as such in a subsequent process stage (e.g. spray-dried powder) or as an intermediate product that will undergo subsequent transformations (e.g. a freshly pressed tile body).

With a view to quantifying implementation of control in the ceramic industry, a number of "automation levels" are defined below (Figure 3.1). The lowest level contains purely manual control and the highest level comprehensive automatic control, involving all production stages and their interactions.

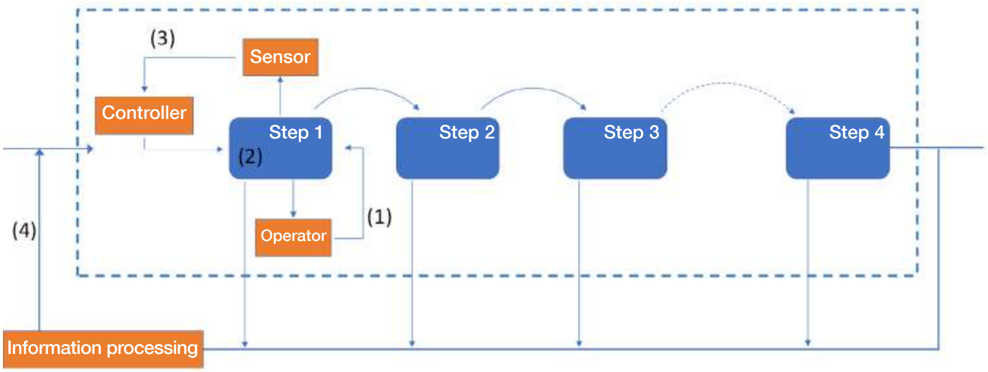


Figure 3.1. Distribution of control levels in the ceramics manufacturing environment: ((1) manual control; (2) machine control; (3) product control; (4) comprehensive control).

Level 1: Manual control

The first level of control may be termed manual. Here, an operator measures one or more variables and, depending on product specifications (settings), manually changes a series of variables. Examples of this type of actions occur in the old passage or tunnel kilns, in which temperature was controlled by means of a hot-wire pyrometer operated by a worker.

However, one need not go back so far in time. Nowadays, at most companies, moisture content of the spray-dried powder produced by the spray dryer is controlled by manual measurement, using an infrared balance, and acting on the burner temperature setting or on some other variable in a discontinuous, manual manner.

Level 2: Automatic control of machine variables

The complexity of many of today's machines (dryers, presses, kilns, etc.) has led to a certain level of control in all of these. Such control involves machine variables, as opposed to product variables, which are the characteristics of the material being processed. This level of control is found in innumerable facilities, such as presses, where the machine variable being controlled is pressing pressure, while the product variables of interest for regulation are, for example, tile bulk density and thickness.

Control levels are not linked to machines, as one might imagine at first, but to sets of input and output variables. Thus, in spray dryers, the pair of variables gas temperature/spray-dried powder moisture content is manually controlled (level 1) at most companies, whereas the pair of variables gas temperature/position of the burner gas valve is a clear example of control of machine variables (level 2).

The use of relatively simple control systems, such as proportional-integral-derivative controllers (PIDs) or programmable logic controllers (PLCs), is typical at this level. The dizzying development witnessed by information technology in the last two decades has led computers to be fitted in many machines of a certain complexity. However, it is somewhat disappointing that, despite the power these devices have, they are mostly just used as data loggers, when they could play a much more active role.

Level 3: Automatic control of product variables

The third level of control features regulation of product variables, incorporating the required sensors. This third level involves at least two different areas of knowledge: that of materials and processes and that of instruments.

Knowledge of the materials and processes involved in frit and ceramic tile manufacture is usually sufficiently advanced to implement a control system. This is partly because, to enable control, it suffices to have an input/output model that relates the changes that take place in an output variable to the changes in an input variable. General techniques, such as design of experiments or empirical identification of parameters, can allow the necessary information to be obtained to perform automatic control.

The greatest difficulties in automatic control almost always lie in having an appropriate sensor to make the measurement or in defining the variables on which to act (manipulated variables). Selecting a new sensor usually tends to be a complex process, as it needs to work with sufficient accuracy and robustness in a field for which, in all likelihood, it was not originally designed. Typical cases are infrared moisture meters, originally designed for moisture measurement in tobacco leaves; radio-frequency meters, used in the wood and gypsum industry; and density sensors by bubbling, applied in the mining industry.

In the example of the spray dryer, the third level of automation would consist of controlling the variable of the intermediate or semi-processed product: spray-dried powder moisture content (as opposed to the machine variable, which is gas temperature).

In the simplest cases, such control may be performed with proportional-integral-derivative controllers (PIDs) or programmable logic controllers (PLCs). However, as the equations governing the processes become more complicated, it becomes necessary to resort to computers. In other industrial sectors, computers are used for anticipatory and predictive control, expert systems, or for dynamic simulation [40]. In all these cases, a process model is implemented in the computer. The model may be theoretical (based on property balances, rate equations, thermodynamic equations, etc.), empirical (neuronal networks or fitted equations), or semi-empirical (based on theoretical equations with experimentally determined fitting parameters).

At present, this type of model is only commonplace in automatic ceramic tile sorting systems. Although studies have been undertaken to apply advanced systems in process control (application of DMC models [41] to milling, dynamic simulation applied to tile drying [42], or implementation of compaction diagrams for tile density control at the press exit [43]), such developments are currently not very widespread.

Level 4: Comprehensive control

The different unit operations that make up the ceramic process (milling, spray drying, pressing, etc.) are interdependent. One operation's output is the next operation's input. Thus, control of spray-dried powder moisture content conditions resulting pressed tile density, which in turn influences tile shrinkage during firing.

Inappropriate execution of any process stage not only affects development of the following stages, but also intermediate product characteristics (porosity, permeability, etc.) and end-product characteristics. The ceramic tile manufacturing process is to be understood as a set of interconnected stages that progressively transform raw materials into the finished product [44]. Automatic control cannot, and should not, limit itself to individual stages. Comprehensive process control constitutes an approach whose application would provide information (and not just data) on the process, for wide-ranging optimisation of tile manufacture and detection of weak points.

The ceramic industry is starting to address this fourth level, albeit in an incipient fashion, and it involves, in particular, acquisition of information. An increasing number of companies have a centralised system in which operators from each stage enter process data, the number of tiles processed are indicated, or tiles are monitored throughout the process. In addition, some manufacturers have already begun to address key aspects to attaining this level. Thus, nowadays, machine intercommunication is often enabled because machinery manufacturers are using communication protocols that are increasingly open and standardised. Closed protocols are still being used only in certain specific cases as a way to assure exclusiveness: in these cases, nobody save the manufacturer will be able to be set up communications with the machine or be able to integrate it into a larger network.

Comprehensive control should also envisage integral actions: that is, manipulating variables and not just acquiring information. Today's technology enables this step to be taken.

3.2 Control and automation of the different process stages

Even though, as noted above, the more advanced levels of comprehensive control have as yet been poorly implemented in the ceramic tile manufacturing process, recent years have witnessed numerous advances in automating controls of product variables. These advances nowadays allow automatic control of critical process variables in practically all manufacturing process stages. A brief description follows of the control technologies that could be deployed in manufacturing plants for each ceramics manufacturing process stage, these being control technologies that, in some form, serve to round off consolidation of the lower levels of control prior to the implementation of advanced control systems in the next steps of the transformation process towards Industry 4.0.

The information detailed below is grouped into the following manufacturing stages:

- Compositions preparation
- Forming (pressing + drying)
- Glazing and decoration
- Firing
- Rectification and sorting

These stages are articulated in a general way in terms of the scheme shown in **Figure 3.2**. The major automatic control technologies are set out for each section, together with the minimum data that need to be acquired in each stage to lay the groundwork for the transformation towards Industry 4.0 in ceramic tile manufacturing plants.

Continuous, automated collection of these minimum data will allow a so-called digital twin to be implemented, which will serve as sole information source for managing in-plant operations.

3.2.1 Compositions preparation

The compositions preparation section usually includes, first, a continuous wet-milling step using ball mills, followed by spray drying of the resulting suspension to obtain the spray-dried powder used in forming the tile bodies.

3.2.1.1 Information management in the compositions preparation section

Production operations in this section are customarily highly automated, there being very little intervention by operators in regulating these operations. In general, however, the systems for collecting and sending critical process data to a higher information system are poorly developed. Thus, for example, though a plant's continuous mills are usually fitted with different automatic control loops, as described below, the data they

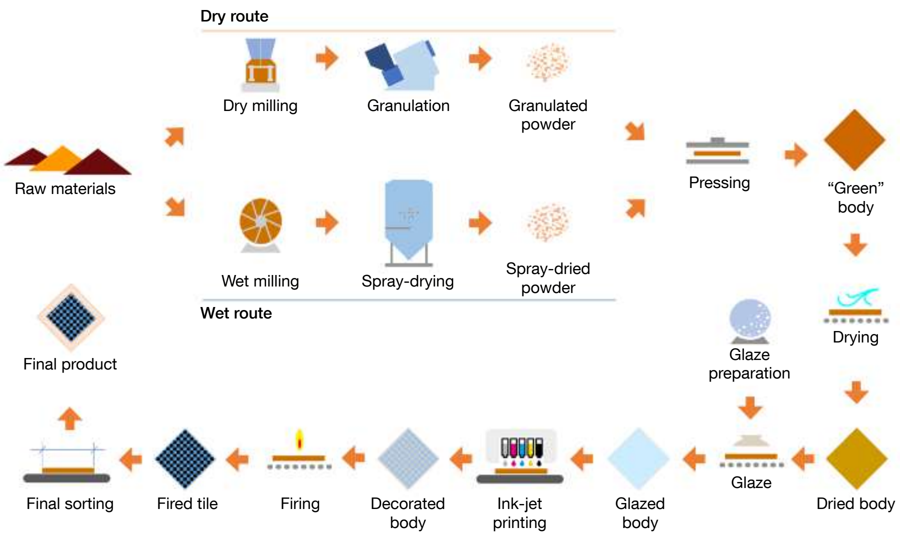


Figure 3.2. Stages in the ceramic tile manufacturing process by the wet method.

generate remain in the facility's own management system, without being exploited at a higher level. It is therefore deemed of interest to be able to develop visualisation interfaces specifically tailored to the needs of the section in order to be able to rapidly evidence anomalous states in the workings of the equipment or operating variables.

Spray-drying plants generally exhibit a lack of information regarding their production efficiencies, though it is true that there are elements, such as the weighing belts installed at the outlet of some spray dryers, which allow an adequate degree of control to be achieved. In this sense, it would be convenient to be able to install data collection tools to control a facility's performance in real time, while at the same time storing the information for subsequent detailed analysis.

This would yield information of greater value than that currently being obtained, customarily by hand, in routine controls from the average data provided by the different control systems. Many of the variables that would allow integrated effectiveness management are to be found in the control systems themselves of the mills and spray dryers. In the case of mills, the visualisation tool provided by the equipment's Scada or management system itself often supplies information on running and stoppage times, operating alarms, and amounts of processed products. These data, once duly integrated, can be used to calculate production performance and to generate useful indicators for optimising the manufacturing process.

As to the variables relating to processed product quality or characteristics, there has generally also been a lack of development both in measurement and data collection, as well as in subsequent data processing to generate information that will help decision making. Though automation of data input might be a first step towards assuring information flow towards integrated data management systems, it is essential to start evaluating the use of continuous measurement systems of process variables, such as those set out in the following section. For some of these variables, such as particle size of the resulting milling suspensions or spray-dried powder granule size, no low-cost measurement techniques have as yet been validated on an industrial level. However, for other variables, such as slip density and viscosity or spray-dried powder moisture content, there are sufficiently robust, proven transducers that can be incorporated into production systems. In any event, it should be borne in mind that integration of these measurement elements must also be linked to implementation of an appropriate information management system for the data they generate to be suitably presented in a customised way for the data users.

Further to the above remarks, it should also be noted that agile systems for real-time monitoring of the evolution of production orders or manufacturing orders relative to planning are often unavailable. Having a system that performs such monitoring and management is critical to assuring appropriate production traceability in order subsequently to analyse production operations and generate information of value that that will enable operations development to be optimised. In an advanced state of implementation of Industry 4.0 standards, the manufacturing orders or production batches to be carried out need to be digitalised for section operators or heads to know when to start them and be able to link all the information generated on the process to each respective manufacturing order. This manufacturing order could even be used for the equipment to automatically load the operating parameters and, if the information were digitally transferred to the other process stages, it would allow workers in other sections to have the process information that could help better perform their work. By way of example, if the critical process information from the compositions preparation section were appropriately aggregated and available, when the resulting spray-dried powder reached the pressing section, anomalies detected in variables such as spray-dried powder moisture content could be signalled in advance.

3.2.1.2 Automatic control systems of critical variables in compositions preparation

3.2.1.2.1 Wet milling

Milling is performed to obtain a homogeneous solids suspension in water, with appropriate particle size distribution (PSD) to carry out the following stages (pressing, drying, etc.), compatible with high solids content and appropriate viscosity for optimum performance of the spray drying operation [45].

The particle size distribution of suspended solids conditions tile body behaviour during processing (compaction, diffusion, etc.) and determines a number of finished tile parameters (end size, porosity, etc.). Particle size distribution measurement is complex and laborious. On an industrial level, the close relationship that exists, for a given material and type of grinding mill, between a solid's PSD and amount of coarse particles for different milling times is therefore used. Indeed, wet milling mainly reduces coarse particle size, narrowing PSD, so that measurement of the residue (sieve oversize) allows the milling operation to be controlled by a simple test.

Density largely determines energy efficiency in the spray-drying stage and must, therefore, be as high as possible. However, for a given composition, increasing density also raises viscosity, and high viscosities adversely affect mill discharge, possibly leading to anomalies in the mill (formation of crusts or agglomerated lumps), decreasing sieving speed, and detrimentally affecting spray drying. Consequently, in the milling stage, it is sought to achieve the highest possible suspension density, while keeping a constant viscosity that allows suspension processing.

These variables are at present measured manually by an operator. In milling, one needs to distinguish between what is done in continuous grinding mills from what is carried out in Alsing-type batch mills. Automation is much easier to implement in the former than in the latter. Therefore, in this section, the discussion will focus on continuous mills.

The machine variables (clay, water, and deflocculant flow rates) are automatically measured. In accordance with the different levels presented in Section 1, continuous milling may be deemed at level 2.

The last few years have witnessed a significant striving to implement automatic density and viscosity control, leaving aside waste control [46,47]. The idea of automatic control in continuous mills consists of continuously measuring suspension density and viscosity and acting on water and deflocculant flow rates (**Figure 3.3**).

The main difficulty in automatic control of this operation lies in reliable density and viscosity measurement and, hence, in the use of appropriate sensors. At present, the issue of industrial measurement of suspension density may be deemed resolved by using Coriolis-effect densimeters (**Figure 3.4**).

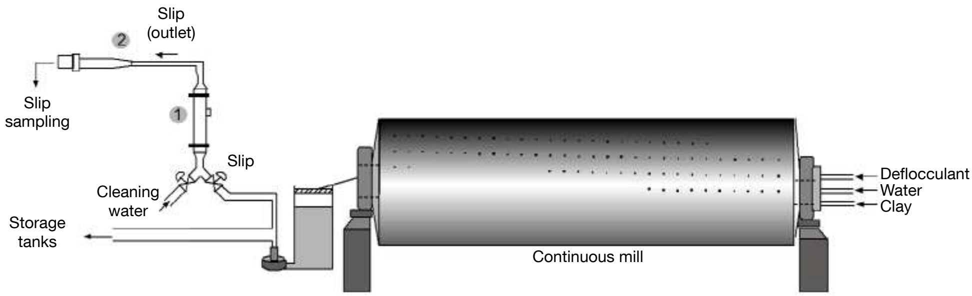


Figure 3.3. Scheme for continuous industrial measurement of suspension density and viscosity at the continuous mill outlet: (1) densimeter/mass flow meter; (2) viscometer.

Figure 3.4. Coriolis densimeter/mass flow meter (left) and viscometer (right) used in ceramic suspension milling control.

The future trend for control in this stage would involve design of an advanced control system that measured density, viscosity, and even PSD. This poses numerous difficulties: interaction between density and viscosity control loops, fine-tuning a viscosity sensor, etc. The incorporation of particle size, though technically possible, raises difficulties that are not expected to be solved in the short term. The control system would need to be smart enough to manage interaction among all variables, which cannot be done by just using proportional-integral-derivative (PID) controllers.

3.2.1.2.2 Spray drying

Spray drying of the suspension obtained by milling is the most widespread granulation method for producing press powder in the Spanish and Italian ceramic tile sector. The two most important press powder variables are moisture content and agglomerate or granule size distribution (GSD).

Moisture content and maximum compaction pressure together determine pressed tile bulk density, which is one of the most important variables in the entire production process, as set out below. The quantitative relationship between density, pressing pressure, and moisture content is expressed in the well-known compaction diagram [48].

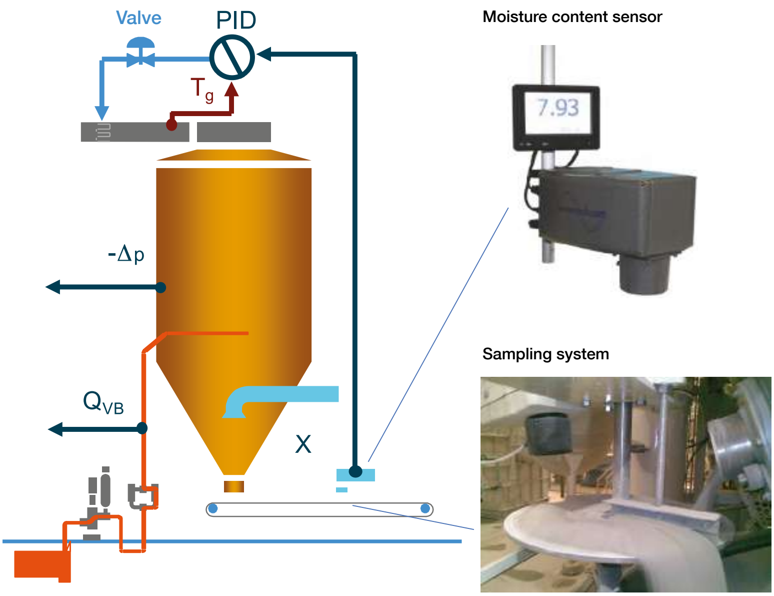


Figure 3.5. Automatic control of powder moisture content at the spray dryer outlet.

Granule size distribution (GSD) determines powder flowability, which affects its behaviour, fundamentally during filling of the press cavity [49,50]. Appropriate powder flowability leads to uniform filling of the press cavity and to uniform bulk density distribution in the compacted tile body. If tile bulk density is uniform, the behaviour of the tile body during processing will also be consistent and, more importantly, end-product geometry will be appropriate. In addition, inappropriate GSD can lead to variations in moisture content distribution (coarse granules are also the wettest) and granule segregation during transport and storage in silos. If granules of different colours are mixed, segregation can lead to the appearance of small colour differences or shades in tiles.

In recent years [51,52] significant advances have been made in controlling the pair of variables: gas temperature setting/spray-dried powder moisture content. At present, many companies have infrared meters, together with a spray-dried powder sampler, to monitor moisture content, though a smaller number use this signal to close the control loop, and not just measure but also control moisture content. The spray-drying operation can be controlled either by modifying drying gas temperature, based on the detected changes in moisture content of the powder made, or by acting on the flow rate of the suspension injected into the drying chamber. The control action on suspension flow rate has the advantage of being faster than that on the change in drying gas temperature. Indeed, the large size of spray dryers involve a very large thermal inertia, entailing long response times when the control system is based on modifying gas temperature. This does not occur when control is performed by modifying suspension flow rate, which practically leads to immediate change in resulting powder moisture content. A disadvantage of the use of slip flow rate as control variable lies in the need to slightly change the spray dryer's production capacity, which can entail modification of the amount of suspension fed into the drying chamber. Recent experiments have also revealed the possibility of controlling the spray dryer by modifying the flow rate of the hot gases fed into the spray dryer, on acting on the rotation speed of the system tail fan.

Granule size distribution could be measured automatically. However, two factors adversely affect control of this variable: the high cost of sensors and the fact that current spray-dryer design, in particular nozzle design, does not allow granule size distribution to be readily modified.

3.2.1.3 Minimum data to be integrated in the compositions preparation section

Finally, to round off the review of aspects relating to the compositions preparation section, **Table 3.1** details the minimum information required for proper management of the operations in this section. The information is broken down into four fields: performance and production management, process variables, resource consumption, and variable costs. Having this information would lay the groundwork for defining a digital twin of this first process stage, which could be integrated into a digital twin of the entire manufacturing process.

Table 3.1. Minimum information required in the compositions preparation section to lay the groundwork for the manufacturing process digital twin.

Table 3.1.1	Proportioning, continuous milling, and stirring tanks
Level of information	**Data/description**
PERFORMANCE AND PRODUCTION MANAGEMENT	Production order, batch reference, or production trace
	Manufacturing order progress relative to planning (%)
	Availability (A) = Production time/Available time (%)
	Performance (P) = Actual production/Theoretical production (%)
	Quality (Q) = Discarded amount of suspension/Produced suspension (%)
	Distribution of reasons for stops
	Overall Equipment Effectiveness (OEE) = A x P x Q (%)
PROCESS VARIABLES	Raw materials moisture content (%)
	Milling water and resulting suspension density (kg/m^3)
	Mass flow rate of milling water fed into the grinding mill (kg/s)
	Mass flow rate of solids fed into the grinding mill (kg/s)
	Deflocculant mass flow rate (kg/s)
	Mass flow rate of solids streams proportioned from primary silos (kg/s)
	Viscosity of resulting suspension (cp)
	Solids content of suspension made (%)
	Temperature of suspension made (°C)
	Mass flow rate of suspension made (kg/s)
	Residue particle size (%)
	Mill running/stop state (Boolean)
	Mill rotation speed (rpm)
	Mill vibration mode (m/s2)
	Tank stirrer running/stop state (Boolean)
	Tank suspension rest time (h)
	Stirrer rotation speed (rpm)
	Slip tank temperature (°C)
RESOURCE CONSUMPTION	Milling water consumption (m^3/m^3 suspension or m^3/m^2 finished product)
	Raw materials consumption (kg/m^3 suspension or m^3/m^2 finished product)
	Deflocculant consumption (kg/m^3 suspension or m^3/m^2 finished product)
	Electric power consumption in milling and ancillary systems (kW h/kg suspension or kW h/m^2 finished product)
	Human resources (HR) consumption (individuals/shift or individuals/m^2 finished product)
VARIABLE COSTS	Raw materials cost (€/m^3 suspension or €/m^2 finished product)
	Electric power cost (€/m^3 suspension or €/m^2 finished product)
	Human resources (HR) cost (€/m^3 suspension or €/m^2 finished product)

Table 3.1.2	Spray drying and silo storage
Level of information	**Data/description**
PERFORMANCE AND PRODUCTION MANAGEMENT	Production order, batch reference, or production trace
	Manufacturing order progress relative to planning (%)
	Availability (A) = Production time/Available time (%)
	Performance (P) = Actual production/Theoretical production (%)
	Quality (Q) = Discarded amount of suspension/Produced suspension (%)
	Distribution of reasons for stops
	Overall Equipment Effectiveness (OEE) = A x P x Q (%)
PROCESS VARIABLES	Spray-dried powder moisture content (kg water/kg powder (%))
	Temperature of spray-dried powder produced (°C)
	Granule size distribution (%)
	Mass flow rate of spray-dried powder produced (kg/s)
	Mass flow rate of suspension feed (kg/s)
	Suspension feed density (kg/m^3)
	Suspension feed viscosity (cp)
	Suspension pumping pressure (bar)
	Pump running/stop state (Boolean)
	Suspension feed solids content (%)
	Suspension feed temperature (°C)
	Drying gas temperature (°C)
	Drying gas flow rate (Nm^3/s)
	Air intake temperature at mouth cooler (°C)
	Static pressure in drying chamber (Pa)
	Differential pressure between drying chamber and tail fan entrance (Pa)
	Tail fan rotation speed (rpm)
	Gas output temperature before cooler or filter (°C)
	Spray dryer running/stop state (Boolean)
	Silo spray-dried powder content (%/silo or kg/silo)
RESOURCE CONSUMPTION	Suspension consumption (m^3/kg spray-dried powder or m^3/m^2 finished product)
	Natural gas consumption (Nm^3/kg spray-dried powder or Nm^3/m^2 finished product)
	Electric power consumption in spray drying and ancillary systems (kW h/kg spray-dried powder or kW h/m^2 finished product)
	Human resources (HR) consumption (individuals/shift or individuals/m^2 finished product)
VARIABLE COSTS	Raw materials cost (€/kg spray-dried powder or €/m^2 finished product)
	Electric power cost (€/kg spray-dried powder or €/m^2 finished product)
	Natural gas cost (€/kg spray-dried powder or €/m^2 finished product)
	Human resources (HR) cost (€/kg spray-dried powder or €/m^2 finished product)

Part of the information detailed in **Table 3.1** can be obtained from the process variables themselves listed in the table. However, it is essential to have the additional data shown in **Table 3.2** in order to be able to properly process all the information indicated. Together with the additional data item involved, **Table 3.2** shows the data origin or source from which it could be obtained.

Table 3.2. Additional data required to obtain the minimum information needed to define the digital twin of the compositions preparation section.

Level of information	Data	Data source
PERFORMANCE AND PRODUCTION MANAGEMENT	Equipment running time (h)	Management PLC and automation or external counting system
	Planned production (m^3 or kg)	ERP information or management system
	Equipment theoretical production (kg or m^3/s)	ERP information or management system
	Cumulative theoretical production (kg or m^3)	Management PLC and automation or external counting system
	Production (kg or m^3)	Manually assigned or automatically recorded by meters
	Reasons for stops	Assigned by operators or directly acquired by PLCs
	Reasons for loss	Assigned by operators or directly acquired by PLCs
RESOURCE CONSUMPTION	Theoretical proportion m^3 suspension/m^2 finished product	ERP, product data sheet, or management system
	Theoretical proportion kg spray-dried powder/m^2 finished product	ERP, product data sheet, or management system
	Distribution of personnel	ERP or human resources (HR) management system
	Work team or active shift	ERP or human resources (HR) management system
	Spray-dryer natural gas consumption (m^3)	Digital gas meter
	Natural gas temperature (ºC)	Pt-100 digital gas meter
	Natural gas supply pressure (bar)	Digital gas meter pressure transducer
	Equipment electric power consumption (kW h)	Digital grid analysers
VARIABLE COSTS	Raw materials and additives price (€/kg)	ERP or management system
	Electric power price (€/kW h)	ERP, supply company contract, or Web scraping
	Natural gas price (€/kW h)	ERP, supply company contract, or Web scraping
	Assigned human resources (HR) average price (€/person)	ERP or management system
	Natural gas heating value (kW h/Nm^3)	ERP, supply company contract, or Web scraping

Combining these variables, on the one hand, with real-time knowledge of equipment run/stop and/or alarm states and, on the other, with information on manufacturing order traceability, would enable accurate determination in real time of the management information detailed in **Table 3.1** for each production batch.

Proper storage in a well-structured system of databases of all the information set out in the above tables will allow analysis a posteriori of specific production batches, provided batch traceability can be assured.

3.2.2 Forming

Ceramic tile bodies are formed in hydraulic presses with different capacities, depending on the tile size to be processed. The presses are fed with spray-dried powder either from the compositions preparation section or, on outsourcing tile body preparation, from the facilities of a supplier from whom the spray-dried powder is directly acquired as semi-processed raw material. Before the spray-dried powder is processed in the forming section, it is left to rest for some time in an array of silos, with a view to homogenising powder moisture content as far as possible. In each press, a system then feeds the spray-dried powder into the cavities of a metal die, whose construction design and mode of operation depend on the characteristics of the product to be made and on the press used. As a result of the force transferred by the press hydraulic circuit to the die punches, powder density progressively increases, and the tile body takes on the desired form. The resulting tile bodies are extracted from the die and fed into a series of dryers, usually one for each press, in which body moisture content is reduced, thus increasing body mechanical strength, to enable the tile bodies to subsequently withstand transfer and processing in the glazing and decoration lines.

Generally speaking, the dies and punches used in the forming sections of ceramic tile manufacturers are fabricated, supplied, and repaired by external suppliers. In some cases, the press supplier may also supply the dies and gear relating to the punches.

3.2.2.1 Information management in the forming section

The degree of automation of production operations in the forming section, as in compositions preparation, is very high, very little operator intervention being needed to regulate these operations. However, the systems for collecting critical process data and sending these to a higher information system are generally poorly developed. Thus, for example, though presses could be enabled by the manufacturer, via a standard communication protocol, to provide a great amount of data on press operation, these data usually remain in the equipment's own management system without being advantageously used at a higher level.

The most advanced presses currently have information systems that enable the evolution of certain operating parameters to be visualised in quite high detail. However, these tools are rarely used to improve operations management, as they are not integrated into a higher level of control and are not particularly user friendly. For this reason, it is deemed of great interest to be able to develop visualisation interfaces specifically adapted to the needs of the section in order to be able rapidly to evidence anomalous states of operation of the equipment or operating variables, avoiding the need for monitoring based on manually compiled information managed by computer applications involving spreadsheets and the like. Thus, by way of example, the planning of maintenance actions, instead of being performed on the basis of information routinely compiled from work slips, could be carried out directly via data collected by the press itself, which would allow such tasks to be simply and readily digitalised and automated.

In regard to control of critical process variables, as set out in the following section, advanced instruments are nowadays available for the relevant manufacturing and quality controls. Thus, for example, the degree of compaction of the resulting tile bodies can be measured non-destructively, using a quick, agile method based on X-ray absorption measurement of body density distribution, thickness, and charge for any press adjustments and start-up of new tile sizes and/or models. Or moisture content of the spray-dried powder press feed may be automatically measured, this being a very important parameter in the forming process.

Regarding the remaining operation parameters in the forming sections, to be noted is measurement of unfired and fired product dimensions, which are used to verify the proper settings of the forming conditions. In floor tiles, dimensional measurement of the fired bodies, obtained by spot tests conducted by operators in the forming sections, is used to evaluate possible departures from rectangularity and calibers between tiles obtained in the same pressing cycle. Although implementation has started of automated systems for non-contact measurement of tile dimensions, measurement benches based on the positioning of manually actuated mechanical pickups are generally used, which can introduce significant uncertainties in the resulting measurements.

In any event, regardless of the measurement system used to control critical process variables, lack of processing may be observed of the resulting data, which are partly collected on paper and on occasions entered in the ERP or quality management tools. It would be necessary for the data flows associated with process variable controls to be duly automated and traced in order to begin to implement analysis tools that allow information of value to be generated from these data flows.

With respect to body drying, systems for control and monitoring of the parameters and variables relating to the drying operation are poorly developed. Although measurements are available of major process variables such as body temperature for appropriate development of the subsequent decoration step, this is only used on occasions as an indication, without a record being kept to enable further use, both for improving dryer operation and for obtaining information that could allow any shortcomings noted in the decoration process to be explained. The following section shows that sufficiently developed technological means are today available to address these issues.

As to the determination and management of production efficiencies, there is a significant lack of data, as press efficiencies are usually only occasionally determined, based on manually noting down the number of press cycles performed daily or sometimes even weekly, without taking into consideration machine availabilities and product qualities. It is deemed feasible, in a relatively simple way, to improve this point, recording the reasons for machine stops and generating information of value for optimising production operations. This requires digitalising management of manufacturing orders through own tools or ERP systems, which serve as the basis for integrating production information into higher levels of control. Such integration obviously needs to be used to enable process variables and parameters to be properly traced in order to establish interrelationships that allow insight and transparency to be generated concerning events that occurred in carrying out the operations.

The ceramic tile manufacturing process does not currently allow traceability in the company's internal processes of the product made. This is fundamentally because, despite appearances to the contrary, the process is not really a typical continuous manufacturing process. Indeed, the existence in most factories of a buffer or midway station, where both unfired material before firing and fired products before final sorting are stored, adversely affects proper production tracing. However, current industrial experiments have enabled development of specific systems for assuring traceability of the product made. Of the different possibilities for tracing production, the option that best matches the needs of the ceramic process is marking DataMatrix (DM) two-dimensional codes on the back of the tiles made.

As illustrated in the scheme of **Figure 3.6**, the system as a whole consists, on the one hand, of a printhead (1) installed at the press exit, which marks the resulting tiles with a unique identifier (UID) (2) and, on the other, of a series of detection cameras located (3) at points along the manufacturing lines at which it is desired to control tile passage.

The system records, in a set of databases (4), the exact time at which each tile passes a given point in the manufacturing line. It is thus later possible to identify the process conditions and other operating events that were occurring precisely when the tile was being processed. To assure coding integrity during tile thermal treatments, the marking system must use ceramic pigment-based inks that remain fixed to the body during firing. The system has great potential. Thus, for example, relationships can be determined in real time, tile by tile, between variables such as tile size at the kiln exit with firing and/or pressing conditions or tile defects, recorded by the automatic inspection systems, and operating conditions or events in the line.

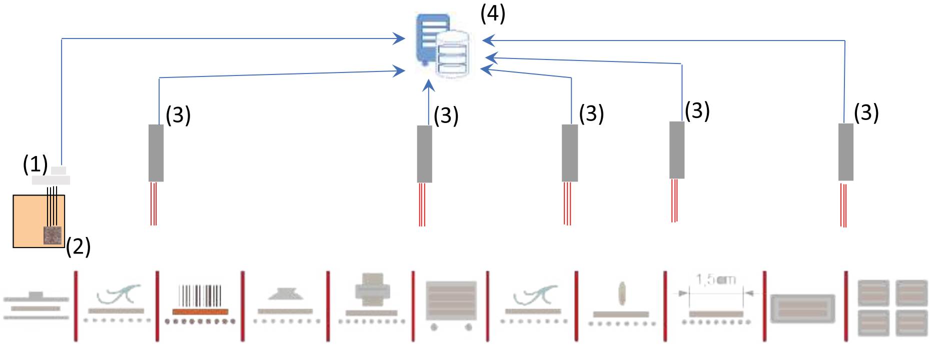


Figure 3.6. Operation scheme of the developed traceability system.

As the photographs in Figure 3.7 show, a first detection camera is located right next to the marker exit. In addition to recording the tiles passing between the pressing and drying stages, the camera allows the integrity of the printed codes to be evaluated. The printing system has a retractable mechanism for periodic automatic cleaning of the printhead or when slightly damaged codes are detected. The detection cameras are positioned in the bottom part of the manufacturing lines, a pressurised air cleaning system being incorporated in areas where the cameras are most prone to soiling.

Finally, it may be noted that, as indicated for the compositions preparation section, it is of interest for production management tools in the forming section to be able to display information, in anticipatory fashion, on critical pressing variables for other sections in the plant. Thus, for example, before tile firing, those in charge of the firing section could be aware of average tile bulk density or bulk density scatter in a manufacturing order, which could be of great help in preventing problems stemming from variations in tile dimensional stability.

Figure 3.7. From left to right: printhead for tile marking, coded tile, and detection camera.

3.2.2.2 Automatic control systems in the forming section

3.2.2.2.1 Pressing

The most important process variable relating to the characteristics of the pressed body is its bulk density, involving both its average value as well as its distribution throughout the tile body.

Bulk density influences tile behaviour during the post-pressing stages and conditions some of the most important characteristics of the end product. Bulk density is the macroscopic variable that reflects a tile's porous structure, which is why it determines tile permeability to gases, mechanical strength, sintering process, modulus of elasticity, etc. Inappropriate bulk density can lead to the appearance of cracks during drying, fracture in the glazing line, black core, lack of dimensional stability (calibers and/or departures from rectangularity) or of flatness in the end product, or inappropriate final porosity [53].

Uniformity in tile bulk density distribution has improved greatly in recent years with the use of hydraulic punches and isostatic plates in the presses. Though lack of uniformity has not wholly disappeared, the main concern today lies in the difference in bulk density between tiles.

Until only a few years ago, bulk density was measured manually or semiautomatically, basically by the mercury displacement method. Studies have been carried out [54,55], to try to replace this test, given its discontinuous, manual, destructive, and harmful character. One of the most advanced techniques in this sense is X-ray inspection. ITC-AICE has developed, patented, and prototyped a revolutionary technique for non-destructive inspection of ceramic tiles. This new technique, based on X-ray absorption and laser telemetry provides density, thickness, and charge distribution maps of the entire tile, with greater accuracy than those obtained by traditional destructive methods. The preliminary prototype is currently fully industrialised. A disruptive technology is involved, used by more than 30 companies worldwide, for controlling tile quality in the forming stage.

Bulk density measurement by traditional methods requires destroying the tile, cutting it up into small pieces with the ensuing loss of time and related resource consumption. In addition, the information provided by these methods is incomplete, as not all the tile surface area is analysed, and only average bulk density values are obtained. DENSEXPLORER®, the density measurement unit's trade name, overcomes all these drawbacks by performing comprehensive, non-destructive inspection of tile bodies.

Using DENSEXPLORER®, all tile bodies obtained in the same pressing cycle are analysed simultaneously. The test provides technicians with colour maps displaying the density, thickness, and mass distribution of all analysed tiles (**see Figure 3.8**), the maps being complemented with numerical information supplied by different analysis tools implemented in the results interpretation software. This graphic information is much more user friendly than the simple numerical information provided by conventional destructive methodologies, entailing a paradigm change for companies using the new technology. Indeed, the comprehensive visual information provided by the system affords greater insight into the physical phenomena at issue in the powder compaction process and faster response to the detected defects.

Though it has been attempted to use ultrasonics sensors in continuous measurement of tile bulk density [56], the accuracy required for automatic control was not achieved in the experiments conducted. In another attempt to obtain continuous measurement of tile bulk density, strain sensors were installed in the press punch for measuring pressure distribution in the tile [57]; however, the system's mechanical complexity made it unfeasible for industrial use as a control system.

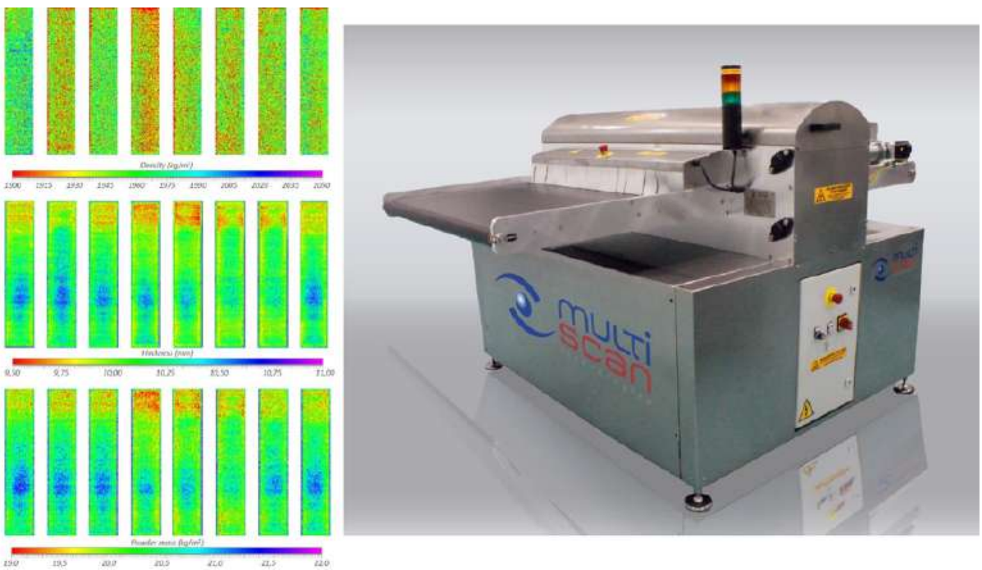


Figure 3.8. Left: tile density, thickness, and mass distribution maps obtained by a typical test performed using DENSEXPLORER® on 8 tile bodies measuring 800 mm x 150 mm, formed in the same pressing cycle. Right: view of the DENSEXPLORER® measurement unit.

An alternative way of addressing the problem consists of using an anticipatory control strategy. Anticipatory control is based on measuring the variable that causes the disturbance, and not the process variable to be controlled, as occurs in control by feedback. The main disturbance variable in the pressing process is moisture content of the spray-dried powder fed into the presses: Therefore, measuring powder moisture content should enable density to be controlled. Powder moisture content can be measured with an infrared sensor, identical to the one used in controlling spray drying, installed at the press exit, and modifying maximum pressing pressure in accordance with the variations in moisture content to keep bulk density constant. This type of control system enables the percentage of calibers, for example, to be significantly reduced, as discussed below.

At present, automatic control of the pressing operation by measuring moisture content of the freshly pressed tile bodies and modifying maximum pressing pressure is a mature technology implemented in particular in presses for producing porcelain tile bodies.

As noted above, variability in average bulk density of freshly pressed tile bodies stems mainly from changes in spray-dried powder moisture content. By way of example, **Figure 3.9** shows how tile moisture content and pressing pressure evolve in a press in which an automatic bulk density control loop has been implemented.

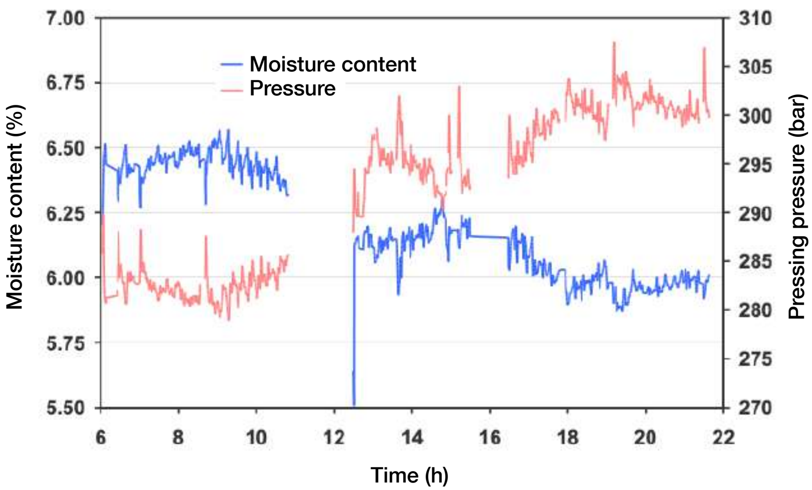


Figure 3.9. Evolution of spray-dried powder moisture content and pressing pressure for a full day's production with the enabled automatic control system.

Variations in moisture content can be offset by varying pressing pressure, so that bulk density remains constant. The evolution of pressing pressure shown was calculated from the moisture content and compaction diagram of the composition used in forming the tile bodies. It may be observed how, as moisture content decreases, pressing pressure needs to be raised.

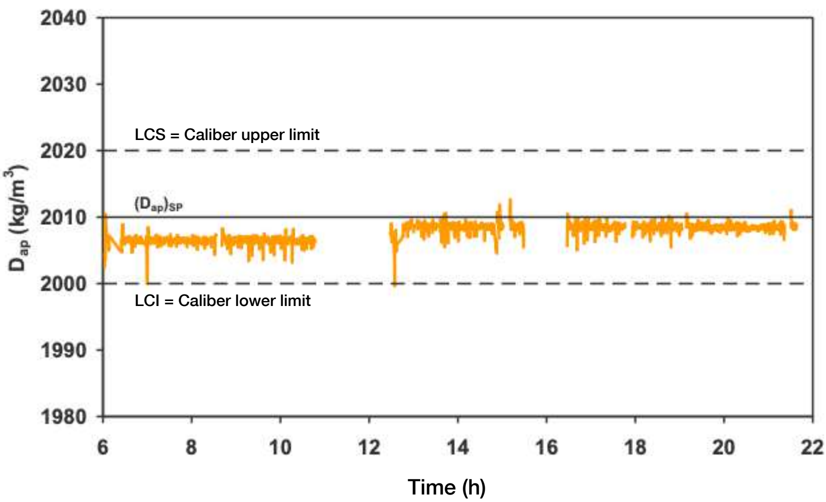


Figure 3.10. Evolution of estimated bulk density for a full day's production with the enabled automatic control system.

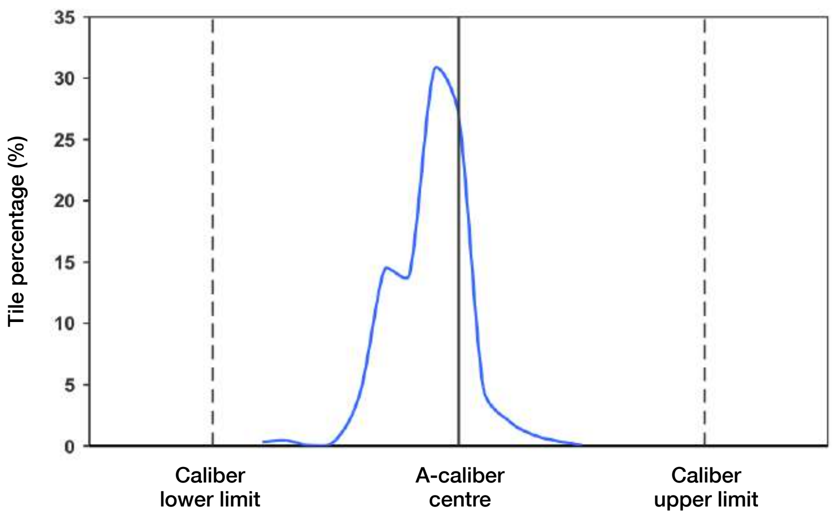


Figura 3.11. Tile size sorting with the enabled automatic control system (Production: 2700 m², size 45 cm x 67.5 cm, porcelain tile).

Finally, Figure 3.10 shows the calculated bulk density values. It may be observed that this value remains within the set specification limits. Figure 3.11 shows the final sorting of the sizes corresponding to the same period of time in which the data in Figure 3.12 were collected. Sorting matched the evolution of tile body bulk density estimated by the control system. In fact, a single caliber was obtained and sorting was centred at the average size of the targeted caliber.

The specification limits were set on the basis of the average density value recorded throughout the analysed period. The limits (+/- 10 kg/m^3) represent the maximum density variation that might occur without there being tiles at the end of the process with a difference in sizes exceeding the set caliber tolerance (+/- 1 mm) for a tile size of 45 cm x 67.5 cm.

3.2.2.2.2 Drying

The freshly pressed tile bodies are dried to reduce their moisture content and acquire an appropriate temperature for the decoration stage to be carried out properly.

The process variables to be controlled in tile bodies after drying are tile temperature and residual moisture content. High body moisture content reduces tile mechanical strength and adversely affects the decoration operation. Temperature affects the glazing stage: inappropriate temperatures can lead to defects (pinholes, etc.) or non-uniform glaze spread on the tile surface.

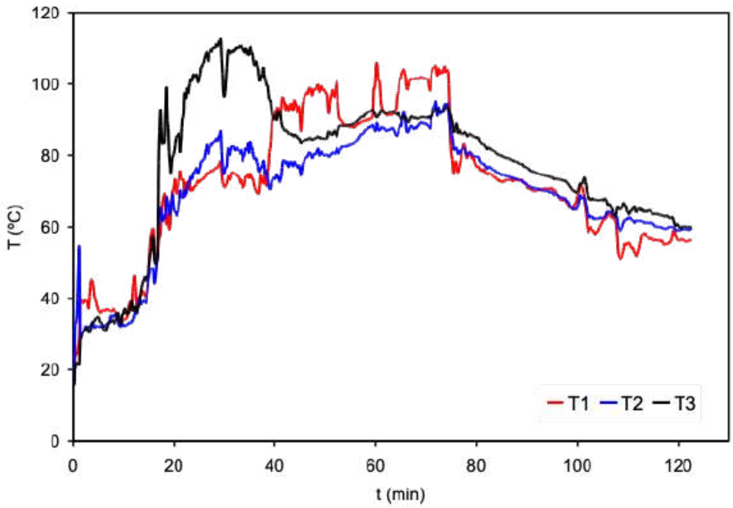


Figure 3.12. Gas temperature in a vertical dryer at different positions in a plane during a drying cycle.

Tile temperature and moisture content at the dryer exit both depend on the temperature distribution and, to a lesser extent, on the relative humidity of the gases in the dryer. The information on the temperature curve inside the dryers is very fragmentary, particularly in vertical dryers (temperatures of the gases entering the dryer and of the recirculated, stack, and stabilisation gases).

There are temperature probes, consisting of data loggers with a series of thermocouples, which are set in the dryer and provide information on the temperature curve of the gases or tile surface [42]. Such probes are used sporadically for dryer diagnostics. **Figure 3.12** shows a gas temperature profile obtained with one of these probes in a vertical dryer at three positions (T1, T2, and T3) in the basket plane.

The information from the temperature curve in a dryer allows areas to be detected in which drying is too slow (with the ensuing loss of efficiency) or too fast (which may lead to fracture problems), enabling more rational design of drying curves.

Temperature at the dryer exit is usually measured by means of optical pyrometers, with an indicator where the operator can read the instantaneous temperature value. There is, therefore, a spot reading of tile temperature as it passes below the pyrometer. Under these conditions, it is impossible to determine tile temperature and position in the plane of a dryer basket. Studies have been conducted in which tile temperature data at the dryer exit have been combined with tile position in the dryer [58]. **Figure 3.13** shows the temperature distribution of tiles at the dryer exit, as a function of tile positions in the basket plane.

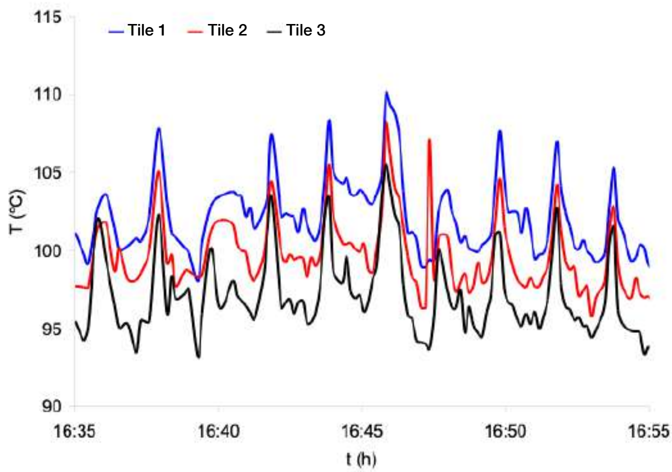


Figure 3.13. Evolution of the temperature of three tiles, located in different positions, at the dryer exit.

These devices can be readily implemented, particularly in vertical dryers, and they contribute very valuable information on dryer operation and thermal stability, both in a steady and a non-steady state.

The second most important variable in industrial drying is residual moisture content. Residual moisture content affects tile mechanical strength [59]: the higher the moisture content, the lower the mechanical strength and, therefore, the greater the likelihood of the tile suffering some type of fracture.

Residual moisture content is usually measured manually on test pieces of industrial tile, which are set on a balance with electric resistances or in an oven. Infrared moisture content sensors, used to control moisture content in spray-dried powder and tiles at the press exit (for anticipatory density control), cannot be used in this case, as they only allow determination of moisture content at the tile surface, not average moisture content. Establishing average moisture content requires using microwave or radio-frequency sensors. There is greater experience in the ceramic tile sector with these last sensors: tests have shown that these devices can be used to obtain accurate residual moisture content measurements.

Knowing the residual moisture content values on an industrial scale allows estimation of tile mechanical strength at the dryer exit by using the relationship between both variables obtained in the laboratory.

3.2.2.3 Minimum data to be integrated in the forming section

Finally, to conclude with the review of the aspects relating to the forming section, **Table 3.3** sets out the minimum information deemed necessary for proper management of the operations in this section and for laying the groundwork in defining a process digital twin.

Table 3.3. Minimum information required in the forming section to lay the groundwork for the manufacturing process digital twin (for the sake of simplicity, a drying technology using a vertical dryer was considered)

Table 3.3.1	Press
Level of information	**Data/description**
PERFORMANCE AND PRODUCTION MANAGEMENT	Production order, batch reference, or production trace
	Article reference
	Manufacturing order progress relative to planning (%)
	Availability (A) = Production time/Available time (%)
	Performance (P) = Actual production/Theoretical production (%)
	Quality (Q) = Amount of tile deemed losses/Amount of tile pressed (%)
	Distribution of reasons for stops
	Distribution of reasons for losses
	Overall Equipment Effectiveness (OEE) = A x P x Q (%)
PROCESS VARIABLES	Spray-dried powder moisture content ((kg water/kg powder (%))
	Average bulk density of pressed tile bodies (kg/m^3)
	*Maximum variation of average bulk density between press outputs (kg/m^3)
	Maximum variation of inner bulk density for each press output (kg/m^3)
	*Moment of first drop relative to feed system advance (% relative to tile length)
	*Average advance speed of the powder feed system (mm/s)
	*Average return speed of the powder feed system (mm/s)
	*De-airing time (s)
	*Advance speed of the moving crosspiece in descent (mm/s)
	*Maximum pressure in the press hydraulic circuit (bar)
	*Maximum pressure setting in the hydraulic circuit (bar)
	Maximum specific pressure on the spray-dried powder (kg/cm^2)
	*First-pressing pressure (bar)
	*Pressure application speed in second pressing (bar/s)
	*Residence time at maximum pressure (bar)
	*Advance speed of the moving crosspiece in ascent (mm/s)
	*Tile extraction speed (mm/s)
	*Extraction pressure (bar)
	Press speed (strokes/min)
	*Oil temperature in the hydraulic circuit (°C)
	*Die temperature (°C)
	Average thickness of formed tile bodies (mm)
	*Average thickness of powder bed deposited in the cavity (mm)
	*Maximum variation of average tile body thickness between press outputs (mm)
	*Maximum variation of tile body thickness for each press output (mm)
	Die cavity Identification per tile
	Caliber dimensional controls per die cavity (mm)
	Departure from rectangularity dimensional controls per die cavity (mm)
	Press running/stop state (Boolean)
RESOURCE CONSUMPTION	Spray-dried powder consumption (kg/s or kg/m^2 finished product)
	Electric power consumption in pressing and ancillary systems (kW h/m^2 finished product)
	Human resources (HR) consumption (individuals/shift or individuals/m^2 finished product)
VARIABLE COSTS	Spray-dried powder cost (€/m^2 finished product)
	Electric power cost (€/m^2 finished product)
	Human resources (HR) cost (€/m^2 finished product)

Table 3.3.2	Dryer
Level of information	**Data/description**
PERFORMANCE AND PRODUCTION MANAGEMENT	As tense flow between press and dryer is involved, the same data as for pressing are considered
PROCESS VARIABLES	Burner 1 temperature setting (°C)
	Burner 1 actual temperature (°C)
	Burner 2 temperature setting (°C)
	Burner 2 actual temperature (°C)
	Stack temperature (°C)
	Relative humidity in stack (°C)
	Stack flue gas flow rate (Nm^3/s)
	Drying time (min)
	Stabilisation zone temperature setting (°C)
	Stabilisation zone actual temperature (°C)
	Fan 1 rotation speed (rpm)
	Fan 2 rotation speed (rpm)
	Stack valve percentage opening (%)
	Tile exit temperature indexed by position (°C)
	Maximum temperature variation between tiles in a plane (°C)
	Maximum temperature variation between tiles in a basket (°C)
	Tile residual moisture content at exit (kg water/kg tile (%))
	Dryer running/stop state (Boolean)
RESOURCE CONSUMPTION	Dryer natural gas consumption (Nm^3/m^2 finished product)
	Electric power consumption in dryer and ancillary systems (kW h/m^2 finished product)
	Human resources (HR) consumption (individuals/shift or individuals/m^2 finished product)
VARIABLE COSTS	Natural gas cost (€/m^2 finished product)
	Electric power cost (€/m^2 finished product)
	Human resources (HR) cost (€/m^2 finished product)

Part of the information detailed in **Table 3.3** can be obtained from measurement of the process variables listed in that table. However, it is essential to have the additional data shown in **Table 3.4** to properly elaborate all the information indicated. Together with the measurement item at issue, **Table 3.4** shows the origin or source of the data from which it could be obtained.

Table 3.4. Additional data required to obtain the minimum information needed to define the digital twin of the forming section.

Level of information	Data	Data source
PERFORMANCE AND PRODUCTION MANAGEMENT	Equipment running time (h)	Management PLC and automation or external counting system
	Planned production (m^2)	ERP information or management system
	Equipment theoretical production (tiles or m^2/s)	ERP information or management system
	Cumulative theoretical production (m^2)	Management PLC and automation or external counting system
	Surface area per tile (m^2/tile)	ERP, product data sheet, or management system
	Cumulative actual production (m^2)	Management PLC and automation or external counting system
	Tiles at press exit (units)	Management PLC and automation or external counting system
	Tiles at dryer entrance (units)	Management PLC and automation or external counting system
	Tiles at dryer exit (units)	Management PLC and automation or external counting system
	Production losses (tiles or m^2)	Manually assigned or automatically recorded by meters
	Reasons for stops	Assigned by operators or directly acquired by PLCs
	Reasons for losses	Assigned by operators or directly acquired by PLCs
PROCESS VARIABLES	Full pressing cycle to obtain critical parameters	Press PLC
	Full powder feed cycle to obtain critical parameters	Press PLC
	Number of die outputs	Press PLC, ERP or product data sheet
	Tile width (mm)	Press PLC, ERP or product data sheet
	Tile length (mm)	Press PLC, ERP or product data sheet
	Product nominal thickness (mm)	ERP or product data sheet
	Number of cycles	Press PLC
	Number of tiles per dryer row	Dryer PLC
	Number of tiles per dryer plane	Dryer PLC
	Dryer number of baskets (units)	Dryer specifications
	Number of planes per basket (units)	Dryer specifications
RESOURCE CONSUMPTION	Theoretical proportion kg spray-dried powder/m^2 finished product	ERP, product data sheet, or management system
	Hopper spray-dried powder level (% or kg)	Distance meter or weighing with load cells
	Distribution of personnel	ERP or human resources (HR) management system
	Work team or active shift	ERP or human resources (HR) management system
	Dryer natural gas consumption (m^3)	Digital gas meter
	Natural gas temperature (ºC)	Pt-100 digital gas meter
	Natural gas supply pressure (bar)	Digital gas meter pressure transducer
	Equipment electric power consumption (kW h)	Digital grid analysers
VARIABLE COSTS	Spray-dried powder price (€/kg)	ERP or management system
	Electric power price (€/kW h)	ERP, supply company contract, or Web scraping
	Natural gas price (€/kW h)	ERP, supply company contract, or Web scraping
	Assigned human resources (HR) average price (€/person)	ERP or management system
	Natural gas heating value (kW h/Nm^3)	ERP, supply company contract, or Web scraping

As indicated in the compositions preparation section, proper storage in a structured database system of all the information collected in the above tables will allow analysis, a posteriori, of particular production batches, provided batch traceability can be assured. Indeed, if tiles are properly assigned or the start and end of the production batch is recorded as soon as tiles assigned to a particular manufacturing order have been made, the information generated would be indexed and linked to each manufacturing order. This would enable full real-time monitoring of the production process, facilitating segmentation of the information for subsequent use by advanced analysis tools.

In the compositions preparation section, owing to the bulk nature of the products processed (solid raw materials, suspensions, and spray-dried powder), production tracing based on the volumes made and equipment operation times suffices. However, in body forming, tiles begin to be processed, and the manufacturing process takes on the form of a succession of discrete events.

From this point on, to assure production traceability it would be advisable to unequivocally identify all tiles made to enable these tiles to be closely tracked through the different process stages and to accurately record the operating conditions under which they are processed. As noted above, one of the most appropriate tracing options involves marking codes of the DM (DataMatrix) type or similar ones on the back of the tiles with ceramic ink for tile monitoring throughout the process using vision cameras. Marking should preferably be done in a bas-relief generated with the die punch to keep friction with the different transport systems from damaging the code in the course of the process and compromising code detection.

3.2.3 Glazing and decoration

In the glazing section, the tile bodies are coated after drying with several layers of materials, generally of a glassy nature, to provide the product on firing with its aesthetic finish and some of its physico-chemical properties. Three types of coating applications are typically found in current glazing lines. First, substrate or base coatings consisting of engobes and ceramic glazes, customarily applied using waterfall and linear curtain glazing systems or spraying. Second, inkjet printing applications, in which the graphic pattern is usually defined. And finally, protective applications that provide the product with specific surface technical properties, such as wear or slip resistance.

The glaze bases used to carry out the different decoration applications in the glazing lines are usually prepared in a plant section equipped with a series of batch ball mills. Except for a few occasions, the mixture of raw materials for glaze preparation comes directly from supplier companies in big-bags of about 700 kg, to which a series of additives and the appropriate amount of water must be added to mill the product for a set time, until a specific particle size is reached.

3.2.3.1 Information management in the glazing section

The degree of automation of production operations in the glaze preparation section is usually not as high as that observed, for example, in compositions preparation or forming, operators taking part in particular in constant cleaning and suspension transfer operations. As in other sections, in general, the system for collecting critical process data and sending these to a higher information system is poorly developed. In this sense, in most cases, no controls are performed on the incoming raw materials. Suppliers only occasionally provide information on some raw materials properties. Controls are essentially performed on the product after preparation, before feeding it into the process. The critical variables measured are suspension density, viscosity in seconds of flow time in a Ford cup, and suspension residue on a sieve with a specific mesh size. These variables are adjusted, first, according to production order specifications and then in-line as a function of each application's requirements.

In regard to decoration lines and the production operations conducted in such lines, the degree of automation is good, though there is still major activity by workers in cleaning operations, regulation of application conditions, and reconfiguration of the lines during batch changeovers. In addition, the systems for collecting critical process information are usually poorly developed. Thus, for example, even though critical decoration process parameters such as glaze density, viscosity, or amount applied on the product are measured half hourly, the data are usually collected manually and are not available in integrated management systems.

In view of the above, it is deemed of interest to develop customised visualisation interfaces for the glazing section in order to be able to rapidly track the operation of the different application systems involved in manufacturing a given product and the evolution of the operating variables. By way of example, though tile temperature is monitored at the dryer exit, as indicated in **Section 3.2.2.2.2**, it only reflects the value of the last reading in a display located right at the dryer exit. Given the criticality of this variable for proper application of the different decoration layers onto the product surface, the data generated by this measurement could be simply processed, for example, to link them to tile position in the different dryer planes. Once this information is stored and production has been appropriately traced, this would be a first step towards determining the direct influence of this variable on the end characteristics of each tile made.

As in the other sections, there is a general lack of information on the facility's production efficiencies. It is therefore deemed of great importance to begin to enable real-time control systems of in-line production efficiencies, availability, and overall equipment effectiveness (OEE), which concurrently store the information for rapid, detailed a posteriori analysis. Many of the variables that would allow such integrated performance management could be generated from tile counts and equipment downtimes. These data, duly integrated into the data from the ERP systems and manufacturing order planning systems, can be used to automate management of production efficiencies and to generate useful indicators for optimising manufacturing processes.

In regard to the variables relating to the quality or characteristics of the products being fabricated, in general, data measurement or collection itself, as well as subsequent data processing for generating information to help decision making, is poorly developed. Although automation of data entry, as occurs at some points in the glazing lines in certain companies, is a first step towards assuring information flow towards integrated data management systems, it is essential to begin to evaluate the use of continuous measurement systems of process variables. Of note is the fact that, nowadays, automatic inspection systems of decorated tile surface quality are used at the end of the line, prior to application of protective layers and loading onto transfer cars. However, unfortunately, this information is usually not stored in a structured way for subsequent use in advanced analysis to link the defects detected by this apparatus to actual production variables.

It is further necessary to add that very few plants have an agile system for real-time monitoring of the evolution of production or manufacturing orders relative to order planning, this also being common to the other sections analysed up to this point. Having a system for such monitoring and management is critical to assuring proper production traceability for subsequent analysis of production operations, in order to generate information of value that will allow operations development to be optimised. In addition, as in-plant work generally involves using manufacturing line downtimes to run glaze and shade trials of the planned manufacturing orders in each line, a system of this type would lay the groundwork for addressing production sequentialisations that took into consideration the needs of pending trials. Thus, production priorities could be recalculated in real time, taking into account all the possible specific cases, with a view to working at optimum productivity levels.

3.2.3.2 Control systems in the glazing section

As mentioned above, decoration is not a single process stage but a set of interlinked substages. Each of these substages has its own independent variables, though there are undoubtedly interactions between the different substages: thus, for example, the amount of water applied with an airbrush influences the quality of the glaze substrate application.

Recent years have witnessed endeavours to implement a system for monitoring and even controlling these substages. It has similarly been attempted to control the amount of glaze applied using load cells. The results have evidenced the difficulty of making sufficiently accurate measurements of tile weight before and after each application.

Controlling the amount of glaze applied using waterfall glazing has been more successful [60] (**Figure 3.14**). In this case, commercial devices are available that have an electromagnetic flow meter that records the glaze flow rate in waterfall glazing, with a view to correcting deviations by acting on a motorised valve.

When the valve is kept in manual position, the variations in flow rate are observed to be significant. They stem from variation in glaze viscosity, resulting from changes in density (by water evaporation) and temperature (by ambient changes and heating caused by the impeller pump).

Figure 3.15 shows the flow rate distribution curve with manual control and automatic control, in which the electromagnetic flow meter signal is used to hold a constant glaze flow rate.

The greatest advance in the glazing section in recent years, which has in addition entailed a disruptive change in the tile manufacturing process, has been the incorporation of inkjet printing systems for generating graphic designs on the tile surface. The emergence of these decoration systems has led to the incipient digitalisation of this manufacturing stage, completely modifying the design, development, and manufacture of ceramic products.

The irruption of inkjet printing in the tile manufacturing process enables design information to be shared between the different sections involved in digitally glazing

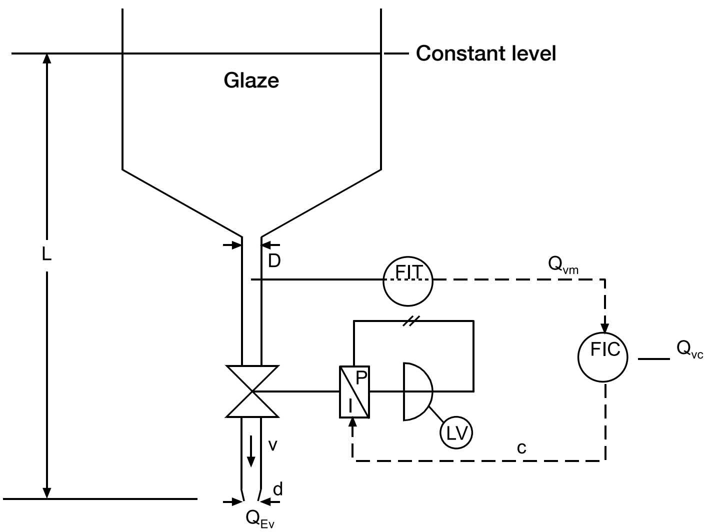


Figure 3.14. Scheme of an automatic control system of glaze flow rate in waterfall glazing.

and developing the product. However, even today, work data are often kept on paper, given the inadequacy of the management tools used at digital level and the need to run multiple trials to equalise tile shades and appearance in a production batch. In this sense, different computer tools have appeared on the market for colour management, specifically adapted to the ceramic tile manufacturing process. The combination of these tools with spectral analysis technologies is contributing noticeably to the digitalisation, optimisation, and improvement of process start-up procedures for new models and/or products.

Many of the problems appearing in the glazing line relate to inappropriate decoration, giving rise to defects that are visible in the glazing line itself. This has led several companies working in automatic visual inspection to study the use of these systems for assessing tile characteristics before firing [61].

The benefits of detecting inappropriately decorated tiles in the glazing line are obvious: only tiles free of decoration defects go on to the next stage (i.e. firing), glaze and energy are saved, production and the percentage of first quality tile grows, etc. However, visual inspection in this process stage faces many difficulties. The first is the presence of dust and water, which makes it necessary for all systems to be protected. The second is the difficulty of detecting defects in the unfired pieces. The technique is promising, but as yet fails to present as high a degree of implementation as fired tile inspection at the end of the line.

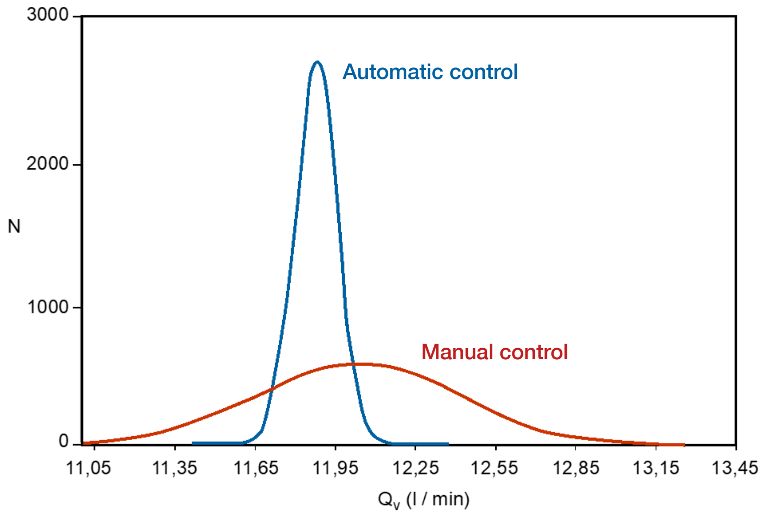


Figure 3.15. Distribution of glaze flow rates with manual and automatic control.

3.2.3.3 Minimum data to be integrated in the glazing section

Finally, **Table 3.5** sets out the minimum information deemed necessary for proper operations management in the glazing and decoration section. As in the previous sections, the information is divided into three fields: performance and production management, process variables, and resource consumption.

Table 3.5 Variables and minimum data required in the glazing section to lay the groundwork for the manufacturing process digital twin.

Level of information	Data/description
PERFORMANCE AND PRODUCTION MANAGEMENT	Production order, batch reference, or production trace
	Article reference
	Manufacturing order progress relative to planning (%)
	Availability (A) = Production time/Available time (%)
	Performance (P) = Actual production/Theoretical production (%)
	Quality (Q) = Amount of tile deemed losses/Amount of tile pressed (%)
	Distribution of reasons for stops
	Distribution of reasons for losses
	Overall Equipment Effectiveness (OEE) = A x P x Q (%)
PROCESS VARIABLES	Tile body temperature at dryer exit indexed by position (ºC)
	Application density (kg/m^3)
	Application viscosity (cp)
	Laydown per tile (g/tile)
	*Glaze temperature (ºC)
	Glaze level in receptacles (% or kg)
	Tile body temperature before printing (ºC)
	Tile body surface moisture content before printing (%)
	Glazing line ambient temperature (ºC)
	Glazing line ambient relative humidity (%)
	Ink application temperature in printer (ºC)
	Tile rate of advance in applications (m/min)
	Average tile rate of advance in entire line (m/min)
	*Tile load position in transfer car plane
	*Tile load plane in transfer car
	Reference of transfer car with tile load
	Average tile in-line residence time (min)
	Statistics of defects detected by unfired tile inspection machine
	Line running/stop state (Boolean)
RESOURCE CONSUMPTION	Glaze consumption (kg or kg/m^2 finished product)
	Ink consumption (kg or kg/m^2 finished product)
	Electric power consumption in glazing line and ancillary systems (kW h/m^2 finished product)
	Human resources (HR) consumption (individuals/shift or individuals/m^2 finished product)
VARIABLE COSTS	Glaze cost (€/m^2 finished product)
	Cost of ink consumption (€/m^2 finished product)
	Electric power cost (€/m^2 finished product)
	Human resources (HR) cost (€/m^2 finished product)

As in the previous cases, Table 3.6 details the additional data that need to be acquired in order to reliably obtain the information indicated in Table 3.5.

Table 3.6 Additional data required to obtain the minimum information needed to define the digital twin of the glazing section.

Level of information	Data	Data source
PERFORMANCE AND PRODUCTION MANAGEMENT	Equipment running time (h)	Management PLC and automation or external counting system
	Planned production (m^2)	ERP information or management system
	Equipment theoretical production (tiles or m^2/s)	ERP information or management system
	Cumulative theoretical production (m^2)	Management PLC and automation or external counting system
	Surface area per tile (m^2/tile)	ERP, product data sheet, or management system
	Cumulative actual production (m^2)	Management PLC and automation or external counting system
	Tiles at line entrance (units)	Management PLC and automation or external counting system
	Tiles exiting applications (units)	Management PLC and automation or external counting system
	Tiles exiting printer (units)	Management PLC and automation or external counting system
	Tiles loaded on transfer cars (units)	Management PLC and automation or external counting system
	Production losses (tiles or m^2)	Manually assigned or automatically recorded by meters
	Reasons for stops	Assigned by operators or directly acquired by PLCs
	Reasons for losses	Assigned by operators or directly acquired by PLCs
PROCESS VARIABLES	Number of tiles per dryer row	Dryer PLC, ERP or product data sheet
	Tile width (mm)	Press PLC, ERP or product data sheet
	Tile length (mm)	Press PLC, ERP or product data sheet
	Number of tiles per transfer car row	Loading system PLC
	Number of tiles per transfer car plane	Loading system PLC
	Number of planes per transfer car (units)	Transfer car specifications
RESOURCE CONSUMPTION	Glaze level in receptacles (% or kg)	Distance meter or weighing with load cells
	Distribution of personnel	ERP or human resources (HR) management system
	Work team or active shift	ERP or human resources (HR) management system
	Equipment electric power consumption (kW h)	Digital grid analysers
VARIABLE COSTS	Glaze price (€/kg)	ERP or management system
	Ink price (€/kg)	ERP or management system
	Electric power price (€/kW h)	ERP, supply company contract, or Web scraping
	Average price assigned human resources (HR) (€/person)	ERP or management system

Finally, it may be noted that it would be very interesting to be able to record the information on the processing conditions under which shades are equalised, in order to be able to start implementing tools that could anticipate chromatic deviations during production batch processing. The use of such tools, together with comprehensive digitalisation of the shade equalisation process, could be of great help in shortening the time devoted to conducting production trials and response times to unforeseen events in carrying out the operations.

Although for this particular part of the glazing section it was not deemed convenient to tabulate the minimum data or information required to integrate it into the process digital twin, it is interesting to note that much of the process information collected, e.g. in the forming, glazing, and firing section, is critical to shade equalisation processes, when it comes to understanding the source of any detected instabilities.

3.2.4 Firing

After tile decoration in the glazing lines, there tend to be two possible ways of proceeding. One involves depositing the unfired tiles on transfer cars, directed by AGV (Autonomous Guided Vehicles) systems, while the tiles await subsequent thermal treatment in a kiln; the other entails feeding the tiles directly into the kiln, right at the glazing line exit. In either mode, during firing the tiles are subjected to a thermal treatment that provides them with their final technical and aesthetic properties.

Firing is generally carried out in single-deck roller kilns following a thermal cycle adapted to the characteristics of the product being made. Kiln heat usually stems from natural gas combustion, using air as oxidiser. Before this air is fed to the gas burners, it is usually indirectly preheated using hot kiln gases at temperatures ranging from 100 to 300°C, depending on the characteristics of the kiln. After firing at peak temperatures between 1100 and 1200°C, depending on the type of product, the material is again loaded onto transfer cars while awaiting further transformation operations, such as rectification or polishing, or moving on to final sorting.

3.2.4.1 Information management in the firing section

As in the forming and glazing sections, at this point of the manufacturing process there is usually a manufacturing order of the product that is to be processed, manufacturing planning being in place for each kiln in the plant. Despite the importance in plant operations management of knowing, at all times, the firing curves for implementing the general planning for product and equalisation trials and the verifications performed from other sections, there are, generally speaking, no applications that provide the state of such planning in a simple way, in many cases copies on paper being used to manage daily operations.

The degree of automation in the firing section, from a materials processing standpoint, is very high. In contrast, such is not the case in control of the properties and quality of the processed material. Indeed, these controls are usually performed manually on spot samples that do not allow the entire production to be inspected. To be noted is control of the following critical parameters:

- Planarity or flatness, which is mainly manually controlled every hour. Though systems are available that automatically measure tile flatness at the kiln exit, they are not widely used.

- Dimensional stability (caliber and wedging or departures from rectangularity), particularly in non-rectified products. Control is usually performed manually on benches with mechanical picks-up actuated by operators. The automatic systems that continuously measure tile flatness at the kiln exit usually also provide information on tile size and departure from rectangularity. However, as already noted, their use is still minor.

- Cooling air by manually actuating valves and regulating direct cooling tube positions.

- Combustion air using a manual pressure gauge and regularly completing control data sheets. The most advanced kilns are fitted with systems that regulate the amount of air–gas from the kiln's own operation console, but this functionality is as yet not widely found in currently running machinery.

Although these critical parameters are regularly and methodically controlled, spot controls are involved and all records tend to be on paper, which makes it very difficult to use them in higher information systems. In some newly implemented plants, data logging systems are used to enable some of the critical controls to automatically assign the results in computer applications, but the information generated is hardly used. In this sense, it is deemed of great importance to incorporate dimensional inspection systems at the kiln exit and connect them to data collection systems in order to have continuous information on product quality right at the kiln exit. This can be of great help when it comes to adjusting firing conditions, providing more detailed information on kiln performance in anomalous operating conditions, such as changeovers in tile size or the presence of gaps of material inside the kiln.

In firing, as in other manufacturing process sections, there are no tools for detailed management of kiln production efficiencies. Although it is important, generally, to have such data for every section, the need is greatest in the firing section, as kilns usually constitute a bottleneck in the ceramic tile manufacturing process when the process is run with an intermediate buffer.

Similarly, in addition to the information regarding the work specifications for each manufacturing order, it is also deemed of interest to have data on the product process controls conducted in the preceding stages. Thus, during firing, certain situations stemming from deviations in manufacturing parameters in preceding process sections could be anticipated.

In-line work is considered essential for obtaining applications that provide automated digital information on the characteristics of the tiles being processed in each kiln channel. Similarly, it would be interesting to have instruments for detecting lateral gradients in firing conditions (mainly temperature and static pressure), which numerous research studies have shown to be a source of significant instabilities in the firing process (**see Section 3.2.4.2**) and of impaired end-product quality. Particular attention should be paid to the kiln cooling stages, in which, with relatively minor investments, additional instruments can be incorporated to provide information of value for improving end-product properties. Thus, for example, direct cooling is generally controlled with a single thermocouple located in the part beneath the roller plane. The incorporation of three thermocouples, one on each side of the kiln in the direct cooling modules, and processing of the data they provide would readily yield the thermal map of a kiln zone that has a great effect on numerous finished product properties. With current kiln control systems, the influence of gaps of material inside kilns on the quality of the products being processed is very great. Having additional instruments in the kiln could be of great help in understanding the causes, such as breaks in material feed in the kiln, of variability in product properties, and open up avenues for process optimisation from this viewpoint.

3.2.4.2 Control systems in the firing section

As indicated above, firing is a key ceramic process stage, as it provides tiles with their final technical and aesthetic characteristics, while also being the thermal stage with the greatest energy consumption. The kiln variables that can be acted upon, which determine tile characteristics and kiln energy consumption, are as follows: temperature distribution and gas pressure and composition (fundamentally the amount of oxygen) in the kiln. In terms of control language, a system with distributed parameters is involved, in which the complete curves and not just a curve value are to be controlled.

In general, though there have been attempts to control the pressure curve and even the oxygen percentage of the gases in the kiln [62,63] only temperature is continuously measured and controlled throughout the kiln. Nonetheless, this measurement is often insufficient and temperature differences across the kiln (transverse profiles) are important. Devices are available for measuring transverse temperature distribution, the most widely known being the multi-thermocouple roller [64] and the Datapaq temperature probe.

Figure 3.16. Measurement of transverse temperature gradients with a sensorised roller.

The multi-thermocouple roller looks like a conventional metal roller (Figure 3.16), but it contains a number of thermocouples that enable the transverse temperature profile to be continuously measured in the lower part of any kiln zone Figure 3.17. Any change or action in the kiln (modification of temperature setting, air pressure, burner nozzle diameter or type, etc.) affects the temperature profile and the system enables its effect to be immediately determined. If another zone is to be analysed, the position of the roller needs to be changed.

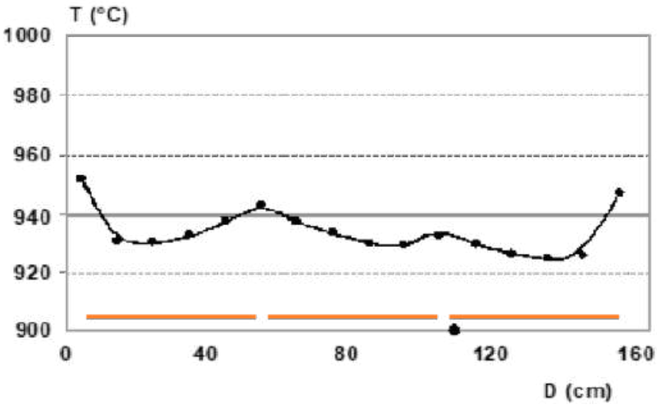


Figure 3.17. Transverse temperature gradients in a single-deck roller kiln.

The Datapaq probe reports the complete temperature curve. It consists of an electronic device set in a box that acts as a thermal barrier and to which a series of thermocouples are connected that are placed on the tile. The assembly is introduced into the kiln and it provides the temperature distribution in a similar way to that of the probe in the dryers, as remarked above. This device provides a snapshot of the temperature distribution. Depending on the installation of the thermocouples, it can record both the temperature at the top as well as at the bottom of the tile surface. The main disadvantage of the device is measurement preparation, which is laborious, and the need to ensure that the introduction of the probe does not disturb the temperature profile and, in particular, that it does not create any gap in the kiln.

Nevertheless, temperature curves, oxygen percentage and pressure are not fired product variables. The variables that really need to be controlled are the dimensions (calibers and lack of rectangularity: wedging), curvatures, and visual appearance (shades, surface defects, and fractures). The problem often lies in the continuous measurement of these properties at the kiln exit, owing to the high tile temperatures at this point and/or the fact that some of these properties may change with time (delayed curvatures).

As noted above, devices are currently available for continuous measurement of tile dimensions and it would, in principle, be possible to have information on visual appearance. Studies have also been conducted on the relationship between thermal variables and curvatures [65]. However, though there are technical measurement resources that can work in heat and the kiln zone that affects the product's final characteristics is often known, automatic control of the kiln has not been attained. The greatest problem lies in defining the variables on which to act and the side effects of such actions. Thus, for example, modifying temperature in a kiln zone to correct calibers could affect tile shade. Curvature control, particularly of irregular curvatures, is even more complex [66,67,68].

3.2.4.3 Minimum data to be integrated in the firing section

Finally, to round off the review of the firing section, **Table 3.7** details the minimum information deemed necessary to properly manage operations in this section.

Table 3.7. Variables and minimum data required in the firing section to lay the groundwork for the manufacturing process digital twin.

Level of information	Data/description
PERFORMANCE AND PRODUCTION MANAGEMENT	Production order, batch reference, or production trace
	Article reference
	Manufacturing order progress relative to planning (%)
	Availability (A) = Production time/Available time (%)
	Performance (P) = Actual production/Theoretical production (%)
	Quality (Q) = Amount of tile deemed losses/Amount of tile pressed (%)
	Distribution of reasons for stops
	Distribution of reasons for losses
	Overall Equipment Effectiveness (OEE) = A x P x Q (%)
PROCESS VARIABLES	Transfer car reference unloaded tiles
	Tile body temperature at kiln entrance (°C)
	Indexing of tile position in kiln row
	Temperature setting at each kiln control point (top–bottom) (°C)
	Actual temperature at each kiln control point (top–bottom) (°C)
	*Stack flue gas temperature (°C)
	Flue gas fan rotation speed (% or rpm)
	Draught set-point regulation pressure (mm ca)
	Draught actual regulation pressure (mm ca)
	Top firing/cooling pressure difference (mm ca)
	Bottom firing/cooling pressure (mm ca)
	*Cooling stack gas temperature (°C)
	*Cooling fan rotation speed (% or rpm)
	Combustion air temperature (°C)
	*Natural gas temperature (°C)
	*Percentage opening ring gas valve (%)
	*Percentage opening combustion air valve (%)
	*Natural gas pressure at burners (mm ca)
	*Combustion air pressure at burners (mm ca)
	Thermal gradient in cooling (°C)
	Thermal gradient in firing zone (°C)
	*Direct cooling air temperature (°C)
	*Opening position cooling air regulation valves (°C)
	Average firing cycle time (min)
	Tile load plane in transfer car
	Reference of transfer car with tile load
	Statistics of defects detected by unfired tile inspection machine
	Dimensions of tiles at kiln exit indexed by channel (mm)
	Tile curvature at kiln exit indexed by channel (mm)
	Kiln running/stop state (Boolean)
RESOURCE CONSUMPTION	Kiln natural gas consumption (Nm^3/m^2 finished product)
	Electric power consumption in kiln and ancillary systems (kW h/m^2 finished product)
	Human resources (HR) consumption (individuals/shift or individuals/m^2 finished product)
VARIABLE COSTS	Natural gas cost (€/m^2 finished product)
	Roller cost (€/m^2 finished product)
	Electric power cost (€/m^2 finished product)
	Human resources (HR) cost (€/m^2 finished product)

As in the other sections, a series of additional data are required for all the information detailed in Table 3.7. The additional data are listed in Table 3.8.

Table 3.8 Additional data required to obtain the minimum information needed to define the digital twin of the firing section.

Level of information	Data	Data source
PERFORMANCE AND PRODUCTION MANAGEMENT	Kiln running time without gaps (h)	Management PLC and automation or external counting system
	Planned production (m^2)	ERP information or management system
	Kiln theoretical production (tiles or m^2/s)	ERP information or management system
	Kiln cumulative theoretical production (m^2)	Management PLC and automation or external counting system
	Surface area per tile (m^2/tile)	ERP, product data sheet, or management system
	Kiln cumulative actual production (m^2)	Management PLC and automation or external counting system
	Tiles at kiln entrance (units)	Management PLC and automation or external counting system
	Tiles exiting kiln (units)	Management PLC and automation or external counting system
	Tile diversion at exit (units)	Management PLC and automation or external counting system
	Tiles loaded on transfer cars (units)	Management PLC and automation or external counting system
	Production losses (tiles or m^2)	Manually assigned or automatically recorded by meters
	Reasons for stops	Assigned by operators or directly acquired by PLCs
	Reasons for losses	Assigned by operators or directly acquired by PLCs
PROCESS VARIABLES	Number of tiles per row	Kiln PLC, ERP or product data sheet
	Tile width (mm)	Kiln PLC, ERP or product data sheet
	Tile length (mm)	Kiln PLC, ERP or product data sheet
	Gap positions in kiln (% or m)	Kiln PLC
	Number of tiles per transfer car row	Loading system PLC
	Number of tiles per transfer car plane	Loading system PLC
	Number of planes per transfer car (units)	Transfer car specifications
RESOURCE CONSUMPTION	Distribution of personnel	ERP or human resources (HR) management system
	Work team or active shift	ERP or human resources (HR) management system
	Natural gas consumption (m^2)	Digital gas meter
	Natural gas temperature (°C)	Pt-100 digital gas meter
	Natural gas supply pressure (bar)	Digital gas meter pressure transducer
	Equipment electric power consumption (kW h)	Digital grid analysers
COSTES VARIABLES	Electric power price (€/kW h)	ERP, supply company contract, or Web scraping
	Natural gas price (€/kW h)	ERP, supply company contract, or Web scraping
	Assigned human resources (HR) average price (€/person)	ERP or management system
	Natural gas heating value (kW h/Nm^3)	ERP, supply company contract, or Web scraping

3.2.5 Sorting

In most plants, the manufacturing process ends at the sorting section, where the material is selected as a function of its final properties and classified into groups or references in which all tiles have the same characteristics, according to pre-set tolerances.

Sorting is one of the stages that has lately undergone major changes from an automatic control standpoint. The arrival of the first automatic sorting systems (Surface Inspection and Massen [69,70]) led many machinery manufacturers to develop their own sorting equipment. Several factors have contributed to the recent success of this type of equipment: development of fast computers, complex computer programs, and high-resolution cameras.

Sorting ceramic tiles is a complex process because the identification of a tile's aesthetic characteristics is difficult to quantify in the mathematical terms needed for computer use. At present, however, for certain types of models, automatic sorting systems make fewer errors than sorting personnel.

Before tiles are fed into the assigned sorting machines, and even during development of the production order itself, continuous samplings are customarily carried out to determine in advance the shade of the product that is subsequently going to be classified. Such thorough control is performed visually in so-called shade booths, though it is deemed that a greater degree of digitalisation could be achieved by introducing colour management methodologies such as those that a number of specialised companies are starting to offer.

In general, practically all end-product sorting equipment manufacturers offer tools that are able to centralise all individual tile data collected by sorting machines. However, this information is not being well used, as it is not correlated with other production variables, and the difficulty has been recognised of using these data to rapidly detect information of value. It is therefore deemed indispensable to be able to develop, in this case as well, visualisation interfaces specially adapted to the needs of the section and to be able to rapidly evidence the progress of the quality parameters of the manufacturing order being carried out.

The control sequence in the selection lines is generally as follows:

- Control of mechanical strength by means of a pressing roller.
- Quality control of graphic design by artificial vision systems.
- Assessment of surface quality by means of specialized operators, even in cases where there is an automatic inspection machine.
- Automated measurement of tile flatness and caliber.

As noted above, if duly integrated and exploited, the information collected in this section has a great potential for providing optimisation solutions for the manufacturing process and for improving decision making relating to product quality. In addition, articulating an appropriate system for monitoring product traceability, linking the information obtained in the sorting section to that from the rest of the manufacturing process, would generate a data structure enabling the manufacturing conditions of all the material transferred to the company logistics area to be established in great detail. Achieving such a level of information would be important not just for improving the processes, but it would also have particular importance in subsequent product logistics and marketing and sales, as it would lay the groundwork for comprehensive tracing of a product's entire life cycle, from its design and manufacture, to its acquisition by the end client.

As in previous sections, tools are usually unavailable in sorting for management of production efficiency based on measurement of parameters such as machine performance and availability.

To round off the review of the sorting section, **Table 3.9** details the minimum information deemed necessary for proper management of operations in this section.

The additional data detailed in **Table 3.10** are required to elaborate all the information set out above.

Table 3.9. Variables and minimum data required in the sorting section to lay the groundwork for the manufacturing process digital twin.

Level of information	Data/description
PERFORMANCE AND PRODUCTION MANAGEMENT	Production order, batch reference, or production trace
	Article reference
	Manufacturing order progress relative to planning (%)
	Availability (A) = Production time/Available time (%)
	Performance (P) = Actual production/Theoretical production (%)
	Quality (Q) = Amount of tile deemed losses/Amount of tile pressed (%)
	Distribution of reasons for stops
	Distribution of reasons for losses
	Overall Equipment Effectiveness (OEE) = A x P x Q (%)
PROCESS VARIABLES	Transfer car reference unloaded tiles
	Side dimensions X (mm)
	Side dimensions Y (mm)
	Side warpage X (mm)
	Side warpage Y (mm)
	Tile caliber
	Caliber distribution
	Statistics of defects detected by unfired tile inspection machine
	Defects detected by inspection operator
	Sorting machine running/stop state (Boolean)
	Packaging machine running/stop state (Boolean)
RESOURCE CONSUMPTION	Cardboard consumption (m^2/m^2 product)
	Consumable materials (plastic, straps, angles, etc.) consumption (m or m^2/m^2 product)
	Electric power consumption in sorting and ancillary systems (kW h/m^2 finished product)
	Human resources (HR) consumption (individuals/shift or individuals/m^2 finished product)
VARIABLE COSTS	Cardboard cost (€/m^2 finished product)
	Consumable materials cost (€/m^2 finished product)
	Electric power cost (€/m^2 finished product)
	Human resources (HR) cost (€/m^2 finished product)

Table 3.10. Additional data required to obtain the minimum information needed to define the digital twin of the sorting section.

Level of information	Data	Data source
PERFORMANCE AND PRODUCTION MANAGEMENT	Sorting machine running time (h)	Management PLC and automation or external counting system
	Planned production (m^2)	ERP information or management system
	Sorting machine theoretical production (tiles or m^2/s)	ERP information or management system
	Sorting machine cumulative theoretical production (m^2)	Management PLC and automation or external counting system
	Surface area per tile (m^2/tile)	ERP, product data sheet, or management system
	Sorting machine cumulative actual production (m^2)	Management PLC and automation or external counting system
	Tiles at sorting machine entrance (units)	Management PLC and automation or external counting system
	Tiles exiting sorting machine (units)	Management PLC and automation or external counting system
	Tile diversion sorting machine (units)	Management PLC and automation or external counting system
	Tiles packed (units)	Management PLC and automation or external counting system
	Production losses (tiles or m^2)	Manually assigned or automatically recorded by meters
	Reasons for stops	Assigned by operators or directly acquired by PLCs
	Reasons for losses	Assigned by operators or directly acquired by PLCs
PROCESS VARIABLES	Number of tiles per box (units)	Sorting machine PLC, ERP or product data sheet
	Tile width (mm)	Sorting machine PLC, ERP or product data sheet
	Tile length (mm)	Sorting machine PLC, ERP or product data sheet
	Number of tiles per pallet (units)	Stacker PLC
RESOURCE CONSUMPTION	Distribution of personnel	ERP or human resources (HR) management system
	Work team or active shift	ERP or human resources (HR) management system
	Box consumption (units)	Management PLC and automation or external counting system
	Consumables consumption (units)	Management PLC and automation or external counting system
	Equipment electric power consumption (kW h)	Digital grid analysers
VARIABLE COSTS	Electric power price (€/kW h)	ERP, supply company contract, or Web scraping
	Cardboard price (€/m^2)	ERP or management system
	Assigned human resources (HR) average price	ERP or management system
	Consumables price (€/unit)	ERP or management system

3.2.6 General situation

Table 3.11 sums up the automation situation in the different ceramic tile manufacturing process stages from the viewpoint of critical process variables. The table shows that the degree of automation is not same in every production process stage, as noted above.

In some process stages, continuous measurement of the variable to be controlled is not yet possible (for example, particle size during milling), a step prior to addressing automation. In these cases, further R&D is needed to find the appropriate sensorial element for measurement before addressing automatic control of the operation.

In other cases, the variable can already be continuously measured, but cannot yet be automatically maintained at the setting values, such as tile temperature and moisture content at the dryer exit. In these cases, less effort is required to achieve this than in the previous case, as the measurement technology is already available.

Finally, in some stages, it has been possible to automatically control some of the most interesting variables, for example in spray drying, enabling automatic control of press powder moisture content. However, in most cases, the degree of implementation of control systems on an industrial scale is very poor, as may be observed in the table. There is an opportunity, therefore, for improving different aspects of the production process, which needs to be used and which, in addition to contributing information on the development of the different stages, can undoubtedly help reduce production costs and improve end-product quality, enhancing the competitiveness of production plants.

Table 3.11. *State-of-the-art* in measurement and control of product variables in the different ceramic tile manufacturing stages.

Stage	Measured variable	Measurement*	Technology for continuous measurement	Manipulated variable	Manipulation*	Degree of implementation
MILLING	Suspension density	A	Coriolis effect sensor	Water flow rate	A	Low
	Suspension viscosity	A	Vibration sensor	Deflocculant flow rate	M	-
	Residue	M	-	Several	M	-
SPRAY DRYING	Suspension flow rate	A	Electromagnetic sensor	Pump pressure	M	-
	Spray-dried powder moisture content	A	Infrared sensor	Burner valve / Temperature	A	Medium
PRESSING	Body moisture content	A	Infrared sensor	Pressure setting	A	Low
	Bulk density	A/M	X-rays	Pressure setting	M	Low
DRYING	Tile temperature	A	Pyrometry	Temperature setting / Gas distribution	M	High
	Moisture content	A	Radio-frequency sensor	Temperature setting /Drying cycle	M	-
DECORATION BY WATERFALL GLAZING	Glaze flow rate	A	Electromagnetic sensor	Valve opening	A	Medium
	Density	M	-	Amount of water	M	-
	Viscosity	M	-	Amount of water / Additives	M	-
OTHER DECORATION APPLICATIONS	Visual appearance	A/M	CCD camera	Several	M	Low
	Several	M	-	Several	M	-
FIRING	Dimensions	A	Linear CCD	Temperature / Others	M	Medium
	Curvature	A	Laser telemeters and ultrasonics	Temperature / Others	M	Low
	Visual appearance	M	-	Temperature / Cycle /Burner air	M	-
SORTING	Dimensions/ Curvature	A	Linear CCD and telemeters	---	A	High
	Visual appearance	A/M**	CCD cameras	---	A	Medium

* A: Automatic; M: Manual
** In some cases, automatic sorting is not yet fully reliable

Chapter 4:
Visualisation tools, digital twin

Chapter 3 of the Guide reviewed the levels of automation in the different ceramic tile manufacturing process stages and the minimum data that would need to be acquired, in a continuous and automated way, directly from the manufacturing process or from other information systems, to be able to implement a digital twin of the ceramic process.

The present chapter describes the other typical in-factory information systems that can contain information of value for the attainment of a digital twin, both of the manufacturing process, in particular, and of the set of business stages in a company. The chapter is rounded off with an approximation of what a digital twin for a ceramic tile manufacturer might look like.

4.1 Visualisation tools and computer-aided management

In the Industry 4.0 context, a series of software tools for visualisation and management of a company's own business processes are commonly mentioned. Ranging from resources planning, through customer relationships management or execution of production, to logistics or finished product store management, all these business processes nowadays use multiple computer-aided tools to manage or execute them. Although these tools are of great importance from the standpoint of Industry 4.0 implementation, they belong to what may be termed the third industrial revolution. Indeed, their irruption in companies is linked to company computerisation which, though an essential requirement for the establishment of Industry 4.0, as noted in the introductory chapter to the Guide, belongs to pre-digitalisation stages. The typical characteristics of the most widely used visualisation and management software tools in production in the ceramic sector are described below. Other tools relating to logistics and marketing, such as store management systems (SMS) or customer relationships management (CRM), are not discussed in this document.

4.1.1 ERP: Enterprise Resources Planning systems

The concept referring to an enterprise resources planning (ERP) system dates back to the 1940s. During the Second World War, the US army developed a methodology for logistic control of its supplies, known as material requirements planning (MRP). In the 1970s, this methodology was progressively transferred to industry with a view to managing the industry's supply chain and to fit it as well as possible to production needs. Initially, MRP was exclusively used for managing stocks, but as industrial processes were progressively computerised, it also began to be used in managing operating times and raw materials purchases.

In the 1980s, MRP systems evolved towards full management of the value chain, allowing the state of inventories and sales processes to be analysed in order to optimise their management. Finally, in the striving to address the needs of new business models, in the 1990s, MRP systems evolved into today's ERPs, in which all the company's areas are centralised in a single management solution, as illustrated in **Figure 4.1**.

By definition, an ERP system needs to integrate data on practically all the company's management areas for use by the different members of the company whenever they need them. Generally, ERP operation is structured in terms of modules, processes, transactions, and programs, which are interconnected through a common database. Each module, such as those shown in **Figure 4.1**, refers to a managemental area that, in turn, uses specific processes to generate transactions that are managed by ERP programs, all working jointly in an integrated way. By appropriate parameterisation, this structure allows the software to adapt to the specific needs of each company, after consulting its own business processes. This operational structure provides ERP systems with a series of advantages over other less integrated accounting or management applications:

- Software adaptability
- Reduced information duplication
- Comprehensive company management
- Improved decision making
- Reduced overall company management costs and complexity

Figure 4.1. Module customarily available in an ERP solution for resources management

Depending on the environment in which data management is performed, three different types of ERP may currently be differentiated. Initially ERP systems were installed in servers or computer systems located at a company's own facilities, constituting so-called on-premise ERPs. Progressive spread of the Internet and of cloud services has led to the appearance of more and more cloud-based ERP systems. Finally, there are also hybrid applications that combine on-premise and cloud information storage. The choice of one type of ERP or another will depend on each company's needs and requirements.

On using an on-premise ERP system, the company is responsible for software security, availability, and management, so that it must have a systems department that devotes part of its resources to infrastructure management. However, the supplier also usually provides integration services and after-sales support. On-premise installation affords advantages, such as greater control, but the initial investment is riskier and many solutions of this type do not support mobile or wearable devices.

Today, ceramic company management is practically inconceivable without implementation of an ERP system adapted to company needs. Generally speaking, from a manufacturing process viewpoint, a ceramic company's typical ERP system needs at least to incorporate modules relating to purchases, inventory, and production. These modules provide the ERP with information on the articles or references of the products that the company can make, including their physical descriptions and most significant parameters (size, finish, name of the model, shade, caliber, etc.). Such information is critical to suitably structuring the relationships between the different company processes, ranging from development to the marketing and sales stages, obviously passing through product manufacture. Linked through a purchasing or similar module with raw materials suppliers, it also assures continuity in the supply chain, enabling agile raw materials supply in time and form.

Although not a direct object of this Guide, other modules like sales and accounting are key to other areas of the company, such as sales and marketing. The information contained in these modules can be of great help, for example, in focusing sales actions and determining sales or market trends.

4.1.2 Production Planning and Sequentialisation Systems

Although ERP systems can provide specific modules for production planning, in many production sectors, such operations are generally performed using specifically devoted software packages. Traditionally, particularly in smaller ceramic companies, production planning has been based on the experience of plant managers and particular market needs. However, in recent years, production planning and sequentialisation systems have begun to be used in medium to large-sized plants, assuring plant operation under optimum efficiency conditions.

Planning systems generally define the product quantities and references that need to be made in a certain period of time, either to have a certain product stock or to carry out a particular series of orders. On the other hand, sequentialisation systems indicate the best processing sequence to be followed for a given product that is to be delivered at a particular time. This optimum sequence can usually be defined on the basis of different criteria, such as achieving the fastest manufacturing time, lowest manufacturing cost, or even obtaining a top-quality product. Generally speaking, the planning systems used in the ceramic industry focus on batch production, in contrast to the planning systems used in other industries, which may focus on continuous or even mass production.

Production planning and sequentialisation exhibit their greatest usefulness when used together, both dating back to the first Industrial Revolution. Though it is true that they played a secondary role at that time, owing to the small size of the product families that were produced in large batches, they already began to become quite important. At the end of the 19th century, the products made displayed increasingly greater complexity and variety. This made it necessary to create so-called production control offices in the factories, these offices being charged with generating production plans, taking into consideration two key concepts in production programming: firstly, priorities (i.e. which manufacturing or work orders were to be performed first); and secondly, manufacturing capacity (i.e. which product quantities needed to be made in certain manufacturing lines, under given operating conditions).

The development of production planning and sequentialisation tools and strategies was led by engineers such as Frederick Taylor and Henry Gantt. The former, known as the creator of the scientific organisation of work, developed the concept of the *Production Control Office*, whose purpose, as mentioned, was creating action, control, and monitoring plans of plant operations and inventory for efficient plant operation. Thus, in 1911, Taylor became one of the fathers of Scientific Administration [71] on developing ideas for improving production work, specifically by optimising use of the resources involved [72]. On the other hand, the American Henry Gantt developed charts for process monitoring, which bear his name and are still being used at present [73]. These charts were designed to enable the planned progress of a production process to be compared with its actual progress.

However, it was the Second World War that really drove research and development of methods and tools for managing production resources properly, initially in relation to the war effort and then in other fields of industry. At the end of the 1930s, the concept of operations research had begun to be used [74], a concept that emerged from the constant attempt to apply the scientific method to production operations. After the war, many research groups realised the usefulness of applying the results of these studies to non-war-related fields. This revolution in operations research stemmed from linear programming, which had been developed in the 1940s [75] and was soon applied to production problems, albeit not directly to sequentialisation. In 1947 [76], George Dantzig invented the Simplex method , a useful and powerful method for solving linear programming manually, which allowed model resolution to be simplified. Subsequently, in the 1950s, development commenced of algorithms focusing on sequentialisation like those of Johnson, namely shortest processing time (SPT) and earliest due date (EDD). Particularly to be noted are the algorithms developed by McNaughton, who in 1959 [77] succeeded in solving the problem of minimising the total time of interruptible work processes in identical machines.

In the 1960s, when the models became more complex, the branch-and-bound resolution method was developed [78], by means of which all the possible solutions to a problem were enumerated and the best one out of all of these was found, enabling a great number of solutions to be discarded beforehand by simple improvement analyses of the objectives set by the model. The advent of computers further enhanced the possibilities. Large complex models were solved simply, thanks to primitive computers that were able to perform a great number of calculations, resolving hitherto unsolvable problems. At the end of the 1970s, Garey and Johnson developed the theory of computational complexity [79], which classified problems according to their structure and difficulty. This also enabled definition of the resources required to solve a given problem of production sequentialisation.

As computers became widespread, software packages specifically intended for process sequentialisation began to be developed, providing production plant managers with techniques previously only available to researchers. These software packages are based on sequentialisation models that may be deterministic or stochastic. In deterministic models, model output is fully determined by the values of the data entered in the model and the starting conditions. In contrast, stochastic models take into account the random component of events: for an exact starting data and conditions input, the model output differs whenever the model is solved. Nature obviously has a stochastic component, but these models are much more complicated. A deterministic model can contribute much information in the field of sequentialisation, as it can predict first-hand what the optimum distribution and order of resources and tasks need to be. In this sense, deterministic models are deemed the most appropriate, as it is the job of Production Control departments to work with reality and take decisions regarding possible deviations from the original sequentialisation.

In the ceramic sector, production planning and sequentialisation is currently being performed in many companies by using Excel spreadsheets. These are generally designed and maintained by a single individual who, in turn, by daily or weekly meetings with salespersons, operations managers, and section heads, is charged with completing them and distributing the workload in different production lines.

This approach stems from the time that production sections were information islands and available industrial management software was scarce. As this is no longer the case, a completely inadequate and inefficient sequentialisation methodology is involved, essentially for three reasons.

First, because it does not allow use of the great advantages stemming from the dynamism in distributing workloads, which assures maximising machine and equipment availability with the ensuing reduction in costs and improvement in production efficiency at all levels. Secondly, because the information provided by production monitoring systems cannot be integrated in real time, which prevents immediate action for redirecting anomalous operating situations. And finally, it does not allow shared management of the information, adversely affecting teamwork and decision-making processes at different levels. Indeed, on subordinating the proper development of a production sequence to one individual, this individual becomes a key element for the company, so that the individual's absence or possible errors could entail a high cost for the company.

Planning and sequentialisation systems are an essential requirement if maximum productivity indices are to be achieved. A good sequentialisation program needs to calculate labour, machinery, and equipment needs in order to finish a certain number of orders in a certain time. Just as the necessary calculations, it needs to be possible in complementary fashion to generate manufacturing orders (MO), indicating the quantity and resources provided for executing the tasks. After an order has been planned and launched, production should also be monitored, based on the data provided, for example by a manufacturing execution system (MES), to verify that planning and execution match pre-set specifications. Otherwise, the system needs to be able to report the detected differences and propose alternatives to redirect the situation. To be able to carry out all these actions, the sequentialisation software must obviously be connected to multiple systems, such as the ERP system, in order to determine the state of the resources and orders or product demand and plant equipment, and to the possible MES management system, in order to ascertain the state of the machines participating directly or indirectly in production, or to the maintenance management system, in order to establish the state of the machinery or even the programmed machine maintenance actions.

4.1.3 MES/MOM systems

The preceding sections have set out several management systems for planning and administering the necessary resources for appropriate development of production operations and business in industrial corporations. It now becomes necessary to discuss the management tools charged with connecting these resources planning systems, such as the ERP or sequencer, with the production plant itself. There are basically two types of systems for managing production and operations execution and linking the plant to higher-level management systems: the manufacturing execution system (MES) and manufacturing operations management (MOM). Although the tool names are similar and there is a certain confusion regarding the usefulness of each system, it should be noted that they refer to different concepts, as set out below.

The acronym MES was established in the 1980s, while MOM emerged a few years later and referred, not just to a wider domain of application, but in particular to a set of operations that are included in standard ISA-95, in terms of architecture and functionalities. In fact, the MOM concept was coined while the ISA-95 standard was being drafted. Roughly speaking, though the aspects covered in MOM were already found, in a certain way, in the original MES functions, MOM stressed quality, maintenance, and supply beyond the production context.

Before the advent of ERP business management systems, computer integrated management (CIM) set MES systems at level 4 of the automation pyramid. However, in the 1990s, when ERP systems became the backbone of business management, MES systems went on to become applications for connecting the production plant to business planning systems. Thus, over time and as a result of advances in automation and the introduction of in-factory digitalisation, MES systems have come to be set at level 3 of the CIM pyramid, according to standard ISA-95, in principle performing the following functionalities:

- Data acquisition
- Production programming
- Personnel management
- Resource management
- Production monitoring
- Traceability
- Quality control
- Process management
- Performance analysis
- Document management
- Maintenance management

Since its incorporation together with the ISA-95 standardisation, the MOM concept has been included, just as MES systems, directly at level 3 defined by the standard. In turn, standard IEC 62264-3:2007 defines the activities included in MOM as those manufacturing activities that facilitate coordination of personnel, equipment, material, and energy used in converting raw materials into products. MOM is therefore deemed a system and method that works as a central distributor of information and data for levels 2 and 3 of the CIM pyramid described in Chapter 2 (**see Figure 4.2**).

Standard IEC 62264-3:2007 defines 4 models that are to be incorporated in any MOM: production operations management, maintenance operations management, quality operations management, and inventory operations management. However, standard ISA-95 (International Society of Automation) additionally incorporates a series of supporting activities, which include:

- safety management,
- information management,
- configuration management,
- documents management,
- management of regulatory compliance
- management of incidents and deviations.

Real-time control and visualisation of production sequences, thanks to the link between factory (level I) and business information systems (level IV and V) make MOM a key element for large companies and multinationals. In contrast, for ceramic companies, before incorporation of a MOM platform, it is generally recommended to have in place an MES system that assures proper execution of manufacturing, directly connected to the highest levels of management.

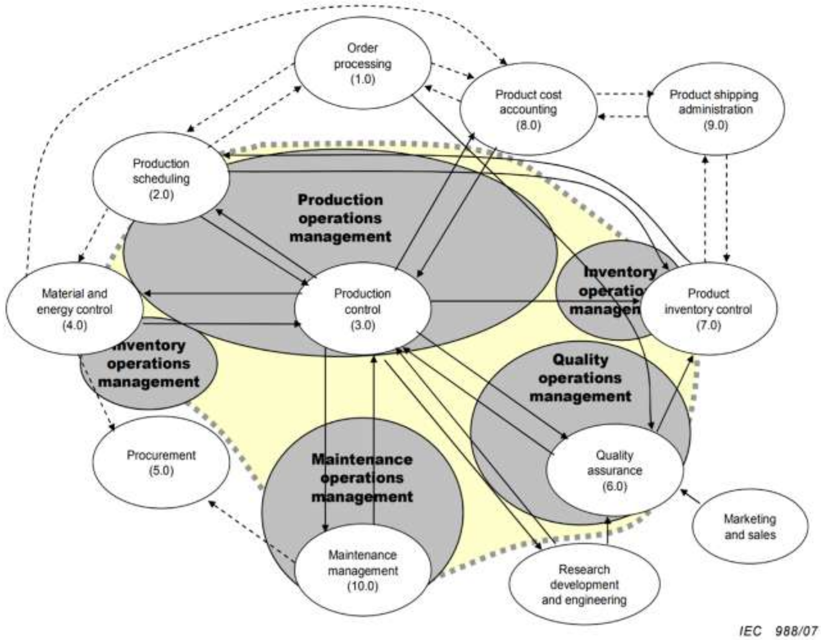


Figure 4.2. General scheme of a MOM model according to standard IEC 62264-3:2007.

Thus, MES and MOM both target the same domain: management and steering of manufacturing operations, observing the modelling and integration standards (ISA-95 and ISA-88). An MES system is, by definition, going to execute manufacturing operations (MOM) in real time and allows plant managers to establish ongoing improvement procedures thanks, for example, to:

- better communication of the information (synchronisation, coordination, and centralisation of information flows)
- simplification of manufacturing processes
- observance of quality standards
- controlled management of inventories and stocks
- optimized monitoring of quality
- systematised traceability of process and products
- regular analysis and improvement of production efficiencies

By way of example, **Figure 4.3** shows a general view of the control point of an MES system for production management of a glazing line in a ceramic plant. As may be observed, the MES system provides information on the MO in course, general production metrics on performance, availability, and quality losses, as well as causes of inefficiency.

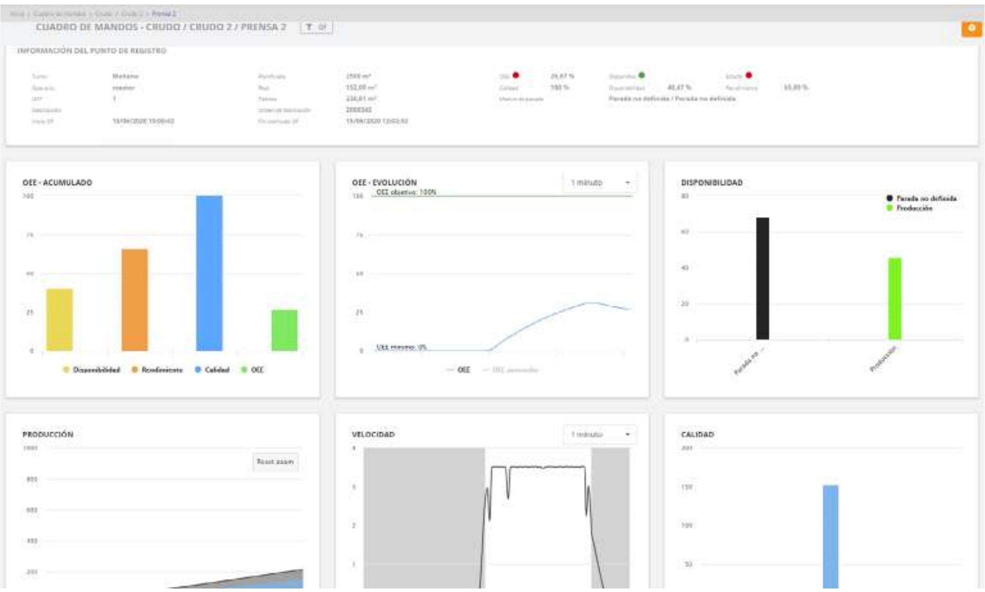


Figure 4.3. General view of data monitoring of production execution at a control point in a ceramic company (glazing line). Source: Nexus Integra.

Though many find it difficult to discern the boundary between the functions of an MES system and those of an ERP system, nothing could be further from the truth. Complementary tools are involved, both being indispensable for proper operations development in an industrial company.

For many years, the industry has focused on automating its processes to gain productivity. Although there are still companies where automation is just starting, this is not the case in the ceramic sector, which has high levels of automation and supervision. In fact, ceramic companies large and small have made major investments in ERP systems for centralising corporate management. As a decisive cross-company tool for resources planning and organisation, ERP has allowed integration of the functions corresponding to the highest level of the CIM pyramid. Nevertheless, for production managers, the most important issue is executing production, and they are the main users of MES systems, which allow fine-tuned operational control of production, thus contributing to company progress.

In this sense, ERP and MES systems complement each other, assure circulation and profitable use of the manufacturing information in the company. In fact, ERP and MES systems do not work on the same time scale: an ERP system hardly ever works below a time scale of a half day's work or production shift, while an MES system works on a time scale of the order of minutes or tens of minutes. This difference in time scale hides another, even more important difference: the ERP was not designed to collect and process data in real time with the fine-tuning found in directing and steering processes and the strong demands of traceability and improvement of production efficiencies.

When there is no MES system, manufacturing needs to take place with no other assistance than simply the manufacturing order generated by the company's own ERP system. In this situation, in the best of cases, on completing each order, the ERP system is provided with an array of data that characterise the order (quantities actually made, raw materials consumed indicating their source, results of production controls: execution times, losses, etc.), directly through forms managed by the ERP system. This translates into extremely laborious assignment operations that depend on user data, which make them relatively unreliable. Aware of this, in many cases entrepreneurs and plant engineers usually charge the integrator of the ERP system with developing a personalised software program that allows data to be collected in the different manufacturing stages and synchronised, and finally have the consolidated information transferred to the ERP system. This involves development, to a certain extent, of a specific MES system, which is not a priori the most appropriate option in view of the great offer of existing solutions on the market, its scalability and, in most cases, the great investment involved in developing custom software.

4.1.4 CMMS systems

CMMS systems (computerised maintenance management systems) are software tools used to help those charged with planning and supervising the activities involved in managing the company's own maintenance services, as well as the operators charged with providing these services.

Maintenance operations in the industry have undergone what may be considered a cyclical historical evolution. Initially, during the industrial revolution, machine maintenance was entrusted to the operators themselves. As the machinery was relatively simple, their daily use provided operators with the necessary knowledge to carry out basic maintenance tasks without this involving any significant loss in work performance. Over time, machines evolved and became increasingly complex, leading companies to create departments exclusively dedicated to maintenance. In the former as well as in the latter case, maintenance was always of a corrective nature, i.e. it always involved carrying out repairs on equipment when breakdown occurred.

As a result of the Second World War, the concept of reliability took on great importance. This led maintenance departments to devote much of their efforts not only to repairing breakdowns, but also to attempting to prevent them from occurring. This gave rise to so-called preventive maintenance.

Subsequently, in the 1970s, it was again considered that it might be cost-effective for the workers in charge of machine operation, who worked every day with a given machine, to also be in charge of maintaining it and ensuring that it was always in the best possible running conditions. This led to the development in Japan of so-called total production maintenance (TPM), which required conservation tasks to be carried out by the operators, and for maintenance personnel to be exclusively concerned with maintenance relating to repairs on breakdowns. This fact, together with the progressive incorporation of computers into the industry and the development of production systems in the automobile industry, such as the Toyota production system, led to the implementation of the first CMMS systems in industrial environments, pursuing the paradigm of zero breakdowns.

The usual structure of a CMMS system consists, basically, of a database with information on the industrial assets of a company, resource management, work orders, and human resources, together with an information analysis system that allows maximum optimisation of decision making in the face of new needs.

Although many CMMS solutions are available on the market, and each develops some specific elements more widely and provides additional tools to cover certain particular needs, a CMMS system generally consists of the following modules:

- **Work orders:** assignment of human resources, material reservation, costs, monitoring of noteworthy information such as cause of a problem, failure duration, and recommendations for future actions.

- **Preventive maintenance:** follow-up of maintenance tasks, creation of step-by-step instructions or checklists, list of necessary materials and other details. Maintenance management programs usually program maintenance processes automatically, based on agendas or readings of different parameters.

- **Asset management:** register of an organisation's equipment and properties, including details, information on guarantees, service contracts, spare parts, and any other parameter that may be of help in management. In addition, parameters such indices of the state of infrastructures can also be generated.

- **Human Resources:** control and management of Human Resources in the Maintenance Area or Service.

- **Control of Inventories:** management of spare parts, tools, and other materials including reservation of materials for particular jobs, register of materials storage, foresight for procurement of new materials, etc.

- **Safety:** management of permits and documents required to meet safety regulations.

The world of maintenance management is trending towards growing sophistication in maintenance, based on the state of the asset. This type of maintenance includes predictive and preventive maintenance processes, which can only be defined in terms of the state of the asset. To do so, physical conditions are regularly or continuously monitored in regard to features such as vibrations, particles in oils, and wear, so that, using specially developed algorithms for processing the data generated by these analyses, the moment can be predicted, with a certain degree of reliability, at which a machine might break down. Preventive maintenance can thus be effected at lower costs, while minimising corrective maintenance actions.

State-based predictive maintenance is, therefore, an alternative to failure-based corrective maintenance, which only repairs assets once they have stopped working, and to use-based preventive maintenance, which starts processes as a function of asset use time or the readings of some parameters. Nowadays, practically all existing CMMS systems in the market have begun to provide utility functions for addressing predictive maintenance. However, it should be borne in mind that, for this to be effectively implemented, it is necessary to adapt company work procedures and to generate a culture of decision making based on generating information of value from data collection.

4.2 The digital twin

Although the management and visualisation systems set out in the preceding point play an important role in Industry 4.0, they do not in themselves constitute tools that will allow the ceramic industry to transform towards Industry 4.0 standards. Extremely useful tools for visualising and managing key information for companies are involved, in order to equip them with the transparency required for Industry 4.0. However, these tools generally lack the analysis utility functions that will allow companies to become agile businesses with self-learning capabilities based on prediction of future events. In this sense, of much greater importance is a so-called digital twin, already introduced in the initial chapter of the Guide. The digital twin needs to be nourished by the data and information contributed by most of the tools indicated in Section 4.1, but it will also have the ability to model manufacturing process performance and to simulate future performance based on a series of starting data. This section describes, first, the basic characteristics of a digital twin and, secondly, the possibilities that exist when it comes to implementing a digital twin of the ceramic manufacturing process.

4.2.1 General characteristics of a digital twin

In increasingly competitive markets, the improvement of decision-making mechanisms relating to digitalisation of manufacturing processes represents a great opportunity for optimising the productivity and efficiency of industrial corporations. Indeed, in a highly complex globalised and dynamic environment, decision making must be properly performed with the greatest possible speed in order to continue maintaining long-term competitiveness. Thus, the economic potential of Industry 4.0 lies in its ability to accelerate corporate decision making and to adapt internal organisational processes to changes in the environment, thanks to continuous analysis of large volumes of data and to the interconnection between cyber-physical systems and individuals [80].

Nowadays, the advanced degree of instrumentation in industrial processes facilitates data collection at multiple acquisition points throughout the production cycle. At the same time, the available technologies allow all events and states occurring in a process to be recorded in real time. This enables a constantly updated digital model of the factory, known as the digital twin, to be obtained [81]. Having a digital twin of the manufacturing process provides, on the one hand, real-time knowledge of what is happening in the process and, on the other, enables decisions to be made based on information generated from real data. Numerous studies have shown that deploying a digital twin is a fundamental step on the road to transformation towards Industry 4.0 for any manufacturing company [82,83].

In this context, the digital twin constitutes a virtual, dynamic representation of the production system. This representation, using different simulation methodologies, is able to keep perfectly synchronous with the physical system thanks to the combination of mathematical models and real-time processing of the data provided by process instruments. The ensemble of digital twin and represented physical environment constitutes the so-called cyber-physical system [84] (**see Figure 4.4**).

Having a digital twin in a manufacturing process such as ceramic tile fabrication would enable simulation and optimisation of the production system, contributing to significant enhancement of competitiveness, productivity, and efficiency. These optimisation actions usually relate to three aspects common to all manufacturing processes:

- Production planning and control:

  - Planning of production orders based on statistical assumptions.
  - Improvement of in-plant decision making thanks to the support provided by detailed production analysis.
  - Standalone planning and execution of production orders based on predictions made by the digital twin.

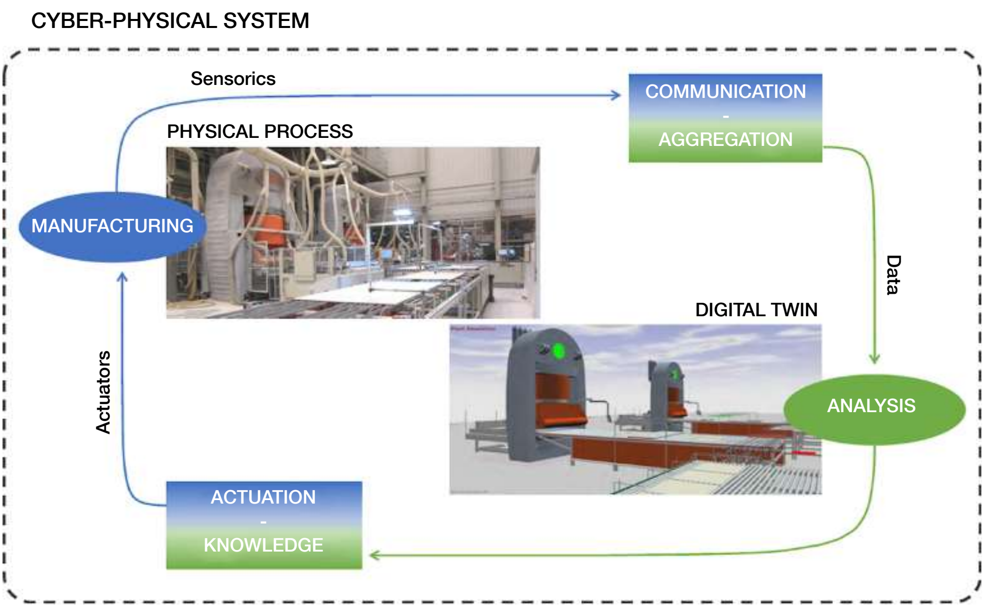


Figure 4.4. Cyber-physical system in a production environment resulting from integration of the digital twin and the physical world.

- Maintenance of production elements:

    - Evaluation of the upstream or downstream impact of changes of state in a given process stage.
    - Identification and evaluation of possible preventive maintenance measures.
    - Evaluation of the operational state of production elements based on descriptive methods and machine learning algorithms.
    - Integration, management, and combined analysis of process and machinery data throughout the machinery life cycle to achieve a greater degree of transparency in the diagnostics of the state of the equipment.

- Management and adaptation of in-plant operations:

    - Real-time comparison of the data processed using a digital twin of the plant working at 100% efficiency to detect and identify deviations more rapidly.
    - Continuous analysis of the production system, evaluating possible changes in planned operations, based on automatic data processing.

In addition to these typical production management aspects, if the digital twin incorporates product constitutive models throughout the manufacturing process, product physico-chemical properties can be evaluated during the process and interrelated with production variables. This possibility not only contributes to improving production efficiency, but also to increasing the quality of the products made and keeping quality at optimum levels.

Obtaining a digital twin requires a series of preceding steps, which are linked to the degree of integration that can be established between the physical process and its virtual copy (see Figure 4.5). It is essential, first, to have a digital model that is a digital representation of the physical process and uses no type of automated data exchange between the physical world and the digital environment. These models can be made up of simulation models, mathematical models, or any other types of models of physical objects, which use no type of automatic data integration.

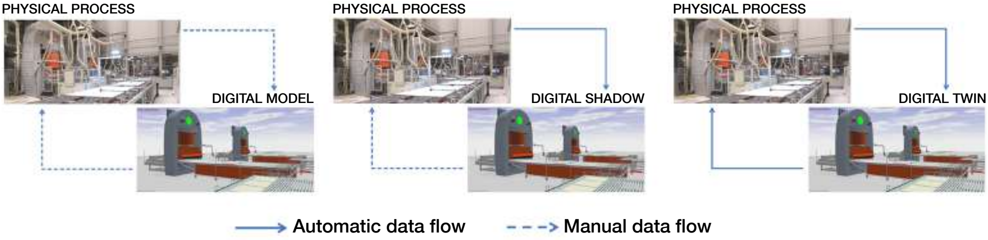


Figure 4.5. Possible information flows between the physical process and the related digital process depending on the degree of integration achieved.

Deployment of the digital model of a process enables generation of its digital shadow by implementing a one-way, automated flow of data between the state of the physical process and the digital world. In this situation, a change in the state of the physical process is directly translated into a change in the digital process, but not vice versa.

Finally, if the data flow between the physical and the digital process is fully integrated in both directions, one may speak of a digital twin. In this situation, the digital process applies control actions to the physical process, such that a change in the physical process leads directly to a change in the state of the digital twin and vice versa.

Implementing a digital twin in a ceramic company is a great challenge, mainly because information is generally decentralised in different data islands, there often not being just one valid source [85]. However, from the viewpoint of implementing a manufacturing process digital twin, recent years have witnessed significant advances in data integration from different production elements. In fact, there have been several pilot experiments, such as that described in the article entitled *"A place-based policy for promoting Industry 4.0: the case of the Castellon ceramic tile district"* [86], which highlights the possibility of full integration of industrial data in a ceramic plant, involving both the process variables in each process stage and the equipment operating variables. In view of this situation, it was deemed of interest to explore the possibilities of generating a digital model of the ceramic tile manufacturing process, using open source simulation and visualisation tools, which lays the groundwork for attainment of a digital twin in the near future.

4.2.2 Digital modelling of the ceramic process

The ceramic tile manufacturing process, from tile forming to final sorting and packing, closely mirrors a type of production matching the principle of discrete events. Indeed, the ceramic manufacturing process develops according to a series of handling and physical transformation operations that take place in well-defined periods of time, one after the other. Each of these operations entails a discrete event, thousands of events per second taking place in all the manufacturing lines of a ceramic plant. Examples of such events include executing a pressing cycle to form a certain number of tile bodies, transporting tiles over a conveying line to transfer tiles from stage to stage, placing tiles on the transfer car of a midway buffer station, or putting tiles in boxes as a function of tile final sorting.

In view of the above, the ceramic tile manufacturing process, from tile forming to packing, fully matches the typology of a discrete process. In contrast to continuous processes, in which the state of the system changes continuously in time, discrete processes are made up of a series of sequences or events that take place at a particular moment in time. Continuous processes customarily involve transformation operations in which fluids are handled, for example in chemical plants or oil refineries.

On the other hand, most manufacturing processes are discrete processes such as the fabrication of ceramic tile, transport systems, public systems such as hospitals or public administrations, and all processes and systems that involve managing queues.

Therefore, for generating a digital twin of the ceramic tile manufacturing process, it might be very useful to use a simulation tool known as discrete-event simulation (DES). This methodology allows a given system to be modelled as a (discrete) sequence of events in time. During the simulation, each event constitutes a change in the state of the system, it being assumed that no change occurs in that state between two consecutive events [87], which allows the simulation to jump directly to the time at which the following event takes place.

DES is generally used in modelling systems that involve management of queues. The system is represented as entities that flow between the different activities that make up the process, these being separated by queues. Queues fill up with entities when these arrive at a given activity at a greater rate than the rate at which they can be processed by the activity. Although it might appear that very few systems could be modelled in this fashion, the application of this methodology is highly varied, there being a great number of systems or processes that correspond to the theory of queue systems, whether physical elements, individuals, or data are being represented by the entities that flow through the system.

In a DES model of the ceramic process, ceramic tiles are the physical entities flowing through the transport systems, stackers, storage systems, and processing equipment that make up the different lines in a ceramic plant. The queues, for example, are the guided transfer car station itself, which may be located between the glazing and firing sections, or the vertical storage buffers commonly known as "compensers", which are usually found in different parts of the manufacturing lines.

A DES model can be implemented using specific libraries developed for high-level programming languages such as C++ or Python®. However, it is preferable, as far as possible, to use open source tools that do not require advanced programming knowledge and allow highly useful solutions to be obtained with relatively short development times. DES simulation packages usually include a graphic user interface, 3D animation engine, and comprehensive set of objects and utility functions for constructing simulation models. Object-oriented solutions are involved, which are extremely quick and scalable up to applications of considerable size (models with more than 300,000 entities have been tested, with acceptable processing speeds).

In addition to exhibiting a steep learning curve, open-source applications are preferred in developing a digital model of the ceramic process because the programming code is usually distributed free. This allows future modification or creation of modelling methods and objects, which will enable, if needed, the developments made to be adapted to the specificities of the tile manufacturing process.

By way of example, Figure 4.6 shows a digital model of a ceramic tile manufacturing plant developed with a DES simulation tool. The model is made up of two forming and decoration lines, both with the same production capacity. Each line has a hydraulic press with a maximum pressing capacity of 64000 kN, a 20-m-long horizontal dryer, with 5 drying planes and 3.7-m useful width, and a glazing line with varying decorative applications. The process is rounded off with a storage area for unfired and fired material and a single-deck roller kiln, 130 m long with 2.7-m useful width. For the sake of simplicity, this example does not include the end-product sorting and packaging section, though it may be noted that the tool used would allow its implementation in the model.

The digital model used to simulate the manufacture of batches of ceramic tiles must take into account all tile sizes that may be processed in the modelled facility. In the case of the example, the tile sizes considered are: 30 cm x 60 cm, 60 cm x 60 cm, 60 cm x 120 cm, 25 cm x 75 cm, and 75 cm x 75 cm. Similarly, to properly simulate operation of the facility, the production regime and equipment capacities must be defined in the model.

Together with all the equipment used in executing the different process stages considered, the model needs to include all the required transport systems for putting the semi-processed product through those stages. The model thus allows, for example, simulation of tile transport across the press exit roller conveyors, row formers for tile entry into dryers and kilns, conveyor belts in the glazing lines, and storage and transport on transfer cars, among others.

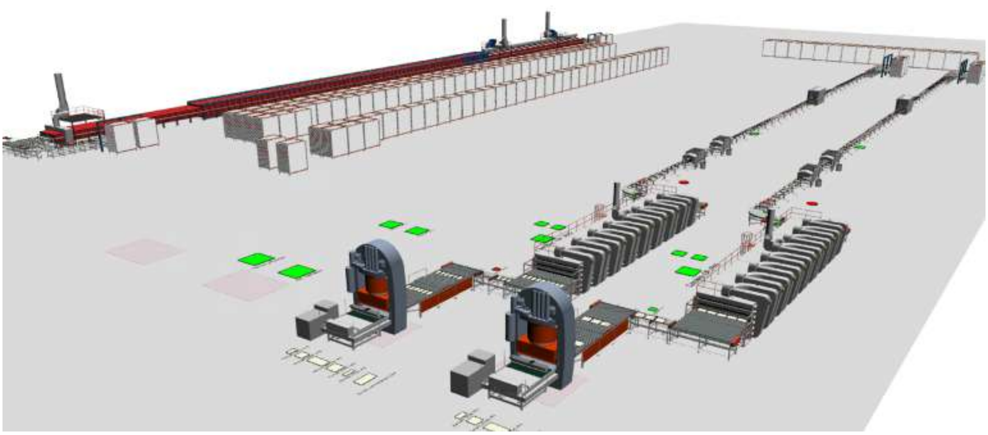
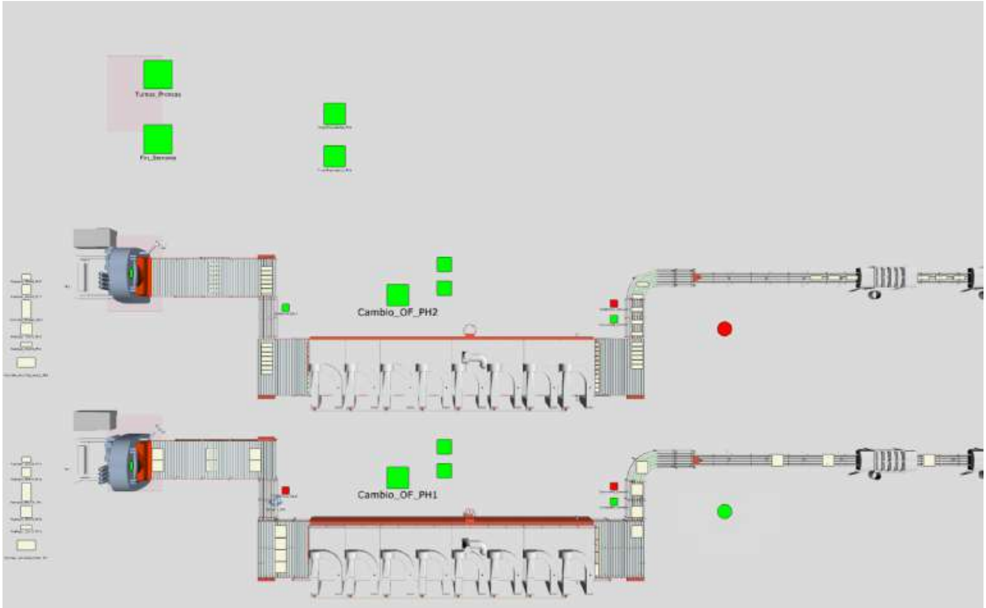


Figure 4.6. 3D view of the digital model of a ceramic plant developed with a DES simulation tool.

Plant simulation



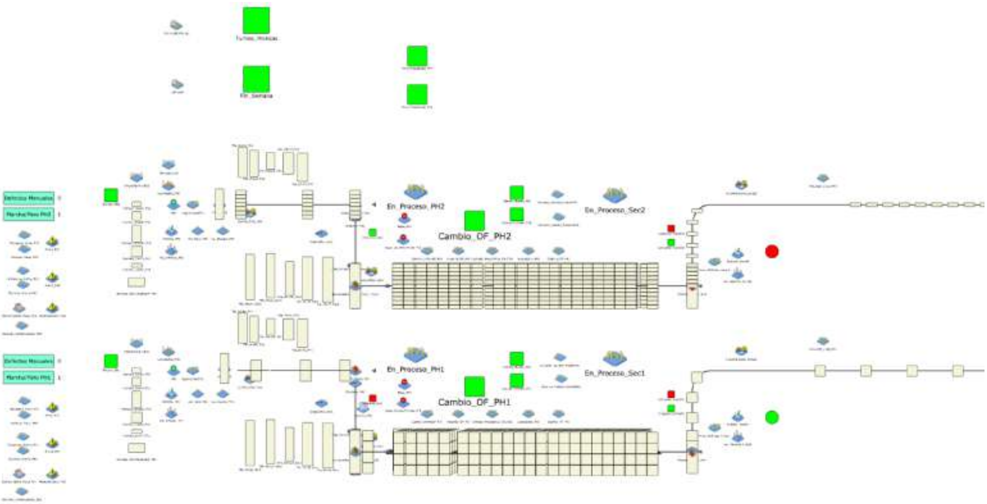


Figure 4.7. View of the forming section and start of the decoration lines implemented in the example of a digital model. Rendered visualisation (up) and schematic view of development (down).

By way of example, Figure 4.7 shows the 2D visualisation of the part of the digital model corresponding to the pressing section and start of the decoration lines, in addition to a schematic view of the same region of the model, displaying the different block diagrams and modules in the programming environment used. In the simulation executed on capturing the image shown in Figure 4.6, line 1 (bottom part) was processing rectangular tiles with a nominal fired size of 75 cm x 75 cm, while line 2 was producing rectangular tiles sized 25 cm x 75 cm.

4.2.3 Integration of the digital model with the manufacturing process for obtainment of a ceramic digital twin

Once the process digital model has become available, the following natural step is its integration with the manufacturing process to generate the digital shadow and then the ceramic digital twin. Such integration involves both direct data acquisition from the manufacturing process and collection of information contained in some of the management systems described in Section 1, such as the ERP system, the planning system, or the MES system.

Configuring the parameters of the different elements that make up the model will usually involve defining a series of heading files, for each tile size to be made. These files, synchronised with the updated data in the ERP system, include, for example, the theoretical speeds of the different transport elements, number of tiles per row processed in the press, dryer or kiln, number of tiles per row and plane on the storage transfer cars, and drying and firing cycle times.

To allow the digital model to simulate actual operating conditions, a series of starting files are also defined that contain the planning to be executed in the different forming lines. To do so, the model obviously needs to be constantly updated with respect to the plant planning system. Thus, the planned manufacturing orders are collected sequentially for each line, with the size and amount to be made in each case. The most common approach is for this synchronisation between the different management applications and the own model to be performed through standard, duly implemented JSON-type files.

Finally, to appropriately simulate process performance, the model needs to receive information on equipment operating conditions and process variability. It is advisable for the connection with plant equipment be made through an OPC server, as it makes data integration very easy. Note furthermore that, when it becomes possible to interoperate the digital twin again with the manufacturing process, this server can be used to send data to the different items of equipment in the plant.

As to process variability, the simplest approach is equipping the model with the variability associated with the industrial processes in order to take into consideration interruptions and losses in production efficiency due to equipment breakdowns, preventive maintenance actions, production losses, interruptions owing to incidents in transport lines, stops for model changeovers, and stoppages relating to changes in size of the product being made. This allows simulation of the evolution of typical production metrics, such as availability, output, and quality, which contribute to overall equipment efficiency (OEE) of production lines.

The most efficient approach is to implement process variability by means of the probabilistic functions provided by the software package used, it being possible to program these function using algorithms adapted from analysis and simulation of models [88]. These functions allow random generation of data that fit a certain probabilistic distribution, with a view to simulating the effect of all variables indicated. The selection of the probability function used in each case is made by analysing the data generated by a traceability system, such as that fine-tuned in the development of the project described in15, or by a suitably parameterised MES system. Some of the probabilistic functions that can describe the variability of the ceramic process in its digital model are indicated below:

- Modelling of the variability associated with process stops

The variability associated with production process stops, whether planned or unexpected, directly affects equipment availability. Depending on the type of stop simulated in each plant section, different probabilistic functions may be considered:

- Interruptions in product flow in manufacturing lines and breakdowns: these stops can be modelled using an Erlang probabilistic distribution to describe interruption frequency and a log-normal distribution for stop times.
- Programmed maintenance: preventive maintenance actions are generally programmed and can be modelled using a predefined time series to reproduce shutdown frequency and a log-normal distribution for shutdown times.

- Modelling of the variability of production takt time

Although production equipment usually runs at constant operating speeds under real manufacturing conditions, when it comes to modelling the process, it is of interest to incorporate a certain variability into this speed to absorb certain process stops that, owing to their short time, are difficult to model in the mode described above. The effect of so-called micro-stops on production element efficiency can thus be modelled. To do so, discrete probabilistic functions that modify the production speeds of each element can be used. For example, in the case of forming presses, a discrete function that indicates the probability of a press working at a pressing cycle value of one minute below the set value can be used.

- Modelling of production losses

Production losses directly affect production quality. To reflect their incidence at different points in the manufacturing lines, generation of losses can be implemented using a Boolean generator that modifies a property assigned to each of the tiles being processed, indicating whether it is defective or not. The probability that the Boolean generator for defects is true is fixed by a mathematical function drawn from analysis of the data provided by the traceability system. Specifically, the model needs to envisage the generation of losses, in accordance with different probabilistic functions at the following points in the process: press exit, dryer exit, end of glazing line, kiln entrance, kiln exit, and sorting line exit.

Chapter 5:
Transparency and predictive capability. Artificial intelligence

The preceding chapter described the different visualisation tools that will allow the ceramic industry to become a 4.0 industry. The present chapter discusses the analysis techniques that will allow systematised exploitation of data. All this is aimed at acquiring the agility proper to Industry 4.0 and the self-learning capability obtained from exploiting the information generated by the manufacturing process itself.

5.1 General

This chapter is broken down into three large groups of technologies: Artificial Intelligence, Machine Learning, and Deep Learning. The general concepts are described for each, together with a basic overview of their main characteristics, their advantages, and some of their main applications in different production sectors, focusing in particular on the ceramic industry.

Before examining each of these blocks, it is of interest to introduce some of their basic general features, as well as how they interrelate. On the one hand, Artificial Intelligence (AI) is, in its broadest definition, any technique that allows computers to imitate human intelligence, and its main objective is to enable computers to reason and learn like human beings.

As schematically illustrated in **Figure 5.1**, AI also encompasses knowledge relating to machine learning (ML), which includes algorithms that are able to learn without being explicitly programmed. For example, ML contains statistical techniques that allow machines to improve their tasks based on experience and analysis of collected data. One of the most famous ML techniques is the artificial neural network (ANN). This type of technique is inspired by the operation of biological nervous systems and serves as a bridge, linking ML and Deep Learning (DL). This last concept is an ML subgroup made up of algorithms that allow a software program to train by itself to carry out tasks such as image recognition or speech. The performance of such tasks in DL is carried out by exposing artificial neural networks made up of multiple layers to enormous amounts of data. To cite Borne (2017): *"Deep Learning is just a complex form of neural network".* [89]

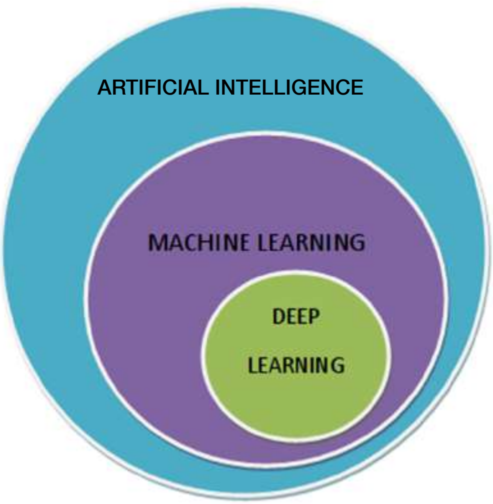


Figure 5.1. Relationship between Artificial Intelligence, Machine Learning, and Deep Learning.

All the above fields are located in stages five and six described in the transformation process set out in the opening chapter of the Guide, which focus on the prediction capability of systems and their subsequent adaptability or improvement of decision-making processes. ML techniques are thus particularly useful in these two stages and, in more specific cases, in which the system must adapt constantly to significant fluctuations in data input, in the DL stages.

5.2 Artificial Intelligence (AI)

AI emerged as a concept in 1956 (John McCarthy, 1955) [90]. Nevertheless, it was not till the 1990s that AI took on importance in society owing to the corporate need to improve company ability to process and analyse the enormous amounts of data that became available thanks to digitalisation.

In this regard, the main idea behind AI is to use all available digital information to simulate human behaviour and thought in specific situations. This has all become possible thanks to the progress in computer science, enhanced computer processing capability, and possibility of handling huge amounts of data in relatively short times. AI can thus acquire and apply learnt abilities and knowledge to solving problems that humans are unable to address or can only do in a very limited way.

5.2.1 Fields of application of Artificial Intelligence

Formally, AI may be defined as the ability of a system, whether a computer, hardware, software, or some other device, to acquire and apply knowledge and abilities. The main objectives of AI include deduction or reasoning, representation of knowledge, planning, natural language processing, learning, perception, and the ability to manipulate and move objects.

An AI system is made up of a finite sequence of instructions or rules that specify the different actions that a computer must carry out to solve a problem. These instructions or rules are known as algorithms and vary as a function of the problem and rules used to solve it.

At present, this discipline includes numerous applications in different fields, ranging from application to the most abstract problems, such as proving mathematical theorems, to application to more common problems, such as quick and efficient data processing or systems identification. **Figure 5.2** depicts the main fields in which AI may be found nowadays, these fields being applied, not just on company or production level, but also in most applications being used daily by people on an individual or personal level. Examples of the presence of AI within reach of any user include face recognition, chatbots, or smart virtual personal assistants.

Though AI is a relatively young discipline, its growth and presence in today's society have increased exponentially. This is evidenced by the big companies currently leading data management and exploitation technologies, such as Google, YouTube, Amazon, Facebook, Apple, and Netflix. Each is developing its own increasingly sophisticated algorithms to equip its products and services with AI. In addition, many of these companies are not working in just one AI field, but in the application of various AI fields as a function of the product or service that they provide. Such is the case of Google, which uses natural language processing (NLP) for text translation, Machine Learning (ML) for image classification, and speech for its virtual personal assistant.

On the other hand, unlike big companies, small and medium-sized enterprises are now beginning to acquaint themselves with or apply AI and its advantages, albeit very gradually. At present most Spanish SMES, almost half of which come from the industrial sector, consider AI to offer more opportunities than risks and, about 70% think that an already available technology is involved, even though much still needs to be developed. In the industrial sector, artificial intelligence has the potential to help process industries achieve significant improvements in performance, generation of value, and the existing business model by optimising user experience and interaction with the customer, in-plant operations, administration, research and development, etc. In any event, it may also be noted that AI does not only improve performance and raise value, but also leads to the appearance of new products and supply of more competitive services.

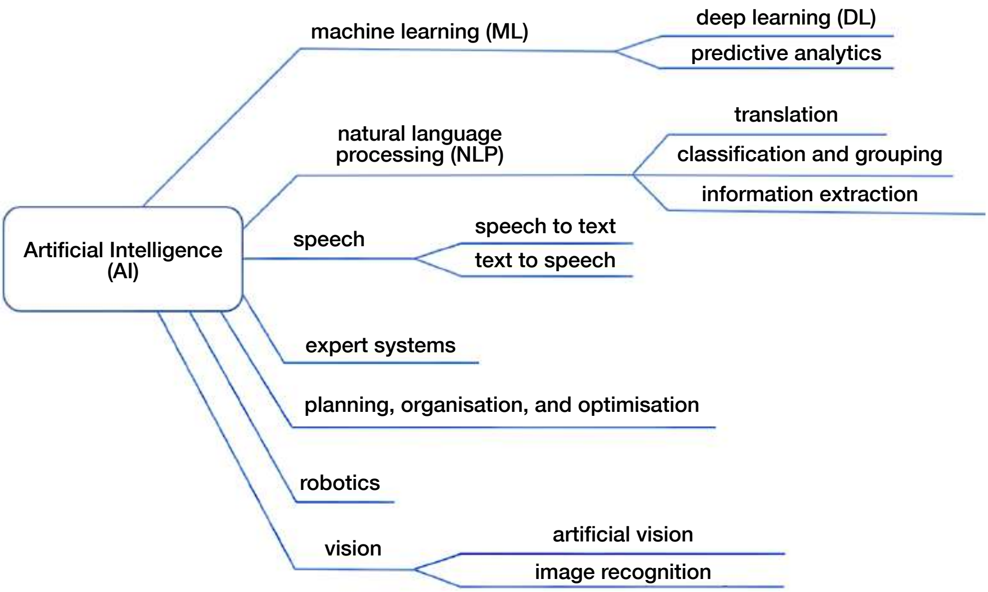


Figure 5.2. Main fields of application of Artificial Intelligence.

As set out throughout this Guide, industrial trends are focusing on a future in which processes will have a fully digital format and will always be carried out under optimum conditions, with maximum efficiency in resources and energy; fully digitally enabled circularity, which will assure maximum collaboration between sectors; and a drastic reduction in times of inactivity. In addition to its irruption into operations, maintenance, and sales tasks, AI is also expected to do so in administrative tasks and scientific stages involving R&D. All these changes will have a great impact on tasks requiring human effort, which will be progressively eliminated and replaced or transformed into operations carried out by individuals that develop, supervise, and manage all AI-based operations.

AI will certainly have numerous positive effects on the process industry and its different components. From a product manufacturing standpoint, AI will provide predictive analyses that help design experiments and interpret results, improve product quality, and speed up new product development. In plant operations, it will improve production process efficiency, reduce energy consumption, and enable control of machinery maintenance routines to avoid failures and stops in production. Furthermore, in regard to supply chains, it will allow creation of new services and flexible, personalised offers, greater insight into customer behaviour, and better prognosis of demand, which will allow storage requirements to be reduced. Finally, it will also affect the contribution of individuals themselves as, on being able to handle enormous amounts of data, AI will accelerate learning, automate tasks that are excessively repetitive, and reduce human participation in physical tasks that may be dangerous.

Despite the process industry's activity in the past, companies have only become interested in the new Information Technology (IT) techniques in recent years. This mirrors the industry's delay in integrating AI-related tools compared to pioneers like the communication industry or social media. This disadvantage is further compounded by the difficulty for the industry to make immediate changes owing to the extensive planning required and to the fact that the investments made are expected to last for decades. On the other hand, a major problem is also data shortage. This is where it becomes necessary to adapt existing Big Data solutions to Smart Data techniques, and thus meet the specific needs of the process industry.

Besides the disadvantages noted in the preceding paragraph, SMES also face another challenge: having access to or having qualified personnel to develop the skills required for AI, such as knowledge or command of ML techniques or even simpler analysis skills. In any event, the great acceptance this discipline is receiving has led to the appearance of an increasing number of tools that provide ML as a service through intuitive graphic interfaces that allow algorithms to be directly evaluated and installed on the available data.

Despite the as yet scarce presence of AI in process industries, a brief glance at the different technologies existing in the ceramic manufacturing process reveals that applications from many of the fields indicated in the scheme in **Figure 5.2** are today already found in the ceramic sector. Thus, for example, there are expert systems for colour management that help plant managers make decision on holding tones in the finished products. Nonetheless, much still remains to be done in regard to expert systems for ceramic process management in general. In this sense, AI techniques could be used for carrying out continuous analysis of the process data generated by the equipment and for interrelating these with end-product quality data. This would yield causal relationships for daily decision making with a predictive character in manufacturing plants.

In the field of planning, organisation, and optimisation, many of the computer systems that could be used to carry out production planning are equipped with specific AI algorithms, which could be used to provide optimum sequentialisation as a function of different optimisation parameters. Nevertheless, in this field as well, there is scope for improvement, as most of these systems are not appropriately connected to the manufacturing process, and it is complicated for them to be able to perform automated training.

In robotics, the most widespread application found in ceramic plants is the laser-guided transport system of transfer cars, which performs automated transport of semi-processed tiles between the different manufacturing stages. There are similarly certain applications in robotics for boxing finished products, such as manipulating large format tiles.

In the field of artificial vision, automatic inspection systems that are able to recognise defects on the finished product have been available for years. To do so, the equipment is fitted with a series of AI algorithms for image recognition and detection of the most common defects on the surface of the tiles made, in both the unfired and fired state. Just as in the rest of the applications, this could be considerably improved, if it were possible to interrelate the detected defects on each tile with the real conditions under which the tile had been processed.

Of the techniques that have to date found little application in the ceramic field, to be noted are the ML techniques, which in coming years are expected to contribute enormously to the implementation of so-called predictive maintenance, not just in the ceramic manufacturing process, but also in other sectors. In addition, ML techniques may be of special interest in solving problems relating to lack of dimensional stability and shades or small colour differences in the finished product. Indeed, detailed analysis of process data and product quality by means of ML techniques could provide information of value that could contribute to the stabilisation of these two critical variables in ceramic tile quality.

5.2.2 Artificial intelligence focuses

The definition of AI has led to four different approaches based on various branches of philosophy and psychology. Figure 5.3 shows the different groups into which AI systems are divided as a function of focus.

1. **Systems that behave like humans:** in this AI focus, it is sought to develop machines that are able to perform functions for which human intelligence would be needed. This focus is related to the Turing Test. This test is based on discerning whether a machine exhibits intelligent behaviour or not. To be able to pass this test, the machine needs to meet the following requirements:

    - Natural language processing that allows it to communicate.
    - Representation of the knowledge to store what it knows or feels.
    - Automatic reasoning to answer questions and draw new conclusions using stored information
    - Automatic learning to adapt to new circumstances and to detect and explore new patterns.
    - Computational vision to perceive objects.
    - Robotics to move and manipulate objects.

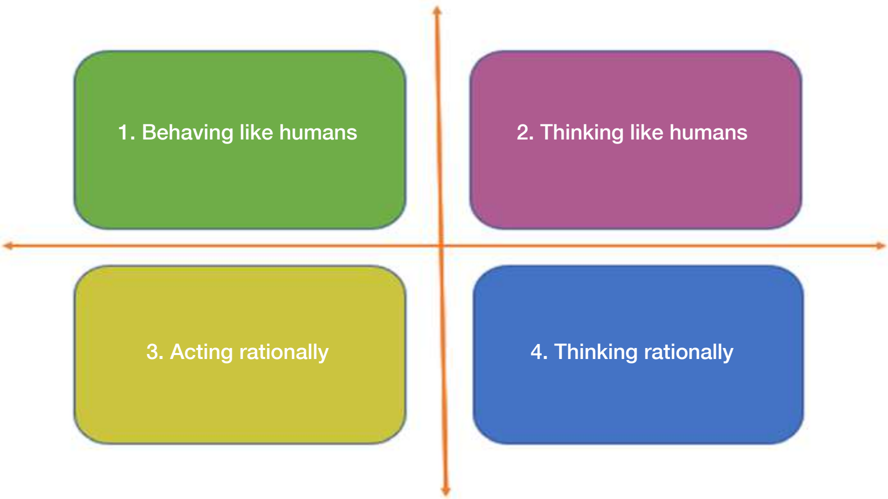


Figure 5.3. The different Artificial Intelligence focuses.

2. **Systems that think like humans:** this focus seeks to equip machines with cognitive capabilities in decision making, problem solving, learning, etc. The focus includes cognitive science, in which computational models of AI converge with experimental techniques from psychology in an attempt to elaborate accurate and verifiable theories on the behaviour of the human mind.

3. **Systems that behave rationally:** the aim is to design intelligent agents. Such intelligent agents are assumed to act autonomously, perceive the environment, persist over a prolonged period of time, adapt to changes, and create and pursue objectives. The purpose is to obtain the best result and, if there is any uncertainty, the best foreseeable result.

4. **Systems that think rationally:** it is sought to discover the laws that govern rational thought, i.e. the calculations that make it possible to perceive, reason, and act. This focus contains the logic that tries to express the laws that govern the way the mind works.

5.3 Machine Learning (ML) or Automatic Learning

The first practical ML application that became famous worldwide was the detection of malicious email in the 1990s. Since then, hundreds of applications of this science have emerged that, silently, feed hundreds of products and functions in daily use. With the current available amount of data, ML applications are very widespread.

ML is the science (and art) of programming computers to extract information or knowledge from the data provided. A more general definition would be: *"Machine Learning is the field of study that gives computers the ability to learn without being explicitly programmed",* Arthur Samuel, 1959. [91]

As **Figure 5.4** shows, ML is a field of study resulting from the intersection of statistics, AI, and computer science. In some areas, ML is also known as prediction (predictive) analytics or statistical learning.

The application of ML methods has become pervasive in daily life in recent years, clear examples being the constant automatic recommendations of which films to see, what food to order, or what products to buy, which are provided in multiple digital formats. At present, every website or device used on a personal or professional level works on the basis of ML algorithms. In this sense, other good examples of the use of ML algorithms are complex websites like Facebook, Amazon, or Netflix, which contain several ML models spread across the website, for rapid and efficient searches or for making appropriate recommendations for each user.

Over and beyond commercial applications, ML has greatly affected how research based on data processing is currently being carried out. A great number of ML tools have thus been applied to solving scientific problems, such as understanding cosmic and stellar phenomena, searching for distant planets, DNA sequence analysis, and development of personalised treatments for curing cancer.

In the first "smart" applications, many systems used hand-coded rules to carry out decisions on how to process the data or fit the inputs provided by the user. This type of rule had too many disadvantages, as the logic required to make a decision was specific to each domain and task. In addition, designing rules required extensive knowledge of how to make a certain decision. An example of where this type of hand-coded rules would fail is in detecting faces in images. The main problem with this approach is that the way in which a computer interprets pixels is very different from how humans detect a face. This difference in perception makes it basically impossible for a human being to create a good set of rules that will specify to a computer what constitutes a face within a digital image.

However, using ML and simply displaying a great collection of images to an algorithm enable it to determine which characteristics and/or specifications are required to identify a face.

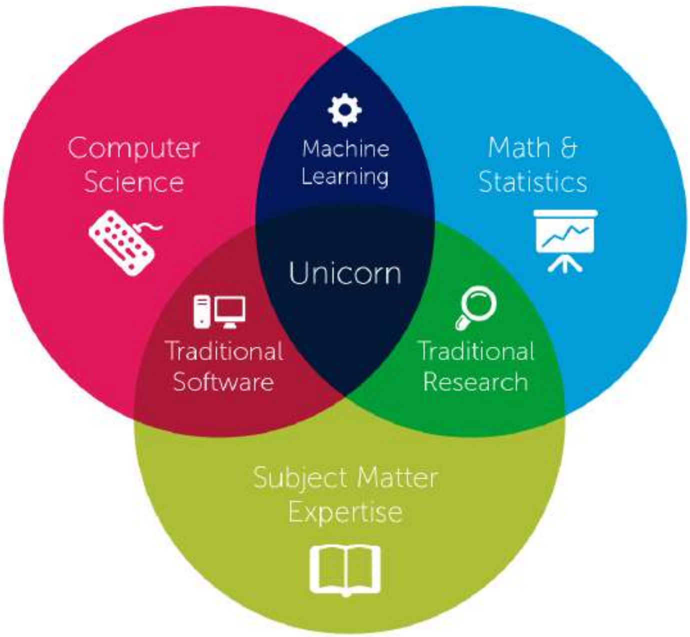


Figure 5.4. Diagram representing the fields making up Machine Learning.

ML is of the greatest use in areas in which the problems put forward are too complex to be solved by traditional approaches or no algorithm is known that solves them. On the other hand, another case in which this kind of technique is typically used is in identifying patterns which may at first not be apparent, in large amounts of data. This search for patterns is known as Data Mining.

In short, the tasks in which ML provides good results are as follows:

1. Solving problems for which there is solution, but whose obtainment requires using many “hand-made” rules.

2. Solving complex problems for which there is either no known solution or the use of known approaches does not provide a good solution.

3. Solving problems with fluctuating conditions, as ML algorithms can adapt to the new data available.

4. Solving complex problems that require manipulating large amounts of data.

There are several ways of categorising ML systems, depending on whether they are trained with human supervision or not, whether they can learn gradually or not as they go along, whether they simply work by comparing new data points with other known ones, or instead detect patterns in the training data and construct a predictive model. Each of these categories is defined below with a little more detail in order to highlight their differences.

5.3.1 Machine Learning systems as a function of type of supervision

5.3.1.1 Supervised learning

The most efficient ML algorithms are those that automate decision-making processes by generalising known examples. A supervised learning algorithm is an algorithm in which the user provides the desired pairs of input and output data, so that the algorithm finds the way of producing the desired output in relation to new input data that had not been previously processed, this all being done with no human help.

In supervised learning, two types of methods are distinguished: a regression method and a classification method.

5.3.1.1.1 Regression

Regression is the supervised learning method that seeks to predict continuous values from labelled data. Figure 5.5 shows a dataset in which the independent variables are “Period” and “Demand”, and the dependent variable is “Prognosis”. In this case, a linear model trained from the independent variables predicts the continuous expected

Period (x)	Demand (y)	Prognosis (Y)
1	133	137
2	292	200
3	283	264
4	283	328
5	302	391
6	400	455
7	505	518
8	608	582
9	667	646
10	783	709
11	785	773
12	799	837
13		900
14		964
15		1028

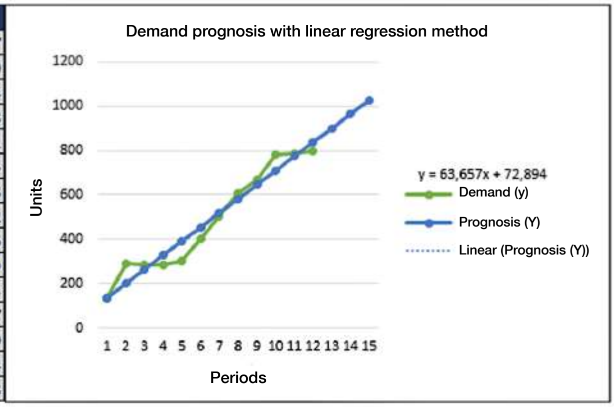


Figure 5.5. Example of supervised learning applying the linear regression method.

value for "Prognosis". The graphic representation of the data is depicted on the right-hand side of the figure, together with the regression straight line obtained from the model, which, for new values of the independent variables, provides the expected value of the independent variable.

5.3.1.1.2 Classification

Classification is defined as the supervised learning method that seeks to classify historical data labelled in different groups. By way of example, Figure 5.6 shows a group of points, each of which belongs to a different class (red or blue). The aim is to predict the class to which the new (black) point belongs.

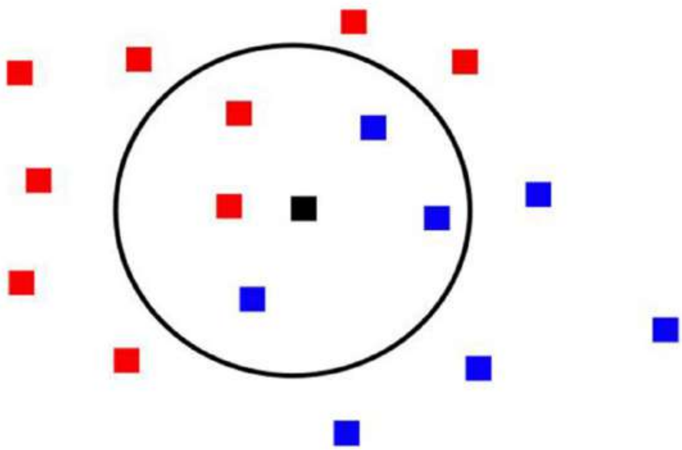


Figure 5.6. Example of supervised learning applying the KNN classification method.

To solve the problem, the so-called K-nearest neighbours (abbreviated as K-nn) classification method, for a k=5, is used. This means that, when it comes to classifying the new point, the 5 points closest to it are taken and the class with the greatest representation is the class that the predicted value for the new point adopts. In the particular case described here, the new point would be classified as blue class.

By way of example, a process industry application of this methodology might be classifying the requirements that a product must meet to pass a particular quality control. Thus, in **Figure 5.6**, if the red points are considered products that failed control and the blue points are products that passed control, using the above k-nn method, the new product to be evaluated would either pass or fail control depending on the largest class represented by the points surrounding the new point to be labelled.

5.3.1.2 Unsupervised learning

On the other hand, unsupervised learning algorithms are algorithms in which the algorithm is only provided with input data without the desired outputs. There are many applications of this type of learning, which can be divided into three different categories.

5.3.1.2.1 Clustering

The Clustering technique basically consists of dividing the set of data at issue into smaller groups called clusters. The aim is to split the dataset such that each cluster includes similar points. In similar fashion to classification algorithms, Clustering assigns a class to each point in the data, indicating to which cluster it belongs.

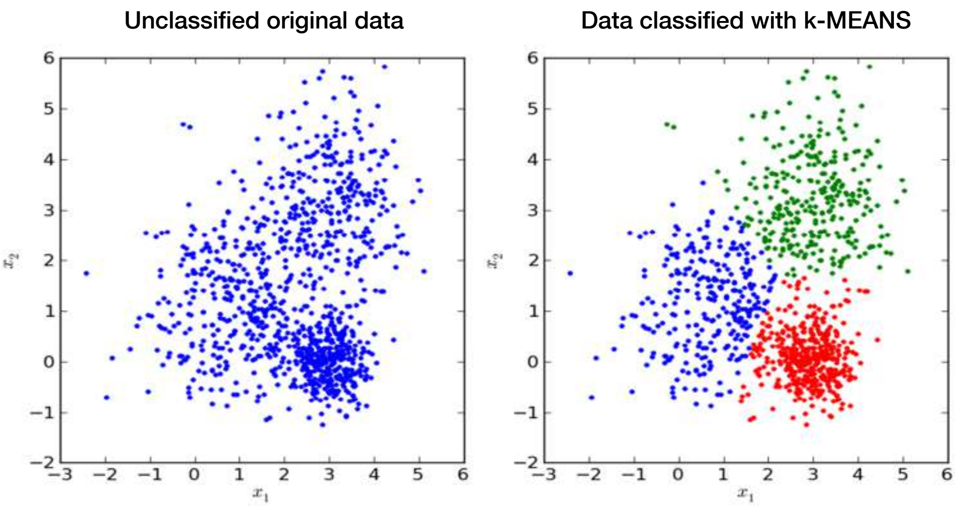


Figure 5.7. Ejemplo de aprendizaje no supervisado de Clustering con el método k-Means.

The plot of an unlabelled set of data is shown on the left-hand side of **Figure 5.7**. On the right-hand side, the figure shows the same dataset after applying the so-called k-Means Clustering algorithm, for k=3 classes. The algorithm tries to find the centre of clusters that are representative for certain regions of the data. This is done by repeating two cyclical steps: assigning to each data point the closest cluster centre and then moving each cluster centre as a function of the mean data points in that cluster. The algorithm ends the process when there are no more changes in the number of points making up each cluster.

The use of algorithms like k-MEANS is very useful for classifying the types of customers a company has. For example, a telephony company has the personal details of each of its customers, the geographic area to which they belong, the prices or products they have contracted, the time they have been with the company, whether they have renewed their services or have changed price, etc. Using all these data, clusters can be created of the types of customers the company has and it can thus be predicted what kind of price or service might be offered or recommended to a customer as a function of the characteristics exhibited by the customers belonging to that cluster.

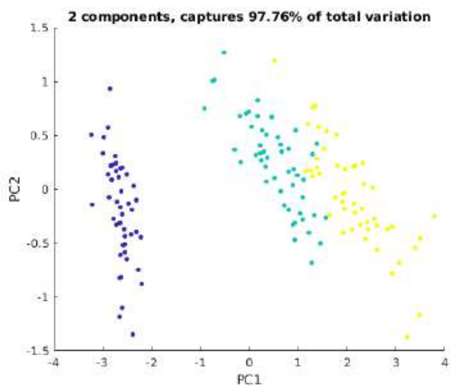
5.3.1.2.2 Visualisation and reduction of dimensionality

Visualisation algorithms generate a representation in two or three dimensions from complex unlabelled data. This type of algorithm tries to explain, preserving the largest possible part of the structure of the original data, how these are organised, allowing existing patterns in the data to be identified.

One task related to visualisation is dimensionality reduction. When the input data contain 4 or more dimensions, it is difficult to make a representation that describes all the available information. Thus, the aim of dimensionality reduction methods is to simplify data without losing too much information. One way of obtaining this objective is to combine several of the related characteristics in the dataset into a single characteristic. The main reasons for using some of the various dimensionality reduction methods are usually to identify and eliminate the irrelevant variables in the dataset, improve computational performance, and reduce the model's complexity and results.

By way of example, the left-hand side of **Figure 5.8** shows a dataset with four continuous variables: length and width of the sepal and length and width of the petal of different types of flowers. In order to apply a dimensionality reduction to the variables of the dataset, the right-hand side shows the result on applying so-called principal component analysis (PCA). The PCA method identifies the combination of attributes (or main components) of the dataset that explains the greatest data variance. Thus, the image on the right shows the two main components obtained by the PCA method (in image PC1 and PC2), which capture almost 98% of the variation of the original data. A dataset with two variables has thus been obtained from a dataset with four different variables, the two variables being a combination of the four original variables.

	sepal length	sepal width	petal length	petal width	target
0	5.1	3.5	1.4	0.2	Iris-setosa
1	4.9	3.0	1.4	0.2	Iris-setosa
2	4.7	3.2	1.3	0.2	Iris-setosa
3	4.6	3.1	1.5	0.2	Iris-setosa
4	5.0	3.6	1.4	0.2	Iris-setosa



Reference: https://www.math.umd.edu/~petersd/666/html/iris_pca.html

Figure 5.8 Example of unsupervised learning by dimensionality reduction applying the PCA method.

5.3.1.2.3 Association rule learning

This type of unsupervised learning method seeks to explore structures with large amounts of data in order to discover relationships between the different attributes existing in the dataset. Association rules have various applications, such as support in decision making, diagnostics and alarm prediction in telecommunications, analysis of sales information, merchandise layout at sales outlets, and customer segmentation based on buying patterns.

A typical example of association rules is market basket analysis. This helps find associations between products that customers purchase, which can influence a company's marketing strategies.

5.3.1.3 Semi-supervised learning

Another type of learning to be taken into account is so-called semi-supervised learning. In this type of ML, algorithms are involved that can handle partially labelled training data. Generally, most of the data processed by this type of models are unlabelled.

The application of this type of learning standard has become increasingly widespread nowadays. A clear example of the application of this type of model is in analysis of call centre conversation records. The aim is to automatically infer characteristics of the callers, their moods, reasons for the call, etc. This requires having a high volume of already labelled cases from which the patterns of each type of call are learned, which is quite time-consuming. For cases in which labelling is scarce, the semi-supervised self-learning method is applied. In the first stage of this method, a classifier is trained with the few labelled data. The classifier is then used to predict unlabelled data and the most reliable predictions are added to the training set. The classifier is then retrained with the new training set. This process is repeated until no new data can be added to the set.

Finally, though not actually a specific category of supervised ML, mention may be made of so-called reinforcement learning. In this type of learning, the system can observe the environment, select and perform actions. Depending on the actions taken, the system obtains rewards or punishments, so that it must learn by itself what the best strategy is for obtaining the greatest possible reward in time.

5.3.2 Machine Learning systems according to their incremental learning capability

Another ML system classification criterion is discerning whether the system can or cannot learn incrementally from an incoming data flow. Cases in which the system can learn from new incoming data are known as online learning; in contrast, those that cannot do so are known as batch learning.

5.3.2.1 Batch learning

This type of ML algorithm needs to be trained using all the available data and is incapable of learning incrementally. This requires much more time and computer resources. First, the system is trained, and it is then launched to production and executed without the system learning anything else. This type of system is also known as off-line machine learning.

If a batch learning system needs to improve its characteristics by incorporating new learning data, a new version of the system needs to be trained from scratch on the entire dataset (old and new data), stopping the previous system that was launched to production and replacing it with a new one. Training with an entire dataset can take hours, so that, if the system needs to adapt to rapidly changing data, it is advisable to find another type of system.

5.3.2.2 Online learning

In online machine learning algorithms, the system is incrementally trained by feeding it with individual data or sequentially with small groups of date. Each learning step is fast and has a low computational cost, so that the system learns on data as they become available. This type of learning is ideal for systems that continuously receive data and need to adapt rapidly and autonomously to changes. Once the system has already learnt on the new data, it can discard them, unless it needs to go back to a previous state.

An important parameter in this type of system is the learning rate. This rate tells the online learning system how quickly it needs to adapt to changing data. If the learning rate is high, the system adapts rapidly to the new data. On the other hand, however, it also quickly forgets the old data. Analogously, at a low learning rate the system exhibits greater inertia: that is, it learns more slowly, but it is also less sensitive to noise in the new data.

5.3.3 Machine Learning systems according to their ability to define predictive models

Another way of categorising ML systems is how they generalise. Most ML tasks consist of making predictions. This means that, given a number of training examples, the system needs to be able to generalise to examples it has not seen before. The aim is not just to run correctly on the training examples, but also on the new problems that are put to it. There are two main approaches to generalisation: instance-based learning and model-based learning.

5.3.3.1 Instance-based learning

The most trivial form of learning is memory-based learning. In such learning, systems "memorise" examples and then generalise to new cases using a measure of similarity known as instance-based learning.

5.3.3.2 Model-based learning

Another way of generalising from a dataset is creating a model from these and then using this model to make predictions. This type of learning is known as model-based learning.

In brief, this type of learning is made up of the following steps:

- Studying the data
- Selecting a model
- Training the model on training data: that is, getting the learning algorithm to find model parameters that minimise the cost function
- Applying the model for making predictions on new cases, expecting the model to generalise correctly

5.3.4 Artificial Neural Networks (ANNs)

To date ML has been defined as a subgroup of AI, in which computers learn to do something without being programmed to do so. However, ML algorithms can be programmed in many different ways.

A common type of problem might be, for example, identifying animals in an image. Training the model would consist, for example, of showing different images of animals, each one labelled with the name of the type of animal appearing in the image. The routine would eventually learn the combinations of characteristics that tend to appear together and associate those characteristics with the animal appearing on the label. Once the model had been constructed, the ML program would test the model and try to identify each of the labels of the animal in a set of images that it had not seen before. The model would then be trialled, its performance evaluated, and progressive adjustments made to the model to achieve a sufficiently high level of accuracy in identifying the different animals. Such an animal identification task can be carried out by different ML algorithms, but one of the most widely used algorithms for this type of task is the artificial neural network (ANN).

Both the nervous system and the human brain are made up of millions of neurons. These neurons are interconnected and carry out certain specific tasks, such as mathematical calculations, memory, and positioning: Neurons are activated and form different groups for each task. Another quality of the brain is acquiring knowledge from experience, i.e. learning from interaction with the environment. ANNs emerged from this interest in learning and are models that resemble, albeit more simply, biological neural networks. ANNs seek to draw upon the abilities exhibited by the brain to solve complex problems, such as vision, pattern recognition, and sensory-motor control.

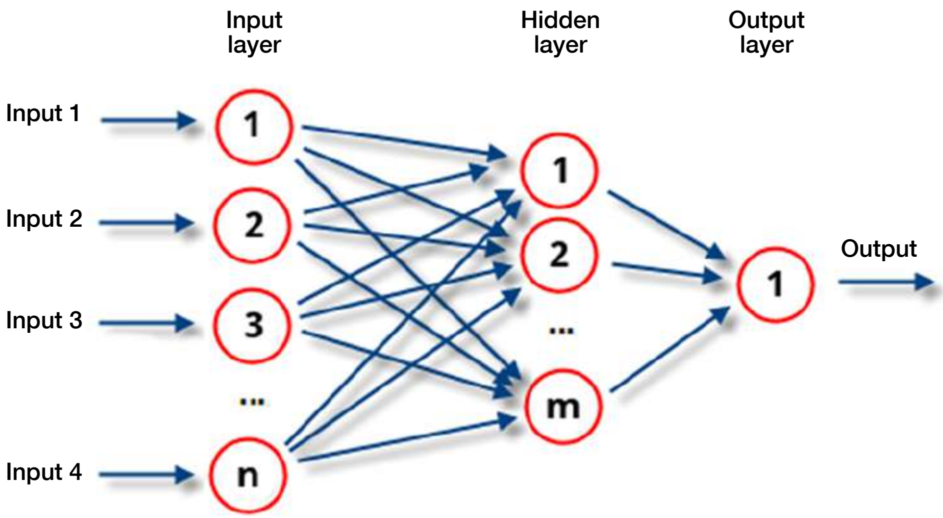


Figure 5.9 Example of an artificial neural network (ANN).

An ANN is a set of algorithms from the AI field for modelling high-level data abstractions using architectures in which multiple non-linear transformations are carried out. ANNs are made up of a set of process elements called neurons. Neurons are distributed in layers, each neuron from the preceding layer is connected to neurons of the following layer. There are thus three types of layers: an input layer, an intermediate layer known as a hidden layer, and an output layer. Information is conveyed through the neural network in the following way: each process element receives an input signal from the preceding units and communicates its output to the following units after applying a non-linear transformation to the incoming signal. The inference of the properties it is sought to obtain takes place in the neurons, and the concatenation of these inferential models gives rise to a single model that embodies the targeted abstraction. **Figure 5.9** presents an example of an artificial neural network with its different constituent elements.

ANNs afford the following advantages:

- They allow non-linear processes to be modelled.
- The learning process consists basically of presenting the network with an example and modifying its synaptic weights (fitting parameters) in accordance with its response.
- The network is able to adapt its parameters in real time.
- Due to the massive interconnection, failure of a processor does not seriously alter the operation.
- Uniformity in analysis and design.

The advantages of artificial neural networks include performance of different AI-related tasks. These tasks may be divided into two large blocks: supervised and unsupervised classification tasks, as noted above. As set out in this chapter, in supervised classification tasks, the neural network starts with input data, creates its own prediction, and makes adjustments as a function of the expected response until, eventually, the foreseen result approximates what was expected. In contrast, in unsupervised classification tasks, the correct response is not communicated to the neural network, and this makes its own associations based on some cost function.

An example of how ANNs might be used in the ceramic manufacturing process would be the ability to anticipate the behaviour of ceramic tile bodies during firing, based on measurement of properties such as density and thickness distribution in tile bodies. Thus, combining the results of non-destructive bulk density measurement and the data provided by a dimensional measurement system at the kiln exit and using an appropriately designed and trained ANN, it would be possible to establish, in a relatively prudent period of time, a predictive model that indicated whether the freshly formed tile bodies were going to tend to exhibit problems of dimensional stability under given firing conditions. Similar examples could be considered for other key parameters of the ceramic manufacturing process, such as the proneness for shades or changes in curvature to appear in the end product.

5.4 Deep Learning (DL)

The traditional ML-based data analytics approach consists of using the available data to train or establish systems with predictive capability, then establishing an analytical model, and finally calculating the parameters (or unknown values) of that model. Such techniques can produce predictive systems that do not generalise well because integrity and correction depend on the quality of the model and its characteristics (SAS, 2019). The promise of so-called Deep Learning (DL) lies in generating predictive systems that generalise well, adapt well, improve continuously as they are provided with new data, and are more dynamic than the predictive systems based on strict rules. Thus, in working with DL, a model is not adjusted, rather a particular task is trained.

The DL approach involves replacing the formulation and specification of conventional ML modelling by ANNs, which are made up of several hierarchically arranged levels. These neural networks need to learn to recognise the latent characteristics of the data. Such learning by the DL network is performed as follows: the network learns something simple at the initial level of the hierarchy and then passes this information on to the following level. The following level takes the simple information, combines it into something a little more complex, and passes it on to the following level. This process is thus repeated across the different levels of the hierarchy until it reaches the output layer. In short, a DL artificial neural network exhibits the same scheme as that shown in **Figure 5.9** except that, instead of having a single hidden layer, it exhibits multiple hierarchised hidden layers.

DL computational models imitate the architecture characteristics of the nervous system, allowing there to be networks of process units, within the overall system, that specialise in detecting certain characteristics hidden in the data. This focus has enabled improvement in the results obtained from the first ANNs, such as in computational perception.

In the above example of the classification of animal images, the starting level of a DL neural network could use the differences between the lightest and the darkest areas of the images to learn where the image boundaries or lines lay. The starting level would pass that information regarding the edges or boundaries on to the second level, which would combine the edges into simple shapes, such as a diagonal line or a right angle. The third level would combine the simple shapes into more complex objects, such as ovals or rectangles. The following level could then combine the ovals and rectangles into whiskers, legs, or rudimentary tails. This process would continue until the top level in the hierarchy was reached, where the network would have learnt to identify each animal.

In the preceding section on ML, a training method was described for recognition of the type of animal that appeared in a set of images, in which each image was correctly labelled with the animal that appeared in it. Each iterative step in testing and refining the model involves comparing the image label with the label that the program has assigned to it, to determine whether the program has been able to identify the type of animal correctly or not, so that a method of supervised learning is involved. Supervised learning is relatively quick and requires relatively less calculation power than some other ML training techniques.

In the real world, an enormous amount of data is collected, such as information on people through social media, hardware, software, application consents, and website cookies, and all these data can be very valuable. The problem arises when most of those data are unlabelled, so that they cannot be used to train ML programs that depend on supervised learning. To address this problem, a possible solution would be to label all unlabelled data, but that is a long and very costly process.

In this field, DL networks stand out in unsupervised learning and are a good alternative to supervised learning algorithms with regard to the issue of unlabelled or unstructured data. In the above problem of animal classification by images, even though these images are unlabelled, DL networks are able to learn to identify the animals that appear in each image.

On the other hand, DL algorithms need much computing power to solve problems. This cost stems from their iterative nature, so that their complexity increases as the number of layers and volume of data needed to train this type of network grow. Nevertheless, the ability of DL algorithms to improve and adapt continuously to changes in the implicit pattern of information, and their efficiency or ability to simplify existing analytical operations make DL a tool that exhibits great opportunities with numerous applications in industry. Some of the most popular commercial applications of DL at present are speech recognition, image recognition, natural language processing, and recommendation systems, which may be found in a great variety of sectors, ranging from autonomous driving to medical devices:

Autonomous driving: Researchers from the automotive world use deep learning to automatically detect objects such as stop signs and traffic lights. In addition, deep learning is used to detect pedestrians, which helps reduce accidents.

Aerospace and defence sector: Deep learning is used to identify objects from satellites that locate areas of interest and identify safe or unsafe areas for troops.

Medical research: Cancer researchers use deep learning to automatically detect carcinogenic cells. Some UCLA teams have constructed an advanced microscope that produces a multi-dimensional dataset used to train a DL application with a view to accurately identifying carcinogenic cells.

Industrial automation: Deep learning is helping to improve worker safety in heavy machinery environments, thanks to automatic detection of individuals or objects when they are at an unsafe distance from machines.

Electronics (CES): Electronic learning is used in automated hearing and speech translation. For example, home assistance devices that respond to a person's voice and know their preferences are based on deep learning applications.

Chapter 6:
Standardisation of Industry 4.0

Chapter 6 of the Guide introduces, first, what the applicable standardisation, normalisation, or regulations to Industry 4.0 are and what they mean from the perspective of digital enablers or tools. The working groups that develop, on an international and on a national level, the different standards applicable to the digital enablers that favour the development of Industry 4.0 are identified. The Spanish standards that establish the requirements for an organisation to be deemed Industry 4.0, as well as the way of assessing these requirements, are then examined in greater depth.

Finally, different models of management or good practices are reviewed, which can be used to facilitate digital transformation of the ceramic industry.

6.1 Standardisation as driver of Industry 4.0

Normalisation or standardisation is aimed at drawing up a series of technical specifications (standards) that are used voluntarily. Spanish law (Article 8 of Act 21/1992 on Industry) defines a standard as "the technical specifications of repetitive or continuous application whose observance is not mandatory, established with the participation of all stakeholders and approved by a Body that is nationally or internationally recognised for its standardising activity".

Standards are drawn up by standardisation bodies (in the case of Spain, UNE, Spanish Association for Standardisation), through Technical Committees for Standardisation, on which there is a balanced representation of all organisations interested in standardisation of a particular matter, which assures transparency, openness, and consensus in their work.

Such committees are made up of stakeholders: representatives of companies, consumer organisations, professional associations, certification, testing, and inspection bodies, environmental and social organisations, authorities and bodies charged with assuring observance of the law, sector associations, trade unions, educational institutions and research centres, among others.

The process of drawing up a standard is subject to a series of phases that ensure the final document is the result of consensus, and that any individual, though not belonging to the working body drawing up the standard, can express opinions or comments.

Standards create a safe basis for technical contracting, assure interoperability in applications, and protect consumers by regulations that lay the groundwork for product development, in addition to allowing communication between all parties involved by standardised terms and definitions.

That is why standardisation is critical to the future success of Industry 4.0. Solid international standardisation, agreed by consensus and officially recognised, is needed, which is why the IEC (International Electrotechnical Commission, organisation for standardisation in electric, electronic, and related technologies fields) has taken the initiative, providing coordination through its Strategic Group IEC 8, I 4.0, Smart Manufacturing.

It is well known that having a model helps focus key points. A reference model is a scheme that consistently describes an aspect that plays a major role in an important situation. A reference model that satisfies these criteria is a standardisable reference model. Once this model has been defined, the second aim is to have a single reference model for a particular situation and to globally use that model as sole standard. However, this cannot always be done. Reference models are never the only true models [92].

Some benefits that standardisation of Industry 4.0 provides for companies may be noted. It provides them with a solid foundation on which to design new technologies and improve their processes. In particular, standards facilitate access to the marketplace, provide economies of scale, and foster innovation. In addition, they serve to increase knowledge of initiatives and technical advances. For SMEs, it is important for the solutions they use to be based on standards, in order to afford independence from suppliers, avoid technology blocks, and enable maximum interoperability with the outside world.

Future manufacturing is oriented towards availability of all the necessary information in real time by connection of every element that participates in the value chain. It needs an unprecedented level of integration of information from every business domain.

To meet the targeted objectives, this information flow needs to be continuous and uniform, and this requires standardised interfaces [93].

6.2 Standardisation and digital enablers in Industry 4.0

Industry 4.0 involves application of a set of technologies across the industry's entire value chain. These changes afford benefits at process, product, and business model level.

As set out in the Guide, digital enablers are the set of technologies that enable this new industry to exploit the potential of the Internet of things. Indeed, these technologies allow hybridisation of the physical and the digital world, i.e. linking the physical to the virtual world to make an industry a smart industry [94].

To interconnect all the systems in research, design, development, production, and logistics processes, as well as to provide related services, standardised interfaces are required.

International organisations for standardisation, the International Organization for Standardization (ISO) and the International Electrotechnical Commission (IEC), have been working in this sense for years. Their standards are already being used in Industry 3.0 manufacturing models, and it is now a matter of developing them further in the relevant aspects [95].

For each technological need in Industry 4.0, there is a standardisation committee providing solutions. These international committees for standardisation have their Spanish counterparts in the UNE committees. Participation on UNE technical committees is open to Spanish industry. Through UNE committees for standardisation, Spanish industry can defend its interests in international forums where decisions are taken [96].

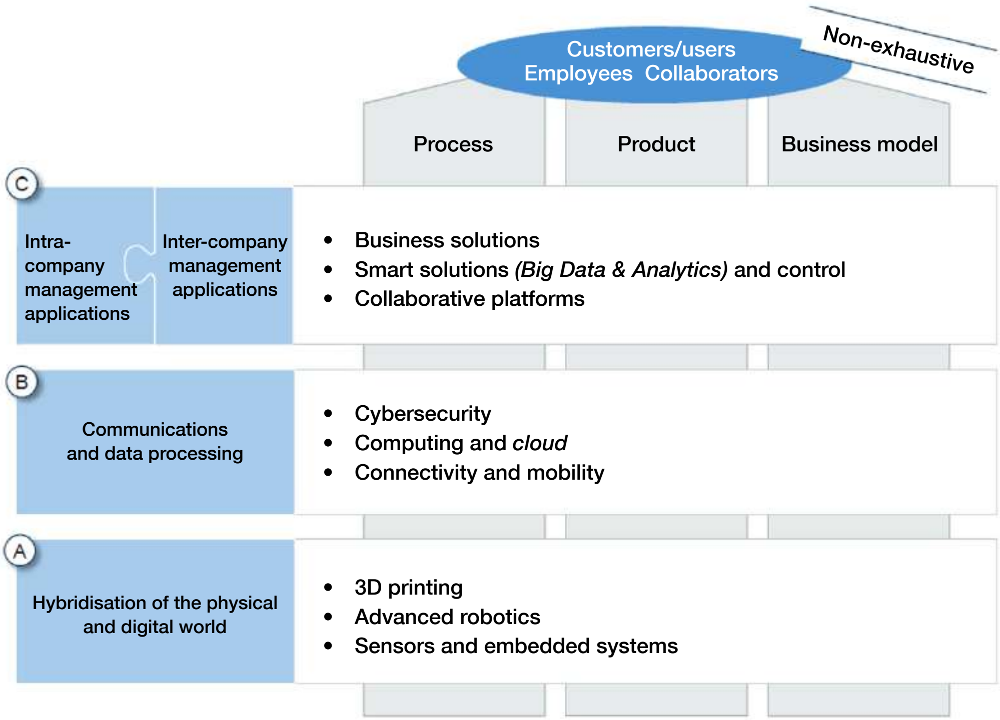


Figure 6.1. Conceptual framework of digital enablers (source: "La transformación digital de la industria española" -Minetur 2015).

In Spain, Technical Committee for Standardisation CTN 71 has been created on Digital Enabling Technologies (DET) in the UNE. This pursues development of new digital technologies in Spain's economic sectors by drawing up and using standards that govern these new markets.

6.2.1 Cybersecurity

The widespread use of information technologies in business and production processes, as well as in products, will afford enormous advantages, but it will also entail the need to assure protection and privacy of the information.

Information will be a company's most valuable asset, and technologies like Cloud Computing and collaborative research and development models will make it impossible to accurately define a protection boundary.

International committee for standardisation ISO/IEC JTC 1/SC 27 Security techniques for information technologies draws up standards for information protection in Information and Communication Technologies (ICTs). In Spain, committee CTN 320 Cybersecurity and personal data protection is charged with standardisation in this field.

ISO/IEC 27000 are the set of international standards on Information Security. Standard UNE-EN ISO/IEC 27000 contains the vocabulary on which the other standards are based.

The most important standards are UNE-EN ISO/IEC 27001 Information security management system, ISMS, which is the set of requirements for implementing an ISMS, and UNE-EN ISO/IEC 27002, a compilation of good practices for Information Security that describes the controls and control objectives. Standard UNE-EN ISO/IEC 2700 1 is certifiable.

Other standards related to this field are ISO/IEC 27032. Guidance for cybersecurity; ISO/IEC 27033. Network Security; ISO/IEC 27034. Application security; ISO/IEC 27035; IT security incident management; ISO/IEC 27036. Information security management in relation to third parties; UNE-EN ISO/IEC 27037. Management of digital evidence; and ISO/IEC 27050. Management of research processes (e-Discovery).

Further to be noted is standard ISO/IEC 15408 "Information technology — Security techniques — Evaluation criteria for IT security", which provides a very useful guide that defines a basic standard criterion for evaluating the properties and security characteristics of a given IT System or product and gives comprehensible arguments and criteria for the different profiles of the stakeholders related to security technologies (developers, security evaluators, and users).

On the other hand, working group IEC/SC 65C/WG 13 Industrial networks. Cybersecurity draws up specific standards for cybersecurity of industrial automation and control systems (IACS).

The standards of the Series IEC 62443 (Industrial Communication Networks - Network and System Security), which further develop the standards drawn up by committee ISA 99 of the International Society of Automation, have also been defined. They define the security control alignments for suppliers making components for process control system, integrators who construct such systems by integrating the components, workers operating the systems, and all organisations involved in process control systems.

6.2.2 Connectivity

Connectivity is another essential area for successful implementation of Industry 4.0. This new industrial paradigm relies on an information flow in which all the components involved need to be connected.

The standards are developed by the IEC TC 65 Industrial-process measurement, control, and automation committees. They are standards applicable to the systems and elements used for measurement and control of industrial batch or continuous manufacturing processes.

Furthermore, international committee ISO/TC 184 Automation systems and integration develops standards for information systems, automation and control systems, and integration technologies. In Spain, the committee charged with developing standardisation in this field is CTN 116/SC5 Industrial automation systems. Requirements for systems integration. This committee has developed standard UNE-EN ISO 11354-1 Advanced automation technologies and their applications. Requirements for establishing manufacturing enterprise process interoperability. Part 1: Framework for enterprise interoperability.

6.2.3 Advanced robotics

The inherent flexibility of Industry 4.0 manufacturing processes will require robots with new capabilities, which interact with the environment (process and even with the product itself).

International committee ISO TC 299 Robots and robotic devices draws up standards used in automatically controlled and reprogrammable, stationary and mobile, manipulation robots. On a Spanish national level, there is committee CTN 116/SC2 Industrial automation systems. Robots for manufacturing. The following standards have been developed by these committees:

- UNE-EN ISO 10218-1 Robots and robotic devices. Safety requirements for industrial robots. Part 1: Robots

- UNE-EN ISO 10218-2 Robots and robotic devices. Safety requirements for industrial robots. Part 2: Robot systems and integration

- ISO TS 15066:2016 Robots and robotic devices – Collaborative robots. Technical specification.

6.2.4 New manufacturing technologies

The new manufacturing technologies will allow companies to go from a production model of large batches of identical products to small batches of personalised products or even to manufacturing individual products at a competitive price.

Additive manufacturing or 3D printing, already widely used in prototyping, is advancing towards production of the end product.

International committee ISO TC 261 Additive manufacturing, as well as Spanish national committee CTN 116/GT 1, are charged with standardising processes, test methods, quality parameters, and supply agreements relating to additive manufacturing. The following standards have been developed by these committees:

- ISO/ASTM DIS 52904 Additive manufacturing – Process characteristics and performance –Standard practice for metal powder bed fusion process to meet critical applications

- ISO/ASTM DIS 52907 Additive manufacturing – Technical specifications on metal powders

- ISO/ASTM DIS 52911-1 Additive manufacturing – Technical design guideline for powder bed fusion — Part 1: Laser-based powder bed fusion of metals

- UNE-EN ISO/ASTM 52915:2016 Specification for the additive manufacturing file format (AMF), drawn up in collaboration with ASTM, which specifies the data exchange format between computer-aided design programs and additive manufacturing equipment

- ISO/ASTM WD 52941 Additive manufacturing — System performance and reliability — Standard test method for acceptance of powder-bed fusion machines for metallic materials for aerospace application

- ISO/ASTM WD 52942 Additive manufacturing — Qualification principles — Qualifying machine operators of metal powder bed fusion machines and equipment used in aerospace applications

There is a similar specific technology for electronic products, printed electronics. With new ways of printing and innovative materials, printed electronics can make products at competitive prices and with new possibilities. International committee IEC TC 119 Printed electronics draws up standards applicable to materials, processes, equipment, products, and the necessary safety requirements for the development of printed electronics technology.

6.2.5 Sensors and the Internet of Things (IoT)

Wireless sensor networks (WSNs) and the Internet of Things (IoT) are two technology resources applicable to the industry, which share an autonomous network infrastructure in which objects are interconnected to measure physical variables and solve problems.

On an international level, committee ISO/IEC JTC 1/SC 41 Internet of things and related technologies develops standards relating to the Internet of Things (IoT) and sensor networks.

Standardisation subcommittee CTN 71/SC 41 IoT and related technologies is developing standards in the field of the Internet of Things (IoT) and sensor networks, aimed at assuring interoperability and reliability of these networks and devices, of both a generic nature as well as for particular sectors.

On the other hand, the Spanish national working group CTN 71/GT 7 Sensor networks has drawn up the following standards:

- UNE-ISO/IEC 29182-1 Information technology. Sensor networks: Sensor network reference architecture (SNRA). Part 1: Overview and requirements.

- UNE-ISO/IEC 29182-2 Information technology. Sensor networks: Sensor network reference architecture (SNRA). Part 2: Vocabulary and terminology.

- UNE-ISO/IEC 29182-6 Information technology. Sensor networks: Sensor network reference architecture (SNRA). Part 6: Applications.

6.2.6 Cloud computing

The possibility of having all the information, processes, data, etc. within an Internet network, such as a cloud, where everybody can access the entire information, without there being a great infrastructure, is a new service that the digital world is providing for companies.

International committee ISO/IEC JTC 1/SC 38 Cloud computing and distributed platforms is charged with developing standards that assure interoperability and portability of data and applications in cloud computing, enabling real scalability without depending on proprietary technologies.

To date, this committee has developed standards ISO/IEC 17788 Cloud computing: Overview and vocabulary and ISO/IEC 17789: Cloud computing: Reference architecture.

6.2.7 Artificial intelligence

International committee ISO/IEC JTC 1/SC 42 Artificial Intelligence develops the standards required to deploy Artificial Intelligence or a system's ability to correctly interpret external data, learn from those data, and use that knowledge to perform tasks and achieve particular goals through flexible adaptation. Standards developed by this committee include the following:

- ISO/IEC 20546 Information technology — Big data — Overview and vocabulary
- ISO/IEC TR 20547-2 Information technology — Big data reference architecture — Part 2: Use cases and derived requirements
- ISO/IEC TR 20547-5:2018 Information technology — Big data reference architecture — Part 5: Standards roadmap

On a Spanish national level, subcommittee CTN 71/SC 42 Artificial Intelligence (AI) and Big Data has recently been created to draw up standards applicable to these technologies, addressing aspects such as reference architecture, risk management, trustworthiness, and other technical matters, as well as other standards relating to ethical and social aspects linked to use of these technologies.

The massive collection of data occurring in Industry 4.0 is pointless, unless the data can be appropriately extracted and analysed. Analysing the data obtained on the plant enables performance of preventive maintenance or process optimisation. The resulting product data yields information that can be used in design processes, in predictive maintenance of products, or in studies on consumer spending habits.

For efficient use of Big Data, it is essential for datasets to be standardised and for there to be a reference architecture. Committee ISO/IEC JTC 1/WG 9 Big Data has started drawing up the international standard that will specify the reference architecture [93].

6.3 Management system for industrial digitisation

In Spain, committee CTN GET24 - Transformation processes for Industry 4.0 (specific group with a temporary character) has been created, charged with standardisation of digital transformation processes in organisations.

The standards developed by this committee allow conformity evaluation, i.e. certification, of industrial companies that meet the requirements set out in the developed standards.

These standards are based on two main principles: analysis, management, and mitigation of the risks of Information Technologies in organisations; and the cycle of ongoing improvement, known as PDCA (Plan, Do, Check, and Act). The cycle of ongoing improvement is the conceptual basis underpinning the standards currently being developed that define management systems in any field of activity.

Two standards have been developed: Specification UNE 0060:2018 Industry 4.0. Management system for digitisation. Requirements; and Specification UNE 0061:2019 Industry 4.0. Management system for digitisation. Requirements assessment.

Standard UNE 0060 defines the management system for guiding the digital transformation process in industrial companies of any size and sector, assuring the maximum interoperability that Industry 4.0 requires. It is characterised by:

- User friendliness, integrable with other implemented ISO management systems
- SME focus, requirements adapted to SME needs
- (Digital) customer orientation
- Key business processes, those that have a significant impact on Company results

The standard's main objective is to foster digitisation of the Spanish industry, through an effective management system. The specification has been discussed in UNE in a multisectoral group in which associations of lighting devices, automotive suppliers, food and drinks, construction, and technology companies, corporations and SMEs have participated, together with direct participation by the Ministry of Industry.

UNE 0060 describes the requirements for an industry of any size and/or activity to be deemed a Digital Industry and to be assessed as such, either internally or by external actors (e.g. certification bodies).

The standard contains the following sections:

- **Leadership,** to overcome the resistance to change that arises naturally in the process of digital transformation and implementation of technological enablers relating to Industry 4.0 in every sector.

- **Planning of digitisation**, for Industry 4.0 to identify the following, in order to act consistently and in a well-planned way upon them:

    i Key business processes in its customer-oriented value chain
    ii Products/services that can be transformed or complemented
    iii Disruptive changes that most impact its business model
    iv Competencies and digital roles that companies need in their activity

- **Support, for the** establishment, implementation, maintenance, and ongoing improvement of digitisation as well as the economic and financial resources required to obtain it. Specifically:

    i Infrastructure that provides support for all organisation processes and allows technologies to be adopted that facilitate digitisation
    ii Human assets with appropriate skills and competencies in the digital field to assure digitisation of processes and activities and their evolution over time
    iii Documented information containing, at least, a chart of the organisation processes, functional organisation chart, detailed planning of digitisation, and explanatory documentation of compliance with the different specified requirements

- **Operation,** to implement and control the necessary processes, particularly those identified as key business processes. In order to meet requirements and develop actions in the digital environment. In addition, to control the planned changes and review the consequences of unforeseen changes, taking actions to mitigate any adverse effect. The implementation and development of digitisation activities must be considered from different viewpoints:

    i Vision of processes, considering at least, key processes such as product design/services, manufacturing, logistics and distribution, and those relating to customers: marketing/communication, sales, and after-sales and customer service
    ii Vision of customers and products/service. Communication with customers, digital transformation in design, development, and production. Digital marketing
    iii Vision of digital data. Use of process information and data
    iv Vision of technology, in relation to connectivity, information and data processing and storage, hybridisation of the physical and digital world, customer applications, and information security (cybersecurity)

- **Innovation,** in order to have a system that allows all knowledge generated in an organisation to be generated, enriched, materialised, and shared effectively with a view to fostering transformation processes through Industry 4.0 that help build a competitive edge with high added value, reducing errors, and improving quality, speed of development, and delivery of products and services.

- **Monitoring, measurement,** and assessment to evaluate conformity to set requirements and assure efficiency of the implemented system.

- **Ongoing improvement** by means of regular analysis of the suitability, adequacy, and effectiveness of the implemented digitisation in activities, processes, and products. Implementation of improvement actions as a result of this analysis.

On the other hand, Specification UNE 0061 establishes the procedure for assessing conformity to the requirements of Specification UNE 0060. Specifically, it defines the duration of the cycle of ongoing improvement; it establishes detailed criteria for assessing compliance with the requirements defined in Specification UNE 0060; and it establishes the minimum criteria for compliance with the requirements for being deemed a Digital Industry.

- **Cycle of ongoing improvement:** A continuous improvement process is a recurrent activity for improving performance. The time for the cycle of ongoing improvement of the digitisation assessment process has been set at 3 years.

- **Requirements assessment criteria:** It defines the assessment criterion of the requirements drawn from Specification UNE 0060. The requirements listed as *Mandatory* must always be considered in the digitisation process of the industrial organisation. Exclusions will only be accepted for regulatory reasons that apply to a particular sector. The requirements listed as Assessable may be excluded from the process if they are not objectively applicable and it is duly justified. The requirements listed as *Non-assessable* are not directly assessed. Their compliance is assessed through other requirements. The number of requirements to be assessed in relation to each section is as follows:

    - Digital industry context: 4 mandatory requirements
    - Leadership: 5 mandatory requirements
    - Planning: 4 mandatory, 6 assessable, and 2 non-assessable requirements
    - Infrastructure: 3 mandatory, 3 assessable, and 1 non-assessable requirements
    - Competencies, talent, and human assets: 4 mandatory and 2 assessable requirements
    - Documented information: 5 mandatory requirements
    - Operation: 2 mandatory and 1 assessable requirements
    - Process vision: 1 mandatory requirement
    - Customer and Product/Service vision: 2 mandatory requirements
    - Digital data vision: 1 mandatory and 1 assessable requirements
    - Technology vision: 2 mandatory and 1 assessable requirements
    - Connectivity: 4 mandatory and 3 assessable requirements

- Processing and storage: 1 mandatory and 4 assessable requirements
- Hybridisation of the physical and digital world: 7 assessable requirements
- Customer applications: 3 mandatory and 2 assessable requirements
- Information security. Cybersecurity: 8 mandatory requirements
- Innovation: 5 mandatory and 1 assessable requirements
- Monitoring, measurement, and assessment: 3 mandatory requirements
- Ongoing improvement: 1 mandatory requirement

- **Minimum criteria for compliance with requirements:** Throughout the cycle of ongoing improvement, in order to be considered a Digital Industry, an organisation must meet the minimum criteria applicable both to the mandatory and to the assessable requirements:

  i Mandatory requirements: 80% at the start of the process; 85% on ending the first year of the cycle of ongoing improvement; 90% on ending the second year of the cycle of ongoing improvement; 100% on ending the full cycle of ongoing improvement.

  ii Assessable requirements: 35% at the start of the process; 60% on ending the full cycle of ongoing improvement.

In addition to being considered a Digital Industry, a level of Excellent Digital Industry can be attained. To achieve this level of excellence, the organisation must meet 100% of the mandatory requirements and 80% of the maximum attainable score in assessable requirements.

6.4 Models of management and good practices

In addition to the standards already mentioned, there are different models and tools that can be used for Industry 4.0 digital transformation [97]:

- ITIL (ITSMF, IT Service Management Forum). The Information Technology Infrastructure Library of the Office of Government Commerce, OGC, UK, is a framework on best practices relating to delivery of IT services, pursuing quality and effectiveness.

- eTOM. The Enhanced Telecom Operations Map of the Telemanagement Forum (TMF) is made up of a group of companies that supply telecommunications services or applications. This is a process reference framework for telecommunications organisations aimed at assuring interoperability in administering networks, commercial systems, and operating systems. eTOM describes the processes required to automate and interconnect systems or elements.

- CMMI. Capability Maturity Model Integration belongs to the Software Engineering Institute, SEI, Research Centre. It is a framework for improving processes focusing on provision of services. The degree of maturity is quantified on five progressive levels, which guide the evolutionary path that can be followed during maturity growth.

- COBIT. Control Objectives for Information and related Technology, of the Information Systems Audit and Control Association (ISACA) and IT Governance Institute (ITGI), is a best practices framework for IT management, using a set of generally accepted control objectives. This reference could be used to define objectives and practices in any framework relating to ICT installations.

- TOGAF. The Open Group Architecture Framework, developed by The Open Group, is one of the most popular methodologies for developing Business Architecture. TOGAF is a tool for assisting in the acceptance, creation, use, and maintenance of architectures. It is based on an iterative process model supported by best practices and a re-usable set of existing architecture assets.

- TRLs. Technology Readiness Levels are a method for measuring the degree of maturity of a technology. Nine levels are considered, and it is widely accepted (U.S. Department of Defence, NASA, European Space Agency, and European Commission). Different definitions are used, depending upon the context; though there are differences between them, they are conceptually similar.

- Gartner hype cycle. A graphic representation of maturity, adoption, and commercial application of specific technologies is involved, in which the initial excess enthusiasm and subsequent disappointment, which generally follow the introduction of new technologies, are characterised. It is a widely used constitutive model for information and communication technologies.

- HADA. Advanced digital self-diagnosis tool. Developed in the framework of the Connected Industry 4.0 initiative in collaboration with the EOI (School for Industrial Organisation), which determines the degree of technological maturity. It consists of a series of questions grouped in 5 dimensions.

- Industry 4.0 Readiness (IMPULS). Industry 4.0 Maturity Model developed by the IMPULS Foundation of the German Engineering Federation. It is a model with a very technological orientation, divided into 6 dimensions, including 18 elements to indicate the degree of maturity represented on 6 levels.

- Industry 4.0 Self Assessment (PwC). Self-assessment tool developed by PwC that considers 6 dimensions and allows identification of needs, as well as classification of a company's level of maturity on 4 levels.

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