Driving Innovation in Product Design and Manufacturing Using 3D Printing

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1. OVERVIEW

The transformation underway in industry is fundamentally changing the way products are designed and manufactured, and what these products can do. In old industries such as the Lime Industry, innovation faces many obstacles. By overcoming many challenges, the Industrial Internet of Things (IIoT) and Advanced Manufacturing will move the Lime Industry into new levels of efficiency and productivity:

- New generation state-of-the-art sensors can capture a much more granular level of operational data and can operate more reliably under harsh process conditions (i.e. a combustion chamber scenario)
- New production techniques, like 3D printing of sensors and devices, will enable the production of prototypes faster, at lower cost and with major flexibility.

Machines today are designed with corresponding virtual representations. The physical and digital counterparts exchange data, which is constantly captured by sensors. This way, companies can detect faults earlier in the development phase – and even monitor machinery and components after distribution.

This article explores, in a real world example, the ability to digitally link together design, product engineering, manufacturing, supply chain, distribution, and remanufacturing (or servicing) into one cohesive, intelligent system – indeed, a level indicator sensor that helps to prevent inefficiency and downtime in a plant that has to run 24/7 on a continuous basis.

2. INTRODUCTION

2.1 What is Lime?

Lime is one of the oldest and most vital materials known to man. Limestone is the raw material for lime-making, and constitutes approximately 10 percent of the sedimentary rocks exposed on the earth's surface. It is formed over thousands and thousands of years by compression of organic substances such as corals, plants and animals. Lime, often referred to as "quicklime," is a term applied to several related materials. Pure lime is calcium oxide (CaO) formed by "burning" a form of calcium carbonate such as limestone ($CaCO_3$). Carbon dioxide gas (CO_2) is released and leaves lime behind. Dolomite, a calcium magnesium carbonate ($CaMg(CO_3)_2$) can also be calcined to form dolomitic lime. These processes are called calcination. Lime can also be mixed with water to form hydrated lime ($Ca(OH)_2$). Before the rapid growth of the chemical process industry, lime was regarded almost entirely in the steel manufacturing, agricultural and water treatment industries.

Since 1900, progressively larger quantities of lime have been used in industry as a chemical reagent. Today, more than 90% of lime is used as a chemical in its oxide and hydroxide forms. Lime products are used in a wide variety of applications in Europe and throughout the world. Although lime products are rarely sold directly to consumers, the average EU citizen indirectly consumes around 150 grams/day of lime products (EuLA, 2013b). Lime products are important in the steel industry and important to produce construction materials, paints, paper and plastics as well as cosmetics, rubber, food and glass. The principal use of quicklime is in the steel industry where it serves as a media to remove impurities (silica, phosphorus, and sulphur) during the refinement of steel[1].

To give an estimate of the Lime market, "Revenue from the sales of lime in the U.S. market is estimated to be valued at US$ 2,538.1M by the end of 2016. The U.S. lime market is estimated to register a value CAGR of 3.7% during the forecast period 2016–2026."[2]

2.2 Kilns: The Hub of the Lime Plant

How do you go from limestone to lime? The calcination process takes place in a lime kiln, where limestone is burned to produce the form of lime called quicklime. The reaction is endothermic and requires approximately 760 kcal/kg to start. An ideal thermal decomposition of 100% pure $CaCO_3$ has a theoretical loss of weight of 44%, in terms of released CO_2.

There are several types of lime kilns, commonly divided into Vertical and Rotary Kilns. Rotary Kilns are generally used for firing coal, oil and natural gas. The next common type of kiln is a Vertical Parallel Flow Regenerative Kiln, or Vertical PFR Kiln. Vertical PFR Kilns, consist of two steel, cylindrical, vertical (refractory-lined furnace) shafts, connected by a single arch (as depicted in figure 1).

The term Parallel refers to the way the fuel and the oxidizers flow into the Kiln while the term Regenerative refers to the fact that the two shafts are fired in sequence to achieve excellent energy efficiency. While one shaft calcines the product, the other preheats the stone. In the burning shaft, the lime is calcined in parallel flow. The hot combustion gases are then transferred through the crossover channel to the non-burning shaft where they preheat the limestone in counter flow in the upper area of the shaft. The flow direction of the gases is reversed at regular intervals. This allows the regenerative preheating of the stone to take place (the stone in the preheating zone of the kiln acts as a heat exchanger) and thus for the maximum use of the heat contained in the kiln gases.

Because the kiln is the hub of the lime plant, it is necessary to monitor the level of the limestone inside the kiln during operation. Through limestone level monitoring, the operator can adjust kiln operation (i.e., adjust waste gas outlet temperature or fine-tune the quicklime discharge system) to optimize final product quality and reduce the unplanned downtime of the whole plant[3].

In a Vertical PFR Kiln, the two shafts are loaded from the top, alternatively, with the appropriate quantity of raw limestone, while the final product (lime) is discharged at the bottom. The kiln

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[1] ***Stork, Michiel, et al.*** *A competitive and efficient lime industry - Technical Report by Ecofys. www.eula.eu. [Online] July 2014. http://www.eula.eu/file/475/download?token=5lpX8a3h*

[2] http://www.futuremarketinsights.com/reports/us-lime-market

[3] ***Qualical International Srl.*** *How QualiCal Produces Lime: Quicklime Calcination. 2014*

works in positive pressure, designed for a maximum operating pressure in a range of 400 - 500 mbar (above atmospheric pressure) and is hermetically sealed during the combustion process. Combustion fumes flow through the combustion shaft and move in the preheating shaft from the connecting arch, flowing in counter current and exchanging heat with fresh limestone just charged, leaving the kiln temperature in a range between 80 – 140°C. The base of the kiln is outfitted with drawers moved by hydraulic cylinders where the lime is discharged. Vertical kiln solutions are regarded as the most efficient technology in the lime domain.

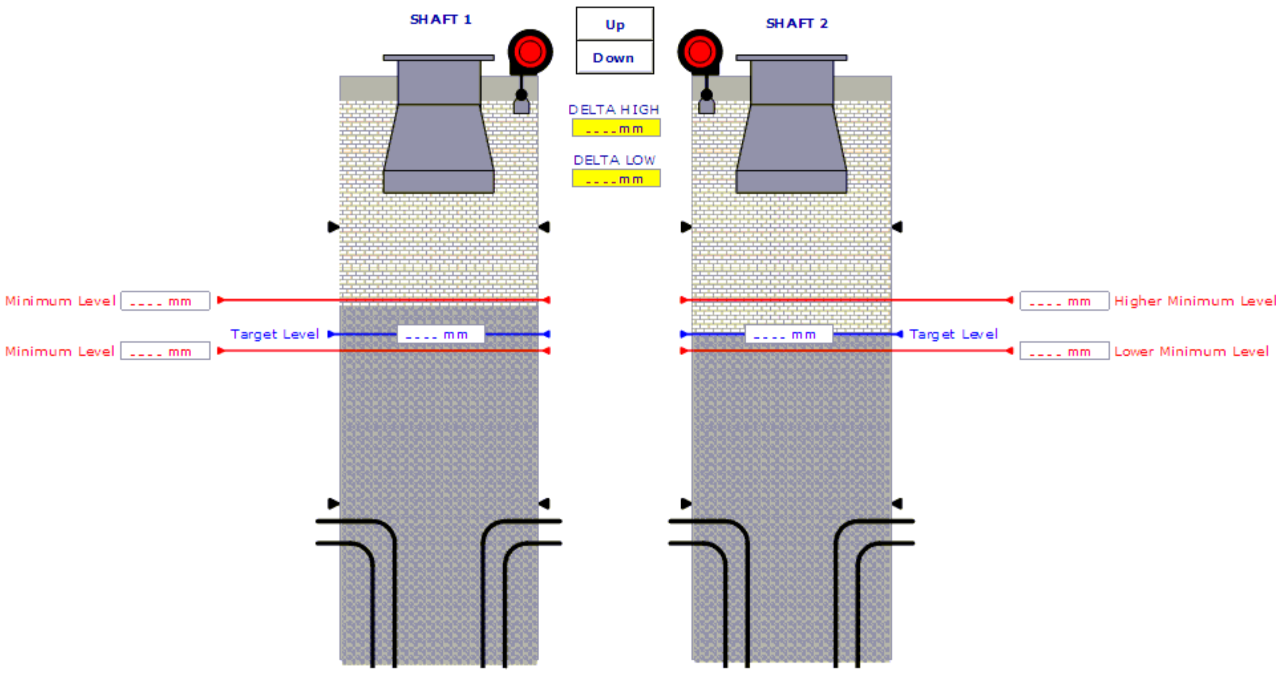

Figure 1 Kiln level representation in a vertical PFR Kiln

3. ADVANCED MANUFACTURING IN THE LIME DOMAIN

To meet today’s industry requirements and large capacity demands, the sedimentary manufacturers cannot be sedentary. The market has become more and more competitive in the latest years, in principal, due to the fall in demand related to the economic global crisis of steel merged with the crisis related to the oil glut. Therefore, the most efficient technology is needed to reduce operating expenses by avoiding unplanned downtimes.

In the process-intensive lime production business, manufacturers diligently monitor the limestone levels in the kilns. Continuous improvements to the monitoring process affects the overall plant’s efficiency and improves the longevity of the equipment. Leading edge Industrial Internet applications leveraging continuous level sensor technology are being developed and deployed within Vertical PFR Kilns. Vendors such as Qualical LLC, are developing and producing sensors using 3D printing, and demonstrating lime production improvements such as optimized performance and output, reduced operational costs, materials efficiency and reduced levels of environmental pollutants released during the process.

3.1 State of the Art Limestone Level Sensors

Limestone level is an important measuring parameter in the industrial lime production domain. Generally, the level is the measure of the height of a substance contained in a tank with respect to a point taken as reference. It is a linear measure, typically expressed in percentage or in millimeters and can be continuous or with point values: The continuous sensors measure the level inside a specific interval and determine the exact quantity of substance in a determined volume, while the point level sensors indicate only if the substance is on or under the measurement point. In the lime production industry, this is tricky business. Bulk stones, dust, high temperatures and other factors, prevent many electronic devices currently on the market from being reliable. Obstacles include:

- Capacitive level sensors, principally developed to provide point value signals, only indicate whether the substance is above or below the sensing point. Generally, they detect levels that are excessively high or low. They have always shown installation and mechanical strength limitation of the probes due to immersion modality in the material.
- Radioactive level devices, such as Gamma Ray types, are regulated by safety and environmental legislation. The accuracy in measuring levels can be compromised and the readings can be confused when layers of dust or foam become substantial or when measuring turbulent surfaces.
- Electromagnetic level sensors are critical from the point of view of the accuracy and reliability of measurement. Calibration must be done precisely according to the material to be measured. It is unsuitable to have dirty applications or processes where magnetite may be produced.
- Ultrasonic level sensors are used when the level cannot make contact with the material under level detection. However, the measurement is not accurate in cases where the material is powder or the surroundings have critical noise, temperature and pressure.

In processes such as twin or more than two shafts kilns in which the lime production processes occur, it is clear that the above technologies have many defects and limitations. It is not possible to use traditional tools, which are not able to resist the working conditions of the calcination process and cannot carry out accurate, precise and continuous measurements. Therefore, there is a need to provide an optimized, simple, practical and efficient sensor, which solves the technical problems described above, plus carries out accurate level measurements for application specific to limestone baking regenerative kilns.

Traditional shaft level indicators are composed of a drum of 500 mm diameter, on which is wound a steel rope that supports a 50 kg counterweight, operated by:

- An electric motor, capable of moving the counterweight along the lime kiln preheating zone in order to select the desired work area (approx. 5 meter height) - The ABSOLUTE LEVEL.

- A hydraulic cylinder, laying down the counterweight on the material bed, giving back on continuous bases, with an absolute encoder coupled to the drum: The RELATIVE LEVEL of the material to be discharged during the calcination process cycle of the Vertical PFR kiln (approx. 800 mm work range).

This system is currently operating in most of the plants in the whole lime domain, but there is plenty of room for improvement. Looking at the insights coming from the shaft level indicators, plant process engineers were able to ascertain that the traditional shaft level indicator was the first cause of unplanned downtime. They were surprised to see the money lost: averaging 20,000 € every year in production losses (calculation based on eight operating kilns worldwide having an average production of 400 tons per day). See Figure 2.

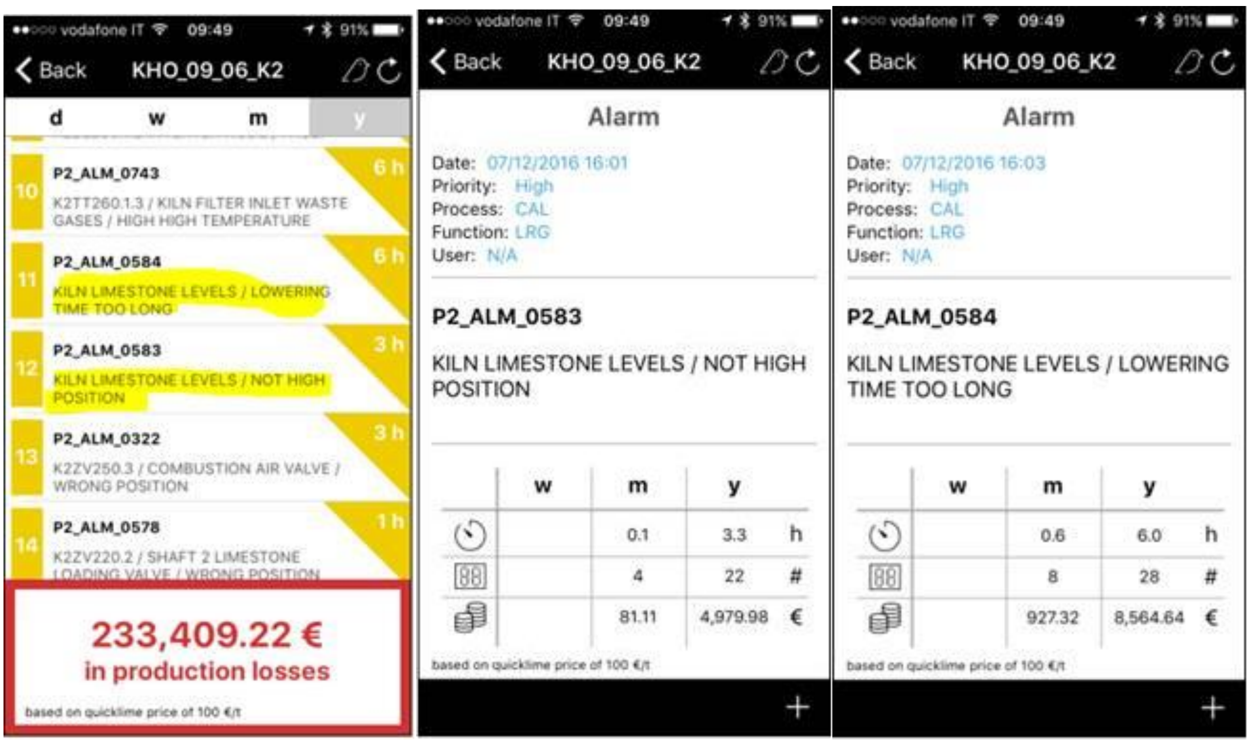

Figure 2 - Screenshot coming from MOSAICO ZERO App related to Kiln Limestone Levels unplanned downtime

By applying innovative design changes to the traditional indicators and adding analytics capabilities, lime plants are beginning to transform an old industry into a brilliant industry.

3.2 Revolutionizing the Lime Industry with IoT Sensors Printed in 3D

Regardless of the approach selected to obtain better measurement results, success is based on process measurements. By adding new measurement capabilities and analytics capabilities, the adoption of the IIoT will move the lime industry into new levels of efficiency and productivity. As an example of one such IIoT development, Qualical has developed an improvement to traditional shaft level indicators with a simpler, more precise and reliable device to be installed on its kilns. Utilizing a new generation of brushless motor and connecting the drum directly to the motor, the device that can operate the system in continuous torque control, laying down accurately the counterweight on material bed, without any extra delicate hydraulic system. The brushless motor allows high flexibility of parametrization, very accurate and continuous torque and weight variation control. This avoids any “blind” moment, guaranteeing seamless contact between the sensor and the material bed. The device, known as METRO, is virtually maintenance free – no longer requiring gearboxes or bearings to be lubricated; no longer wearing out parts due to mechanical friction; eliminating failures due to overheating of components.

The electric supply and communication is redefined as a plug-and-play solution connecting an electric power cable and a data cable. The measuring system is managed by a drive controller installed in a specially designed electrical cabinet. See Figure 3. Functional parameters can be programmed directly into the driver during workshop assembly phases and engineers can further fine-tune them during plant operations remotely if needed. At the same time, Asynchronous Statistical Data (ASD) can be collected by adopting the IIoT architecture to deploy analysis on various parameters related to its functioning (i.e., the actual speed in descending movement and the actual current consumption while operating). This data is collected to strictly observe and address proactively any malfunctioning that could result in a general plant unplanned downtime.

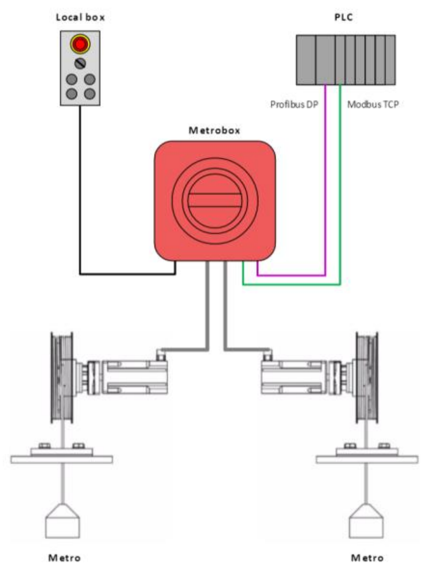

Figure 3 - METRO Schema

METRO is a brilliant machine by nature: it is a sensor itself and is equipped by sensors.

With continuous and loop fine-tuning of its operations by means of a Proportional-Integral-Derivative (PID) controller plus feedforward fine-tuning allows a machine to:

- respond to the present through the proportion term,
- insert past experience through the integration term,
- anticipate the future through the derivative term, and
- leverage operators and engineers’ knowledge.

Feedforward's spontaneous indicators enable the machine to deliver immediate results and channel them in the right direction when anomalies or mistakes are noticed. Applied to a specific case, feedforward is like an operator that gives direct indication to the system and manually changes the drawer speed to follow the theoretical discharge line.

On the other hand, the PID system allows the machine to correct itself, look to the past to understand if corrective actions are working, directly respond to its operation or predict future trends to be prepared for upcoming events[4].

The brain of METRO continuously monitors its condition and operating modes, such as actual position, applied resistance torque, internal temperature, and so on. The data are evaluated in real time by the PID algorithm into appropriate action commands to, for example, manage the proportional valve which moves the discharge tables or adjust the motor torque control to guarantee seamless contact between METRO and the bed of material.

PID allows the establishment of a continuous loop – monitor, analyze, correct – between METRO and discharge drawers comparing the limestone's theoretical position, calculated every second given the starting and target levels defining a descending profile, and the limestone's effective position measured by METRO, along the entire cycle.

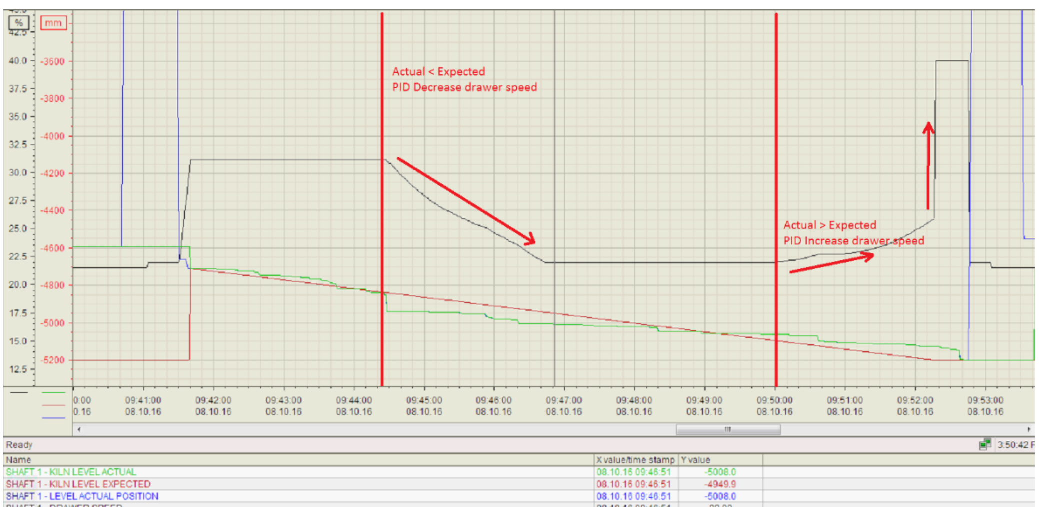

Figure 4 Typical discharge system PID cycle

An added benefit of the device described above, is that it may be printed on a 3D printer. Engineers can "print" one part, test it and, based on the test feedback, quickly adjust the digital design and reprint an improved version of the parts using the same additive manufacturing machine. This accelerates the cycle of design, prototyping and production. Adjustments to the production process, as well as to supply chain and distribution logistics, can be calculated and enacted in real time. As a result of this flexible design and development methodology, the original

[4] ***Langdon, Morris.*** *Creating Innovation Culture, InnovationLabs White Paper. 2007*

device was drastically scaled down, creating a much lighter instrument with optimized components. See Figure 5.

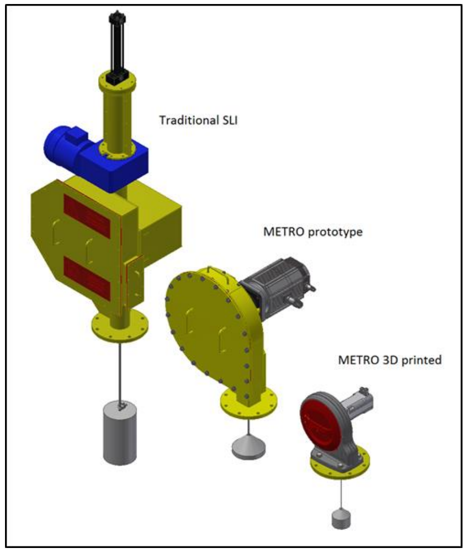

Figure 5 - From traditional shaft level indicator to 3D Printed METRO

4. What Does This Mean for the Lime Industry

Enhancements through 3D printing save up to 90 percent of the raw material costs, reducing waste of material nearly to zero. The materials used are lighter and weight optimization is enhanced compared to traditional production technologies.

These advantages allow a faster, and more affordable feedback loop between design, prototyping, production and customer experience to achieve the best version, correcting all defects and criticalities. The process is also very flexible and produces identical shapes, but with completely different properties, according to the material used in the printing process. All this information is stored and collected in the manufacturing process history, helping engineers and designers to cross-match information, identify any underperformance or quality issues and correct it quickly.

Finally, being so flexible and reconfigurable, the printing process brings immeasurable benefits for customers willing to transform themselves from the final user to the producer, providing a printing machine and skilled engineers. Spare parts and entire equipment could be printed directly on site. In an ideal future, entire plants will be produced directly on site: eliminating the need to transport heavy steel parts; eliminating storage of parts in warehouses waiting for assembly and erection. Everything could be produced when required and be completely independent from third party companies.

To compare the old solution with the new 3D printed model, the whole life cycle must be considered, from material purchase to maintenance activities. With a ranking of 1 to 10, the optimization of each life cycle aspect is evaluated to ascertain how far each product is from an ideal solution. See Figure 6.

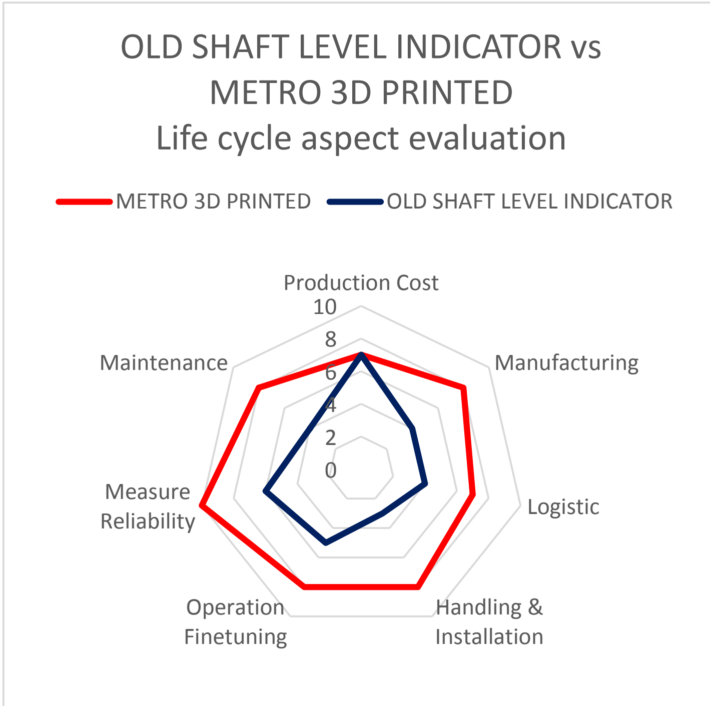

Figure 6 - Comparison between traditional shaft level indicator and 3D Printed METRO.

Considering the reduction of periodic maintenance on a set of 2 METROs, the Return on Investment (ROI) is 41 months for the low production kilns (180 tpd) and 9 months for high production kilns (800 tpd). With IIoT, equipment alarms data is collected and, translating the unplanned downtimes related to old shaft level indicator in loss of production, it has been estimated that the real ROI is 13.5 months for 180 tpd kilns and 3 months for 800 tpd kilns.

It has been estimated that upgrading the traditional shaft level indicator to the new 3D printed solution can save approximately 120 €/tpd every year. Considering a lifetime projection of 10 years, upgrading to the IIoT solution can potentially increase revenue up to 1,400,000 € over the lifetime of the equipment, considering plant availability and maintenance optimization.

Evidence of the strongly reduced unplanned downtime are visible in the “Year Unplanned Downtime Cost Impact” report (see Figure 7) showing how few occurrences were related to METRO.

MOSAICO

BERGMANN KALK GMBH

YEAR UNPLANNED DOWNTIME COST IMPACT

REPORT FROM **01/01/2016** TO **31/12/2016**

http://tinyurl.com/j46tanc

DOWNTIME DETAILS

Description	Total Alarms (#)	Total Downtime (#)	Cost (€)
ZV220.2 / HVC / SHAFT 2 LIMESTONE VALVE - WRONG POSITION	270	42 h 05 m 53 s	31,748.95
FT290.1.2.1/2 / NGA_FMD / MEASURING UNIT - GAS INLET FLOW - TRANSMITTERS DISCREPANCY [SAFE]	2	11 h 45 m 49 s	9,410.89
ZV220.1 / HVC / SHAFT 1 LIMESTONE VALVE - WRONG POSITION	83	09 h 34 m 45 s	6,944.90
ZV260.2 / WBV / KILN FILTER - BYPASS VALVE - WRONG POSITION	129	09 h 19 m 19 s	6,797.25
ZV250.7 / AFV / SHAFT 1 AIR-FUMES VALVE - WRONG POSITION	99	08 h 38 m 42 s	6,627.83
PT250.4.1 / COM / COMBUSTION AIR PRESSURE - HIGH HIGH	238	07 h 05 m 01 s	5,755.43
NGA_FMD / MEASURING UNIT - GAS RAMP NOT ENABLED [SAFE]	196	07 h 22 m 45 s	5,196.16
ZV280.10 / LDV / SHAFT 1 LIME DISCHARGE VALVE - WRONG POSITION	97	06 h 38 m 37 s	5,121.12
TT230.1.1 / KFU / KILN CONNECTION CHANNEL - TEMPERATURE 1 - TOO HIGH [SAFE]	19	04 h 44 m 59 s	3,760.20
COM_KOO / PROCESS AIR - BLOWERS NOT ENOUGH FOR EAN SETPOINT	21	04 h 53 m 20 s	3,279.63
BL292.1.2 / LCU / LANCES COOLING AIR BLOWER - INVERTER FAULT	2	03 h 28 m 58 s	2,757.20
BL292.1.1 / LCU / LANCES COOLING AIR BLOWER - INVERTER FAULT	3	02 h 50 m 33 s	2,439.81
LED / SHAFT 2 QUICKLIME EXTRACTION - TOO SLOW	4	03 h 08 m 37 s	2,213.63
ZV220.4 / SCV / SHAFT 1 CLOSURE VALVE - WRONG POSITION	22	02 h 01 m 10 s	1,497.75
TT230.1.2 / KFU / KILN CONNECTION CHANNEL - TEMPERATURE 2 - LOW LOW	10	01 h 43 m 17 s	1,312.56
ZV220.5 / SCV / SHAFT 2 CLOSURE VALVE - WRONG POSITION	15	01 h 26 m 33 s	1,009.75
ZV250.8 / AFV / SHAFT 2 AIR-FUMES VALVE - WRONG POSITION	27	01 h 15 m 52 s	979.94
PT230.1.3 / AIR / KILN CONNECTION CHANNEL - PRESSURE - LOW	39	01 h 14 m 07 s	947.05
PT250.4.1 / COM / COMBUSTION AIR PRESSURE - LOW	27	00 h 59 m 03 s	709.42
PT250.4.1 / COM / COMBUSTION AIR PRESSURE - LOW LOW	7	01 h 07 m 58 s	656.07
ZV290.4 / NGA_FMD / INVERSION UNIT - GAS TO LANCES SHAFT 1 VALVE - WRONG POSITION	7	01 h 17 m 44 s	647.78
BL250.1.1 / COM / COMBUSTION AIR BLOWER - FAILED TO START	31	00 h 45 m 48 s	534.33
BL250.1.3 / COM / COMBUSTION AIR BLOWER - FAILED TO START	10	00 h 39 m 20 s	518.98
ZSC280.15.1 / LDG / SHAFT 2 INSPECTION DOOR - EXTERNAL PIPES SIDE - OPEN	3	00 h 53 m 43 s	410.34
ZV280.11 / LDV / SHAFT 2 LIME DISCHARGE VALVE - WRONG POSITION	6	00 h 21 m 44 s	353.17
PT250.6.1 / KOO / LIME COOLING AIR PRESSURE - HIGH	2	00 h 36 m 13 s	352.11
ZSC280.14.1 / LDG / SHAFT 1 INSPECTION DOOR - EXTERNAL PIPES SIDE - OPEN	1	00 h 16 m 01 s	333.68
ZSC280.15.2 / LDG / SHAFT 2 INSPECTION DOOR - EXTERNAL BACK SIDE - OPEN	3	00 h 26 m 51 s	303.93
TT230.1.1 / KFU / KILN CONNECTION CHANNEL - TEMPERATURE 1 - TOO LOW [SAFE]	1	00 h 22 m 17 s	294.02
ZSC280.11.3 / LDV / SHAFT 2 LIME DISCHARGE VALVE - INSPECTION DOOR OPEN	2	00 h 15 m 38 s	287.70
SLI / METRO LEVEL SYSTEM - LOCAL EMERGENCY BUTTON PRESSED	8	00 h 19 m 31 s	283.26
PT230.1.3 / AIR / KILN CONNECTION CHANNEL - PRESSURE - HIGH HIGH	4	00 h 17 m 35 s	213.69
BL250.2.1 / KOO / LIME COOLING AIR BLOWER - FAILED TO START	7	00 h 17 m 52 s	179.91
ZSC280.15.4 / LDG / SHAFT 2 INSPECTION DOOR - INTERNAL BACK SIDE - OPEN	2	00 h 11 m 56 s	145.85
TT230.1.1 / KFU / KILN CONNECTION CHANNEL - TEMPERATURE 1 - LOW LOW	7	00 h 12 m 44 s	129.99
ZSC280.14.2 / LDG / SHAFT 1 INSPECTION DOOR - EXTERNAL BACK SIDE - OPEN	2	00 h 04 m 24 s	85.56
TT230.1.2 / KFU / KILN CONNECTION CHANNEL - TEMPERATURE 2- TOO LOW [SAFE]	3	00 h 09 m 10 s	56.02
PT250.6.1 / KOO / LIME COOLING AIR PRESSURE - HIGH HIGH	5	00 h 04 m 26 s	55.42
NGA_FMD / MEASURING UNIT - TIGHTNESS CONTROL FAILURE	2	00 h 04 m 21 s	45.31
BL292.1.1 / LCU / LANCES COOLING AIR BLOWER - FAILED TO START	1	00 h 02 m 57 s	39.54
ZSC280.10.3 / LDV / SHAFT 1 LIME DISCHARGE VALVE - INSPECTION DOOR OPEN	2	00 h 02 m 47 s	27.06
ZV290.5 / NGA_FMD / INVERSION UNIT - GAS TO LANCES SHAFT 2 VALVE - WRONG POSITION	2	00 h 03 m 22 s	21.04

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Figure 7 - Year Unplanned Downtime Cost Impact

5. OVERCOMING INNOVATION BARRIERS IN THE LIME INDUSTRY

In old industries such as the Lime Industry, innovation can face many obstacles. Whether you are trying to lead an industry, create a new market or just do things differently, innovation is difficult. The following barriers are frequent and difficult to overcome:

- Short-term focus
- Lack of time, resources or staff
- Leadership expects payoff sooner than is realistic
- Management incentives are not structured to reward innovation
- Lack of a systematic innovation process
- Belief that innovation is inherently risky[5]

Within the Lime Industry, introducing a completely new solution capable of providing the desirable outcomes and simplifying user operation has not been easy. Even with the promise of many advantages, it hard to convince process-driven businesses to shift the old (but still working) shaft level indicator, to a completely new system. Even if it means simplifying and rewarding the workday of everybody in the plant, and giving a sense of modernity to an old industry such as the lime industry, the notion of IIoT was scaring many lime producers.

However, we are now seeing real deployed solutions and tangible benefits. Innovation is among the top priorities for the majority of the world's large companies. To minimize uncertainty and risk of innovation, it has been necessary to find the correct way to do it, lead, manage and create a strategic intention – one that is reliable and oriented to meet the planned goals. The necessity of innovation is now universally accepted, but beyond their enthusiasm for bright ideas, most leaders know that to be successful over the long term they must develop a strong innovation culture[6]. In the Lime Industry – sedimentary no longer means sedentary.

[5] *Overcoming the barriers to effective innovation.* ***Loewe, Pierre and Dominiquini, Jennifer.*** *1, 2006, Strategy & Leadership, Vol. 34*

[6] ***Langdon, Morris.*** *Creating Innovation Culture, InnovationLabs White Paper. 2007*

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