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MIND COURSE SUPPORT

LECTURE 5. Smart Manufacturing and Automation with Industry 4.0

Contents

ACRONYMS USED IN THIS LECTURE

Acronym	*Phrase*	*Domain*
ABS	Acrylonitrile-Butadiene-Styrene (3D printing)	plastic material
AGV	Automated Guided Vehicle	mobile robot
AI, ML	Artificial Intelligence, Machine Learning	principles
AMQP	Advanced Message Queuing Protocol	protocol
AOI	Automated Optical Inspection	principle
AWB	AirWay Bill (shipment tracking)	document
CRI	Color Rendering Index	metric
CV	Computer Vision	principle
ERP	Enterprise Resource Planning (industrial layer)	software
FFF	Fused Filament Fabrication (3D printing)	process
FDM	Fused Deposition Modeling™	process
I/O (IO)	Inputs, Outputs	components
I4.0	Industry 4.0	principle
IIoT	Industrial Internet of Things	principle
IoT	Internet of Things	principle
IPC	Industrial PC	device
KPI	Key Performance Indicators	metric
M2M	Machine-To-Machine (communication)	principle
MES	Manufacturing Execution System (industrial layer)	software
MQTT	MQ Telemetry Transport (IBM MQ – product)	protocol
MTBF	Mean Time Between Failures	metric
NIR, FIR	Near InfraRed, Far InfraRed (sensing)	spectrum bands
NTP	Network Time Protocol	protocol
OPC-UA	Open Platform Communication – Unified Architecture	protocol
PLC	Programable Logic Controller	device

QC, QA	Quality Control, Quality Assurance	operation
ROI	Return Of Investment (financial)	metric
RTC	Real Time Clock	component
SLA	Stereo Lithography Apparatus (3D printing)	process
ToF	Time of Flight (depth sensing camera)	principle
UPT	Universitatea Politehnica Timisoara	university

2. *OBJECTIVES OF THE LECTURE*

This course aims to develop the general and specific skills of the students within the MIND project consortium. This course is one divided into two types of approaches, with theoretical objectives as well as practical objectives. The theoretical objectives are those of producing, as well as of improving the understanding related to the concept of smart manufacturing as a modern way of manufacturing. The aspects covered in this lecture are used in different fields of education, such as mechatronics engineering.

Practical aspects focus on improving the understanding by explaining the core elements of smart manufacturing via carefully crafted imaginary examples but also through real-life, factory-proven examples. Alongside are presented some components promoted by the key players involved in advancing the industry 4.0.

General objectives:

- Formation of notions related to the concept of smart manufacturing and automation,
- Formation of ideas on the advantages of Industry 4.0 implementation,
- Understanding the relatively complex topics about smart manufacturing and automation with Industry 4.0

Specific objectives:

- To know the main Industry 4.0 paradigms with which they interact,
- Knowledge of the steps required to develop smart manufacturing solutions,
- To understand smart manufacturing concepts for manual processes,
- To know how smart manufacturing helps energy efficiency,
- To identify the opportunities for possible production optimization.

3. Introduction – general concepts of smart manufacturing for Industry 4.0

Smart manufacturing and automation for Industry 4.0 is a combined denomination that represents a broad set of manufacturing procedures and technologies. It employs computer integrated manufacturing, high levels of adaptability, components interconnection and flexible workforce training [1].

The successful implementation of this concept relies on heavy hardware and software automation [2], but also on highly skilled workforce – because manufacturing is hard.

The beauty of a high-quality product, manufactured in a smart way, results not only from cutting-edge tech, big data or heavy automation, but from a well-managed combination of good technology, good machines, and good human craftsmanship and oversight [3].

Figure. 1 The smart manufacturing concept

Everyone has a picture in their mind (fig. 1) [4] when hearing about Industry 4.0 and Smart manufacturing so we'll try to introduce the reader in this world through an example that might look at first like coming from the distant future. But it's not, and with current technology and skills, a fully automated, smart manufacturing, Industry 4.0 compliant plant can be envisioned.

The smart manufacturing topic is also very present in the academic and professional research [5, 6, 7, 8]. The trends are set for several years now and discussions around this topic lead to similar conclusions, but real-life implementation convergence is still unknown.

An imaginary smart factory example

Let’s invent a roadmap – from customer desire to product in hand – and we’ll call this the “i3D4U” online service, (not really) hosted at https://www.i3d4u.biz:

A person wants a gift for someone and thinks that a personalized decorative art object will be suitable. He or she, while searching the web, finds about i3D4U and learns that this is a website where you can import 3D models, use simple graphic tools to personalize that model, have it 3D printed in color for a surprisingly good price, and delivered in 2-3 days. Hmmm… attractive!

How it works? *Smart and automated!*

The front shop/website hosted on a cloud platform guides the user in designing the model, offering a selection of ready-made objects. Some of these are from other customers who agreed to make them public. When the design is finished, the company’s AI-enabled ERP system will try to figure-out based on previous data what 3D printing process is optimum, based on required material, color palette, size, and printing finesse. It turns out that the object is suitable for SLA resin printing and FFF ABS printing with similar percent.

The factory itself has SLA, FFF, powder-FDM and Laser wire sintering machines, but filament printers are in higher number. So, cost factor dictates that the part should be printed with ABS filament. Cost and method are computed, a preview and a price are served to the front webpage. The customer likes the preview (fig.2) [9], closes the deal and makes the payment.

Figure. 2 A 3D model and the printed part – baby Yoda

Now production can start. Required filament is compared against factory stock and it comes out that after this part is printed, only 10% of that filament type remains in storage, so

MES instructs ERP to order automatically a refill batch of ABS rolls to the contracted supplier, along with automated in-advance payment.

MES system will send the user's 3D model to the slicer software and will pre-allocate the next free suitable filament printer. That machine still has 2 hours of printing from its current job. When it finishes and the part can be removed from the bed, a robot arm with an adaptive gripper comes in and grips the part correctly, without damage, because the shape and position of the part is already known, and coordinates and gripping points were sent by the MES to the robot's controller via the OPC-UA server.

The electrical energy monitoring system detected a current spike higher than average, when the robot moved, so it instructed the robot controller to reduce acceleration on the joints for the next job, to save energy. If this happens again a warning will be triggered, as it might be the time for robot joint lubrication.

Our part begins printing. During the process, a laser sensor monitors raw filament quality, in order to prevent bubbles and hollow spots on the finished part. An array of smart sensors monitor the printer itself to ensure mechanical and electrical optimum functionality. A combined NIR+FIR sensor, coupled with a ToF and RGB camera, and a high-CRI white LED are monitoring the printing and temperature in real time, the contraption being assembled around the extruder's nozzle. Any quality problem, warning or error is sent to the cloud, saved, and a notification can be relayed to someone's phone.

The print finished after 8 hours successfully and the robot arm comes to pick up the printed part. The robot slides on a long 7th axis and can move between 2 rows and 2 columns of 3D printers, the types described above. 24 of them, 22 are printing. At the end of the 7th axis is a conveyor that sends the printed part to a paint booth. Here another robot, hanging from the ceiling sprays collimated jets of water-based ink, in a rapid fire, onto our part (more or less like an ink-jet printer). The result is what the customer wanted to color the object. Conveyor is restarted and the finished object arrives at the QC station where a smart 3D scanner confirms the dimensional quality and color design of the product.

Next stop, the packaging station, where a cardboard box, just a little bit larger than the part, waits preassembled and half-filled with flakes of recycled paper. The part falls at the end of conveyor track in the box, a dosing system releases from above some more paper flakes, and the pneumatic packaging arms close and seal the box – with the object inside. Labeling machine does its job and also generates the AWB for the delivery service.

The box is shuttled down to the delivery lobby by a pneumatic cylinder, and waits there for the courier to arrive and to pick it up.

All product data so far is logged into the company's rented cloud as production tracing.

Delivery boy comes to the factory, scans his badge at the entry, is recorded and accepted inside by the security system, takes the waiting boxes and leaves. Another delivery boy goes to storage, is accepted by the security system and unloads some boxes with fresh new filament and some resin bottles.

This factory has only one employee (the owner actually) who makes sure that the printers are supplied with raw material, by checking online into the MES each printer's status. Sometimes he receives notifications on his phone that certain machines need refilling or certain machines have different than normal behavior. The rest of the time is free to do whatever he wants (he is his own boss after all). The adaptive ERP modules make sure that machine supplies can last overnight so only during day time is intervention required. Faults at machines trigger automatic production rescheduling.

The customer receives the box and is really happy about the product. Decides to keep it and orders another one for the friend's gift. Th QR code on the box leads him to the company's ERP where he can see the invoice, order status and so on, in his account. Customer behavior data is analyzed by a rented AI/ML module (yes…, the cookies he accepted when visiting the site) and prediction for future orders and all things related are updated. *Happy end!*

In this fictional factory we had: 1 employee, a cloud based ERP and MES with integrated logistics and customer analysis, a cloud stored front-shop webpage, 24 3D printers with different technologies, a robot with a long additional axis, a fully automated spatial ink-jet printer (serial robot based), an automated packaging and labeling machine, delivery and reception secured storage areas, full machines monitoring, real-time QA & QC during printing and after ink coloring, energy monitoring system, total traceability and a cloud-based push notification system for when human intervention is necessary.

- Smart manufacturing: yes
- Automation: 99%
- Industry 4.0 compliant: 100%
- Profitability: maximum
- Overall ROI: ~3 years (with govt. incentives)
- Customer satisfaction: 5/5 stars

4. *Smart manufacturing paradigms*

The above example came with several notions and sub-concepts that are systematically detailed in the following paragraphs. They are the building blocks of the Smart Manufacturing concept and are described as in an implicit comparation to the classic manufacturing ways:

Machine networking

In a smart factory no machine is stand-alone, it has to be integrated in the factory's network. MES and ERP systems must be able to access its productivity, status and health data. The machine must be able to receive orders, configurations and commands from supervisory systems.

At the same time the machines related to the same manufacturing process must be able to exchange data between them put in a transparent way, through the MES. So, the first step in creating a smart factory is to network everything with scope of interrogating and controlling all devices (fig.3) [10].

Figure. 3 All things connected

It means all thing connected. From shop floor to top floor.

- advantages: remote configuration and diagnosis, event-based workflow interruption, faster changeover between orders, (big) data generation for the next systems.

- disadvantages: higher machine complexity, denser and more difficult to maintain networks, compatibility issues, security issues, better qualified personnel, higher installation costs

Smart equipment

Of course smart manufacturing implies the use of smart equipment, and this starts at the lowest automation level, with smart sensors and smart actuators. These are connected to controllers with higher processing capabilities, and software routines that not only control the production cycle but also monitor health status, efficiency and productivity of an entire machine. Current crop of PLCs and IPCs can deal with this level of complexity and are suitable, given proper integration, for smart production equipment.

- advantages: simpler maintenance, better process control, ease of integration in a higher order control system

- disadvantages: more technological complexity, better qualified personnel, a mild increase in initial cost compared to classic machine design approach.

Advanced robotics

When we say smart automation or smart manufacturing or I4.0 inevitably we think of robots (robotic arms motly). Robots will do this, robots will do that, they will be so smart that will adapt manufacturing on the fly. Well, not yet... But robots working alongside humans is a different story. New safety systems, collaborative robots (fig. 4 left) [11] and intuitive robots programming (fig. 4 right) [12], are the current trend. Classic industrial robots still have a strong share of the shop floor in a smart factory, and is an obvious fact, but human-robot collaboration makes manufacturing really smart, and way more efficient.

Figure. 4 Working with collaborative robots (left) and intuitive collaborative robot programming at UPT (right)

- advantages: increased flexibility compared to classic robotization approach, more efficient workplaces for human operators, faster tasks repurposing

- disadvantages: people are scared of robots no matter how safe they seem to be, collaborative and intrinsic safe robots are more expensive, some robot programing paradigms don't apply and programmers need a change of mind when installing such devices

New manufacturing concepts

How fast can we go from product idea to production ready? It mostly depends on prototyping/testing steps and on tooling and machine selection.

Additive manufacturing (3D printing in all its forms) is a great asset and an ubiquitous presence in any smart factory. Aside faster prototyping, the technology concept matures quite rapidly and is already suitable for low volume production. It will expand in the next years and we might see in a not so distant future printed mass production parts instead of classic manufactured ones.

- advantages: almost no tooling, easy parts customization, versatile process, energy efficient and raw material efficient (depending on compared classic technology)

- disadvantage: technologies not mature enough to be truly competitive for mass production, slow process, expensive raw material, parts quality difficult to guarantee, more prone to fail in mid-work.

Connected devices and services

All machines, robots, sensors and actuators are interconnected. Great! But not enough. For a smart manufacturing implementation to work as expected we also need smart automation. Not only at the production level but also at decision, logistics and management levels. This mean that we need to integrate even more things, like smartphones, tablets, trucks, GPS units, AGVs to name a few. And here the standardization is thin, so we need to bring in new services (as in software apps and people input).

Figure. 5 Connecting a factory to cloud services – Siemens MindSphere

A smart factory is connected to the internet, to cloud services, online shops, suppliers, customers, auditors, legal entities and so on. A local branch is connected to the remote ones for efficient production split, that may be located on different continents. What links all the above are cloud services that can transport data between heterogenous entities (fig. 5). One example of such a cloud service is Siemens' MindSphere [13].

- advantages: no information bottlenecks, fast data exchange at all levels, rapid decision making, flexible production, efficient logistic planning, faster overall problem solving

- disadvantages: cybersecurity concerns, increased need for new applications and software (which needs to be fully tested and bug free and fault tolerant and with short deploy times), dependent on remote computing, increasingly difficult to migrate to other services providers

Big data & machine learning

Smart machines and smart sensors generate a continuous flow of data. Huge amounts of data. This raw data must be split into useful and useless streams, categorized, filtered, and analyzed in its context, based on specific rules. So big data seems not so attracting at first. But then even low amounts of manufacturing data can overload human analysts quite rapidly.

Then we need ML and AI to analyze this data. But successful training of ML and AI software needs large data sets. So, in the end big data is good, as long as our automated analyzing software can make use of it, for learning and for giving appropriate results.

- advantages: manufacturing adaptation made easier, trends prediction more accurate (process, financial, customer behavior), improvement in product quality

-disadvantages: powerful computing required, storage space for data becomes expensive over time, algorithms difficult to tune, prone to undetected misinterpretations that can lead to bad manufacturing decisions, analysts and software specialists are still required

Product traceability

Total product traceability is a must for the smart manufacturing concept. It helps a lot in improving quality for future products and for optimizing processes. And also helps solving customer reclamations much faster.

It actually means that every single part produced will carry along its digital twin with production parameters and sensor data from each step since raw material to delivery (fig. 6) [14]. This data can be accessed later, for example when a used product is replaced at a customer, taken in and inspected for wear (common practice in the automotive industry).

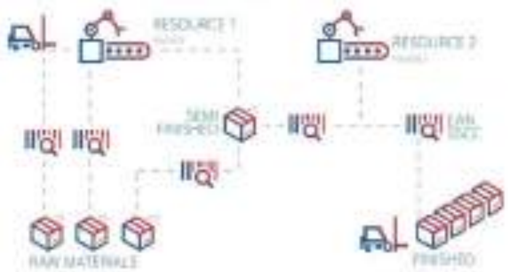

Figure. 6 Traceability in manufacturing

Random quality check fails can be analyzed and the problem can be easily pinpointed, by comparing traceability data for parts processed when the quality issues appeared. No guess work anymore.

- advantages: better quality products, production optimization easier to implement, faster response times in case of production problems, increased confidence in machine setups

- disadvantages: massive storage space required and much of the saved data may never be used, computing power, network load, can get expensive compared to the outcomes

Real-time production scheduling

Assigning production tasks to machines is straight forward for most production planners (humans or software). The smart thing here is to adapt the scheduling and make re-planning on the fly. An interruption in the supply chain for certain material (truck with plastic pellets had broken down the road) can be automatically relayed to the factory in a matter of seconds by the integrated logistics monitoring cloud app. This means that machine X will not be able to start its planned production when expected. So, an ERP arbitration module will automatically look for the order with the highest priority that can be sent to that machine with minimum retooling effort (maximized profitability). After decision confirmation, will request the tool shop and material storage to proceed to machine changeover and will allocate the available and suitable (skill comparison) workforce. All this can happen in a minute or so, and that machine will not have production dead time.

- advantages: less production downtime, ability to process urgent orders from high-ranked customers, fill-in free machine time with less critical tasks, distributed manufacturing decision made faster for similar machines

- disadvantages: the software cannot "see" all aspects on the factory floor and may generate inappropriate decisions, adaptive ERP and MES modules are notoriously expensive and require long coding and testing times, services integration along the value chain must be completely integrated and fully functional (no human-in-the-loop).

Quality assurance & quality control

QA & QC can converge in a smart manufacturing layout and can be automated.

Since we already have smarter machines, we can add more sensors and more algorithms in the manufacturing cycle so that product parameter control is done continuously while producing a certain part. It works well on automated machines and can detect defects that appeared mid-process. In this case that part will be discarded without further processing saving time, material, energy, and a potentially unsatisfied customer.

Automating QA & QC for manual or semi-manual processes is a trickier business. The current approach is to use computer vision, 3D scanners and operator guiding systems (info-tools) to ensure correct and qualitative manual production.

CV/AOI is well established as QA/QC steps in several industries, like electronics manufacturing and we can see the results in very reliable electronics despite component dimensions and usage cases.

Figure. 7 A 3D scanner for Quality Control

For other fields, such as mechanical parts production and assembly processes this is more difficult, but better, faster and cheaper 3D scanners are increasing in numbers in factories.

High resolution ToF IR scanners coupled with high-speed cameras can read a part and provide an appropriate point cloud in sub-second time, becoming attractive for production QC. Only a few years ago these scanners were only seen in QC labs (fig. 7) [15].

- advantages: less scrap, higher quality, faster delivery, testing labs unloaded of some procedures

- disadvantages: complex and sensitive systems, require highly qualified personnel to install, setup and maintain, expensive, not fast enough for some production processes.

5. *Communications and technology overview for complementing machine automation*

Diving further down technical details one can observe that machine to machine communication is one of the gold keys of I4.0 and smart manufacturing.

M2M communication standards

All manufacturers that deliver components for factory automation face a challenge regarding communication: how to communicate with equipment from their own company and

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how to communicate with equipment from other vendors. One way is to use proprietary protocols (hardware and/or software) which ensure intellectual propriety protection, immunity against various factors and control over compatibility between own equipment. But this approach limits the sales in the end, as no one will only use equipment from a single manufacturer when building a machine for factory automation tasks.

So, the opposite approach is to adhere to a published standard that is embraced by as many vendors as possible. The last years saw a constant decrease in proprietary protocols and a strong increase of common available (mostly open) protocols, implemented for compatibility reasons.

There are at least 2 distinct levels where things happen:

- The field level (in the machine and around it)
- The upper communication level (between machine controllers and between controllers and MES/ERP systems)

At field level, the highest growth in the last 2 years was seen in IO-Link nodes, followed closely by Profinet nodes (fig. 8) [16].

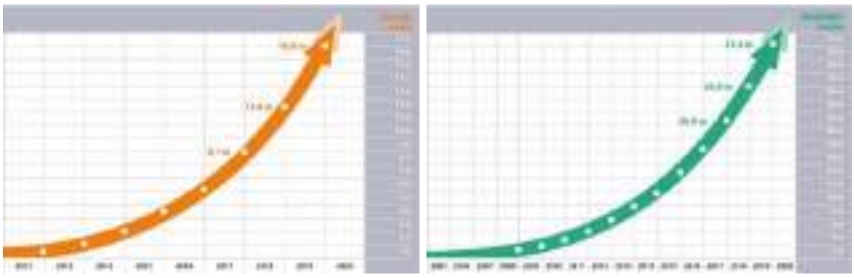

Figure. 8 Number of installed IO-Link nodes (left) and Profinet nodes (right), in the world

The well-established Profibus (more than 60 mils. nodes installed worldwide at end of 2019), Modbus and other protocols are still here, but don’t see such strong growth anymore. Truth is that Smart Factory, Smart Automation and in general I4.0 needs fast, reliable, versatile and simple to install devices, fieldbuses and protocols in order to function as expected (ie. Smart).

IO-Link is a point to point communication protocol, fieldbus independent, and very easy to install (3-wire, standard M12 connectors). It is best suited for sensors and actuators and can provide process data (digital I/O, analog values) – which are transmitted cyclically; device data (serial number, parameters) – on request, and event data (warnings, errors) – automatically, unbuffered. Each connected device acts as a slave and slaves are connected to an IO-Link master which in turn is connected to the machine controller (fig. 9) [17], via a fieldbus.

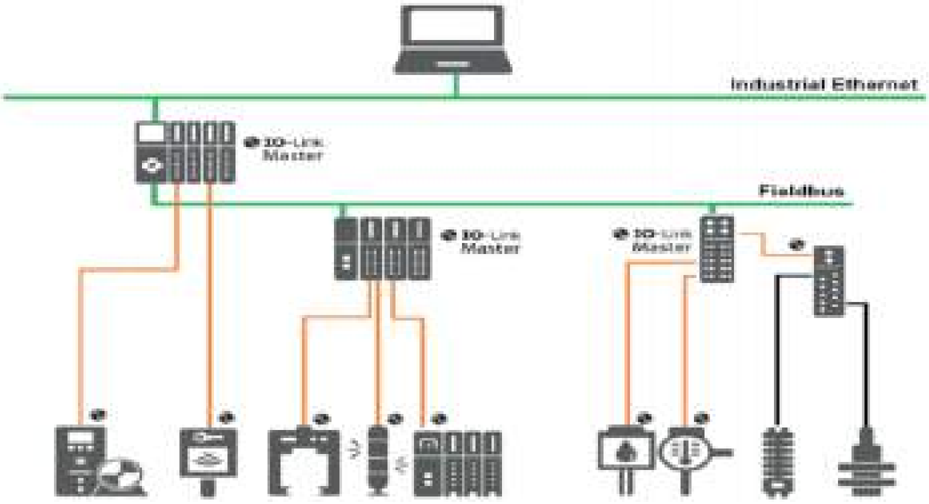

Figure. 9 The IO-Link connectivity layout

IO-Link represents, as noted in 2018 and 2019, the future standard for smart I/O at the field level, and is almost exclusively used for I4.0 compliant machines.

Profinet is the fastest growing fieldbus on the market with over 32 mils. nodes installed at the end of 2019 and is now supported by almost all manufacturers of controllers, drives, smart sensors etc. It is a fast, real time cyclic protocol that is suited for both field level and upper level. But it is more difficult to set-up than IO-Link and devices tend to be more expensive due to the complexity of the protocol and hardware. One advantage of Profinet is that it can share connectors and wiring with the standard Ethernet hardware layer (twisted pairs 4-wire and RJ45) and many producers now offer only this type of connection to their devices. An example is Siemens with their PLC range (fig. 10) [18], as of 2019 all series have RJ45 (Ethernet/IP and/or Profinet) connector.

Figure. 10 Current crop of Siemens PLCs, all with Ethernet communication – left to right: S7-1500, ET-200, S7-1200, LOGO

At the upper/supervisory level the established path is to connect devices via Ethernet and sometimes even wireless. Industrial wireless communication seems appealing, as lack of cables could enhance factory layout but at this time, concerns regarding reliability and security of wireless communications are hot topics in many factories' IT departments.

Regardless of the physical implementation, communication between machine or robot controllers and MES/ERP systems must exist for smart manufacturing and that means software standardization.

The widest spread is the OPC-UA protocol, which can link machines to machines and to software apps. It is a platform independent and open protocol but it is also quite complex and heavy on the data traffic, requiring strong bandwidth and processing power [19].

In last years as more and more devices need to talk to each other in a smart factory, a heavy communication load may result in dropped messages, long queues and even comm. failures. So, a novel model, that of publisher-subscriber is more and more used for non time-critical applications. The OPC foundation has this specs published (OPC-UA PubSub) [20], but MQTT [21] and AMQP [22] protocols are more well-known, and also best suited for unreliable networks, like mobile networks. Very useful when factory personnel use phones and tablets to monitor what happens in a smart factory and need to send data to apps and machines.

But MQTT and AMQP implementations must be coded individually as they are application specific protocols and this affects integration. They hold a strong foot in the IoT world, which is making its way to industry, as IIoT.

As a top-down view of a smart factory networking, the ERP connects to the cloud via established internet protocols and to MES via Ethernet / OPC. This link continues down to machine/robot controller level, where a change happens, moving towards fieldbuses and specific protocols (fig. 11) [23].

Figure. 11 Industry 4.0 automation pyramid

The current most used protocol for top level is now OPC-UA, and the most used network is Ethernet. The current most used fieldbus is Profinet, and the current most used communication protocol for sensors and actuators is IO-Link.

Aside the protocols presented above, another aspect needs attention, the configuration of smart devices, since integrating them into a new machine means setting up parameters, limits, addresses and so on. One key player in this area is the FDT Group [24] which supports the development and standardization of the Field Device Tool. The newest standard ecosystem is 3.0 and now includes IIoT services and a new configuration framework

The role of CV/ML in smart manufacturing

Computer vision and machine learning are incredible useful tools for a smart factory, as such systems can provide data and take decisions during production flow. In product quality terms, defective products can be discovered and discarded as soon as the defect emerges and is visible during the production, without human supervision. This acts like a real-time quality monitoring system spread across a production line. CV + ML can be employed also to certain manual assembly tasks to ensure correct fitting and that all parts are being mounted on a product.

High-speed CV can also be used for machining supervision, and together with other machine sensors the system can predict failures in operation and tools wearing.

Complemented by an integrated logistics plan new tools can be automatically proposed for ordering to the supplier. The only thing remaining, is order confirmation by a line technician.

Another application of CV, in automated smart manufacturing is related to our imaginary 3D printing factory: cameras monitor the printing process in real-time (fig. 12) [25], with wide spectrum sensors (visible + NIR + FIR) and CV app compares the current state of the printed part with the same geometrical projection of the sliced model, and looks for filament temperature variations. When differences exceed certain limits the part printing can be stopped, as something went wrong and that part is defective.

Figure. 12 Monitoring 3D printing in real-time

ML per-se also plays an important role in the smart manufacturing paradigm as an application can be trained to optimize machine speeds, cooling, lubrication and other parameters by learning form raw sensor data, published by the machine (fig. 13) [26] to the company's cloud.

Figure. 13 Manufacturing parameters and statuses usable by machine learning

6. *Smart maintenance – the key to keep a factory in top condition*

Smart maintenance or Smartenance represents the I4.0 implementation of maintenance jobs. If regular process revolves around human communication, paper technical documentation and engineering experience, the new approach tends to be way more digitalized.

Machines benefit from smart sensors connected to the cloud that can report failures or possible break-downs of machines.

Technicians benefit from interactive digital documents to better guide them in the repair jobs. Augmented reality is a big player here, the current trend being that of overlaying digital content onto live video stream at the machine parts (fig. 14) [27].

Figure. 14 Augmented Reality for smart maintenance tasks

Maintenance plans and reports are stored in the cloud; incidents can be reported via a dedicated app; tickets can be received, edited and closed digitally.

Let’s imagine a scenario:

The classical maintenance approach

- A maintenance technician is in his office, planning the machines for inspection.
- An operator is working at a machine on the factory floor, when the machine starts to make some strange noise, throws an error message “Err-100” and stops. The operator informs the line supervisor, who calls the maintenance technician. This guy goes to the machine, asks for details on the problem, opens up the machine, looks to find the problem, and decides that a part is broken. Goes back to his office, looks in the technical documentation

of the machine for that part’s code and details, goes to the storage room to find a replacement and, after some time, emerges with the new part. Now he asks a colleague to come down with him at the machine and help him replace the part, by following the procedure described in the documentation. In the end, after some trial and error and some tests, the machine is functional again and can resume production. Everyone believed that the repair will take about 1 hour, in reality took more than 4 hours in total.

- The tech guy now needs to write down the incident report and inform the machine producer about what happened. The line supervisor needs to inform the production planning to make adjustments in the ERP.

The Smartenance approach

- The well-trained maintenance technician is in his office synchronizing the maintenance calendar on his tablet, from the company’s cloud.
- An operator is working at a machine on the factory floor when the machine starts to make some strange noise and, shortly after, stops in a safe manner and displays an informative message: “Please wait, maintenance personnel will arrive shortly”.
- The smart machine detected that a part just broke by fusing data from current, encoder, vibration and noise sensors. The PLC program then stops the machine safely, displays the message, and reports to the company’s maintenance cloud application via Ethernet/IP and OPC-UA the status “defective” and part no. “X”, along with the timestamp, and machine ID.
- The cloud application’s program sends the readable formatted message to the maintenance technician’s tablet, together with the shelf/box were the replacement part can be found in the storage room.
- The technician acknowledges the message and sends a request message to the storage room for part delivery at the machine’s location, while going to the machine. Meanwhile the maintenance application indexed the technical documentation and found an entry regarding the interactive replacement procedure for part “X” and sends this link to the technician.

- Once arrived at the machine the tech guy receives the part from storage delivery guy, opens the procedure and follows the animated guide for optimal part replacement process. Shortly after, the machine is restarted and performs self-tests, which finish successfully. The maintenance tech receives a confirmation message for the repair and allows the operator to resume their work.
- The entire operation took less than one hour and was fully logged into the cloud for future reference.
- Supplementary, a notification email was sent to the machine producer to inspect their design for future MTBF improvement. The production delay was automatically reported in the ERP in order to adapt production rescheduling.
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Figure. 15 The smart maintenance apps available to the technician’s tablet

Smart maintenance is time saving and money saving for both scheduled and unpredicted machine interventions. It is a key link in Smart manufacturing, allowing for interconnected, optimized procedures and in the end increasing profitability. But one thing must be taken into account, the maintenance personnel must be fully trained and besides specific technical knowledge, strong digital competences are required in order for a successful Smartenance program implementation (fig. 15) [26].

6. Examples of smart manufacturing in other areas

Smart manufacturing and Industry 4.0 automation does not necessarily reflect a fully robotized, fully automated, dark and human-less factory. On the contrary, smart integration of machines, robots, operators and maintenance personnel, with the right computer, AI and human supervision is the key to future smart and sustainable factories.

Smart manufacturing for the energy-save challenge:

Smart manufacturing also means to meet the challenge for energy saving and this is a field of high importance in processes optimization

Auto shut off for secondary and tertiary energy supply during machine idle times

During machines idle times (production breaks or non-working shifts) there is always the possibility to allow some machinery to be powered on. Either to communicate with other working machines on that production line or maybe just forgotten. During in-shift brakes (10-20 mins) actually no one powers off the machines. This means that some energy is being wasted and the machine should go to sleep somehow.

One of the energy sources that remains active during such brakes is the compressed air supply and this rises a problem. Even on newer machineries there is a chance that pneumatic lines are not fully air tight and some leakage occurs. Considering that the pneumatic energy is the most expensive (about 20 eurocent/m^3) makes sense to know when to interrupt the supply without pre-programming of the machine.

One approach is to detect small leaks that persist for a longer period of time than that of a working cycle, right at the machine entry point. This can be done with the help of a smart compressed air service unit. Compared to a classic service unit a smart one has (besides the manual on/off valve, pressure regulator, filter and electric on/off valve) a compound sensory and valve attachment that is tuned to be able to measure normal (high) flow rates but also very low flow rates. A very low and constant flow indicates a leak and it can be detected only when the machine does not work. In such a case, the unit’s own processor dictates the supply shut-off and continues to monitor the pressure after the shut-off valve. When the machine is restarted the pressure will drop and the service unit knows that air is requested and re-opens the closed valve, for normal operation.

In addition to the energy saving function such service units can continuously monitor the pressure and flow/consumption and feed this measured data to a server, either via Profinet (most common) or wireless. The second smart thing is that an ERP software module can calculate the real costs per machine and also estimate a trend in air consumption and of course raise a flag when the idle flow (leaks) is too high, meaning that a tube is coming loose or a cylinder or valve gasket is leaking. This triggers an automated maintenance plan and the service personnel is requested to further inspect that machine.

Since there is a processor in such a unit it also makes sense to add diagnostic functions for the other components, like monitoring the current in the on/off valve's coil or the water level in the filter's bowl. This last data can be used (besides purging) to know if there is a problem with moist air, and can trigger a service requirement to the facility maintenance (compressor unit).

An example of such a smart service unit and is function is presented in fig. 16, aside to its classic (non-smart) counterpart, both in the current production by FESTO [28].

Estimated savings when using such a device are in the range of several thousand Euros per year (ROI is ~1 year), depending on the machinery of course.

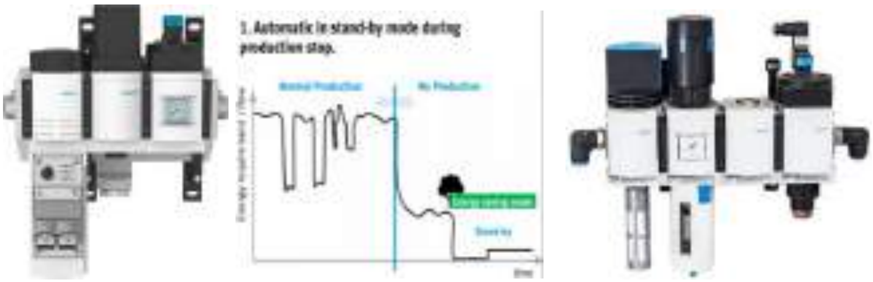

Figure. 16 Smart compressed air service unit MSE6 (left) and classic version MS6 (right)

The same "sleeping" or idle function is desired for the other energy consumption on a machine but the approach here is usually different. This applies to hydraulic power, heating/cooling, auxiliary lighting and electrically actuated devices (motors mainly).

The idea is to "guesstimate" when the machine is not used and shut off what is not process critical or safety-related functions. Most of the times this cannot be preprogrammed by the machine manufacturer for the client (machine user) so an algorithm gets implemented in the machine's main PLC or computer, similar to how computer operating systems implement sleeping times.

Since apart from pneumatics, mostly everything else on a machine is electrically powered (including hydraulic pumps) there is a general trend to provide high power machines (injection molding, presses, CNCs etc.) and robot cells with certified smart power meters to monitor both active consumption and idle consumption, and report this data to some ERP software module in order to reduce as much energy waste as possible. Many manufacturing companies already partner with power meter manufacturers and equip their factories in this direction.

So, green certification for energy consumption in factories is a fact and leads to lower production costs, less pollution and through careful energy data analysis, to less machine downtimes and better maintenance.

Auto dark zones at break time

Since energy saving is tightly related to smart manufacturing, automating the general lighting in a factory is also a trend. The current approach is to shut down the lighting during brake times (10-20 mins every 4 hours) and during cyclic non-working times (eg. Weekends). In a classic factory this is the job of someone on the shop floor but as noticed repeatedly those persons will leave the lights on, on many “saving” occasions. So, it makes sense to implement and automated switcher. One solution is to use a cheap PLC that can override the manual switches but the implementation must take note of some key aspects. Neither switch-off nor switch-on cannot be done at the same time for all lighting zones in a factory building, because, even with LED lighting, the power for standard building workshops is around 9 kW, and the effect can lead to tripping the circuit breakers.

The solution comes from timed switching points with a delay of a few seconds between zones. The time of day periods with lights off are usually hard-implemented in production planning so the PLC can use its RTC to switch the outputs when required. Problem is that RTC will drift (on most cheaper PLCs – which are the best suited for this task) and the hard-implemented switch times will change on occasions, depending on the production and maintenance requirements.

The smart solution is to use a network-enabled cheap PLC that can connect to an ERP software module and read the on/off required times, along with a true clock (usually this is an

NTP client). The current series of LOGO mini PLCs from Siemens can do that, and an example of a smart lighting automation add-on unit is presented in fig. 17, custom made for a manufacturing client by MV RobSol [29].

Figure. 17 Smart lighting automation add-on unit and configuration program

The use of such devices generate important energy savings and ROI is around 3 months.

Examples of Smart Manufacturing for manual processes:

Smart factories need smart workforce, and in the examples below some optimization routes are presented.

Operator performance monitoring

Operator performance is one of the most variable aspects of the smart manufacturing and automation process. Monitoring operators is useful to determine the optimum norms for production in such a way that the yield is high enough but with stress levels low enough. Traditionally this is done by a supervisor at some point in time during production, with a stopwatch and a time chart. The resulting data becomes the norm for operators working on that product at that machine. But humans are not the same, an some will be slower, others will find further movement optimizations. It makes then sense to implement an electronic way of tracking performance, for optimum workers team composition and for finding the most suitable operators for certain working tasks. This monitoring is most suited to processes with many manual operations like assembly, packaging or testing.

One smart solution is to add a computing device with a display and a simple operator interface (e.g. a pushbutton). The process end is signaled by the operator trigger, the computer records and displays process time along with updated KPI for that process (efficiency, norm, products left etc.). The software in charge will communicate with the ERP server and exchange the operator performance data and production planning for the next timeframe, and can optimize the norms on the fly towards higher yields, together with the optimization of changeover times between processes. If the process ends with an end-of-line testing station (this is standard for many assembly processes) then the OK/NOK signal from the tester can be considered as process end-time, without the intervention of the operator. The same applies for packaging stations where the final labeling machine (or barcode scanner) can trigger the process-end. Displaying in real-time the performance for the operators to see it, might seem as a stress factor but has been proved that is an self-adaptation factor instead, and operators - reluctant at first - became quickly involved, as they were more driven to find better ways to move in the work cell and optimize the manual process according to their own working habits.

An example of such a monitoring solution is given in fig. 18 made by MV RobSol [29] for manufacturing companies.

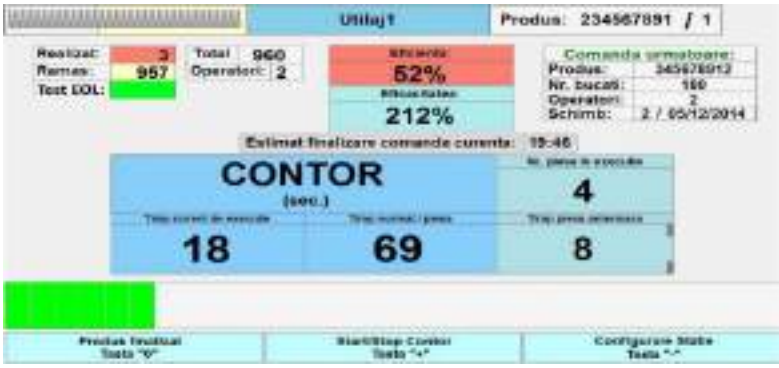

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Figure. 18 Operator performance monitoring software

Such a solution targets manual processes but smart manufacturing is not always fully automated and the smart and adaptive management of process norming is the key to improving what cannot or should not be machine-automated.

Such monitoring alongside norming optimization and operator distribution can generate added value in the range of tens of thousands of euros per year, with very good ROI time.

Adaptive pick by light

Pick by light or pick to light systems are widespread in the retail packaging and distribution systems, like online orders form warehouses (e.g. Amazon). The process implies a paperless method so that a person collecting goods to be packed and delivered will pick the right objects and the right amount from storage. It relies on a wired or wireless mesh of simple LED displays affixed to the bulk goods containers (fig. 19) [30]. The lights (red/green) will light-up as the order is transmitted from the warehouse's ERP and the operator will collect and confirm sequentially. It is a reliable method with picking errors less than 0.1 %, as advertised by the leading pick-to-light systems manufacturers [31].

Figure. 19 Pick by light system for warehouses

The same principle can be applied in a smart I4.0 factory, especially for assembly and packaging processes. This time each box with parts has a led display and a sensing device that is tuned to detect the operator's hand, but no confirmation button.

The order of picking is imported from the ERP by the system's software and the green light is light up to a single box at a time, in the required sequence of picking. If the operator picks the right part (hand detected where green light is on), the system will switch off the LED for that box and switch on the next box, and so on. If the operator inserts the hand in another (wrong) box, the red light comes up and a buzzer sounds. Manual confirmation for error correction is required then. When the operator completes the process, the system's computer will record the time needed for each part, compare it to the normed time and how many erroneous pickings were detected and for what part. This data can be further analyzed to improve on the objects' location (change boxes for some components) and to increase the ergonomics of the work place. Another factor for this adaptive system is that it can be deployed at the same installation complexity for several types of processes and the sequence and data analysis will rely on what comes from the ERP as normed (and adapted) values. A test model was developed at UPT (fig. 20) as a graduate thesis [32] which proved the concept of adaptive pick by light. Untrained users were able to extract parts from the required bins with no errors when completed.

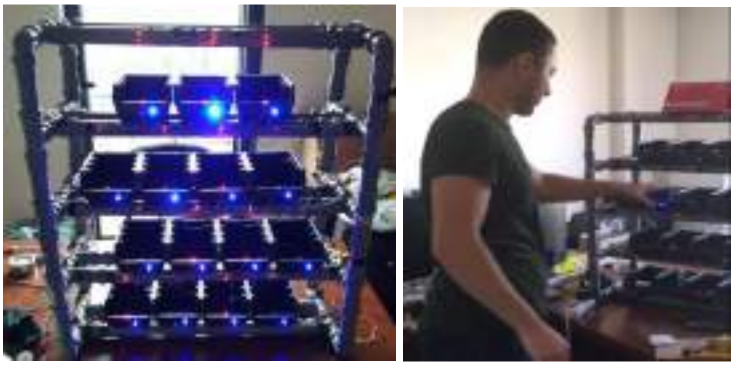

Figure. 20 Pick by light system - test model

Of course, the wrong pickings occurred but were detected by the system and corrected mid-work (red light and buzzer).

7. CONCLUSION

Smart manufacturing is an interesting and attractive concept. It is an endeavor to optimize the manufacturing over different levels by interconnecting and automating the processes.

At this point is a concept with general guidelines rather than an accepted published framework, but we're getting there.

What is important for those who want to achieve smart manufacturing and automation for Industry 4.0, is to be able to see the big picture.

To find ways of linking all machines and components in a common informational network. To select software tools that are cloud based, secure, compliant and expandable. To integrate value-chain specific services that might seem unrelated or too expensive at first. To look for technologies that are process optimized and smart by default. And of course, to approach the workforce with high digital skills and the most updated qualification levels.

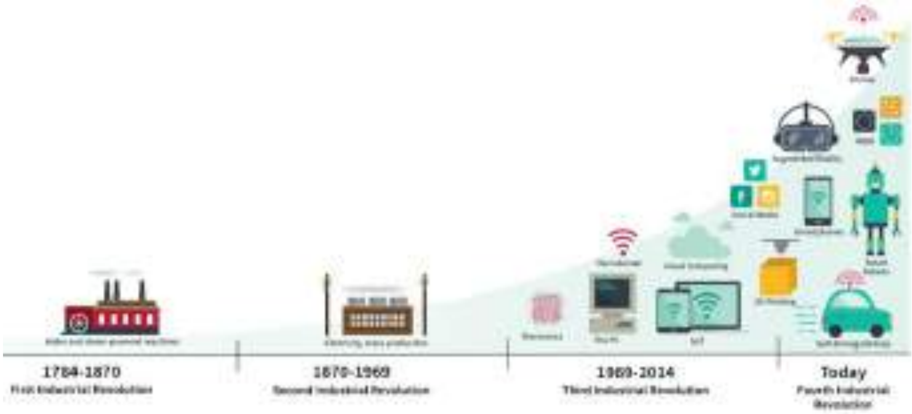

Figure. 21 A vision of Industrial Revolutions, form abas-ERP [33]

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