X-FACTORY

A PARADIGM FOR SMART CONNECTED FACTORIES

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WHAT MAKES A FACTORY SMART?

The way we manufacture goods, and the very nature of the factories producing them, are going through profound changes. The world's major economies have all recognized the need to rapidly evolve their manufacturing capabilities, as reflected in Germany's Industrie 4.0, Made in China 2025 (MIC 2025), and the more loosely defined 'smart factory' concept in North America. Key components of this transformation include:

- **Physical-Digital Systems**—Smart connected machines and systems form the core of manufacturing, transportation, and distribution systems.
- **Autonomous Collaborating Production and Logistics Equipment**—Production machines, logistics equipment, and their systems operate autonomously, communicating and coordinating with each other at different levels in a hierarchy; e.g. a welding station coordinates several welding arms, precisely synchronized with the conveyor system, driven by chassis-specific instructions; each stage of production synchronized with the next; guided by production scheduling, transportation optimization, inventory levels, and ultimately by end demand.
- **Personalization and Mass-Customization**—The ability to do short runs, or 'runs of one' with the same efficiencies and costs as large runs. Mechanisms for end customers to easily visualize, personalize, and configure the options they want.
- **Agile Design and Manufacturing Processes**—The ability to frequently and incrementally adjust and improve the design of a product and manufacturing processes.
- **Visibility and Coordination Across Value Chains**—Each smart factory is a 'team player,' integrating across the smart digital supply chains it participates in. Precise visibility is shared across nodes of production, transport, and distribution, which can then be co-optimized, not isolated.
- **Automation of Routine Tasks/Human-Machine Fusion**—Machines can't do it all alone. The next generation factory optimizes and unifies the roles of the people, the machinery, and the intelligence uniting them. People are freed from repetitive, dangerous, and injury-prone work to work on processes and tasks where they add the most value. Human Machine Interfaces become increasingly seamless, intuitive, and integrated with factory workers (e.g. via wearables such as smart glasses and smart gloves).
- **Participative Work Design and Learning**—Front line workers are empowered with knowledge, authority, and trust to constantly improve the manufacturing processes, and are provided with the tools to continuously learn and progress professionally.
- **On-going Resource Efficiency Improvement**—Incentives, tools, and systems are in place to continually reduce materials and energy use.
- **Safety and Security**—Architecture, design, policies, training, and testing ensure data is protected, hackers can't subvert machines, and employees can work safely side-by-side with autonomous machines.

Translating this grand vision into reality has many challenges. Manufacturers are saddled with existing brownfield factories with various levels of automation, autonomy, and smart factory capabilities. The challenges in visualizing the possibilities and figuring out where to start in retrofitting existing facilities can slow down the pace of adoption. PTC decided to help by doing, rather than talking. With a number of partners, they have put together a demonstration factory, building real products, to provide a paradigm to help manufacturers imagine what is possible. They call it the X-Factory.

THE PRODUCT: SIGMA TILE

The X-Factory is a demonstration factory, but making a real product, the PTC Sigma Tile, which is a low-cost IoT device that can be used for demonstration or IoT application development and testsing.

The hexagonal shaped device contains a Raspberry Pi 3 processor, with a Sense HAT (with sensors for temperature, humidity, pressure, acceleration, and orientation/gyroscope), an LED digital display, and USB and Ethernet connections. The device is built from off-the-shelf components such as the Raspberry Pi PCBs, sensors, display, and connectors, in a custom designed 3D-printed chassis.

THE FACTORY: X-FACTORY STAGES AND WORK CELLS

The X-Factory was set up at LiveWorx 2018 in Boston and members of the public were encouraged to experience it first hand by performing some of the steps in the assembly and testing operations of the factory. The X-Factory is now being featured at PTC's Customer Experience Center (CxC). There are six stages (stations) in the X-Factory: 1) Engineering and Design, 2) Chassis and Cover Manufacturing, 3) Assembly, 4) Testing and Packaging, 5) Warehouse, and 6) Production Management. Across these are 13 applications, all built on ThingWorx, running at the edge in an HPE Server. In addition, the factory included an autonomous robot doing automated material handling between the various work cells.

ENGINEERING AND DESIGN

The engineering and design station of the X-Factory includes Creo (PTC's parametric 3D solid-modeling CAD system) with simulation capabilities to help engineers test out different solutions to issues that arise. The use of 3D printing further allows mechanical designs to be prototyped and tried out rapidly. These proved their worth during the deployment of the X-Factory. At one point the specifications of the printed circuit board (PCB) in the Sigma Tile changed slightly which made the

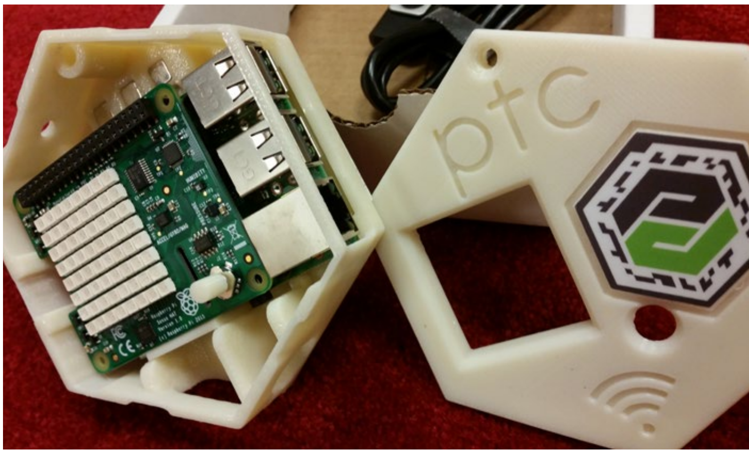

FIGURE 1 – Sigma Tile with Cover Off

connection between the Sense HAT board and the Raspberry Pi board slightly looser, resulting in intermittent failures in quality assurance (QA) tests. Engineers used Creo to add a small 'bumper' onto the cover, which applied pressure on the connector. This succeeded in making the connection reliable, but caused the cover to lift up slightly. Engineers changed the solid bumper to a flexible spring, used Creo's topology optimization to design just the right amount of pressure—enough to keep the connection reliable without lifting up the cover. With the 3D printers, they were able to rapidly iterate through these prototypes to arrive at a final design.

AUTOMATED MATERIAL HANDLING

At LiveWorx 2018, the movement of materials between each of the work stations or cells was handled by a HIROTEC Mobile Robot consisting on an OTTO 1500 self-driving vehicle with a Yaskawa Motoman dual-arm manipulator. Each station has two sets of gravity-fed rolling rack transfer stations: one set for input materials, the other for output materials. The autonomous self-guided robot carried small blue bins of parts or finished goods from the output racks of one station to the input racks of another. These racks are outfitted with sensors that drive an automated Kanban-like approach to production. The removal of a bin from an input rack or addition of a bin to an output rack can trigger the robot to come resupply inputs to or remove outputs from each station.

FIGURE 2 – HIRIOTEC Robot Transferring Materials Between Work Cells in the X-Factory at LiveWorx 2018

CHASSIS AND COVER MANUFACTURING

The chassis and cover manufacturing station is a Formlabs Form Cell, which has five Form 2 3D printers,[1] automated post-processing, and a robotic gantry system. As soon as each piece has been created by a 3D printer, the gantry system moves it to the post-processing unit for support removal and washing, and then to the output rolling rack transfer station where gravity feeds the finished units to the back of the station. They are positioned to be picked up by the HIROTEC's Mobile Robot which delivers them to the assembly work cell.

3D printing is not suitable for all manufacturing (see side bar). However, it was a good fit for X-factory, especially at this stage where they are producing low volumes. 3D printing supports the rapid development and iterative refinement of the product and processes. Just in getting ready for demonstrating at LiveWorx, they went through several iterations of the design, serving as a good example of how agile development dovetails with agile manufacturing.

The 3D printing station has a dashboard showing the status of each printer (idle/starting/printing/finished, which part is being printed, print time remaining, etc.); status of the post-processing machine, gantry, and transfer module; and controls to configure, calibrate, and control the subsystems within the Form Cell. While the machine can be entirely controlled through this panel, larger shops will typically control the station via an MES system. PTC's strategy is to configure, calibrate, and control the subsystems within the Form Cell. While the machine can be entirely controlled through this panel, larger shops will typically control the station via an MES system. PTC's strategy is to work with existing MES systems, rather than forcing customers to 'rip and replace.

As with most 3D printers, overhanging features need to be temporarily supported from underneath so that they don't fall down when each subsequent layer is printed. 4 shows the Sigma Tile cover with supports. Form Labs provides software that automatically add the needed supports.

[1] These are stereolithography (SLA) printers that use a laser to cure a liquid photopolymer resin into solid isotropic parts, one layer at a time. SLA has the advantage of requiring less post processing than some other 3D printing techniques.

FIGURE 3 – 3D Printing Station at LiveWorx 2018

The Expanding Role of 3D Printing in Manufacturing

While 3D printing will not replace injection molding for high-volume manufacturing soon, it is playing an important and rapidly evolving role in manufacturing:

- Rapid Prototyping—3D printed prototypes get the kinks out before committing to high volume production. Combined with simulation, this enables agile engineering and manufacturing.
- Personalized Parts/Products—3D is ideal for customized parts, such as dental splints and dentures, surgical guides, prosthetics, custom jewelry, custom shoes, and custom glasses; all custom fitted to the individual.
- Generative Design—In special situations, such as in aircraft where weight reduction is extremely valuable, generative design can be used to glean further weight reductions with optimized designs that can only be manufactured on a 3D printer.
- Spare Parts—Especially useful for slow moving, expensive, or out-of-production parts.(cont'd below) work with existing MES systems, rather than forcing customers to 'rip and replace.
- The Expanding Role of 3D Printing in Manufacturing

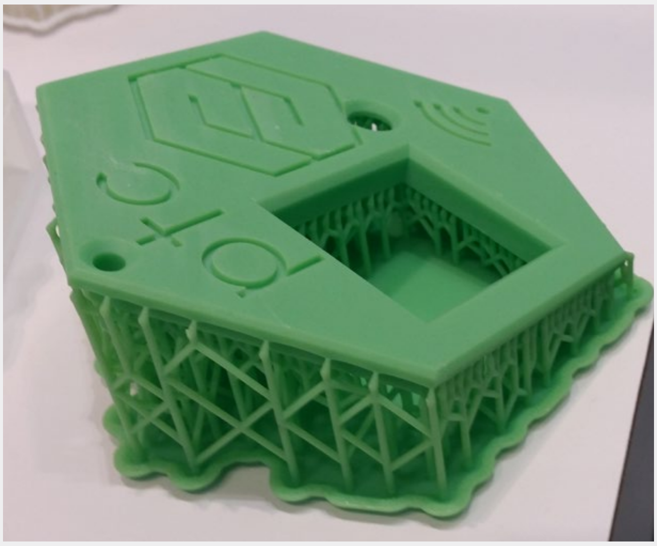

FIGURE 4 - Temporary Supports on Sigma Tile Cover

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Expanding Role of 3D Printing, continued

- **Personalized Parts/Products**—3D is ideal for customized parts, such as dental splints and dentures, surgical guides, prosthetics, custom jewelry, custom shoes, and custom glasses; all custom fitted to the individual.
- **Generative Design**—In special situations, such as in aircraft where weight reduction is extremely valuable, generative design can be used to glean further weight reductions with optimized designs that can only be manufactured on a 3D printer.
- **Spare Parts**—Especially useful for slow moving, expensive, or out-of-production parts.
- **Short Run Production**—3D printing may be suitable for short runs, such as X-Factory. This can include field testing products before committing to high volumes.
- **Tooling**—3D printing is being used to create soft tooling during production ramp. This is a rapid, lower risk approach—tooling costs are much lower, turnaround faster, and mistakes less disastrous. Manufacturers then transition to hard tooling for higher volumes.

As the cost of 3D printing continues to drop, capabilities continue to rise, and the ability to do volume production increases, we see a continual increase in the dividing point (number of units) at which 3D printing makes sense.

ASSEMBLY

This is a 'hands on' station, where visitors can assemble each unit. Visitors are doing this assembly task for the very first time, with no training. This sets a very high bar for ease of use. It provides a good proving ground for PTC's Vuforia augmented reality technology, which is used to deliver visual work instructions that guide the visitor/worker through each step of the process. These work

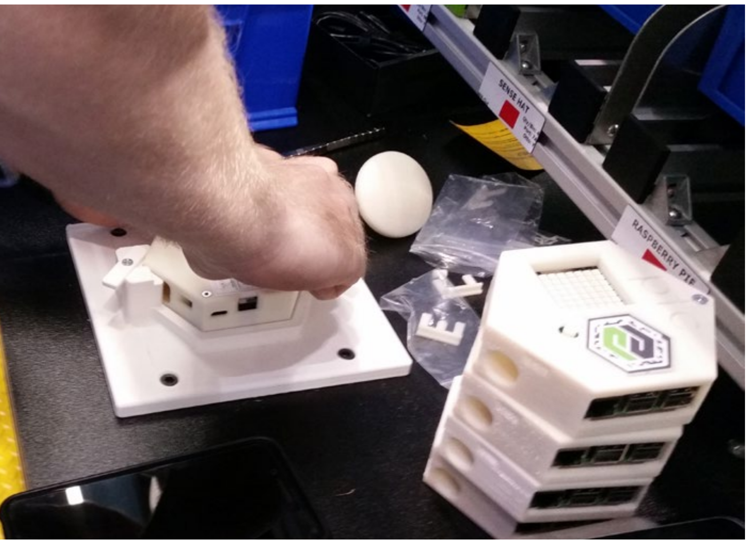


FIGURE 5 - Example Visual Assembly Instructions

instructions are also available via a ThingWorx web application to allow comparison of various means of operator execution. Kits of parts are delivered to the station automatically by the HIROTEC robot and assembled by the visitor-worker following digital step-by-step procedures. Each step is automatically logged, including readings from connected tools, to measure productivity in real time. This helps power agile optimization of the manufacturing process.

TESTING AND PACKAGING

As with assembly, this is also a hands-on work cell for visitors. It also offers several different ways of presenting the work instructions (AR, written instructions, video). The visitor-worker performs a built-in self-diagnostic test of the unit. If the product fails, the connected test application logs the result for quality tracking purposes and prompts the visitor-worker to place it into a different location, to be sent for further testing and rework. Units that pass the test are put into the product package, along with a USB cable and memory stick.

The worker puts the packed box on a scale which serves to double-check that the right pieces are in the box by checking that it is between a minimum and maximum weight. This weight measurement is connected to ThingWorx thru a local Comtrol gateway. The ThingWorx application at the station simultaneously notifies the operator of a PASS/FAIL state on the screen and logs the result in the MES system to keep a record of quality- related process results. This is an example of systems that were previously disconnected and are now being connected directly into the process. The ThingWorx application and platform orchestrates the operator's actions, the connected hardware, and the manufacturing software tools, thereby practically eliminating manual errors and providing a precise digital paper trail. Boxes that pass inspection are put on the output rack/transfer station of the work cell to be taken to the warehouse.

WAREHOUSE

The warehouse is used to store the incoming raw materials, as well as the finished goods after assembly, test, and packaging. In the X-Factory, the 'warehouse' is simply another station within the same space as the other stations. Materials are conveyed from the warehouse to the stations and back by the HIROTEC mobile robot. For larger operations, the warehouse would normally be a separate facility, potentially with its own warehouse management system. The ordering and delivery of raw materials into the warehouse, as well as the delivery of finished goods to customers are outside of the scope of the X-factory. However, the X-factory provides the real- time visibility and control to allow those processes to be synchronized and optimized with the actual production in the factory.

PRODUCTION MANAGEMENT

JDA Factory Planning & Sequencing is used to model and schedule production in the X-Factory. It has a model of the factory that incorporates resource constraints and SKU attributes. The sequencing application would typically receive orders from a Master Planning system. An ideal schedule is calculated to start production.

Throughout the day, ThingWorx takes live machine sensor data and feeds that real-time data to the sequencing system. This enables the system to see which stations are running ahead or behind schedule. It then dynamically replans the sequence and schedule as needed. The sequence is typically sent to an MES system which interfaces with each work cell, providing the instructions on which items to work on next.

THE PARTNERS: INTEGRATING MULTIPLE SOLUTIONS

With few exceptions, virtually all factories are multi-vendor environments—a combination of equipment, software, intelligence, and expertise from multiple suppliers, all working together to integrate into a single, synchronized operation. There are more than a dozen partners involved with PTC in deploying the X-Factory including:

- Allied Reliability—Reliability engineering, predictive maintenance.
- Averna—Quality testing software.
- Axiomtek—Industrial embedded processors for edge processing within the local devices.
- Banner Engineering—Infrared sensors that sense when a bin is put on or taken off each transfer rack.
- Callisto—Integration of the stations and operator work instructions designs.
- Comtrol—IO-Link industrial protocol gateway, turning sensor inputs into Kepware-understandable tags.
- Doran—Smart connected scales.
- Elisa—Factory management and optimization, with a 3D UI showing a digital twin of the X-Factory.
- Formlabs—3D printers for creating the chassis and cover.
- Hewlett Packard Enterprise—Highly scalable edge servers running ThingWorx IIoT platform locally.
- HIROTEC—autonomous self-guided robot to transfer materials between the various X-Factory stations.
- Ingersoll Rand—Connected tools, such as a smart connected screwdriver that ensures proper torque.
- JDA—Factory planning and sequencing.
- Vuzix—Smart glasses for augemented reality, such as showing assembly and test instructions.

In addition, PTC recently announced a major parternship with Rockwell Automation, an industry-leading partner in industrial automation and controls. Rockwell is investing a billion dollars in PTC.

The X-Factory is made possible with the tremendous support from our partners:

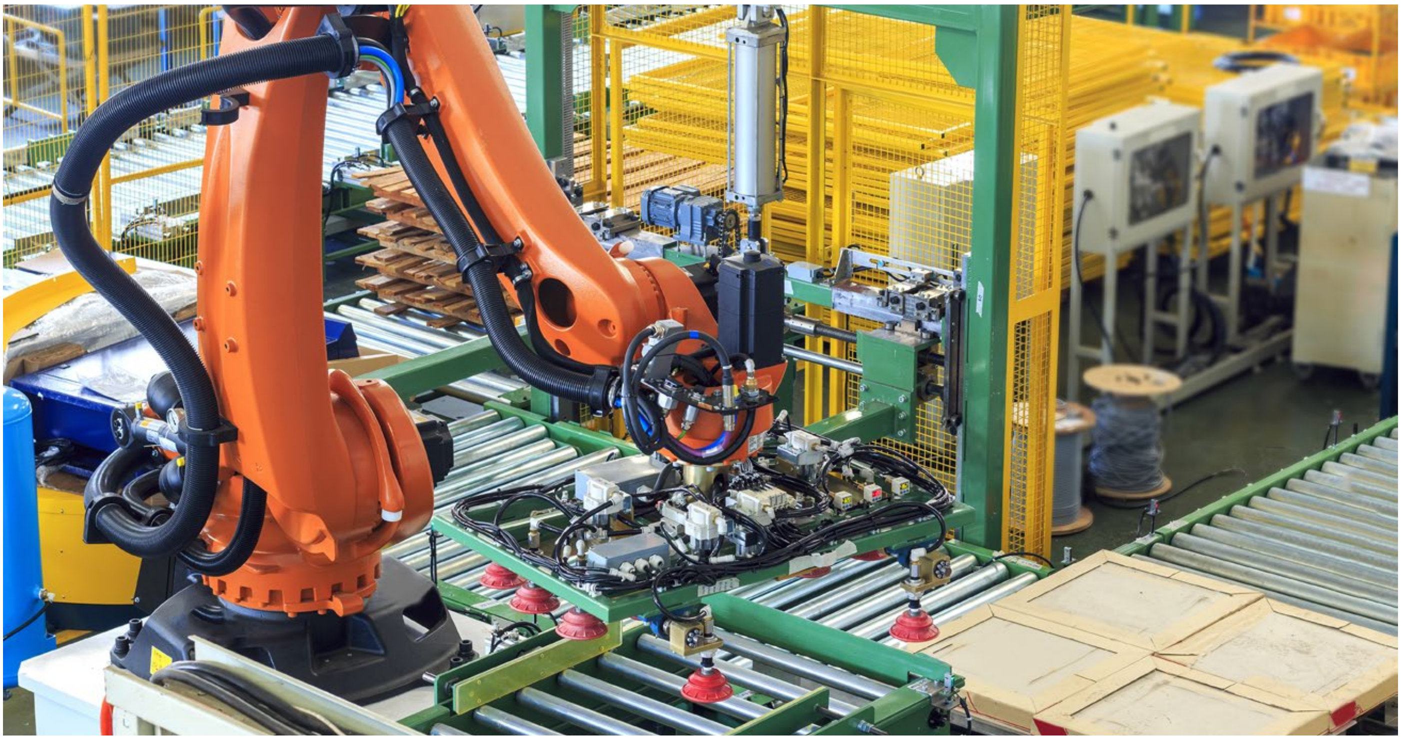
AGILE MANUFACTURING: THE ROAD TO INDUSTRIE 4.0

Agile design tools and methods[2] are used in X-Factory. An example is the use of simulation and 3D printing to iteratively prototype and try different solutions to secure the HAT board to Raspberry Pi board connection (as described above). Rapid iterative prototyping also helped in transitioning from hand assembly to robotic assembly—tabs were added to aid the robot in aligning the pieces—and iterations for other adjustments needed.

Agile manufacturing, a core component of Industrie 4.0, is the ability to respond quickly to changes in customer demand and cost effectively do mass customization with ultra-short runs, even to single-item production.

Enablers of agile manufacturing include modular product design (a platform approach allowing many variations), engineering-manufacturing integration (ability to quickly and iteratively fix design problems), modular work cells (providing flexibility in use of labor and machine resources), SMED (single minute exchange of die— the ability to very rapidly reconfigure manufacturing machines), and IT and factory systems that support mass customization (such as interleaving of orders). X-factory was designed with agile manufacturing in mind, in particular with independent work cells, the use of 3D printing, and integration of engineering and manufacturing.

Another part of Industrie 4.0 is sustainability and energy efficiency. Sensors throughout X-Factory provide comprehensive, fine-grained, real-time visibility which can help to measure and optimize energy use. Dash- boards for each cell and factory-wide views allow for continual improvements in OEE (Overall Equipment Effectiveness). Variance is minimized in X-Factory in various ways, such as via smart connected tools (like the smart screw driver, ensuring exactly the right torque is applied), the use of robots (ensuring precise repetition of tasks), and integrated QA inspection. Analytics can quickly recognize indicators that something has changed and needs adjusting, whether it is because of a new batch of parts, or a changed equipment setting, changes in humidity, or other factors.



[2] Agile hardware development tools and methods are continually advancing, enabling engineers to rapidly and incrementally refine designs. One example is CAD-Integrated Continuous Simulation, which provides simulation in near-real-time, right within the design tool.

GETTING FROM HERE TO THERE

Most factories are not greenfield. They often have a diverse mix of production equipment of different ages, from different manufacturers. They may have no MES, a homegrown MES, or a packaged solution. And most companies have a diverse mix of enterprise applications such as ERP systems, sourcing and procurement, supply chain planning, WMS, and so forth. Thus, the journey to a smart factory is by necessity a step-by-step process, rather than 'rip and replace.' That is why the integrative capabilities of the underlying platform are so important. X-Factory uses Kepware to provide connectivity to virtually any legacy equipment and protocols.

X-Factory is built on the ThingWorx Industrial Innovation platform, providing connectivity to internal and external systems. ThingWorx was designed for rapid development and deployment of IoT applications. Additionally, X-Factory uses Vuforia, which was designed for rapid development and deployment of Augmented Reality applications, interwoven with IoT data, delivered in a way that lets human operators intuitively consume the information and interact with systems. Thereby, the factory can rapidly and incrementally add new sensors and capabilities, as well as more intuitive hands-free human-machine interfaces, continually getting smarter, more connected, and more agile. That is why it we consider X-Factory to be a paradigm for the smart connected factory.

ChainLink Research

ChainLink is a recognized leader in custom research and advisory services, with a focus on supply chain, Internet-of-Things, and blockchain. Founded in 2002, our emphasis from the start has been on inter-enterprise interactions and architectures ('the links in the chain'). We have conducted over 75 primary research projects, interviewing and surveying over 10,000 executives and professionals. Much of our research focuses on industry-specific use cases, business cases and ROI, and drivers/inhibitors of technology adoption, and business change. As a result, we have developed a deep, multi-industry practice, founded on real-world, validated, supply chain-wide, end-to-end perspectives that have helped our clients understand, plan, and succeed as they move into the future.

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