Industrie 4.0 Breakthrough: Flexible Manufacturing Becomes Reality

ARC Strategies
July 2024

This report tracks the progress that has been made implementing the key features of Industrie 4.0, both in the process and discrete industries. The three steps in realizing the vision are 1) flexbile, reconfigurable plant; 2) global manufacturing networks of flexible, configurable plants; 3) the integration of the previous step with digital, certified, encrypted product definitions. The result enables to make any product, any time in any location, with genuine product certificates.

By Valentijn de Leeuw
Vice President

ARC
Advisory Group

CONTENTS

Executive Overview

This report looks back on the implementation strategy of Industrie 4.0 at the time it was defined and reviews what progress has been made over the years, both in the discrete and process industries. We discuss the early experiments, the ones realized and those that are still needed. We review successive implementation attempts and successes, initially covering only part of the scope of the Industrie 4.0 vision. We describe how recent developments in combining digital twins, modular automation and agent-based flow control realized the vision of flexible, configurable manufacturing plants producing high-mix, low-volume products. We discuss successful implementations at industrial scale.

The meaning of "product definition" in this article

How to manufacture a product is contained in the bill of materials (BoM, describing materials and parts required) and bill of process (BoP, describing steps in the manufacturing process: how to assemble or process the materials and parts). In the pharmaceutical or CPG industry the term recipe is often used. The Industrie 4.0 documentation refers to product engineering, to describe the same information.

In this report we will often use the ISA-95 generic term "product definition." According to the context, this can refer to BoM and BoP, recipe, or engineering information.

This report describes ongoing developments enabling make-to-order production in global, configurable and flexible manufacturing networks. The ongoing development of standardized and encrypted product definition information must be completed to realize end-to-end digital product definitions that can be executed on any plant with suitable capability without risk of loss of intellectual property. Together, current realizations and ongoing work will enable the full Industrie 4.0 vision.

The report concludes with the potential opened by the capabilities discussed and their associated benefits. We discuss the applicability in European and American contexts. For fast-moving goods, ARC believes this is a breakthrough in both contexts and we predict major benefits over time using these approaches.

Foresight of the Industrie 4.0 Strategy and How It Evolved

In 2013, the Industrie 4.0 Working Group, a consortium of German authors that became known as Platform Industrie 4.0, published their

"Recommendations for implementing the strategic initiative INDUSTRIE 4.0." The dual strategy to become a leading market and a leading supplier includes the following key features:

- Development of inter-company value chains and networks through horizontal integration.
- Digital end-to-end engineering across the entire value chain of both the product and the manufacturing systems.
- Development, implementation and vertical integration of flexible and reconfigurable manufacturing systems with businesses.

The question the report poses regarding the third point is: "How can cyber-physical systems be used to create reconfigurable manufacturing systems?" It provides the answer as well: "A set of IT configuration rules will be defined that can be used on a case-by-case basis to automatically build a specific topology for every situation, including all the associated requirements in terms of models, data, communication and algorithms."

The Smart Manufacturing and Manufacturing Renaissance concepts in the US have very similar goals although the philosophy to realize them may differ somewhat. This report discusses the potential of applying Industry 4.0, also from an American perspective. Early experiments with modular production were followed by a long pause precipitated by several factors.

Early experiments with modular production in the process industries have been reported by the [F3 Factory project](#). Digest use case reporting can be found [here](#). [This DECHEMA report](#) provides a clear analysis of benefits and drawbacks. Some of the F3 Factory projects used [process intensification](#), an engineering approach to miniaturize process plants, in order to maximize production at strongly reduced resource requirements .

The Importance of Process Equipment Assemblies

The first of these factors is the availability of modular process equipment assemblies (PEAs) -- a prerequisite for the Industrie 4.0 concept to work. "Process" in this case must be interpreted as the generic term for a manufacturing process, not as process versus discrete manufacturing. PEAs can dynamically be reorganized and connected to execute a bill-of-process (BoP) for a discrete product or a recipe of a batch process. Although less likely, it could also execute a continuous process to produce a product with specific qualities that cannot be produced on a different configuration of the line. In discrete and batch processing, PEAs can be placed adjacent to a network of conveyor belts or on islands in the production hall and mobile autonomous robots (MARs)

can provide flexible intralogistics and bring the intermediate product or work in progress (WIP) to the next relevant production unit.

To enable fast plant reconfiguration, modular plants also require modular automation. Instead of programming automation systems for each reconfiguration, the PEA comes with an interface exposing its catalog of capabilities and an orchestration layer requests services from the different PEA to execute the production steps. Internally PEA translates the requests to setpoints of its controllers. This concept took a few years to develop and to standardize (module type package or MTP in the process industries and BaSys in the discrete industries). The PEAs can now be delivered with their modular automation packages and a catalog of services it can provide. Reconfiguration of plants by connecting PEAs only requires a high-level product definition for the orchestration layer.

Large-scale modular plants in the process industries?

Engineering science has not solved the question what the optimal module size for industrial production scale would be. In theory, this would enable to add modular production lines of intermediate size to achieve the equivalent of scale-up. Scaling up is financially risky if the demand fluctuates. If production lines could be shipped to regions with more demand or reconfigured to produce other end-products it would reduce risk and increase agility. Investing in developing PEA or modular lines while operating large scale plants has never happened. Sharing of equipment among owner-operators has probably not been considered. See also this ARC report.

Both process and batch industry applications were successful. They are being used in chemical pilot plants used to shorten time to market for new product variants. Modules are taken from an inventory owned by a single company. Also, the integration of package units into brownfield plants was very successful. The integration of two brands of automation systems is done far more quickly using modular automation. These topics are discussed in detail in this ARC report. In the discrete industries, industrial-scale production has been implemented, and will also likely be implemented soon in the CPG industry, as we will discuss below.

Foundation: Production Flow Control in Modular Plants

The Industrie 4.0 vision must be constructed bottom up and start with production flow control in modular plants. It can be implemented by placing PEAs on islands in a production hall to create what is colloquially called a *ballroom*. Digital twins of the units inform of the capabilities the unit has, its current state (such as producing, stopped, idle etc.), and any time-dependent or constant production conditions.

Mass customization and increasingly agile supply chains with shorter fulfillment times require managing increasing variability. To reach full make-to-order production, optimize fulfillment, and minimize storage, production orders contain a mix of product variants or different products. These are not organized in campaigns for identical products, but in a sequence of incoming orders. Each production order is associated with an individual bill-of-process (BoP) specifying the production capabilities required and the production steps to execute.

A *capability matching service* determines which equipment can execute the production operation's next step. Then a *scheduling service* determines which operations will take place next on which equipment, reduces bottlenecks, and optimizes flow. An *execution engine* executes the BoP and takes care of orchestrating shop floor resources in real time to meet the production schedule. When bottlenecks emerge orders can use upfront defined priorities, or real-time scheduling priorities from the execution engine.

A network of conveyor belts or autonomous mobile robots (AMRs) takes care of the transport of the materials and the finished products from and to on-site storage. This process is virtualized using digital twins of AMRs, digitally scheduled and executed using a *logistics dispatcher*, which is the equivalent to the production execution engine.

In the implementation we witnessed recently, the information exchanges between matching service, executors, scheduler, and equipment are made visible in close-to-real-time in a similar way as mobile phones represent text message exchanges between people. For example, an intermediate product ready to leave an equipment will let the BoP execution engine know it is ready for the next step, and BoP execution engine will assign the next optimal production station, and the logistics dispatcher will assign a robot to bring it there. Each step leaves a message in the trail, while steps in the work order will gradually show up in green, to indicate completion. This provides insight to the operator or supervisor as to what the

Implementing Digital Twins

To implement the digital twins in flexible manufacturing the most logical choice is to use the standardized asset administration shell (AAS), connecting the hardware to the associated software, including the capability description, and connecting the associated software to the matching, scheduling and execution services. AAS can be embedded, run on the edge. The capability description and the modular automation enabling the actuation and the sensing in the equipment should use the MTP or the BaSyS standard.

Standardizing capability descriptions

For capability matching of integrated flexible plants, uniformity in capability descriptions is required. A company can define its internal standard. To integrate multi-company flexible plants, a global standard would be the best option. Siemens' taxonomy could be taken as a starting point for this endeavor.

"system" does. Industry's experience with automatic optimizers indicates this is of critical importance for adoption by personnel, and making sure the system remains switched on. In the implementation we have seen, BopEx was deployed on Siemens' automation-adjacent Industrial Edge Platform indicating BoP execution engine's efficiency in terms of compute and memory resources.
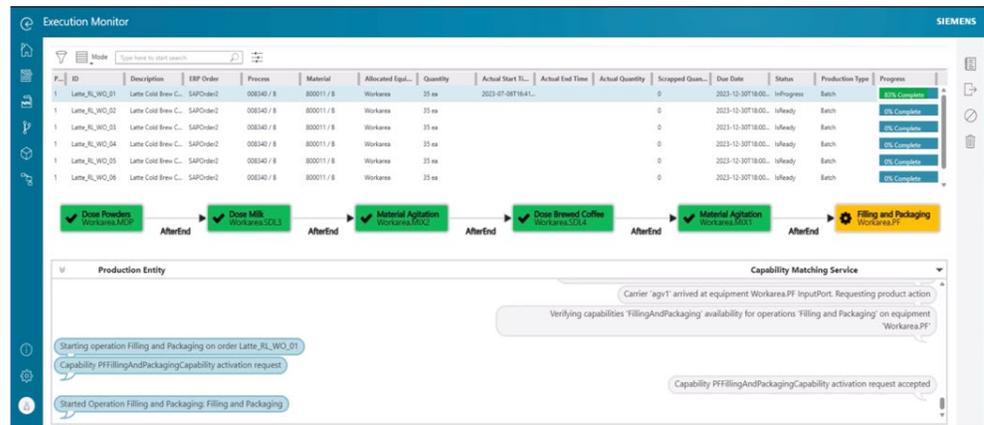
**Interactive Workflow Execution and Messaging Display**
Source: Siemens

Applications: Flexible Line and Flexible Plant

In its simplest application, the description above corresponds to a flexible production line. This line can be reconfigured to produce different products or product variations.

Increasing the scope, a flexible plant could increase return on assets and overall equipment effectiveness, as PEAs could be shared to execute BoPs of product variants. This is what Siemens applied in its Amberg, Germany plant that produces electronic automation products. The plant has been a laboratory for Siemens, where many technologies and methodologies from industrial software to automation have been applied to test, improve and optimize both the plant and those technologies. Challenges for the plant include 5,000 work changes per year, of which 20 percent are due to component discontinuation. The plant produces around a million products per month, and 300 different configurations at any point in time.

A network of conveyor belts enables smart carriers to reach any of the workstations and machines. Each carrier contains an electronics product under construction. A carrier has an RFID tag, can be located and identified anywhere on the belt system. A carrier is assigned to a work order, with an associated BoP. The capability matching, scheduling, and execution services

route the carriers using the most efficient trajectory at any point in time going through the steps in the BoP to fulfill the order.
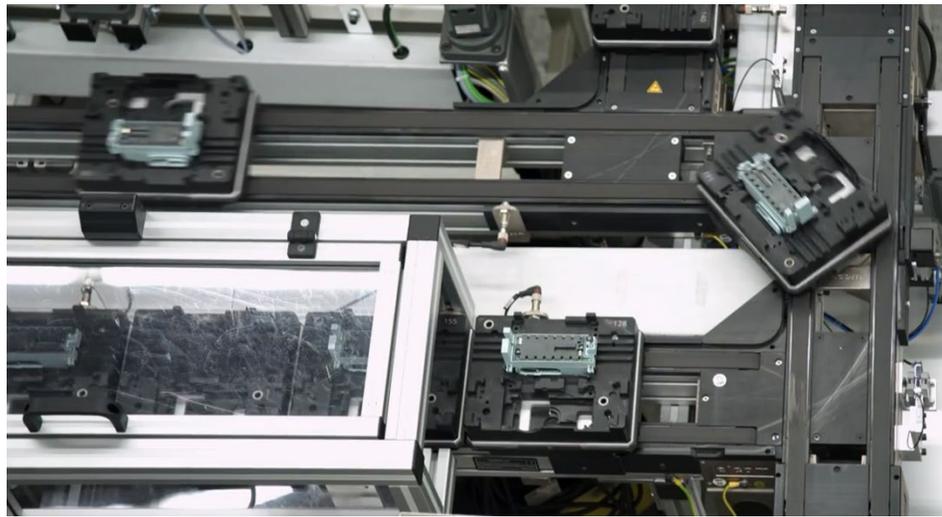
Carts Carrying Products in Progress at Conveyer Belt Crossroads
Source: Siemens

The example of the Amberg electronics plant is the irrefutable proof that flexible manufacturing controlled by a system of digital twins applied to high-mix, low-volume production is feasible and profitable, even in a high-wage country as Germany. This is the realization of the third key feature of the Industrie 4.0 vision, the flexible and reconfigurable manufacturing plant.
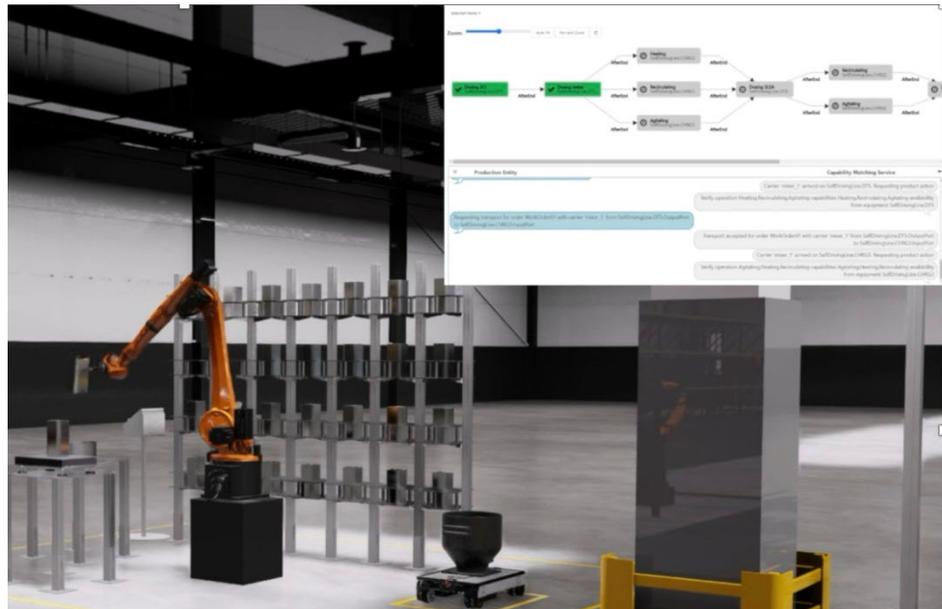
Flexible Production Plant with Intralogistics Using AMRs
Source: Siemens

An alternative to conveyor belts is to use AMRs with PEA's distributed over a production hall. This provides additional flexibility as well as complexity. An intermediate solution can be to use robots for intralogistics standing in the middle of PEAs or workstations to execute production, possibly complemented by AMRs to carry materials. As batch sizes in CPG and in pharmaceuticals are decreasing and producers are moving away from highly automated continuous processes, handling of large vials by operators becomes more frequent. This can cause musculoskeletal disorders, and robot assistance with these tasks has a lot of future potential.

The Next Level: Integrated Networks of Flexible Plants

Fixed lines are often constrained to specific products and product variants. In general, this leads to producing specific products at a specific location and making up for the rigidity of the production system by shipping components and products over large distances. Composite, weighted travel distances vary from a thousand miles for a yogurt with fruit and sugar to an estimated 240.000 miles for a smart phone. A network of flexible, reconfigurable plants could be leveraged to cut significant cost, carbon emissions and complexity from traditional supply chains. This study indicates a value of $4.6 trillion of exports could shift across regions when near-shoring is implemented. In pharmaceuticals, electrical, electronic, mechanical equipment, and automotive this would range between 20 and 50 percent of exports.

To decide if a product should be made in one plant or another one needs to consider the location of delivery, the operations included in the product's BoP and the capacities of the capabilities plus capacity at different locations of the production network. A global logistics optimization taking sourcing

Carbon Footprint Reduction by Producing Locally
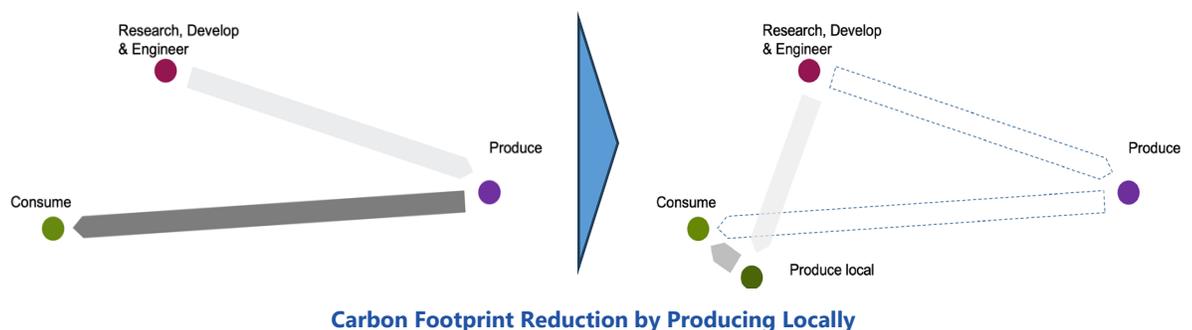
and delivery objectives into account is needed for an optimal decision. This optimization should also include carbon footprint as an optimization variable.

Companies could expose this functionality to potential buyers, who could buy on-demand rather than from inventory, given the product definition and weigh cost, footprint and fulfillment time against each other. This is straightforward with current optimization capabilities.

How to Specify Operations to Obtain Identical Quality on Different Lines?

When executing BoM, BoP or recipes specified in terms of operating conditions, the result on equipment of different lines or plants is different. This explains the use of generic "master" recipes and control recipes that are fine-tuned to specific instances of a production line. In this approach the recipe is defined in terms of process conditions (such as time, temperature, force) this introduces a lot of complexity, which becomes unmanageable in a high-mix, low-volume scenario.

To guarantee an identical product quality from identical recipes for different lines, the operations must be defined with a setpoint value and tolerance of a specified property (such as composition, strength, color or size), which requires "quality control" by the PEA's automation, based on instrument or sensor information. This is still unusual in pharma, but since a few years it is promoted by the FDA.

Considering a network of plants where some produce intermediates or parts and others final products and including logistics for work in progress between plants would transform today's produce-to-stock practices with buffers between value chain partners into a much more agile on-demand production of the value chain. A European view could imagine the ordering, production control and delivery process as a use case of a data space like Catena-X, where several value chain partners collaborate and execute a common, secured process. All regions could benefit from approaches that have traction in the US such as using encryption, blockchain, non-fungible tokens (NFTs) and physical anchors could be applied to enable a trusted platform such as DiMaX.cloud.

The Last Mile: End-to-End "Digital Engineering" Throughout the Value Network

New product introduction is a frequent process in CPG, pharmaceuticals, and fast-moving goods manufacturing, not only for commercial size batches but also for tester packages and clinical trials. Today, new product testing involves sending a PDF with product definition information, encoding it in the control system, try it out and find in the majority of cases that the trial was not successful, after which an engineering change is made, and a subsequent test is executed. The effort to execute this process is huge. If product definitions were written in terms of equipment capabilities and operations, this would avoid programming and come with important time gains. This approach would also open

the possibility for product and process developers to execute product definitions to toll manufacturers.

Today, product and process owners outsource production to toll manufacturers to various degrees. The transfer of the product definition by means of PDF to a third party is a risk for intellectual property leaks. In addition, encrypting product definitions would protect the owner. Specific data space technology could control the number of executions of the product definition. We are aware of development work allowing product definitions composed of sections from several authors, with respect to each other and the manufacturer.

Flexible manufacturing design, engineering, and simulation of new products is feasible with current design and engineering software. Product definitions can be exported in a standardized manner and expressed in terms of capabilities and operations, thereby realizing "end-to-end digital engineering" as described in the second Industrie 4.0 key feature, which would complete the implementation of the full Industrie 4.0 vision.

Conclusions

Development, Implementation, and Vertical Integration of Flexible and Reconfigurable Manufacturing Systems

The vision of Industrie 4.0 has been realized step by step. Modular production and standardized modular automation were both key first steps that have now been created and successfully applied. Modular automation has turned digital twins into asset agents capable of exposing capabilities and executing requests for services using those capabilities.

To transition to high-mix, low volume production has become possible using the approach to flow control interpreting product definitions of individual products and executing them by a combination of capability matching, logistics schedulers, executors interacting with digital twins of assets, and (if required) AMRs. This enables a high degree of on-demand and customized products at an industrial scale. Industrial-scale applications are limited to isolated cases in electronics and automotive, but this could change quickly.

Development of Inter-Company Value Chains and Networks through Horizontal Integration

Combined, those solutions also open the possibility of an integrated network of flexible and reconfigurable plants. Comparable plants across regions enable plant selection to produce locally and reduce footprint. More diverse plants could collaborate and produce components and intermediates, which are integrated and processed to end products in a coordinated value chain operating in a make-to-order mode. A scenario where buyers and consumers directly source a product from the network becomes feasible in this configuration.

In cross-company value chains, collaboration among partners would best be implemented in standardized, secure data spaces. In addition, a standardized way of expressing capabilities, plus a specification-controlled manner of defining an operation is required to produce homogeneous product quality across the network. Prototype implementations could be realized today using standards defined by the value chain partners.

Flexible, reconfigurable manufacturing	any product, any time
global flexible manufacturing networks	any product, any time, any location
Global manufacturing networks with certified, encrypted product definitions	any product, any time, any location, with genuine product certificates
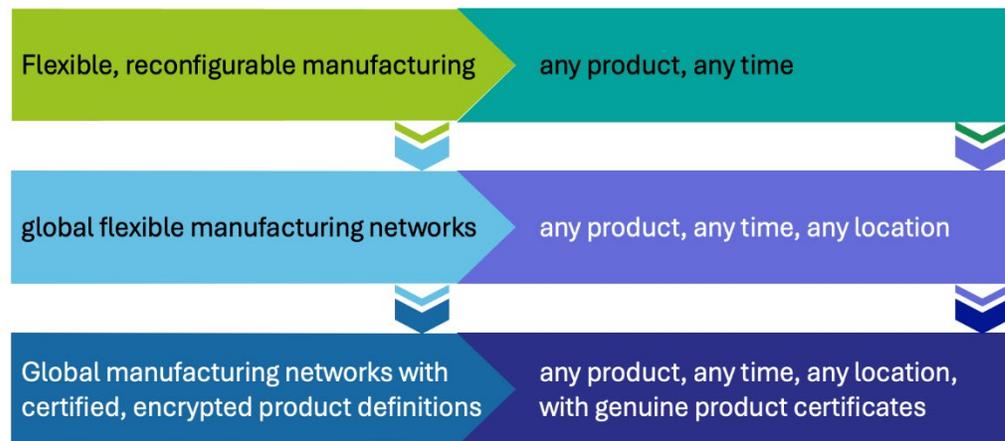
Steps in Realizing Industrie 4.0 and Associated Potential Benefits

Digital End-to-End Engineering Across the Entire Value Chain from the Product to Manufacturing Systems

Finally, when innovation centers could create product definitions executable on standard equipment capabilities, using specification-controlled operations, a major decrease in time-to-production and time-to-market could be realized. If in addition these product definitions would be encrypted and certified, this would protect intellectual property of the innovator and enable quality and labels guaranteeing genuine products. The benefits of realizing the Industrie 4.0 vision are summarized in the following table:

Category	Redefined Requirements	Implementation Strategy	Potential Benefits
Supply chain and carbon footprint	Reduce make-to-stock Transition to make-to-order Broaden catalog Enable customization Reduce transportation	Producing on-demand of - distributors - customers Producing locally	Strongly reduce inventory Improve service levels Decrease delivery times Decreased carbon footprint
Production	Increase - OEE - flexibility - resilience Decrease physical effort by operators	Flexible production on a PEA network with distributed flow control Use robotics for intralogistics	Increase OEE and ROA More healthy and productive workforce
Quality	Genuine product guarantee Guarantee uniform quality throughout plant network	Use certified BoM and BoP Use specification-controlled BoP	Premium product value
Maintenance	Improve uptime Standardized modular automation	Reroute production upon maintenance request Switch PEA in short time	Increased resilience and uptime Reduced maintenance effort
PLM and IP protection	Facilitate NPI Shorten transition and startup times Allow innovation from internal and external laboratories and design hubs Protect intellectual property	Standardize production capability descriptions Execute BoM and BoP or recipe rather than program automation system Allow production sections from several innovation companies Encrypt BoM and BoP or recipe	Increase efficiency and lower cost of - product test runs - clinical trial materials

Requirements, Implementation Strategies and Associated Potential Benefits of Industrie 4.0

Recommendations

The time has come to consider and plan an overhaul of production facilities and make a step-change in efficiency, reliance, flexibility and performance combined with increased service levels and client satisfaction. Technically, nothing stands in the way of implementing Industrie 4.0 flexible

manufacturing in fast-moving products. A business case is required as always, but ARC believes it is likely these will lead to many positive decisions. ARC believes the approach to digitalize and encrypt product definition could enable important time savings and simplify product quality and genuine product certificates.

Although Industrie 4.0 may not be a concept largely adopted in the Americas it is consistent with Smart Manufacturing and Manufacturing Renaissance, in its goals and philosophy. The flexible, reconfigurable manufacturing approach originating in Industrie 4.0 is fully translatable and usable and create significant benefits in the American context. ARC recommends watching the developments in this space closely in multi-plant and multi-partner applications of integrated flexible manufacturing networks.

Acronym Reference:

AMR	Autonomous Mobile Robot	**NFT**	Non-Fungible Tokens
BoM	Bill of Materials	**OEE**	Overall Equipment Effectiveness
BoP	Bill of Process	**OT**	Operational Technology
CPG	Consumer Packaged Goods	**PEA**	Process Equipment Assembly
IT	Information Technology	**PLM**	Product Lifecycle Management
MTP	Module Type Package	**ROA**	Return on Assets

ARC
arcweb.com