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Smart Factory Implementation and Process Innovation

A Preliminary Maturity Model for Leveraging Digitalization in Manufacturing

Moving to smart factories presents specific challenges that can be addressed through a structured approach focused on people, processes, and technologies.

David R. Sjödin, Vinit Parida, Markus Leksell, and Aleksandar Petrovic

OVERVIEW: The development of novel digital technologies connected to the Internet of Things, along with advancements in artificial intelligence and automation, is enabling a new wave of manufacturing innovation. “Smart factories” will leverage industrial equipment that communicates with users and with other machines, automated processes, and mechanisms to facilitate real-time communication between the factory and the market to support dynamic adaptation and maximize efficiency. Smart factories can yield a range of benefits, such as increased process efficiency, product quality, sustainability, and safety and decreased costs. However, companies face immense challenges in implementing smart factories, given the large-scale, systemic transformation the move requires. We use data gathered from in-depth studies of five factories in two leading automotive manufacturers to analyze these challenges and identify the key steps needed to implement the smart factory concept. Based on our analysis, we offer a preliminary maturity model for smart factory implementation built around three overarching principles: cultivating digital people, introducing agile processes, and configuring modular technologies.

KEYWORDS: Smart factory, Process innovation, Industry 4.0, Digitalization, Maturity model

The development of novel digital technologies connected to the Internet of Things, along with advances in artificial intelligence and automation, is enabling a new wave of innovation in manufacturing (Blackburn et al. 2017). Industrial equipment that communicates with users and with other

machines, automated processes that require little or no human intervention, and even mechanisms that facilitate real-time communication between the factory floor and the market are generating dynamic process innovations (Iansiti and Lakhani 2014; Porter and Heppelmann 2014). The

David R. Sjödin is an associate professor in entrepreneurship and innovation at Luleå University of Technology, Sweden. He conducts research on the topics of servitization, advanced services, digitalization, process innovation, and business model innovation in collaboration with leading global firms and regularly consults to industry. He holds a PhD in entrepreneurship and innovation from Luleå University of Technology. He has published 20+ papers in distinguished international journals, including *California Management Review*, *Long Range Planning*, *Journal of Business Research*, *Research-Technology Management*, and others. He is the recipient of multiple awards for his research, including the Entrepreneurship Forum Young Researcher Award 2018 for his research on the servitization of industry. david.sjodin@ltu.se

Vinit Parida is a professor of entrepreneurship and innovation at Luleå University of Technology, Sweden, and visiting professor at the University of Vaasa, Finland. His research interests include organizational capabilities, servitization, business model innovation, digitalization of industrial ecosystems, and the circular economy. He has published 60+ journal papers in distinguished international journals, including *Strategic Management Journal*, *Industrial Marketing Management*, *Journal of Management Studies*,

Production and Operations Management, *Journal of Cleaner Production*, and others, and he is an editorial review board member for *Industrial Marketing Management* and *Journal of Business Research*. He is the recipient of multiple awards for his research. vinit.parida@ltu.se

Markus Leksell is a management consultant at Accenture focusing on the automotive industry, digitalization, and organizational transformation. He holds an MSc in industrial engineering and management with a specialization in strategic business development and innovation and a BSc in business administration with a specialization in digital marketing. markus.leksell@accenture.com

Aleksandar Petrovic is a management consultant at Deloitte focusing on capital project implementation, organizational transformation, and smart factories. He developed his interest in smart factories through prior experience in automotive manufacturing (mainly process engineering in assembly) and through academic research. He holds an MSc in industrial engineering and management with specialization in strategic business development and innovation and a BSc in business administration with a specialization in digital marketing. alepetrovic@deloitte.se

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outcome is what we define as a *smart factory*: a connected and flexible manufacturing system that uses a continuous stream of data from connected operations and production systems to learn and adapt to new demands. According to some analysts, smart factories will drive a new industrial revolution that has the potential to seriously disrupt incumbent companies (MacDougall 2014). To stay competitive, manufacturers must adopt—and adapt to—these new technologies.

Leading manufacturers are heeding the call and beginning the journey toward implementing the smart factory concept. The automotive manufacturer Tesla has established a smart factory in which a network of devices, sensors, and robots works together within an integrated system to produce cars and batteries more efficiently. The Swedish truck manufacturer Scania, which traditionally has maintained its competitiveness by innovating in its production processes (for instance, by being among the first to integrate industrial robotics, programmable logic controllers [PLCs], CAD/CAM, and Lean management techniques), is now seeking to transform its operations through smart factory technology.

At its core, smart factory implementation is a process innovation. Process innovation is the “implementation of new or significantly improved production or delivery methods. This includes significant changes in techniques, equipment and/or software” (OECD 2005, p. 9). A principal challenge in process innovation stems from its systemic nature—change in one part of the production system will affect other subsystems and processes. The implementation of any process innovation may lead to unanticipated technological challenges, new duties and skill requirements for operating personnel, and significant changes in work processes all the way down the manufacturing line (Gopalakrishnan, Bierly, and Kessler 1999). Add in the complications that come with implementing novel technologies, and the scale of the challenge becomes clear. These complexities make process innovation, particularly in the context of smart factories, a highly challenging endeavor requiring ongoing adjustments that may extend well beyond the initial implementation of specific technologies (Robertson, Casali, and Jacobson 2012).

Even as urgency builds behind the move toward smart factories, most firms lack insight into these key challenges, or into the activities and capabilities required to support a successful smart factory implementation. Studies of such implementations are still at a nascent stage, which means companies can find little guidance in the literature. We begin to address this gap with an in-depth study of five factories operated by two automotive manufacturers who are leading the way in adopting the smart factory concept. Based on these firms’ experiences, we identify key challenges related to smart factory implementation and propose a maturity model for smart factory implementation.

The Study

This study takes an exploratory case study approach to investigate innovation in manufacturing in five factories

operated by two leading manufacturers—referred to throughout as Truckcorp and Carcorp—widely recognized as frontrunners in process innovation and smart factory implementation. These firms were selected based on three attributes:

- Both firms have made significant financial investment in smart factory transformation. In practical terms, that means they have devised explicit strategies to ensure successful implementation.
- Both firms are members of part of the largest automotive manufacturing groups in the world and, therefore, can serve as proxies for a study of the far-reaching industrial implications of the smart factory concept.
- We were able to secure interest and commitment from both firms, giving us access to appropriate respondents in all five factories.

The five factories selected for this study were all actively engaged in smart implementation programs, although they were at different points in their transformation (Table 1). To provide broader insights and validate factory-level findings, the central technology development unit at Truckcorp, which was responsible for supporting all factories in smart factory implementation, was also included. Initially, the study was focused on four factories at Truckcorp; one factory at Carcorp was added to provide additional validation for the Truckcorp findings.

These cases provided the opportunity to capture the real-life experiences associated with successful smart factory implementation. In addition, the selection of multiple factories made comparison possible, allowing for preliminary identification of potential best practices.

The study began with six workshops in which three to five participants from Truckcorp—all senior and middle management—were asked to map out the key challenges the company had faced in implementing its smart factories. These sessions enabled comprehensive mapping of the challenges faced by the factories in our study, allowing us to identify the highest-impact challenges in smart factory implementation. These findings were later validated via interviews at Carcorp. Including participants from multiple factories facilitated advanced discussion and helped validate the challenges across the sample. Thus, this approach allowed us to identify a diverse range of challenges and to better understand

TABLE 1. Case description

Factory Pseudonym	Country	Employees	Primary Product
X. Franklin (Truckcorp central unit)	Sweden	1,300	Smart factory systems
1. Nobel (Truckcorp)	Sweden	3,000	Cab production
2. Newton (Truckcorp)	Sweden	1,100	Gearbox machining
3. Curie (Truckcorp)	Brazil	3,000	Chassis assembly
4. Einstein (Truckcorp)	Sweden	1,400	Chassis assembly
5. Chatelet (Carcorp)	Germany	60,000	Automobile manufacturer

their impact on the steps needed for smart factory implementation.

The insights from the workshops provided the basis for further investigation of the specific practices adopted by individual factories to manage challenges as they emerged; this investigation was undertaken through interviews. We conducted a total of 31 in-depth interviews with senior and middle managers from all five factories—four at Truckcorp and one at Carcorp—and from the central technology development unit at Truckcorp. All interviewees were active in driving the smart factory implementation and could, therefore, provide insight into how the transformation unfolded and how challenges were addressed. In addition, we made a total of 10 site visits to TruckCorp factories, reaching all of the factories except Curie, and studied internal documentation regarding the smart factory implementation in each factory. Follow-up contact with the Carcorp factory was made virtually, and Curie representatives met with researchers in person in Sweden.

In analyzing the interview data, we focused on identifying key activities in smart factory implementation across the factories studied. We used thematic analysis (Braun and Clarke 2006), which is a systematic method for discovering themes in complex data sets by coding and categorizing common phrases and themes expressed by interviewees. This process identified a diverse set of practices for implementing smart factories. We then identified patterns among the themes to define the aggregate dimensions underlying our framework and, finally, mapped links between the aggregated dimensions to create a structured maturity model.

Challenges in Smart Factory Implementation

Implementing process innovation, especially one as extensive as the smart factory concept, is often highly problematic and entails significant costs (Robertson, Casali, and Jacobson 2012; Sjödin, Frishammar, and Eriksson 2016). Identifying and understanding the high-impact challenges likely to arise in the process is crucial to a successful implementation. We used a challenge-mapping protocol (Parida et al. 2015) to define key challenges and assess their importance based on data from the workshops and interviews. In that process, we asked each workshop participant to describe the most prominent challenges his or her factory faced in implementing the smart factory concept. We then asked participants to work together to identify common challenges in the individual narratives. Individually, each participant then assigned each challenge on the common list an impact score for his or her factory, on a scale of 0 to 100. We aggregated those impact scores and calculated a mean score for each challenge. The result was a list of the most significant challenges Truckcorp had experienced in its smart factory implementations with an assessment of the relative importance of each one (Table 2). Interviews with informants at Carcorp validated these results.

Challenges fell into three broad categories: people challenges, technology challenges, and process challenges. Coincidentally, the three most significant challenges, based on their impact scores, spanned these three categories:

1. *People*: Factory staff frequently *lacked a common vision* for and understanding of smart factory implementation. In addition, factory personnel communicate using diverse

TABLE 2. Challenges in smart factory implementation

Challenge	Impact Score	Exemplary Quotations
Lack of common understanding and vision among employees	92	“What we lack is a common language of what smart factory means for the whole organization; roadmaps and general definitions are preferred when uniting the scope of the smart factory program prior to requirement gathering.” (Project Engineer, Franklin)
Technological complexity creating uncertainty in the business case	91	“It is an area of uncertainty between potential benefits and the cost of smart factory projects, especially since some basic systems need to be implemented before other, more beneficial systems can. It causes frustration and hesitancy because those basic investments [new technology] do not deliver benefits until later.” (Head of Digital Production, Chatelet)
Difficulties in adapting traditional routines and work processes to digital transformation	89	“We used both Agile methods for addressing missed functions and a traditional Stage-Gate model to achieve implementation. Only Agile methods didn’t work due to delays and changes in organization.” (Lead Architect, Franklin)
Struggle to keep up in the face of rapid development	83	“The level of connectivity is dispersed amongst the production areas; some technology is still disconnected and some IT systems are not up to date, resulting in a growing technical debt.” (IT Coordinator, Einstein)
Difficulties in long-term planning due to high turnover	78	“To make the projects successful, we need to allocate more resources on a longer time frame and fewer in the short term. However, this makes for difficult since tech-savvy people tend to advance in their careers after a year or so.” (Manager, Franklin)
Lack of understanding of smart factory potential limiting benefits	72	“Neither the technicians nor supervisors understand the possibilities with the new systems. If they were able to, our processes would look completely different today.” (Supervisor, Einstein)
Data overflow hindering critical decision making	65	“The problem with all the information our new factories give us is what to do with it and how to store it. . . . it will hopefully give us an answer in increased data transparency.” (Lead Architect, Franklin)
Lack of cross-factory collaboration between implementation teams	62	“One of our major issues is the lack of transparency across the departments and brands, which is why we want to initiate wider collaboration across our separate smart factory initiatives.” (Head of Digital Production, Chatelet)

language around the scope of the smart factory transformation and the need for capabilities development. Further complexities are introduced by attachment to the prior generation of production technologies and the perceived threat to established competencies.

2. *Technology*: The highly complex nature of smart factory technologies and systems makes it is hard to gauge the potential benefits, creating an *uncertain business case* for implementation. Indeed, the systemic nature of smart factory implementation creates uncertainty about the particular adaptations that may be needed with regard to other technologies, processes, and workforce capabilities. The very high cost of smart factory implementation, particularly during the early years, exacerbates the uncertainty, as the benefits of investment will accrue in an uncertain time in the future.
3. *Process*: Manufacturing companies face *difficulties in changing traditional routines and work processes to effect the digital transformation*. Factories frequently lack a systematic approach to adopting modern project models that enable more agile and flexible results and faster time to market. Often, manufacturing processes have been executed in essentially the same way for a long period and have become embedded as traditional practice. This rigid culture can be difficult to change. Modern business transformation models are needed in these contexts, both to enable the transformation and to attract the people with the competencies to support it.

These challenges add complexity to the systemic process of implementing smart factories, which extends throughout the organization. Interviewees highlighted the need to develop and implement structured step-wise approaches to manage the large-scale organizational transformation of people, processes, and technologies.

Progress toward a Maturity Model

To implement the smart factory concept, companies must address significant challenges and develop internal capabilities. After identifying the high-impact challenges via the workshops, our next step was to focus on developing insights into how these challenges were addressed by the smart factory innovation teams, through in-depth interviews at the factories.

Our analysis of interview data revealed three overarching principles underlying a successful smart factory implementation:

- *Cultivate digital people* to drive smart factory implementation during and after the transformation. The introduction of new digital technology introduces people challenges; the entire workforce needs to evolve as the digital transformation process unfolds. Informants emphasized that competencies and skills must develop in step with environment changes to enable employees to cope with rapid technological advancement and overcome organizational inertia. Thus, managers responsible

for smart factory implementation must focus on recruiting and empowering people with digital competencies while simultaneously developing digital skills in the existing workforce.

- *Introduce Agile processes* to leverage rapid technological development. The traditional Stage-Gate model and similar techniques for developing and implementing process innovations cannot keep up with the pace of technological change. Agile implementation processes, incorporated into formal work approaches, provide autonomy and flexibility in smart factory implementation. Sprints, daily stand-ups, short development cycles, and minimum viable solutions create a continuous evaluation cycle that provides opportunities to continuously improve production processes in the face of changing demands. Thus, process improvements that incorporate Agile elements provide the flexibility to redirect effort as new technology and new opportunities emerge.
- *Configure modular technology* to manage the complexity of digital systems. Smart factory technology creates massive opportunities, but, at the same time, it can breed frustration with the number and complexity of choices. Dividing technological solutions into modules and delivering each solution step by step as training is ongoing will help to build acceptance and minimize overwhelm while constructing the foundations and infrastructure of a solutions architecture that is both mobile and modular. Capabilities required to support the desired functionalities can be acquired over time, and teams can work with greater autonomy to expedite action. Moreover, modularity provides opportunities for continuous innovation and reduces lock-in to particular technologies.

Within these three areas—people, process, and technology—our interview data identified key activities that underpin the development of smart factory capabilities; this structure fits with the dimensions defined by prior studies on change management (see, for instance, Blackburn et al. 2017). We categorized these key activities by maturity level to create a smart factory maturity model (Table 3).

Level 1. Connected technologies

The first level of maturity is highly correlated with understanding the technological requirements for a smart factory concept and developing a vision for connecting the various systems. This vision enables essential groundwork and creates the foundation for smart factory implementation.

These challenges add complexity to the systemic process of implementing smart factories.

At level 2, organizations must create models for structured data gathering and sharing.

People. Interviewees highlighted the importance of creating an inclusive culture for smart factory implementation by involving the workforce in developing the vision. For example, a plant manager at Einstein described how the implementation team worked to involve people from the early stages: “It is far more important to define what the smart factory is for the whole company. Roadmaps and general definitions are preferred when delineating what the actual implementation will achieve; this also enables us to communicate the business case.” To further stimulate implementation and manage the deficit in internal competencies, several interviewees underscored the need to start recruiting people with digitalization competencies. A number of interviewees mentioned the need to recruit people with an understanding of both the manufacturing processes and the digital architecture who can bridge programming and manufacturing and enable the organization to access the full potential of the data stream. At the same time, the roles and responsibilities related to digitalization must be defined. Bringing in the right people and defining their roles will amplify the organization’s digitalization potential.

Process. Interviewees spoke of the need to formalize smart factory implementation processes. One beneficial way of introducing greater structure to the implementation phase, interviewees told us, was by combining a Stage-Gate project model with Agile elements. Furthermore, interviewees considered it important that processes be detailed and systematic, as the lead architect at Franklin described: “Some processes need to be evaluated by management, i.e., recruitment of the product owner and scrum master, methods for setting up cross-functional teams, cooperation with other factories, and how delays in deliveries should be handled.” In addition, many interviewees emphasized the need to create a process for involving external actors in the development of a connected platform. Indeed, the active involvement of suppliers, contractors, and end users in the development of the communication platform between technologies was seen as an important keystone in building a smart factory.

Technology. Interviewees stressed the need to apply a digital lens to the mapping of existing and new technologies to move smart factory implementation forward in this early phase. In this process, the desired functionalities to be incorporated into smart factory processes must be mapped onto existing capabilities. As a supervisor at Einstein remarked, “We need everything adapted to every specific production process, but, at the same time, I understand that the system must be standardized to obtain the necessary support and to keep the costs down. Maybe a modular system is the answer.” In addition, organizations embarking on a smart factory implementation must maintain a clear focus on connecting existing applications across data flow to create a common platform. A plant manager at Einstein described the

TABLE 3. Smart factory maturity model

Maturity Level	People <i>Cultivate Digital People</i>	Process <i>Introduce Agile Processes</i>	Technology <i>Configure Modular Technology</i>
Level 4. Smart, predictable manufacturing	Create a culture of continuous smart factory innovation. [X, 1, 3] Create specialized roles and responsibilities geared toward predictable production. [X, 1]	Develop processes for integrating data visualization into decision making. [X, 1] Create proactive processes for forecasting and planning future production. [X, 5]	Create systems to monitor and visualize critical operational analytics. [1, 2, 5] Integrate digital system insights from external partners to enable supply chain predictability. [X, 1]
Level 3. Real-time process analytics and optimization	Organize sense-making sessions with suppliers, users, and other stakeholders. [1, 2, 4, 5] Recruit data analysts and data scientists to optimize production. [X, 1, 5]	Use insight analysis and data interpretation to streamline operational processes. [1, 2, 3, 5] Create processes for evaluating optimization opportunities. [X, 5]	Implement systems for real-time performance analysis. [1, 2, 3, 5] Implement simulation systems to test, prototype, and optimize the digital factory. [X, 5]
Level 2. Structured data gathering and sharing	Educate people to develop the ability to exploit connected data systems. [1, 3, 4] Revise production staff roles to proactively coordinate digital insights and knowledge sharing. [X, 1]	Create specialized insight-mining processes to support information gathering across departments. [1,3,4] Build cross-functional digitalization networks to facilitate knowledge sharing. [1, 2, 3, 4, 5]	Increase accuracy of data collection from technology. [1, 2, 3, 5] Create automated processes for data mining and sharing across functions. [X, 5]
Level 1. Connected technologies	Create an inclusive culture for implementation by involving workforce in vision development. [2, 3, 4] Recruit people with digitalization competencies. [1, 3, 4]	Formalize hybrid smart factory implementation processes. [X, 1] Create process for involving external actors in development of connected platform. [1, 2, 4, 5]	Apply a digital lens to map existing and new technologies. [1, 4, 5] Connect existing technological applications to create data flow. [2, 3, 5]

Numbers in brackets indicate source cases for each principle.

motivation for connecting equipment: “With all the information regarding our KPIs stored in the same place, our work would be more precise and effective.”

Level 2. Structured data gathering and sharing

At this stage, organizations must create models for structured data gathering and sharing to facilitate the development of improved data management practices and processes that allow for efficient storage and utilization of the growing amount of production data being collected.

People. A key activity at this level is educating people to develop the ability to exploit connected data systems. This could mean conducting training sessions on how to access data from different equipment or how to set up common routines in the digital interface. It is also important to revise production staff roles to proactively coordinate digital insights and knowledge sharing. The senior manager at Franklin was convinced that the smart factory concept would transform current job descriptions: “With the new smart factory system, assemblers will have to develop the skills to become digital operators. We will have to increase their competence level through training and education.” This would mean that assemblers would need to have insight-mining and data-structuring competencies.

Process. In terms of new processes, interviewees referred to the need to set up specialized insight-mining processes to support information gathering across departments. Indeed, several interviewees asserted that more efficient data-mining and insight-gathering processes would lead to greater predictive capabilities. For example, the head of digital production at Chatelet remarked, “One of our major issues is the lack of transparency across the departments and brands, which is why we launched this successful collaboration.” To facilitate this, the data-gathering process would need to be updated and distributed across the production cycle. Transparency is achieved when insights are shared simultaneously with involved parties in the right forum and at the correct level of abstraction. Thus, organizations need to build cross-functional digitalization networks to enable rapid knowledge sharing.

Technology. A key activity at this level is the reduction of irrelevant information flow through increased accuracy in data collection. Interviewees emphasized the value of exploring and classifying information to avoid storage of “dark data” (data that are collected but never used) in the same group with actionable and insight-driven data. Increasing accuracy in classification entails focusing on improving both data generation, to ensure the right information is collected, and data quality, to reduce signal interference. A test manager at Nobel described how a failure to reduce irrelevant data and increase accuracy of data collection could create major problems: “The information overflow caused a critical signal to be delayed for eight hours. Imagine what happens when the system says your stock is full, then suddenly it is empty.” In addition, interviewees identified the need to create automated processes for data mining and sharing across functions. The necessary tools and

technology ought to be in place and ready for use to facilitate data collection; for example, business intelligence software must be integrated with the infrastructure for storing, sharing, and classifying data.

Level 3. Real-time process analytics and optimization

The third level of maturity yields beneficial effects of collecting and communicating data; in this phase, organizations build competencies for real-time process analytics and optimization. The focus shifts toward benefiting from the data and the system.

People. On this level, it is important to focus on involving people with experience in analyzing the production environment. To capture key knowledge, interviewees also described the need to organize sense-making sessions with suppliers, users, and other stakeholders in order to benefit from their competencies. A test manager at Nobel described how that factory used an expert user to help solve implementation problems: “With several internal super users, we are able to make sure our operators get the aid they need to work with the new systems.” In addition, informants stated that to fully leverage smart factory benefits, it was vital to recruit big data analysts and data scientists to optimize production. A number of interviewees emphasized the importance of identifying and embracing such experts, who may be difficult to find.

Process. At this level, organizations begin to use insight analysis and data interpretation to streamline operational processes. One way to engage with this process is to create routines for using historical and real-time data analytics in the work process. This approach enables the maintenance process, for example, to be tailored to increase operational efficiency. For example, machine suppliers can contribute to smart factories by offering advanced service solutions that leverage cloud-based operating data and real-time condition monitoring of machines and present vital opportunities for learning. Another key activity mentioned by interviewees was creating processes for evaluating optimization opportunities in operational processes. A senior manager at Franklin said that a key activity at this level is to create processes for identifying and evaluating the benefits that can be gained by optimizing processes: “Evaluation of value-creating activities at the end of an implementation program will limit changes in prior steps. If evaluation is included at every step, smaller adjustments can be performed iteratively to fit the client.”

Technology. On the technology side, interviewees said that the key to this phase was to implement systems for real-time performance analysis. These systems can enable automated analysis of operational information and provide warning signals that maintenance or recalibration may be

At level 3, the focus shifts toward benefiting from the data and the system.

These findings suggest preliminary benefits, but the implications of smart factories are wide ranging.

needed. The integration of these functionalities increased quality in many factories. It is also important to prevent the growing amount of information that is being stored from becoming dark data from which no value is drawn. Another key activity for factories at this stage is to implement reality-based simulation systems for testing, prototyping, and optimizing the digital factory. Cost reduction was at the top of the agenda for the project engineer at Franklin, who claimed that digital simulations of the factory can yield insights while preventing waste of raw material, time, and products: “A major part of a smart factory, and many cost benefits, could come from testing and visualizing production of a factory digitally.”

Level 4. Smart and predictable manufacturing

As the factory reaches the top of the maturity model, continuing the focus on smart and predictable production requires continuous innovation and improvement. Efforts to create predictability in manufacturing make it increasingly possible to know in advance what to expect, leading to greater production reliability and greater profits.

People. Our interviewees said that the key to this level is to create a culture of continuous smart factory innovation in which technology is viewed as the solution and not the problem. This culture is particularly important given the fast-paced development of digital and smart manufacturing technologies. A supervisor at Curie reinforced the point: “When implementing smart factory technology, we cannot forget about our culture of innovation and continuous improvements since this is what has made [this company] the success that it undoubtedly is.” In addition, specialized roles and responsibilities geared to predictable production need to be established to formalize and prioritize these important tasks.

Process. Interviewees in leadership positions underlined the potential of developing processes for utilizing data analytics and visualization for real-time decision making. Interviewees at Franklin described how having visual representations of activity in the factory helped key decision makers attune to the need for ongoing adjustment and improvement. Another process development at this stage involves creating proactive processes for predicting, forecasting, and planning future production. Production activities should be planned in a proactive setting with an emphasis on predicting future requirements. Interviewees at Einstein asserted that they could predict possible production stops and plan maintenance accordingly. A process engineer at Einstein described the benefits of this approach: “As data increases, the information for

up/downtime, MTBF, MTTR and failure rates of machines and equipment can be analyzed and subsequent maintenance predicted and managed accordingly to reach a more sustainable factory, both in economical and eco-friendly aspects as the lifespan is extended and durability increased.”

Technology. To secure full benefits at this maturity level, interviewees sought to improve technology by establishing systems for monitoring and visualizing critical operational analytics. For example, several interviewees mentioned the concept of a war room-type operations center as part of their vision for smart factory implementation. The object is a truly holistic system that is systematically interconnected from simple components (for instance, fiberoptic and optical-fiber sensors) through to complex AI-driven machines (for instance, mechatronics innovations or integrated CAD/CAM/CNC). In addition, interviewees indicated that integrating external partners’ digital system insights to enable supply chain predictability, by integrating the technological interface with the sales platform and perhaps even with customers’ internal systems, was an important step. This integration enables stronger interaction with end-customer operational data, providing insights into future quality problems that could be fed back into the production improvement program to create a seamless customer experience.

The factories we studied varied in the maturity levels they had attained, with Franklin and Nobel showing the highest maturity, having implemented cutting-edge technology and advanced processes (Figure 1). Newton and Chatelet are advancing in their journeys, building smart factory capabilities in a step-wise progression. Einstein and Curie have begun the process but are facing a significant transformation journey.

Benefits of Smart Factory Implementation

The implementation of smart factories is a challenging undertaking that requires a continuous commitment to advancing organizational maturity and capability. However, the commitment can yield important benefits; our analysis identifies four primary outcomes as factories progress toward higher levels of smart factory maturity (Figure 2):

- *Increased process efficiency* is achieved through continuous analysis of operational data, facilitating the identification of process-performance bottlenecks that can be eliminated. As a production supervisor at Curie described it, “Many notifications in production that used to be unseen are instead revealed, so that smaller bottlenecks are brought to the surface.” Such self-correction, which increases process efficiency, is a key differentiator of smart factories from traditional factory automation. As our interviewees noted, process efficiency translates into lower equipment downtime, optimized capacity, and reduced mean time to repair, to name only some of the potential benefits.
- *Lower operational cost* is achieved through process optimization that enables cost-efficient resource utilization. As an automation engineer at Franklin described, “Resources

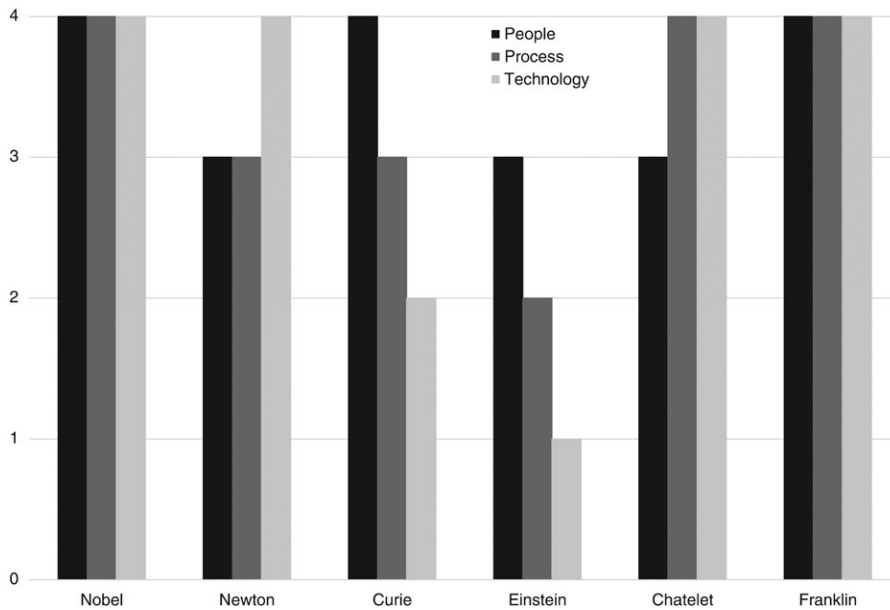


FIGURE 1. Case factory maturity levels for people, process, and technology

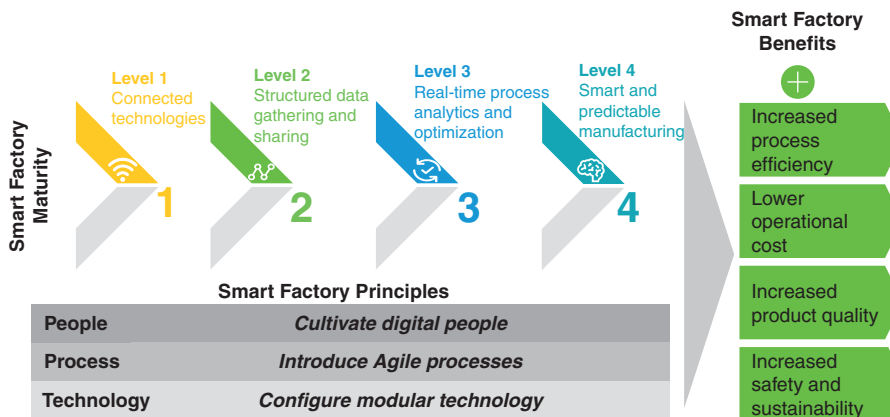


FIGURE 2. Key principles of smart factory implementation

can be allocated more intelligently and based on facts as KPIs are gathered.” In this context, interviewees identified more predictable inventory requirements and supplier management, more effective staffing decisions, and reduced process variability as sources of cost savings.

- *Increased product quality* is achieved through real-time monitoring and the continuous optimization that is characteristic of the smart factory. Enhanced predictive and detective approaches allow quality defects to be spotted sooner than later. As a supervisor at Curie remarked, “The new smart traceability and stop system reduced the amount of quality deviations in my area of responsibility from 20/day to 0–1/day.” In addition, the system can facilitate identification of the root causes of defects, whether they are human, machine, or environmental. Interviewees cited the benefits of lower scrap rates and lead times, as well as a reduced incidence of product defects and recalls.

- *Increased safety and sustainability* is achieved through operational efficiencies that reduce the factory’s environmental footprint compared to conventional manufacturing processes. In addition, greater process autonomy may reduce the potential for human error, including industrial accidents—for example, sensors can detect an operator or assembler in a machine cell or other prohibited area and stop the operation. Finally, repetitive and fatiguing work activities can be replaced by more rewarding tasks that give greater job satisfaction, reducing injuries and staff turnover. For instance, as a team leader at Einstein noted, “By implementing new and smart technology, unnecessary manual lifts can be avoided.”

These findings suggest preliminary benefits, but the implications of smart factories are wide ranging. Leveraging digitalization across the entire production process will ultimately revolutionize manufacturing; some analysts predict seven-fold increases in overall productivity by 2022 (Capgemini 2017). But fulfilling this potential will require managers to think broadly, across the three overarching principles of our maturity model: cultivating digital people, introducing agile processes, and configuring modular technologies.

Conclusion

Developing and implementing smart factories can be a difficult and risky undertaking, but our evidence points to numerous benefits. Companies that succeed with smart factory implementation can increase value creation by lowering the costs of production, increasing quality and flexibility, and reducing the time to market. Ultimately, a strong smart factory implementation offers the prospect of higher sales growth, greater market penetration, and increased firm profitability. To achieve these benefits, companies must design their smart factory implementation with three guiding principles in mind: cultivate digital people, introduce Agile processes, and configure modular technologies to optimize production. The model we have offered provides practical guidance for implementing the smart factory and carrying through a digitally driven transformation of production processes, leading the way to the next generation of process innovation.

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