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## SMART FACTORY: FROM CONCEPTS TO OPERATIONAL SUSTAINABLE OUTCOMES USING TEST-BEDS

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**ABSTRACT. Background:** The concept of “Smart Factory” is a new paradigm. Past studies in literature point out several conceptual understandings of Smart Factory and their classifications. This paper answers the following scientific questions, where does the Smart Factory stand? What are its core characteristics and capabilities? What are the operational outcomes of the currently developed system? How can these pieces of equipment be integrated into an R&D methodology?

**Methods:** Smart factory test-beds are used as a supporting case for this research work. A top-down hierarchical methodology is used to review the recent studies and analysis of the Smart Factory test-beds. The study follows these different steps 1) Literature review on the Smart factory concept on recent studies 2) Reasoning to capture the key characteristics and capabilities from the current developments 3) Experimental investigations to analyze the performances and explicit the sustainable impacts of different cases.

**Results:** We present the Smart Factory “from the concept to operational outcomes”. The results stress: key characteristics, capabilities, influencing factors. Two case studies (literature and own investigation) illustrated the operational outcome and their sustainable impacts.

**Conclusions:** The presented framework summarizes the current body of knowledge of the Smart Factory from review to the operational outcomes.

**Key words:** Smart factory, Industry 4.0, sustainability, Smart production and warehouse, Environmental impacts.

### INTRODUCTION

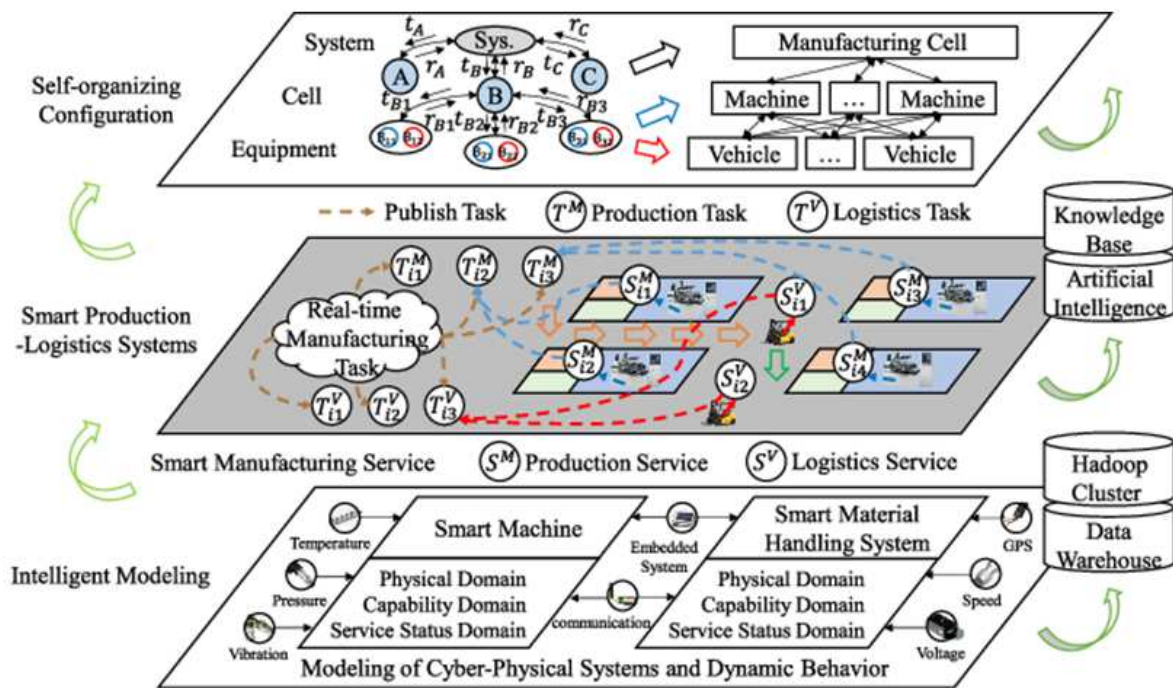
In today’s world, the Industries are focusing on digitalized transformation as an industry revolution 4.0, which encompasses numerous areas of innovations in the value chain and creates new market dynamics. This part of the shift from automation to digitization corresponds to a new way of organizing the means of the complete value chain of the industry. The core of this transformation refers to the intelligent networking of machines, processes, people with the help of smart technologies [Sun, 2018]. The technologies, which encompass the Internet of things (IoT), Big-data technologies, Cyber-physical systems, and cloud computing [Schlund,

2018], support the industries to achieve the objective of customer-oriented solutions, achieve competitive market demands, and resource-efficient circular economy [Sun, 2018]. Industry 4.0 fosters the Smart Factory concept. This term describes the factory whose degree of integration that has reached the level of self-organizing functions possible in production and all business processes relating to production [Platform Industrie 4.0, 2016]. It combines and integrates the physical and virtual world of production in networked modules.

The global Smart Factory concept can expand to smart production-logistics networks [Zhang, 2018]. Figure 1 specifies the globalized networked of Smart Factory

production and logistics system. [Monostori, 2014] stated that a future system is “autonomous and cooperative elements connecting in situation-dependent ways, on and across all levels of production, from

processes through machines up to production and logistics networks, enhancing decision-making processes in real-time, response to unforeseen conditions and evolution along time”.



Source: Zhang, 2018

Fig. 1. Globalized networked Smart Factory production-logistics system

Several past studies point out a conceptual understanding of the Smart Factory and its benefits. However, there is a lack of studies on switching from concept to reality from a Smart Factory perspective.

Smart Factory test-beds were introduced in recent years to put forth step forward the concept into reality. These test-beds are a universal factory of the future, which are modular, networked, and adaptable factories. They can assist industries and universities in experimenting with industry 4.0 solutions in real-time. [Abele, 2015]

The next section specifies the scientific aim and methods used in this study.

## SCIENTIFIC AIM AND RESEARCH METHODS

This paper aims to support the common understanding of the Smart Factory concept, and to give visibility for a larger audience of researchers and practitioners. This paper addresses the following questions: where does the Smart Factory concept stand? What are the core features and capabilities from initial development? What are the sustainable operational outcomes?

To achieve this, the analysis follows a top-down methodology, Cf. Figure 2.

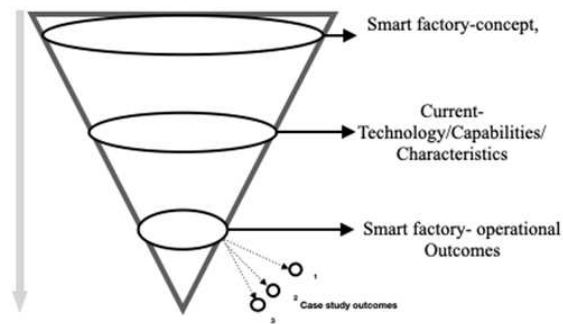


Fig. 2. Top-down hierarchal methodology followed

The framework is categorized into different levels:

- Level-1: Where does the Smart Factory concept stand? – Literature review
- Level-2: Key Technology level- Recent studies and test-beds
- Level-3: Key Characteristics and Capabilities level- test-beds
- Level-4: Operation and outcomes level- Case study investigation on test-beds and analysis of the operational outcomes.

This study firstly reviews the current literature to give a brief explanation, and history of smart factories and their stands. Secondly, we analyze the currently developed smart factory test-beds on different levels and categorized, starting from the technology to capability of the system. Finally, the test-bed case studies are investigated to explicit the operational outcomes and analyze its sustainable impacts.

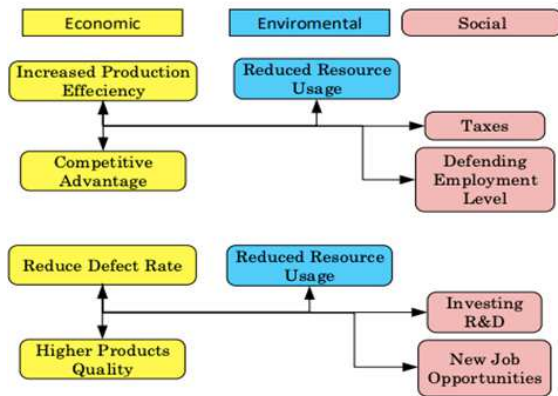
## INDUSTRY 4.0

Industry 4.0 is a strategic initiative introduced by the German government in 2011. Its goal is the transformation of industrial manufacturing through digitization and exploitation of potentials on new technologies [Abele, 2006]. Industry 4.0 corresponds to a new way of organizing the means of a complete value chain of the industry [Odważny, 2018]. After the initiatives of Industry 4.0, the visionary concept of the Smart Factory emerges [Strozzi, 2017].

## Level 1. Smart Factory concept and standpoint of implementation

The concept and current standpoint of Smart Factories are specified in this section. The smart Factory is a visionary concept. In Hannover Trade Fair 2014, the German-based organization called ‘Smart Factory kl’ introduced a concept called smart Factory. They demonstrated how the production line of the industry 4.0 paradigm in the future should be. According to Platform Industrie 4.0 [Platform Industrie 4.0, 2016], the Smart factory denominates a factory who reached a level that makes self-organizing functions possible in production and all processes relating to production. It is composed of diversified areas in the production eco-system [Strozzi, 2017], from smart production to smart logistics networks.

The core function of Smart Factory is self-configuration, self-organizing, self-sensing, self-decision making [Jung, 2016]. These foreseeable functions, elements, and advanced technologies of smart factories will lead to less waste, fewer losses, and resource depletion to satisfy all three sustainability pillars (Economical, social, and environmental) [Odważny, 2018], see figure 3. From the economic perspective, this factory will indeed improve the overall process and performance, producing a quality product, while being highly flexible to customized market demands. This shift will require a considerable amount of capital investment on deployment and implementation [Yuan, 2017]. However, thanks to the operational and running cost perspective, it will bring economic sustainability to the organization. From an environmental point of view, the factory will reduce resource usage and material waste [Thiede 2018]. On the Social view, it is expected to foster significant changes in how industrial workers perform their jobs. The high technology-centric with advanced automation of work processes are expected to have a deskilling impact [Dworschak 2014]. At the same time, the factory should increase the demand for new jobs.



Source: Braccini, 2019

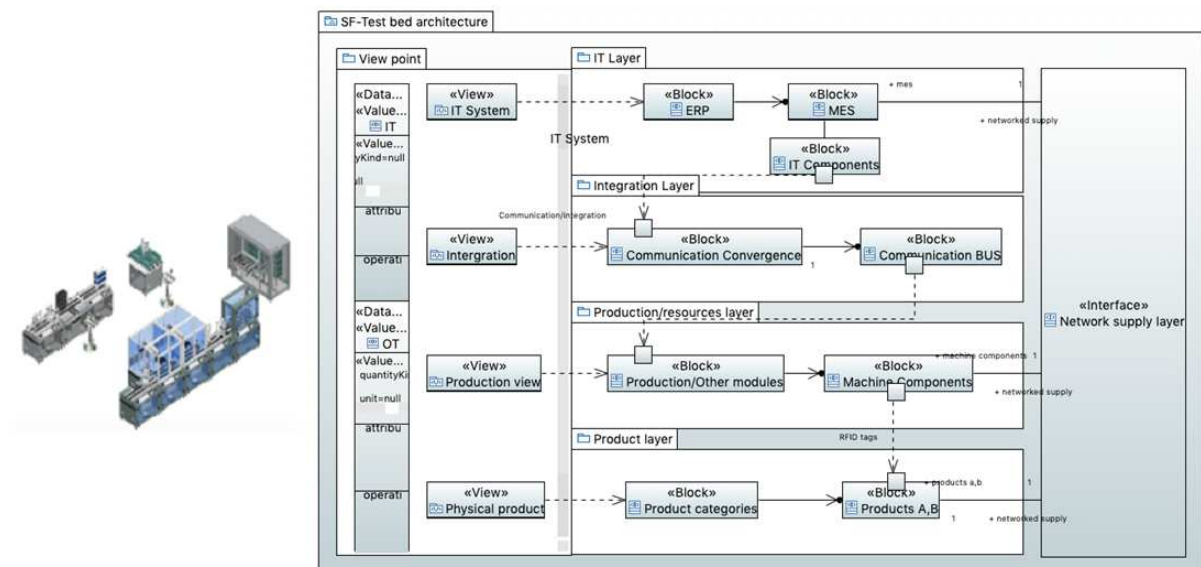
Fig. 3. Interactive benefits in Triple Bottom line concept due to factory 4.0

The transition from the traditional production and logistics systems into “smart” will bring many values added service to the firm. According to the United Nations Industrial Development Organization [UNIDO, 2019] 81 % of industries are currently investing in Smart Factory initiatives; however, 70 % are still in pilot purgatory because of a lack of values and return on investment (ROI) (according to the World Economic Forum) [WEF, 2019].

As for now, only smart factory test-beds are completely emerged [Zuehlke, 2008]. These testing-beds are replications of Smart Factory and serve for many purposes like training, experimental tests, analysis. They assist industries in deploying in real system technologies. They incorporate a variety of industry 4.0 technologies and present the ecosystem as like future. The next section shows the smart factory test-bed architecture.

## SMART FACTORY TEST BEDS

This section shows a description of Smart Factory test-beds and its architecture. The test-beds illustrate the comprehensive, modular, expandable, and networked factory model. Figure 4 represents test-beds [Festo,2017] and system architecture using SysML (system modeling language syntax), which are arranged in RAMI 4.0 frame (Reference architecture model Industrie 4.0) and represented in black-box view. It is divided into four main layers that group the different types of modules. The main layers include the product layer, production layer, integration layer, and IT system layer.



Source: authors work

Fig. 4. Test-beds architecture

The production layer combines all types of equipment to produce the product. They can be workstations, logistics systems, and other stations. They are modular (with standard interfaces) and automated, which ensures and

creates the preconditions for the integration of a new production process with minimal physical effort configurations. The modules/workstation components have a networked supply that incorporates to have

communication exchange between the modules.

The product layer includes all the products to be manufacture which stays in this line.

Integration layer- This layer connects the production and IT layer and groups all modules that makes up the communication connection, for example, the communication b/w layer. It serves as a standardized service, which is responsible for the integration of the data interface between IT systems and production modules.

The IT layer encapsulates elementary services, analogous to the production components of the production layer.

The above-specified architecture corresponds to currently developed test-beds, which is arranged in a RAMI 4.0 frame. However, the technologies used, advanced principles, and benefits specified in the upcoming section.

### Cluster2 Technology level

In this section, the key technologies used for smart factory are specified. Smart factories will be based on advanced intelligence technologies, autonomously functioning, and mechatronic modules. Figure 5 shows the technologies used in Smart Factory using the layer described in the previous section.

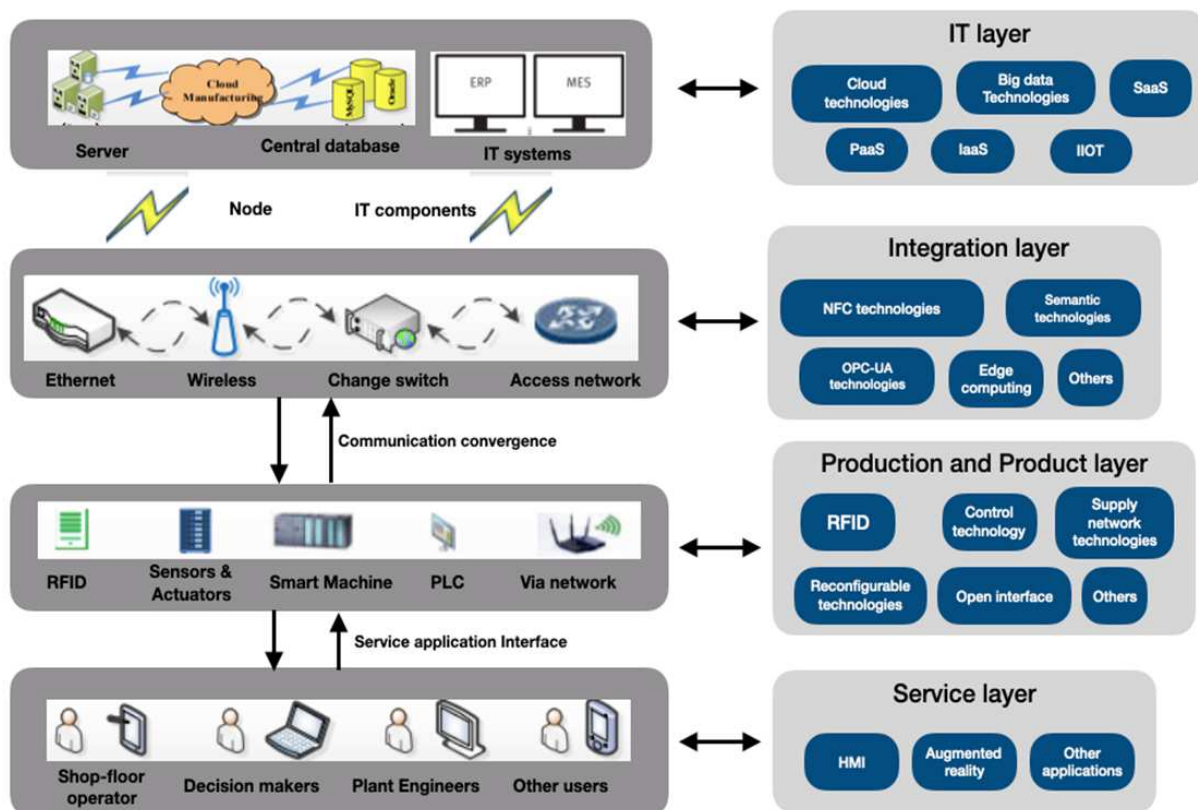


Fig. 5. Key Technologies of the smart factory in a layer-wise

The technologies, used throughout the entire layer, which includes- IIOT (Industrial Internet of things), build on identifying and communicating with each other which links in the industrial value chain: machines, products in production, employees, suppliers, customers, infrastructures, etc. In today's smart machines, IIOT excels accurately and

consistently in capturing and communicating data, enabling less downtime and better overall efficiency of machines.

A cyber-physical system is an application in which the collaboration of physical and software components that are deeply intertwined, which can operate and interact

with each other was a change in context. It transforms technologies and enables the connection of the operations of physical assets and computational capabilities [Bagheri, 2015].

Along with the generic technologies, some of the technologies used in Smart Factory test-beds on specific layers whereas,

1. IT layer- Big data technologies refer to a new generation of technologies that extract value through discovering, capturing, and analyzing very large volumes of a wide variety of data [LaValle, 2011]. In connected production, it generates a considerable amount of data (big data) that enables analysis and determines to improve its operation and remain competitive. Cloud computing and technology refers to the delivery of resource and service demands over the Internet. It helps to store and access data through the Internet rather than a computer's hard drive. Main services are offered in cloud computing SaaS (Software as service), PaaS (Platform as a service), and IaaS (Infrastructure as service). It helps to share services on a large number of customers. [Oliveira, 2014]. These technologies support each entity in discovering, capturing large volume of information in the eco-system.
2. Integration layer- Near field communication (NFC) technologies allowing to exchange of information between the devices, machine to machine communication within the specified distance and has the capability of wireless connection. The communication protocols are used in the lower level, close to the machines and at a higher level, close to cloud or enterprise information systems, which enables the contactless communications, information sharing, and networking the ecosystem. The instrumentation used in the layer TCP/IP, PROFINET, RFID, OPC UA, Ethernet-Wi-Fi are currently developed test-beds. Semantic technologies can provide common standards for communication that help machines understand data [Janev, 2011]. It provides an abstraction of existing IT technologies that enables bridging and interconnection of data, content, and processes.
3. Production and product layer - The RFID technology used in wireless products to send signals and communicates with the stations, which enables us to know their histories, routes, and data memories through network and communication ability. Control technologies used in Smart Factory test-bed are modernized control, whereas, Industrial PC, PLC, human-machine interface (HMI), drive controller, Plug and play control used to facilitate controlling the systems, which enable them to achieve the desired performances. [Festo, 2017].
4. Service layer- This layer integrates humans with the technologies, which enables to achieve the smart service in the eco-system. Augmented reality plays a vital role, it allows for visualization of the real world, sharing entities' information to the users. It enhances and offers the personal benefits with distinctive experiences of the eco-system [Damiani, 2018]. This technology allows the operators to control and operates the machines. Other technologies, like enhanced touch, and gesture interface, virtual technologies are also there in the service layer.

These generic advanced technologies are widely used for smart factory concepts in literature and test-beds [Schlund, 2018].

### **Level 3 System: Key capabilities and characteristics level**

In this section, the Smart factory system's key capabilities and characteristics are summarised. Everything in the eco-system has a certain degree of built-in intelligence. The intelligence in the central system moves to each small entity of the system [Zuehlke, 2010]

The enabling technologies (presented in the previous section) form potential technical capabilities. These capabilities enable to successfully perform a particular job or task. The smart factory has advanced abilities and characteristics to achieve foreseeable objectives. We have grouped their capabilities and characteristics into five aspects based on set of relations to have better readability (see Fig 6).

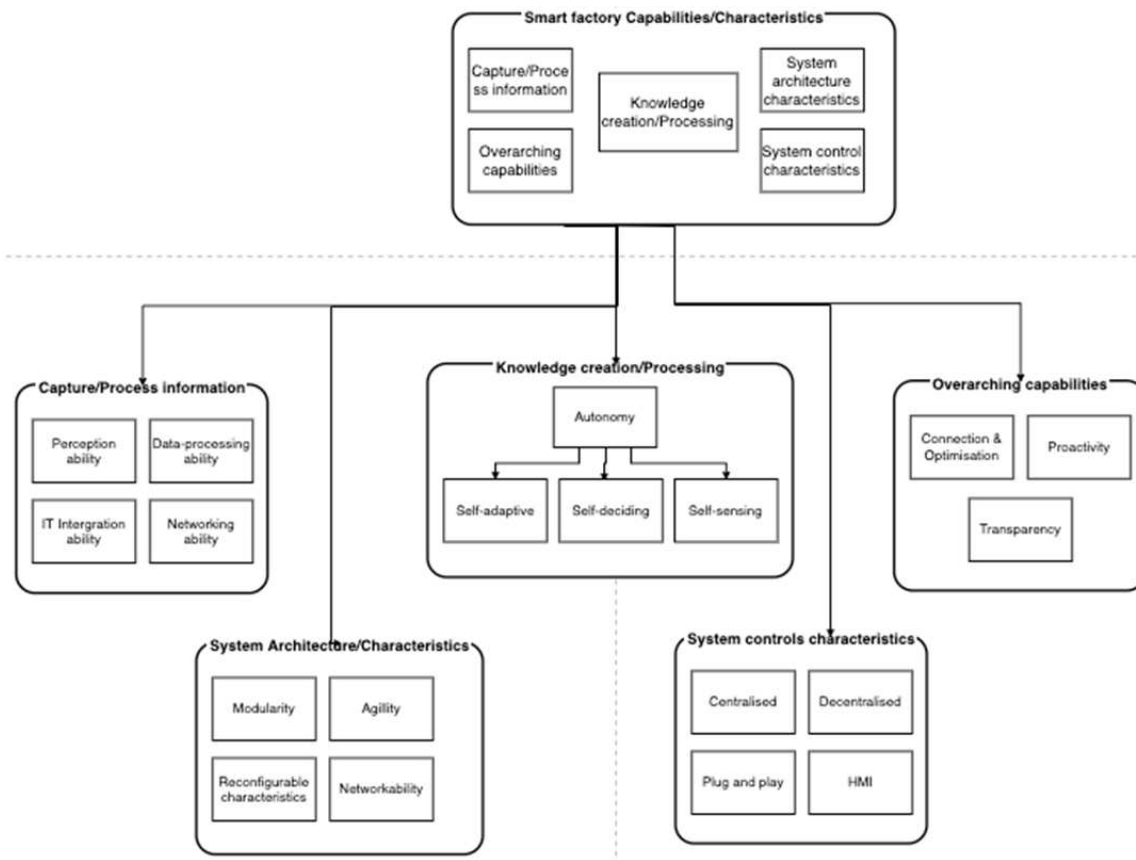


Fig. 6. Grouping of Key capabilities and Characteristics

### Grouping of Capabilities/characteristics based on set of relations

We have grouped the key capabilities and characteristics into five categories based on set of relations. They are:

- 1. Capturing/processing the data and information** – It is the ability of the system to handle itself and its environment. It relates to the set of Data-processing ability, Networking ability, Perception ability, IT integration abilities.
- 2. Knowledge creation/Processing ability** - It assists the system creating and processing the knowledge to its entities in a concrete situation. The set of relations for knowledge creation/process is the autonomy where the machine makes the decision with the following aspects of autonomy- self-deciding, self-adaptive, and self-sensing.
- 3. Overarching capabilities** - It is the natural ability of the smart factory eco-system. It assists more informed decision-making and help eco-system in a wide perspective. The set of characteristics are, Connected & optimised, Agile, Proactive, Transparent system.
- 4. System architecture characteristics** - The key architecture characteristics, and set of relations include the modular, agile, networkable and reconfigurable characteristics.
- 5. System Controls characteristics** - The system has modernised control ability. It controls itself and the external environment on different levels. The set of relations and levels of control are Centralised, Decentralised, Plug and Play, HMI Controls.

The five categories are detailed below.

#### Capture/processing of data and information

##### *Data processing ability*

The smart system has a complex and rapidly changing behavior, which involves



enormous quantities of data that can be able to access different database and process information on time. Especially, the data processing is accessible quicker when it is distributed on the different modules in the eco-system.

#### *Perception ability*

The perception ability of the system describes the perception to recognize the entity that affects itself or its environment. It is dependent on the data processing ability and be influenced by sensor fusion and a variety of sensors. This ability has many advantages, which include, for example the ability to recognize the workstation and determines that the work piece was not well aligned or broken.

#### *Communication & Networking ability*

The networked and communication ability describes the network connection of each entity in the eco-system that allows them to set up, transfer information between the modules, and maintain a reliable infrastructure. For example 1) In current developments, the Workstation able to read work piece operation through barcode and do operations, 2) RFID tag on each work piece can send a signal to the work station and enables to know their histories, routes and data memories through network and communication ability.

#### *IT integration ability*

IT system is integrated into the overall system architecture, it serves as a comprehensive solution and connects the modules to obtain the greatest benefits. In test-beds, the IT integration encapsulates as elementary services, which analogous to the production components. It provides standardized data interface services between the IT system and production modules (see Fig 6).

### **Knowledge creation/ reasoning**

Knowledge creation and reasoning ability describes the intelligent system. It can create its knowledge to understand its environment or to access its knowledge and thereby even

understanding the reason for a problem and find a solution. For example: 1) Workstation learns some samples before so that it can classify the work piece on the main operation run. 2) Based on the appearance of a work piece, the workstation can create reasoning. 3) The work station module is self-awareness as like humans on the operation.

This category includes the ability to decides, sense, adapt, and organize themselves on their own. Below shows the ability with possible categories,

#### *Autonomy*

Autonomy is an important factor in the future generation of the system. The current development of the test-beds system needs human interventions to make decisions (See Fig 7. Current developments trend on autonomy). It is possible in the capability view; certain degrees of autonomy affect other factors like socio in the future. Some of the self X capability functions in current developments are:

- Self-sensing: the system captures the data and critical information from the environment involving product, quality, materials, machines etc.
- Self-deciding: the system makes the data-driven decision in manufacturing, including the identification, collection, communication, analysis and learning.
- Self-adaptive: the system adapts to changes in real market demands and adapts to uncertain situations.

#### *Over-arching capabilities*

Over-arching capabilities play a vital role in enabling decisions that are more informed and can help organizations improve the production process. The over-arching capabilities allow operations to execute with minimal manual intervention and high reliability. It assists in different aspects of the ecosystem whereas, high values of automated workflows, synchronization of assets, improved tracking and scheduling, optimized energy consumption that inherent the smart Factory on increasing yield, uptime, and quality.

The key overarching abilities of the smart factory are connected, transparent, proactive, and agile. It assists in the overall supply network efficiency of the eco-system. The categories are described below.

#### *Connection and optimization*

The main characteristic of a Smart Factory is its connected and optimized nature, which is one of its most crucial sources of value. The Connected nature indicates integrating at various levels from small agents to the entire business production eco-system. It enables a holistic view of upstream and downstream supply chain processes, driving greater overall network efficiency.

#### *Transparency*

The transparency is a real-time data-visualization, which captures from the field and physical production products that are, convert them into actionable insights, information exchange for human and even autonomous decision-making. The visibility across the modules ensures the organization to make accurate decision making by providing real-time views, alerts, notifications and real-time monitoring of the system.

#### *Proactivity*

Generally, proactively helps the system can anticipate and act before the issues or challenges arise, rather than reacting to them. In a smart factory, the ability is to predict the future outcomes on real-time data that can improve uptime, yield, and quality. It also enacts processes that, enabling them to digitize an operation and move beyond the automation and integrate into predictive capabilities.

### **System Architecture characteristics**

In current developments, the fundamental change in the system characteristics are redefining the numerous areas in the eco-system. The involved main characteristics are modular, agile, networkable and reconfigurable characteristics. The system modular architecture has standard interface, which allows to exchanging the other modules in

a minutes of time. In addition, it has the capacity to quickly changeable and reconfigurable on the specific customer product variants. Specifically, the system has the networked communication between the machines, products and people.

#### *Modularity*

The system architecture is a module-based design. Each module is physically independent from the rest of the system. These individual module structures assist in quickly changeable, customer's specific product variants. It allows the system performance effective, and foster the diagnosis changes.

#### *Reconfigurable characteristics*

Reconfigurable characteristics give the potential of a rapid change in its structure of software and hardware components. The core characteristics are changeability, integrability, customizability, convertibility, scalability, diagnosability. It quickly adapts its production capacity and functionality within a part family in response to change in market demands or intrinsic system change.

#### *Agility*

Agility can move fast and quick. In current test-beds, each module has an agility function, which is an asset on increasing the factory uptime and yield by minimizing the changeover in a few minutes. It enables flexible scheduling, rapidly changing, and structuring the ecosystem.

#### *Networkability*

The networkability describes the network connection of each entity in the eco-system. It ensures the communication between the machines, products and people to perform a corresponding and overall task.

### **System Controls**

The modern control systems are the foundation for the industry 4.0/IIOT based concepts. In contrast the diverse level of the controller on various aspects is used in current

developments. The key controllers/Open interfaces are Industrial PC, Programmable logic controller (PLC), Human-machine interface (HMI), Drive controller, Plug, and Produce control-which is a new development for decentralized module control. It is facilitated with smart, interoperable modules with standard interfaces. However, this category includes the modern controls and open interfaces, which is described below.

### Centralization and Decentralization

The module-based developments incorporate both the centralized and decentralized controls. Figure 7 shows the current development trends towards the need for both the control architectures that enable human intervention. In current test-beds, the decentralized and federative system is comprised of sub-systems that communicate and work well with each other with or without human intervention on a certain degree of autonomy. It provides the necessary freedom to act in the eco-system.

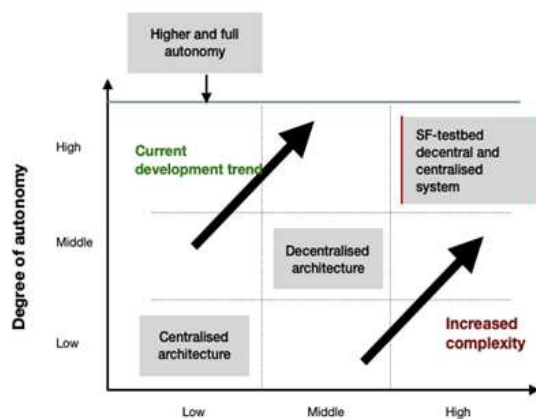


Fig. 7. Current development trends on the degree of autonomy

### Plug and play principle

Plug & play principle and control are introduced in current test-beds, whereas it is borrowed from computer sciences. It processes the elements and then leading to changeable or reconfigurable systems. It assists the reconfiguration in production that can then be quickly accomplished. It facilitates the use of smart, interoperable modules with standard interfaces.

### Human-machine Interaction

The human-machine interaction (HMI) or human-computer interaction is discussed for a long time. According to currently developed test-beds, human-machine interaction (HMI) implies that human and machine agents can be no longer be considered in isolation. It should be regarded as a dynamic unit or team collaborating towards an overall task and allocates among the participants.

This explicit analysis is described based on real capabilities on test-beds without any conceptual intervention from the literature. Next section 4.3 specifies the operational outcomes of the smart factory.

### Level 4 Operational outcomes

#### Test-beds case study

This section deals with currently developed Smart Factory test-beds operational outcomes in a case study investigation. Two different case-studies are described using the following axes:

1. Smart Factory- Production and warehouse- Authors investigation and outcomes
2. Smart Factory- Environmental Impacts- Literature case study

#### Case study-smart production/warehouse (authors work)

The test-bed used in this case study consists of smart production and warehouse modules, combining a variety of applications. The system assembles mobile phones for different strategies: standard production, mass-customized production, and personalized production.

The question is whether the smart production and warehouse provide sustainable operational outcomes.

The experimental case study compares different demands' scenarios and evaluates the operational outcomes of the modules for standard production (S1), mass customization

(S2), and personalization (S3) operation. The standard (S1) operation is taken as a reference scenario to calculate the other scenarios from the given metrics. For each scenario, 20 customer's orders are launched in the factory separately.

In the mass customization portfolio the diversity of final products is enabled by the multiplicity of shape and color (Figure 8).



Fig. 8. Product portfolio

Table 1. Operation Scenarios and diversity Product portfolios

Mode	Number of colors	Number of shapes	Diversity fuses	Size of portfolio
Standard (S1)	1	1	4	4
Customization (S2)	4	1	4	64
Personalization (S3)	4	2	4	$\alpha$

### Evaluation of KPI

We have selected and classify KPI based on the Equipment's reliability and how the equipment is responding to the demanding entities (see Table 2).

Table 2. KPI's description and formulation

Performance Attributes	Key Performance Indicators (KPI)	Description	Formulation
Equipment Reliability (Production and Warehouse)	OEE	OEE is the estimation of equipment is truly productive	(Availability factor * Performance factor * quality factor) * 100
	Utilization	The proportion of time equipment is used	Actual Operation time(At)/Possible time(Pt)) * 100
Customer satisfaction	Quality products produced	Proportion of products produce to the demand	Good product/Total product * 100

Customer satisfaction evaluation the match between product produced and product required.

The utilization of the system is leveraging its full capacity or work potential in a given period. Here, this indicator is measured based on the different sensors on the equipment:

Overall Equipment Efficiency is a measure of how well manufacturing operation (facilities, time, and material) are utilized compared to its full potential during the periods when it is scheduled to run. Here, OEE is evaluated based on three factors,

1. Availability: Machine available for production/total time

2. Performance: duration of production/total time
3. Quality: time spend on producing good products/total time

The monitored results, coming from the machines, are shown in the bar graphs (Fig. 9, Fig. 10, and Fig. 11) The white bar indicates Availability, Gray bar indicates quality, Black bar indicates Efficiency, and Blue bar indicates OEE.

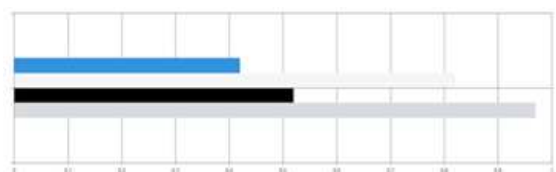


Fig. 9. Standard (S1) Operation

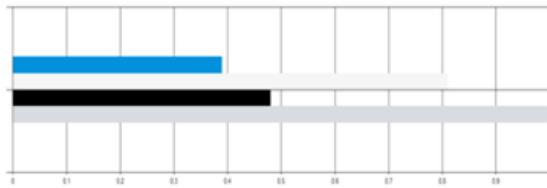


Fig. 10. Customized (S2) Operation

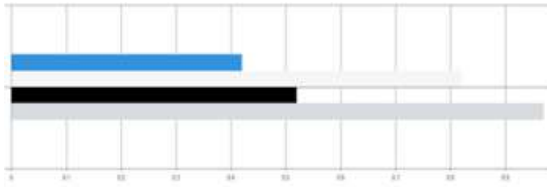


Fig. 11. S3-personalized Operation

It calculates the OEE and OEE factors- Availability (A), Performance (P), Quality (Q) factors of the three scenarios.

Table 3 shows the results of the experimental investigation.

Table 3. Results of Evaluated Key Performance Indicators

KPI	Scenario 1	Scenario 2	Scenario 3
OEE	0.42	0.41	0.39
Utilization	51 mins	49 mins	50 mins
Customer satisfaction	19/20	20/20	19/20

From the overall experimental case study, the results indicate that the factory is efficient and flexible since it can operate with the same performance for 3 different production strategies.

#### Influencing value-driven factors

From the case study analysis, it can be observed that the technology and characteristics influence the modules and drive value in the operation.

Figures 12 and 13 show the value-driven influencing factors of a Smart warehouse and production.

The Smart production module provides the value of “Fast conversion” “Transparent production” “optimized production” and “shorter product life cycle”. It signifies that the modules are reactive and change in the uncertain situation that leads to a sustainable operational outcome.

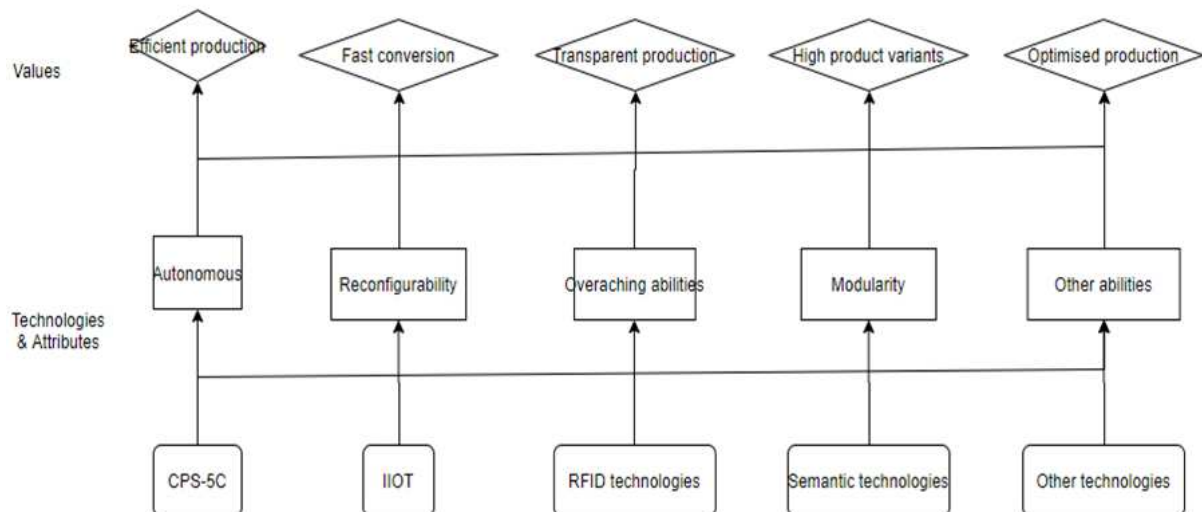


Fig. 12. Smart-Production influence factors

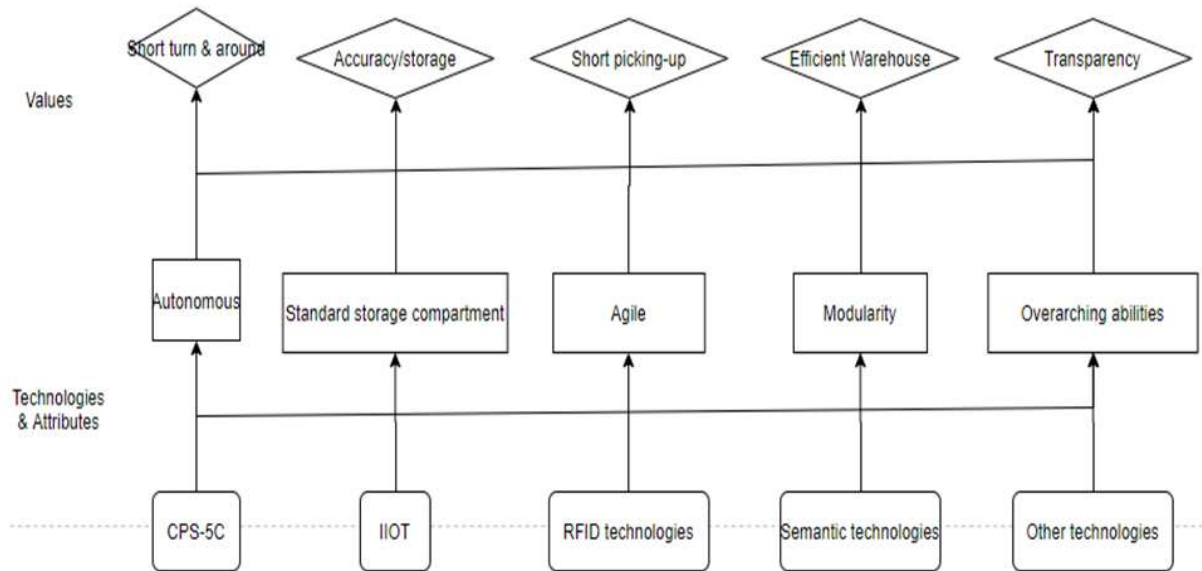


Fig. 13. Smart Warehouse influence factors

*Case study example-Smart Factory Environmental Impacts (EI) [Thiede, 2018]*

This case study investigates the Smart factory environmental performances. In this work, [Thiede, 2018], the environmental feasibility of smart factory in manufacturing is investigated and the study analyses the environmental impacts on qualitative consideration then proposing a generic methodology to assess the smart factory environmental aspects. The work is summarized through the case studies and the life cycle assessment (LCA) methodology is used to investigate the system.

The study is divided into two different case studies. In case study-1, the authors stress the environmental impacts of the smart factory. The authors added an additional smart component like sensors, devices and computer peripherals in the system. This study is evaluated through the continuous energy monitoring system to calculate the energy for this case.

In case study-2 the authors remove the incorporated additional component and test the system. They then analyse the environmental impacts without the smart components. This study is evaluated through a thermal 3D emission monitoring system for this case.

These two environmental assessment case studies are evaluated for 3 years separately.

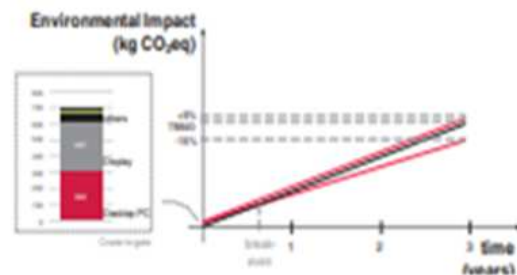


Fig. 14. Environment impact of case study-1

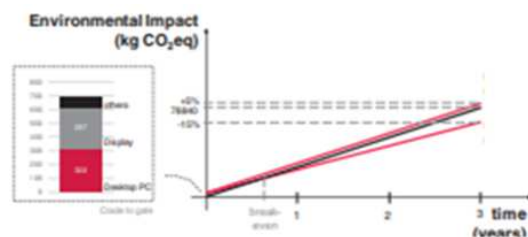


Fig. 15. Smart Warehouse influence factors

For case study-1, the result (shows in Fig 14) stresses that, over the 3 years along with environmental impacts, the potentiality of the system improves in the production.

In addition, the Energy flow is improved. This overall improvement, below 10% would not lead to breakeven in three years. It is noted that, the additional smart component of the

system has minimize the environmental impact of the physical production.

*Thermal 3D emission monitoring (Case study-2)*

Case study-2 investigates environmental impacts without the smart components. Fig 15 shows the environmental impacts of case study-2. It is noted that, energy improvement (cradle to gate(approx. 700 kg CO<sub>2</sub> eq ) is a bit lower in this case due to less complex infrastructure. In contrast, energy improvement during the use phase is significantly higher (4.00 kg CO<sub>2</sub> eq) since the computer needs far more energy for the complex simulations. The result indicates the potential improvement of 20% is gain a positive feasibility for the CPPS. Its actual potential is 5-8% more realistic values that clearly shift the breakeven point towards the three years.

From the investigation, the authors point out as a general synthesis, the environmental feasibility of CPPS is high on specific cases, depends on configuration, operation modes and general circumstances. In addition, the energy consumption is more without the components than with smart components.

**CONCLUSIONS**

Using a top-down hierarchal methodology, this paper clarifies the concept and where the smart Factory currently stands. The study also stresses the key technologies and categories the capabilities of currently developed Smart Factory test-beds. To realize the concept into reality, the operational experimentation of smart factory test-bed presented on two different case studies. From the authors and literature investigation, it summarized and analyzed the sustainable operational outcomes.

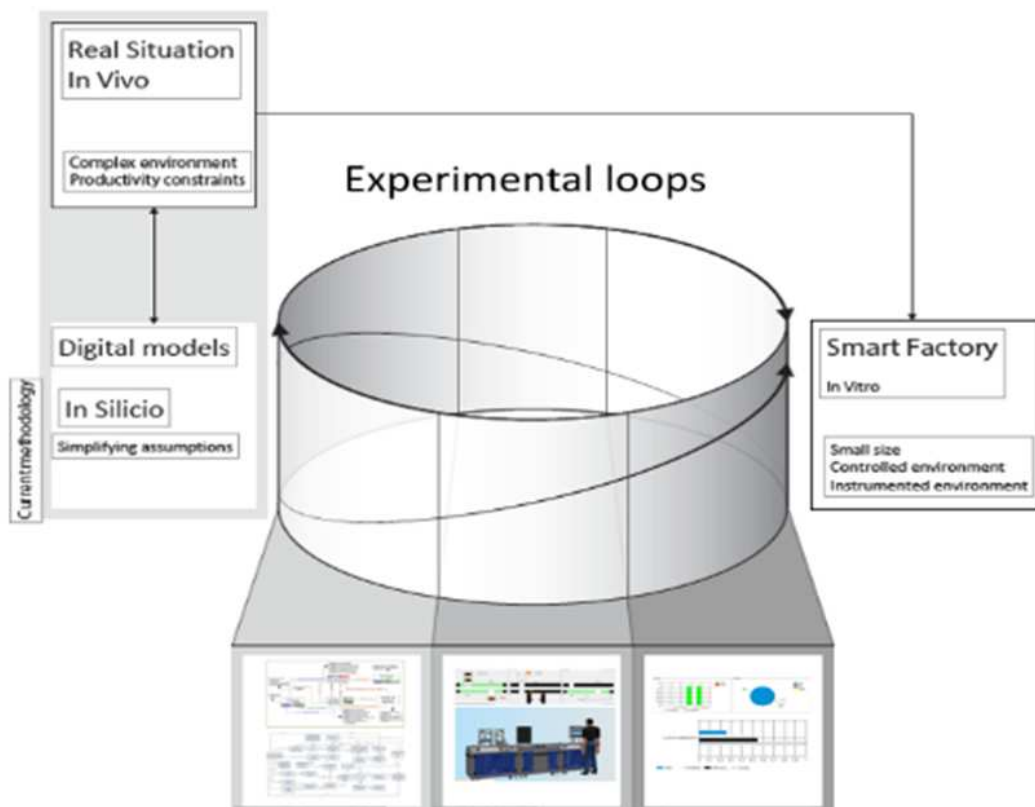


Fig. 16. Smart factory Experimenting loops

*Case study-1.* The factories smart Production and warehouse modules is efficient

and flexible which brings the operational sustainable outcomes.

*Case study-2.* The smart factory and their components energy consumption is less and has feasible environmental impacts which bring sustainable outcomes.

With the findings from this article, we can conclude that Smart Factory test-beds enable us to implement a new research methodology. This methodology relies on experimental loops between the digital model and the Smart Factory test-beds (see Figure 16). This real size test-bed is a controlled and instrumented environment that can mimic real situations without having productivity constraints.

It is, therefore, feasible to test a solution, and if discrepancies between expected and observed performances are observed, the digital models may be enhanced. Only a solution performing both in silicio and in vitro will then be implemented in vivo, in the real industrial environment. This methodology will benefit industries, by avoiding the costly implementation of ill-fitted solutions, and academia, by improving the digital models.

The presented study puts a step forth on the concept into reality by summarizing a framework of the current body of knowledge of smart factory from concept to sustainable operational outcomes. This study assists as visibility for a larger audience of researchers and practitioners in a wider perspective.

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## SMART FACTORY: OD KONCEPCJI DO ROZWIĄZAŃ OPERACYJNYCH PRZY ZASTOSOWANIU PANELI TESTUJĄCYCH

**STRESZCZENIE. Wstęp:** Koncepcja “Smart Factory” jest nowym paradygmatem. Najnowsze badania naukowe wskazują na co najmniej kilka znaczeń pojęcia Smart Factory oraz ich klasyfikacji. Prezentowana praca odpowiada na następujące pytania naukowe: na jakim etapie rozwoju jest Smart Factory? Jakie są jego najistotniejsze cechy charakterystyczne i zdolności? Jakie są operacyjne wyniki i możliwości z obecnie rozwijanych systemów? Jak różne elementy wyposażenia mogą być zintegrowane w metodologię R&D?

**Metody:** Panele testujące są używane do wspomagania pracy naukowej. Pionowa hierarchiczna metodologia została zastosowana do analizy ostatnich badań naukowych oraz używanych paneli do testowania Smart Factory. W badaniu można wyodrębnić następujące etapy: 1. Przegląd literatury dotyczący koncepcji Smart Factory, 2. Określenie podstawowych cech charakterystycznych i zdolności w oparciu o najświeższy etap rozwoju, 3. Badania eksperymentalne mające na celu analizę działania i wpływu na rozwój zrównoważony różnych scenariuszy.

**Wyniki:** W pracy przedstawiono Smart Factory od przedstawienia koncepcji do operacyjnych wyników. Wyniki obejmują: cechy charakterystyczne, zdolności, wpływ czynników. Dwie analizy (literatury oraz badania własne) ilustrują wynik operacyjny i jego wpływ na rozwój zrównoważony.

**Wnioski:** Zaprezentowana praca podsumowuje obecny stan wiedzy na temat Smart Factory w oparciu o przegląd rozwiązań operacyjnych.

**Słowa kluczowe:** Smart factory, Industry 4.0, rozwój zrównoważony, zaawansowany technologicznie magazyni dom, wpływ na środowisko

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