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Smart Factory Reference Model for Training on Industry 4.0

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ABSTRACT

Technological disruption and rising labour costs are impacting the future of manufacturing in Malaysia and its competitive position. Nevertheless, the understanding on smart manufacturing in the context of Industry 4.0 is still lacking in the academia and industry. Thus, this work describes the development of a smart factory reference model as a guide to upgrading an existing production system towards the vision of Industry 4.0 using readily available components. The reference model consists of (i) a principle solution describing the concept of a smart factory and (ii) a working prototype demonstrating the functionality of a smart factory. The smart factory prototype is a modular production system connected to a server accessible locally or through the internet and able to produce up to eight variants of a product. The SCADA software was used to interface various systems together and create the user interface. The prototype was evaluated using VDMA Industry 4.0 Toolbox. This work provides a way to integrate theory and practical Industry 4.0 applications into tertiary education curricula. It showcases the potential applications, benefits and proof of concept of new technologies for industry adoption.

Keywords: *Industry 4.0, Smart Factory, SCADA, Industry IoT, Systems Engineering*

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Introduction

Technological disruption brought by the Internet and digitalization has influenced our daily routine not just socially but also economically [1]. The next revolution in the industrial world is driven by the Internet and Communication Technology (ICT), thus Industry 4.0 is introduced as one of the German strategic initiatives to establish Germany as the market leader and provider of advanced manufacturing solutions [2]–[4]. It is said to be the fourth revolution in the industrial world after the previous industrial revolutions of steam power-mechanization, electricity-mass production line, and computer-automation. Industry 4.0 also can be interpreted as a cyber-physical system in which advanced manufacturing, automation and ICT are linked together and connected to the Internet [3]–[6].

Among the applications of Industry 4.0 is a smart factory. Smart factories are interconnected, highly automated and intelligent. Information technology plays a vital role in interconnecting standalone automated systems so that they could communicate and transfer data between each other especially through the Internet [6].

In this work, a reference model for a smart factory, as shown in Figure 1, has been developed. The reference model consists of a principle solution and a prototype. On one hand, the principle solution describes a system model and how the system elements are interconnected. On the other hand, the prototype demonstrates the operation of the smart factory. Such a model is needed to enable an intuitive understanding of the concept of smart factory in the context of Industry 4.0.

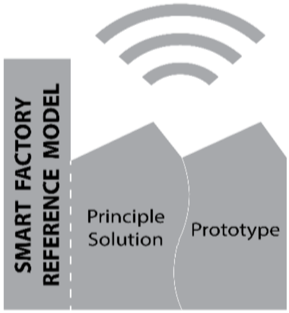


Figure 1: The smart factory reference model consists of (i) a principle solution describing the concept of a smart factory and (ii) a prototype demonstrating the operation of the smart factory.

Motivation

In contrast to the previous industrial revolutions which were defined after it took place, Industry 4.0 is being defined while it is taking place. Thus, the fundamentals, architecture and methodologies for Industry 4.0 are still emerging [7]–[9]. Although several solution providers are currently developing the solutions, high capital investment is often required [10]. In 2018, the national policy on Industry 4.0 was launched by the Prime Minister of Malaysia [11]. The government of Malaysia has announced to providing support to prepare Malaysia for the era of Industry 4.0. Government agencies have been tasked to enable the required infrastructure and ecosystem, funding and incentives, talent and human capital, technology and standards, and SMEs facilitation.

It is a challenge for training institutes, i.e. technical universities and TVET institutions in Malaysia, to train future workforces with the necessary skills and competency required in the era of Industry 4.0. Without a reference model, it is hard to evaluate the feasibility of a smart factory. It must come at a reasonable cost [12]. In most cases, high upfront investment is unaffordable by industries and training institutes in Malaysia. To supplement these developments, a reference model utilizing off the shelf components to evaluate the feasibility of a smart factory of Industry 4.0 and to train students and workers is desperately needed. One of the solutions is to upgrade or convert an existing system with Industry 4.0 elements. The challenges include the identification of the Industry 4.0 elements that can be integrated into an existing system and also how to interface these various devices and components, and connect it to the Internet.

Smart Factories in the era of Industry 4.0

Factories around the world are transforming and becoming smarter with the implementation of automation system throughout the factory. Components and devices on a production floor will be interconnected with one another [3]. It will also be connected to various other systems such as the facility management system and other departments such as logistics, and maintenance. In this manner, data could be exchanged between various systems and department making operations smoother and more efficient [13]. By connecting to the internet, production control and monitoring could be done outside of the factory compound [14].

Another criterion of a smart factory is the flexibility or modularity of the manufacturing system [7][14]. Manufacturers have to satisfy the target consumers group which would have different needs. While doing this, the price must still be competitive which is hard to be achieved with too many product variations [15]. Therefore a production line must be easily modified to suit the product that it will be manufacturing [2]. The product itself will be designed so that it could be modular, manufactured using common manufacturing processes and customizable. Parameters of the machine or the specification of the product are kept, for instance, in a radio-frequency identification (RFID) tag [7], or even in cloud storage. Therefore, if parameters of the machines or specification of products have to be changed, this could be done through the internet without reprogramming the controller. Smart factories are equipped with various sensors used to collect data that will be used for monitoring and analysis. Advanced sensors are installed throughout the whole production line in order for the machines to make certain decisions [16]. It also implements a decentralized control strategy in which each production station comes with its own controller.

Specification of Principle Solution

The principle solution is described using the specification technique CONSENS [17][18] or *CONceptual design Specification technique for the ENgineering of complex Systems.* Such a principle solution is illustrated in the upper part of Figure 2. It comprises six aspects of a smart factory, i.e., environment, application scenarios, requirements, functions, active structure and behaviour.

The lower part of Figure 2 exemplifies the active structure for a smart factory. It shows all the internal and external system elements of the smart factory as well as the interconnection between the system elements in terms of material flow, energy flow and information flow. The server hosts a database and a supervisory control and data acquisition (SCADA) software is used to create the user interface. This interface can be accessed locally or remotely. With this, the user does not necessarily need to be in the factory to interact with the system. The same interface is used not only by the production team but also by the other users, from the customer to the sales and maintenance personnel. A router is used as a gateway to the Internet. Each main element of the system and the server has its own static IP which is managed by the router. The system is mainly connected using an Ethernet connection using various protocols. In this production system, two energy sources are used which are electrical power and pneumatic power. Electrical power is used to power up all the electrical/electronic components and pneumatic power is used to actuate the pneumatic components.

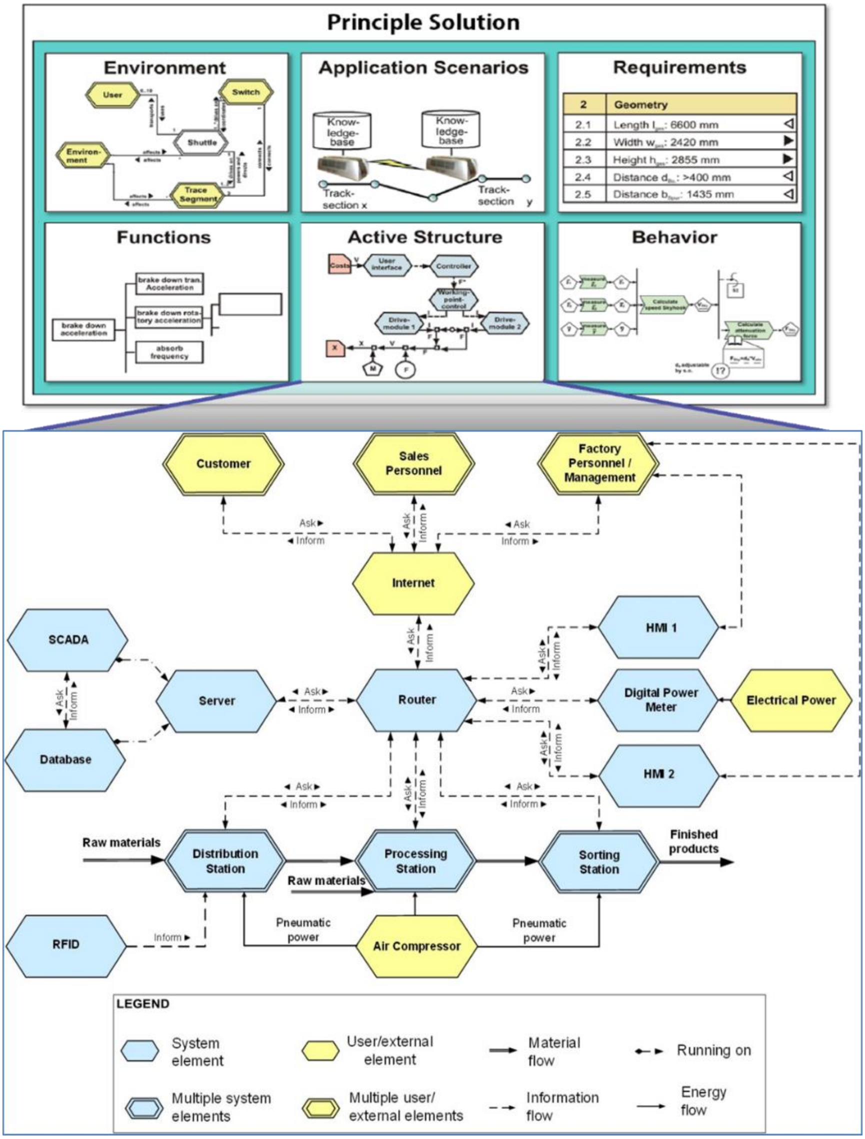


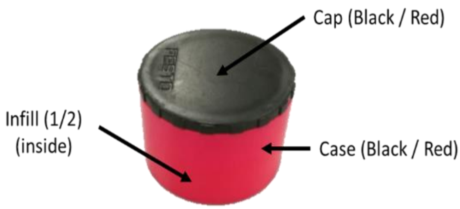
Figure 2: Cut-out from the active structure describes the system level architecture for a smart factory.

Development of Smart Factory Prototype

In this section, the product that will be manufactured as well as the hardware and software of the smart factory prototype are described.

Product description

In this prototype, eight variants of product could be manufactured using the same production line without reprogramming effort. The idea is to demonstrate the configuration of common product items to create a combination of choices according to the customer preferences. The product consists of three main elements, i.e., a cylinder case, an infill and a cap. Figure 3 describes the eight variants of the product that can be selected by the customers. Two colour options (black or red) are available for the case and the cap. Similarly, there are two different infills (I1 or I2) to be chosen. For the purpose of product variants identification, an RFID tag is attached at the bottom of the cylinder case.



Variants	Case	Cap	Infill
V1	Black	Black	I1
V2	Black	Black	I2
V3	Black	Red	I2
V4	Black	Red	I1
V5	Red	Red	I1
V6	Red	Red	I2
V7	Red	Black	I2
V8	Red	Black	I1

Figure 3: Configuration of the manufactured product.

Hardware development

A prototype has been developed to demonstrate the workability of the smart factory concept specified in the principle solution. The prototype was set up by upgrading an existing didactic trainer system. It composed of three production stations built based on a modular and decentralized production concept. Figure 4 shows the overall layout of the prototype. The RFID technology is used for the identification of a product [19]. The products are equipped with RFID tags that will be read by RFID readers on the station. Data are stored in the database running on the server. This database can be updated with orders coming from the customers via the internet. It can also be used for aftermarket services.

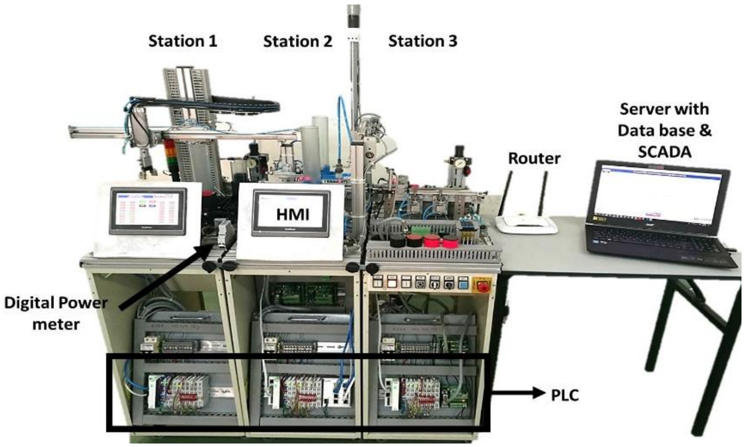


Figure 4: Prototype for an Industry 4.0-compliant smart factory.

The three production stations are controlled independently by three PC-based controllers. These three controllers are linked to a router through a network switch. Communication between the controllers and the router is established through an Ethernet connection. The router is connected to the Internet and a server is added to the network to host a database and SCADA software. The SCADA software acts as the backbone to interface various systems including linking the system to the database. The setup of the network is illustrated in Figure 5.

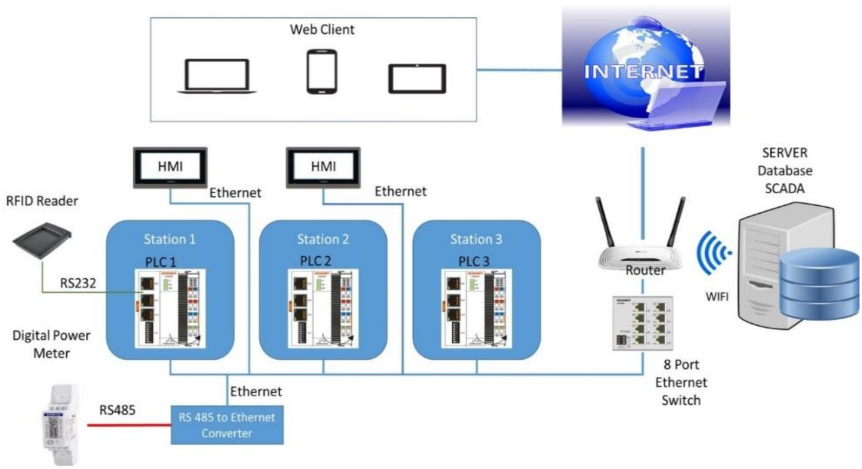


Figure 5: Overall network setup of the smart factory prototype

The first production station which is a “Distributing Module” and is responsible for separating different colour (black or red) of cylinder cases from the stack magazines. Then a pneumatic linear drive with a gripper arm is used to pick and place the cylinder cases. An RFID reader is installed in this station to identify a tag attached at the bottom of each cylinder case. The RFID reader is connected to the controller via the RS232 connection. Also, a touchscreen monitor that acts as Human Machine Interface (HMI) is connected to the station. The HMI is linked to the controller and thus enable the input/output components as well as the machine to be visualized.

The second production station is known as a “Processing Module” and is dedicated to the process of filling the case with infill I1 or I2 as well as putting the cap. Note that, in this prototype, the process of filling the infill is just represented by blowing air from two different nozzles. For the capping process, a gantry module powered by an electric linear drive is employed. The module picks the caps (black or red) from the cap dispensers by means of vacuum suction and place it on the cylinder case.

The third production station is a “Sorting Module”. It has the function to check and sort the good products from the rejected products. Optical sensors are used to identify the colour of the product and check whether the cap is on the cylinder case or not. The product is then transported by a conveyor belt to electro-pneumatic gates for sorting purposes. The products are sorted into two different slides (Slide 1 and Slide 2) according to the delivery regions. Another slide, Slide 3, is devoted to the rejected products.

Software development

The software development involves the programming of the controllers, development of the system interface and the configuration of the database. The controllers are programmed using several PLC languages, among others, the sequence function chart, structured text and ladder diagram. For this purpose, TwinCAT 2 is used. For the SCADA, Indusoft Webstudio 8.0 is used to create the user interface displaying various data on the screen, and to carry out a certain process. The SCADA software is developed to be able to handle multiple user roles, for example, a customer or an engineer. A customer can only access the system to order products or check the order status while an engineer could check the status of the entire production line. A HMI is used as a control panel and to visualize the input and output signals. The layout is programmed using PM Designer 2.0. In comparison to using physical control panels, the usage of graphical user interface offers greater flexibility as it allows the layout of the interface to be changed or added to accommodate future needs of the physical production line. Figure 6 shows one of the user interface pages. The system is linked to a database using SQL language.

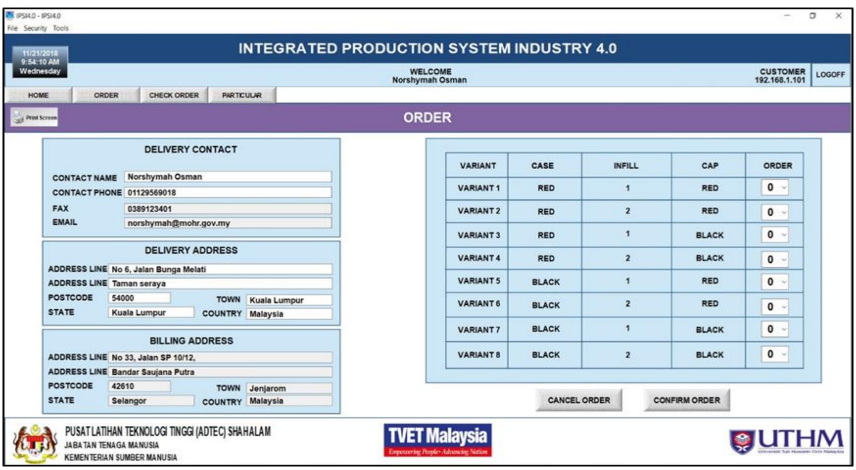


Figure 6: Ordering page of the Human-Machine Interface (HMI)

Operation Flow of the Production Line

Figure 7 shows an overall operation flowchart of the developed production line. The operation starts with an order placed by a customer. The customer selects the colour of the case, the infill as well as the cap. The order will be written in the database. The SCADA will check the database for new orders every two seconds. If there is an order, a request is automatically sent to the production line and the order is queued up for production. After the product is manufactured, it is then sorted according to the region of delivery. Throughout the production, customers could monitor the progress of the production. The production and maintenance team could also check if there are any errors or problems during the manufacturing process.

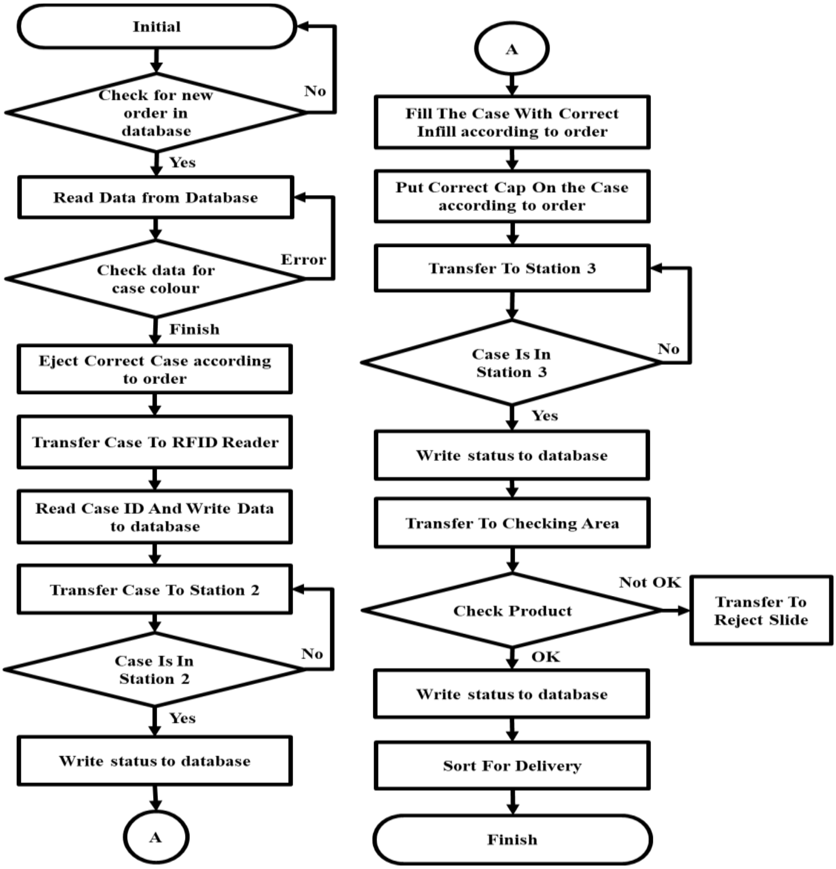


Figure 7: Overall operation flowchart.

The process starts at the Station 1. It is first initialized and wait for a request from the SCADA. If there is an order, the system will read the database that contains the order details. Then, the right coloured case is dispensed. An alarm is triggered if the stack magazine module is empty. Else, the case is picked up by a gripper and transports it to the RFID reader. After reading the RFID tag, the ID is written into the database. Then the case is transported to the next station. As the production line is running, the customers can check the status of the orders through the user interface. Engineers, on the other hand, can monitor the system such as monitoring the IO signals of the stations.

For the Station 2, after the initializing, it will wait for the cylinder case from Station 1. If a reject signal is received, the case is transferred directly to Station 3. Else, the station reads data from the database to determine the type of infill and colour of the cap. The case is then filled with the infill ordered by the customer. Subsequently, the station dispenses a cap accordingly. The gantry module picks up the cap and places it on the case. Note that, as long as the product is still not manufactured and the station has not read the data, the customer can still modify their order.

Lastly, Station 3 will first wait for the workpiece from Station 2. If a rejected signal is received, it will be transferred into the third slide or the reject slide. Otherwise, the product is transported to the checking point in which the product will be checked. The system checks the colour and whether a cap has been put on the case or not. Then it will sort the finished product into the respective slides.

Evaluation using the VDMA Industry 4.0 Toolbox

The smart factory prototype was developed using an existing didactic trainer system. After retrofitting and upgrade according to the principle solution, a smart factory prototype has been built. To evaluate the smart factory prototype, the VDMA Industry 4.0 Toolbox as shown in Figure 8 was used. This toolbox is used to determine the Industry 4.0 application level of a system [8]. Six aspects of the system were evaluated and each of the aspects is divided into five criteria level from level zero to level four. The prototype is evaluated against the criteria of each level to determine the level it has achieved. The arrows shows the improvements between one to three levels up in the specific aspects.

The first aspect is data processing in the production line. Acquisition and processing of data are one of the fundamentals of Industry 4.0. It starts with data acquisition until the analysis of data for an automated process planning and control. This prototype manage to achieve a level one. The system is connected to SCADA software used for data acquisition from various devices and is able to connect to a database to store and extract data. The system also has the capability to display and record the trend of certain parameters for analysis. For example, it is constantly monitoring the electrical parameters such as voltage and energy. This system only monitors and display the data and does not analyse the data it received. But then, the platform for data analysis is already provided. The acquired data can be analysed by developing an algorithm for the analysis function and program it into the devices. Previously, the system is not connected to any database and therefore rated at level zero.

The second aspect is the machine to machine communication (M2M). M2M communication is important for data exchange in an interconnected system. For this aspect, the prototype manages to obtain a level three. M2M communication can be done using field bus technology to reduce the wiring but thus involves data communication which the data need to be encoded and later decoded. A faster system is to use industrial Ethernet which is able to connect to more devices and can transfer a larger size of data. This system uses an Ethernet connection for most of its communication. All of the main components are connected to a gateway which has Internet access. Here, the SCADA software acts as the interface for remote access from the Internet hence this system achieved a level three. Previously, the system was rated at level one. Depending on the type of communication of the PLCs, it uses field bus communication for M2M communication.

The third aspect is the company-wide networking with production. This prototype managed to achieve a level two as it is not really implemented in a company. The prototype is connected to the main network. Various information exchange method can be used and can be set in the SCADA software. The system is able to be accessed by various users from various departments using the same interface. The SCADA software acts as the main interface for data exchange between various devices. Previously, the system was rated at level zero as it was not connected to any network.

The fourth aspect is the infrastructure of information and telecommunication technologies in production. This aspect focuses on the connectivity and exchange of data. This system managed to achieve level three. The prototype is connected to a central server which hosts a database. Various data such as users and orders details are stored on this server. It could also be accessed through the Internet. Customers can track their order through its user interface. Some data are exchanged automatically, for example, when the system has finished a process, it will update the status of the production on to the database on the server. Previously, the system was rated at level zero as there was no connection to any storage server or to the Internet.

The fifth aspect is the human-machine interface. Human must be able to give orders or to receive information or the status of production from a system. This prototype has managed to achieve level three. The user of this system could interact with the system locally using a touch screen HMI on-site or using the SCADA interface locally or remotely within the network or through the Internet. The SCADA software also provides a centralized monitoring and control interface. Previously, the system has only a local interface and was rated at level one.

The sixth aspect is the efficiency with small batches. Nowadays, the trend is leaning towards a more individual, customizable product that is produced in small batches, or even lot size one. This will lead to a more complex production process whilst maintaining an affordable price. The integration of ICT in the production system will help reduce errors in production and increase efficiency [20]. The prototype has managed to achieve level two. The product produced by this system uses a modular concept. It uses identical parts but the users could mix and match these identical parts into variants of their own. The products are still manufactured using the same production layout and process. Previously, the system was rated at level zero. It can only produce products in batches.

Conclusion

In order to understand and to embrace Industry 4.0, a reference model consisting of a principle solution and a working prototype has been developed to learn and teach this topic. The model showcases the capabilities of a smart factory in compliance with Industry 4.0. The prototype has been developed using off-the-shelf components including PC-based controllers and network components, thus making it available immediately at an affordable cost especially to training institutes. With this smart factory model, companies will be able to conduct a feasibility study and evaluate the concept of Industry 4.0. In addition, the academia can use this model to train the concept of Industry 4.0 and determine what are the skill sets and competency required for future engineers in the era of Industry 4.0 so that it could be adopted in the current curricula.

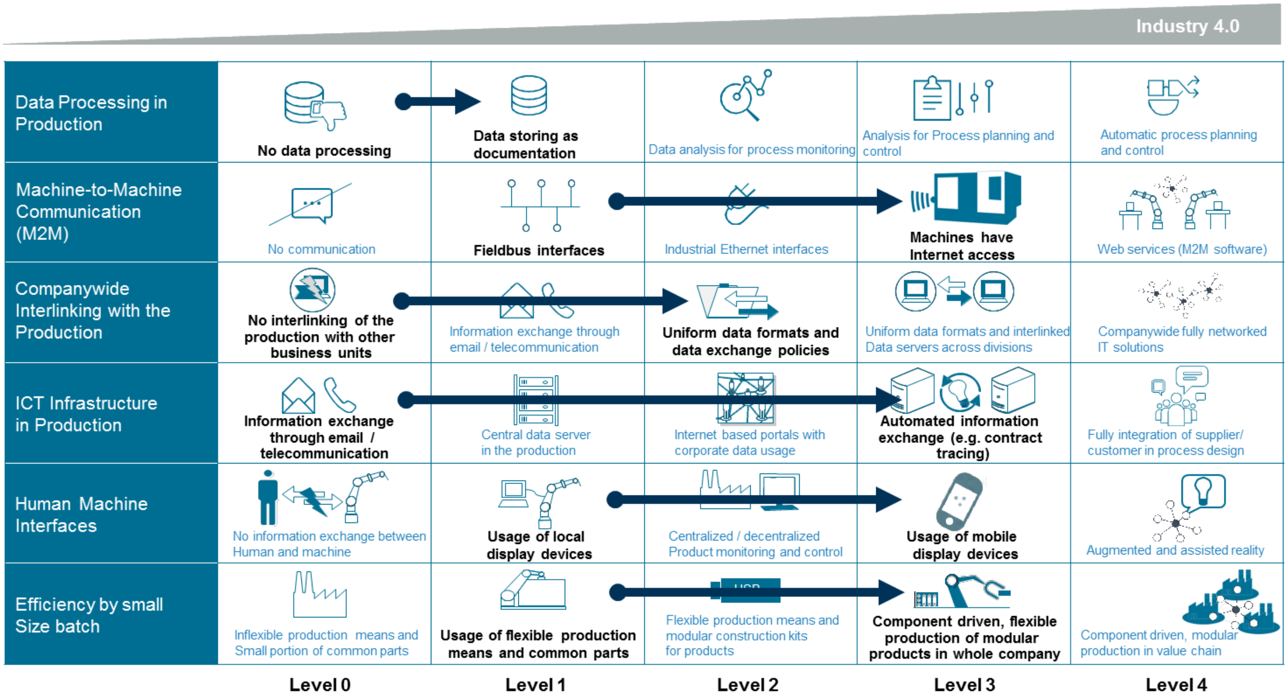


Figure 8: Evaluation for the six aspects of the VDMA Toolbox

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