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ORIGINAL ARTICLE

Challenges and Requirements for the Application of Industry 4.0: A Special Insight with the Usage of Cyber-Physical System

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Abstract Considered as a top priority of industrial development, Industry 4.0 (or Industrie 4.0 as the German version) has being highlighted as the pursuit of both academy and practice in companies. In this paper, based on the review of state of art and also the state of practice in different countries, shortcomings have been revealed as the lacking of applicable framework for the implementation of Industrie 4.0. Therefore, in order to shed some light on the knowledge of the details, a reference architecture is developed, where four perspectives namely manufacturing process, devices, software and engineering have been highlighted. Moreover, with a view on the importance of Cyber-Physical systems, the structure of Cyber-Physical System are established for the in-depth analysis. Further cases with the usage of Cyber-Physical System are also arranged, which attempts to provide some implications to match the theoretical findings together with the experience of companies. In general, results of this paper could be useful for the extending on the theoretical understanding of Industrie 4.0. Additionally, applied framework and prototypes based on the usage of Cyber-Physical Systems are also potential to help companies to design the layout of sensor nets, to achieve coordination and controlling of smart machines, to realize synchronous production with systematic structure, and to extend the usage of information and communication technologies to the maintenance scheduling.

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1 Introduction

Ever increasing global competitive pressure, shrinking product lifecycles and fast changing technologies are driving companies, towards networking to remain in competition [1]. Here, networking not only refers to the collaboration of companies within the supply chain, but more extents to the Internet of Things [2]. Ranges of such Internet of Things varies from robot, machine and workers within the workshop, to individual factories within the production system. Besides, all possible units cycled within the value chain are also supposed to be interconnected [3]. That means, boundaries among these objects would be weakened, where relative information can be collected and communicated autonomously for the intelligent support of decision maker. This is also the main scenario of Industrie 4.0. Here, Industrie 4.0 is defined as the trends for the increasing use of information and communication technologies for the autonomy within the manufacturing environment [4].

Since the first announce in 2011, Industrie 4.0 has become a top priority of current industrial development. Two perspectives of 'fascination' have been witnessed in the worldwide [3]. First, being aware of the importance of Industrie 4.0, many similar strategies have been launched in different countries. They are 'National strategic plan for advanced manufacturing' in the United States [5], 'The future of manufacturing: a new era of opportunity and challenge for the UK', 'Summary of the

White Paper on Manufacturing Industry' in Japan, 'Made in China 2025', and so on. Many relative funding programs and research initiatives have also been flourished under the support of government. This brings with the second perspective of fascination – the hot pursuit of academic researchers, where contributions related to the topics of Industrie 4.0 are prospered within a short time. Some attempts to describe on 'what is Industrie 4.0', where similar terminology, such as Internet of Things [1], Cyber-Physical System [6] and Smart factory [7], have been highlighted for the understanding on this special object. Considering the visions listed out by the key promoter Industrie 4.0 Working Group [7], there are also others who tried to design principles for the shape of Industrie 4.0 scenario in companies [3]. Additionally, exploration and introduction of enabling technologies (e.g., visual computing) are composed as another research stream [5]. All these help to establish a theoretical basis which aims to open the unexplored ex-post of Industrie 4.0. However, one major shortcoming can still be found: though it is widely researched, the common results on the researches of Industrie 4.0 are criticized to be too general to put into practice; or too detail to focus on one special industry and could not implicate to others [4]. A reference architecture with the detail perspectives of Industrie 4.0 is, therefore, highly required for its implementation in practice. Moreover, considering the idea that Cyber-Physical System is one of the key enabler for the realization of Industrie 4.0 [8], challenges for the application of Industrie 4.0 also emphasize on the solutions of Cyber-Physical System realization in companies. To cope with this, and with a vast study on the state of art in theory [1–4] and also state of practice in companies [5–7], a big gap can still be found between academy and practice. Therefore, in order to bridge channels between these two, experiences with applied cases are encouraged for the reveal and implication in industries.

Taken together, the purpose of this work is to provide an in-depth insight on the challenges and requirements for the application of Industrie 4.0. General work begins with the state of art. And based on the setup of a reference architecture, all relative enablers and perspectives are listed out for the interpretation and understanding of the item Industrie 4.0. Further work goes on with the establishment of Cyber-Physical System, which attempts to shed some light on the possible solutions for the implementation of Industrie 4.0. To close the gap between research and practice, some cases related to the application of Industrie 4.0 are further listed out for the demonstration.

2 Theories Related to the Application of Industrie 4.0

2.1 Key Enablers for the Application

Industrie 4.0 was first advanced as a forward-look project in the high-tech strategy of the German government. Then after, under the high demands of flexibility and responsiveness, and because of the intelligent capability of current technologies, Industrie 4.0 has further been trended as the pursuits of industrial environment. Based on the experiences of Industrie 4.0 Working Group, three key enables have been gathered for the implementation of Industrie 4.0 in companies. They are Internet of Thing (IoT), Cyber-Physical System and Smart Factory [7]. In general, these three are not independent, but overlapping with each other.

According to TECHOPEDI [9], IoT is considered as the scenario that all physical objects can be recognized and connected to surrounding objects and database. In industries, via the adopting of information communication technologies (e.g., RFID, sensors), IoT allows to embed the information of physical objects into virtual world, and in the end brings with the merging between real and virtual systems. Therefore, IoT is to somehow foundation for the construction of Cyber-Physical Systems. In other words, IoT is the technical infrastructure for the realization of Cyber-Physical Systems [10]. Based on the employment of IoT technologies, Cyber-Physical System can not only help to map physical systems to virtual world, but also apply on the back-loops from virtual digital system to the operation and controlling of physical processes. With the fusion on the integration between real and digital world [11], Cyber-Physical system helps to realize Smart Factories. Here, Smart Factory is considered as a major vision of Industrie 4.0. And according to Miragliotta, et al. [12] and Hopf, et al. [11], the main characteristics for the interpretation of 'smart' are:

- Integrated functions for identification, localization and diagnosis of internal parameters.
- Capability to detect on the physical data and measuring on the performance.
- Capability to process data for the determination on relevant information.
- Capability to interact with other smart objects and centralized information system.
- Standardization with uniform standards or protocols.
- Openness for accessibility.
- Multi-functionality for different applications.

Thus, via the interconnection of smart objects, Smart Factory enables companies with flexibility, efficiency and effectiveness. Besides, with the combining and interactions of these three enablers, the applications of Industrie 4.0 would be enhanced continuously. Under the scenarios of Industrie 4.0, companies are supposed to achieve the manufacture of “even one-off items” with profit [13]. The advantage of allowing “last minute changes” also enables the production of companies with more flexibility [13]. In addition, with the end-to-end transparency over the manufacturing process, Industrie 4.0 is also potential to facilitate optimized decision-making [13]. In general, there is no doubt about the possible benefits of Industrie 4.0. However, despite its attractiveness, still big challenges are existed for the realization of this strategic scenario. Further question arise on: ‘how to implement Industry 4.0’? To deal with this, a derivative question that should be clearly understood is: ‘which perspectives should be taken into account, so as to help to realize Industrie 4.0 with more detail’. Thus, in the following stages, tasks of the study will be moved from the macro understanding to the implementation aspect of the object.

2.2 Reference Architecture of Industrie 4.0

Considering as a revolution, the concept Industrie 4.0 is criticized to be “lack of knowledge of the details” [14], especially when it comes to the detail applications of this industrial strategy. With this in mind, and in order to support to execute Industrie 4.0 in companies, a reference architecture has been established as in Figure 1.

As illustrated in Figure 1, four major perspectives have been emphasized for the execution of Industrie 4.0. They are issues related to the manufacturing process, devices, software and engineering. With the employment of IoT technologies, all ***possible processing and transport functions of the manufacturing process*** would be mapped and recorded as in the virtual information system with real time. Moreover, ***devices*** within the manufacturing system would be considered as ‘Things’ or ‘objects’. These include *(smart) automation devices, field devices, fieldbuses, programmable logic controllers, operating devices, mobile devices, servers, workstations, web access devices* and so on. Relative embedded technologies will also be used to merge these physical devices with virtual systems. And the conditions of the physical devices would be recorded automatically to the information system. The software perspective emphasizes on the ***software realization*** for the *interfaces and integration among items from the physical-, cyber- and automation-levels.* Possible existing software includes business management software, production management software, control and regulation software and so on. And the application of these software not only brings with interactions among “Things”, but also enables users to achieve planning, organizing, coordination and controlling of “Things”. The perspective of ***engineering*** in the manufacturing system *is more related on the Production Lifecycle Management*. With the using of data derived from the manufacturing process, analyze to plan the necessary resources in terms of both machinery and human resource. And the tasks of resource allocation include issues related to production design and development, production planning, production engineering, production, and services.

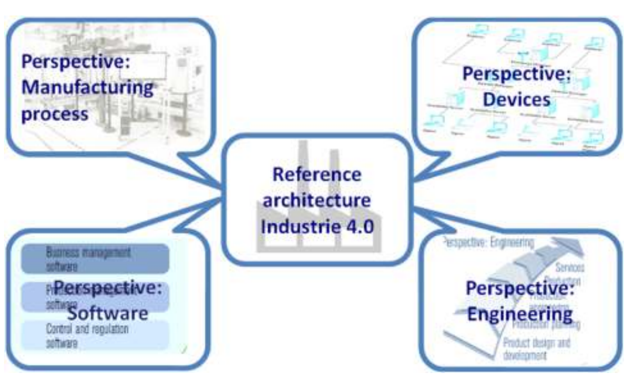

Figure 1 A reference architecture of Industrie 4.0

In general, these four perspectives work together as in a reference architecture, which helps to detail the application of Industrie 4.0 into the implementation level. And the former two focus on the mapping and merging between real and virtual systems, while the late highlight on the fusion and application based on the integration of these two systems. Thus, considering the usage of IoT technologies as the foundation, further challenge for the implementation of Industrie 4.0 lies on the issue “how to realize fusion for the autonomous decision”. Here, the application of Cyber-Physical Systems was suggested as one of the most efficient channels [3].

2.3 Structure of Cyber-Physical System

Cyber-Physical Production System refers to “physical and virtual, local and global, horizontally and vertically networked systems, dynamic system boundaries, partial or complete autonomy, active real-time control, cooperation and comprehensive cooperation between human and system” [14]. It comprises smart machines, warehousing systems and production facilities that have been developed digitally and feature end-to-end Information Communication Technology-based integration, from inbound logistics to production, marketing, outbound logistics and service. Based on the Final report of the Industrie 4.0 Working Group [7], general structure of Cyber-Physical System has been gathered as in Figure 2.

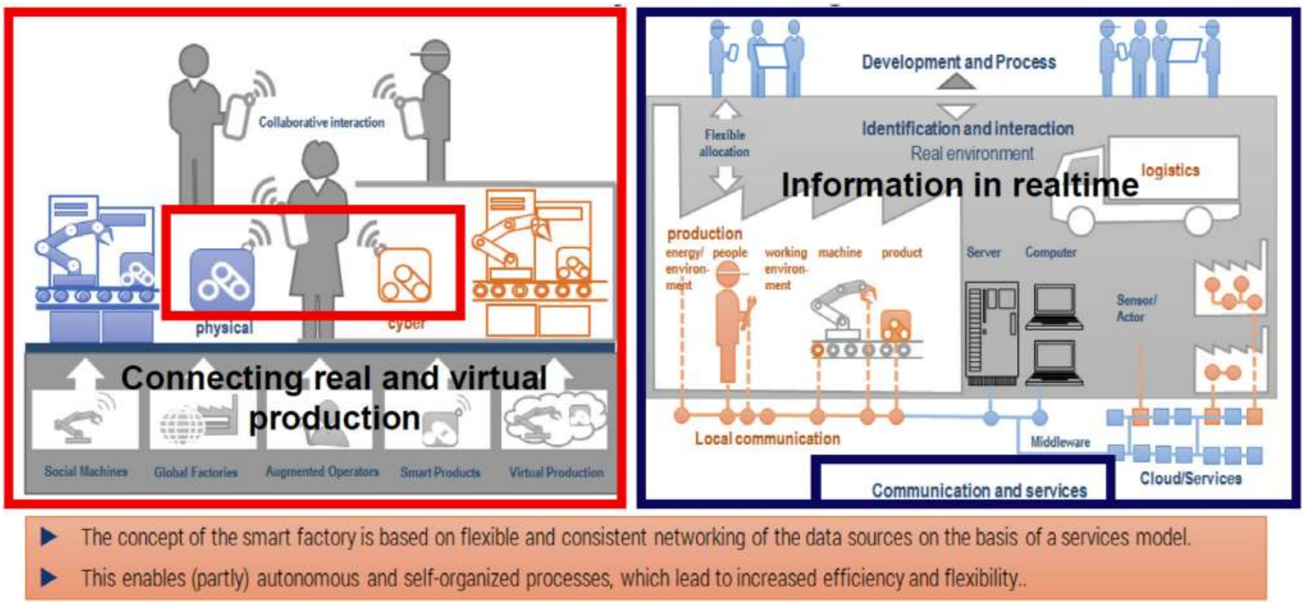

Figure 2 General structure of Cyber-Physical System [7]

As illustrated in Figure 2, the basic logic for the establishment of Cyber-Physical System is the connecting of real and virtual production. It is developed based on the establishment of virtual system with real time information (shown as in the left side of Figure 2), and goes beyond the scope of IoT. In others words, Cyber-Physical System is the sublimation for the application of IoT. General focus for the usage of Cyber-Physical System lies not only on the gathering of real time data from the physical environment to the digital system, but more on the structure analysis of data sources for (partly) autonomous and self-organized processes. Thus, the back-loops of virtual information system to the operation and controlling of physical processes is considered as the spirit of Cyber-Physical Systems. And with the establishment of Cyber-Physical Systems, Smart Factory is enabled to be possible in companies. Here, Smart Factory "constitutes - key features of Industrie 4.0" [7]. And under the Smart Factories, "in addition to condition monitoring and fault diagnosis, components and systems are able to gain self-awareness and self-productiveness, which will provide management with more insight on the status of the factory. Furthermore, peer-to-peer comparison and fusion of health information from various components provides a precise health prediction in component and system levels and force factory management to trigger required maintenance at the best possible time to reach just-in time maintenance and gain near zero downtime" [15]. Taken together, it is of great importance for the realization of Industrie 4.0 in companies. And in order to provide an in-depth insight on the possible solutions on the application of Industrie 4.0, experiences with applied cases will be worked out as in the following stages.

3 Cases for the Application of Cyber-Physical Systems

3.1 Self-sustaining Intelligent Sensor Nets for Production

In a production system, sensor technique plays an important role for the operation of IoT and Cyber-Physical Systems. A sensor is "a mechanical device sensitive to light, temperature, radiation level, or the like, that transmits a signal to a measuring or control instrument" [16]. It is a useful device that converts information from physical world into data in cyber system [17]. However, concerning the application of sensor, general problem arises on 'how to interlink these information islands efficiently'. With this in mind, the project 'Self-sustaining intelligent sensor nets for production (AiS)' has been carried out in the *Technische Universität Chemnitz, Germany*. In this project, together with another three universities, we dealt with the issues on 'how to design the sensor nets', 'how to realize sensor communication' and 'how to achieve self-sustaining of the intelligent sensor nets'. General aim of this project is to integrate a sensor nets into the production environment, and realize energy efficient and reliable sensor communication. All these are based on the utilization of Experimental and Digital Factory (EDF) in the *Technische Universität Chemnitz*. Here, EDF is well known as a

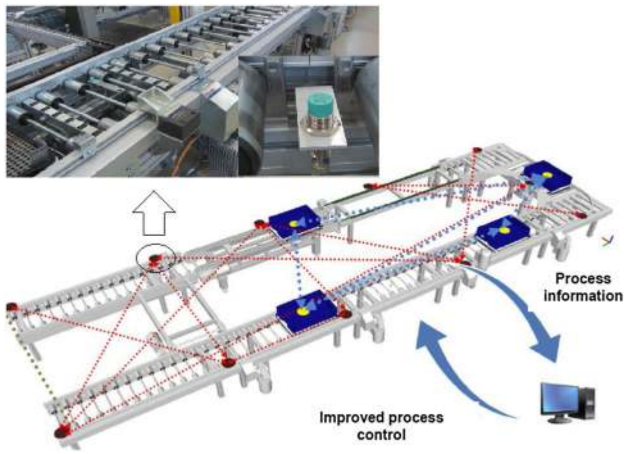

Figure 3 Self-sustaining intelligent sensor nets [19]

representation of a "complete mini-factory" with all the essential processing and logistic components. The overall goal of EDF is to implement symbiosis between virtual and real factory [18]. As the laboratory environment within EDF represents current state of technology in reality, it enables the application of innovative technologies and/or concepts within the companies with a reality-inspired means. In general, basic logic for the designing of the intelligent sensor nets is worked out as in Figure 3.

From Figure 3, we see the basic foundation for the establishment of sensor nets is to gather and transfer the real time information from the manufacturing system to computers; and with the network algorithms in cyber systems, the improved instructions will be transferred back to the physical system, so as to realize better controlling of the process. In this applied project, acoustic sensors have been used for the abrasion detection of the logistic devices. Based on the monitoring of the real conditions, optimal maintenance periods would also been obtained and forwarded to the physical system via sensor nets. Another innovative design of this system is 'self-sustaining'. That is, to provide reliable ambient energy supply for singular sensor knots and realize wireless energy transmission to moving objects. Taking as a whole, results of this project not only help to in-depth the theory on 'how to construct the sensor nets', but also work as the bridge to combine sensor theory to the intelligent application in industries. In fact, this well-validated intelligent sensor nets have already been used successfully in a famous automobile company in Saxony, Germany.

3.2 Virtual Space for the Controlling of Double-arm Robot

In a Cyber-Physical System, smart machines work together for the realization of common targets. And the coordination and controlling of these machines is one of the keys to bring about 'smart'. In this work, the controlling of the

Figure 4 Double-armed robot within the EDF

doubt-arm robot has been taken as an example (seen as in Figure 4). This is based on the results of an applied project carried out for one of the biggest automobile company in Germany. In this case, double-arm robot is programmed for the material distribution in the assembly line, and the target of the arrangement here is: 1) self-recognize of the roller providing line. That is, these over 20 kg material boxes are transferred by the roller line to the double-armed robot (seen in Figure 5). And when there are only two boxes left, the sensor located by the roller line can recognize this and will give the information to stop the further picking up activities of the robot. 2) Self-control of the movement. For the distribution of the material boxes to different rows, the double-arm robot can move like a human being. Its arms will not move with the shortest path, but with the continuous way. As a result, the general time needed for the material distribution would be the shortest. Moreover, with the help of sensors surrounding the shelf (marked as green), robot can "see" if the shelf is full or not. When it is full, robot can stop the distribution activities itself. 3) Safety control of the operating space. This is based on the utilization of the so-called technique 'safety-eye' (shown as in Figure 6). From Figure 6, we can see a virtual space has been defined as in red. And the function of the virtual space is to monitor the environment and keep safe during the operation of the robot. In other words, when these is someone or other machines (e.g., automated guided

Figure 5 Double-armed robot with virtual space

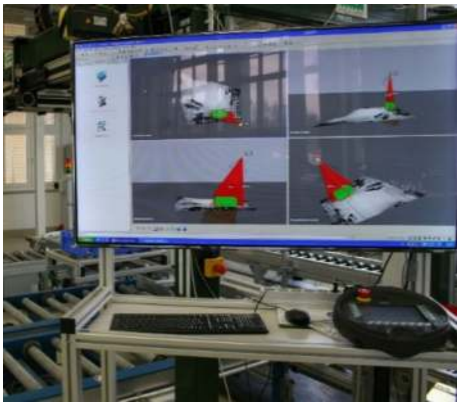

Figure 6 Function of safety eye

vehicle) disturb to the red virtual space as shown in Figure 4, the system can recognize the risk and the movement of the robot will be stopped. At the same time, a special sound will be heard to remind the operator. When the risk is removed, the operator can reset the system and the movement of the robot will be start again. In general, the application of sensors and the setup of the virtual space would be efficient to bring 'smart' to the operation of the double-arm robot. And the principle of this function can also be used in other industrial environment.

3.3 Synchronous Production through Semi-autonomous Planning and Human-centered Decision Support

One of the biggest challenges for the application of Cyber-Physical systems, is the "real-time" link of physical production and digital factory. Besides, with a view to different information technology systems existing in companies, how to merge all these relevant data from different systems to the implementation of Cyber-Physical systems arises as another problem. With these in mind, a synchronous production model has been developed based on the carry out of the project "synchronous production through semi-autonomous planning and human-centered decision support (SOPHIE)" (seen as in Figure 7).

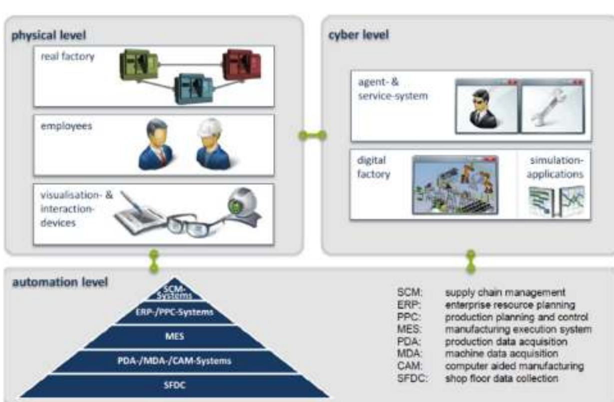

Figure 7 Synchronous production model [20]

As shown in Figure 7, three levels of objects have been constructed for the implementation of synchronous production. They are physical level (*including real factory, employees, visualization and interaction devices,* etc.), cyber level (*including agent-service system, digital factory, simulation applications and so on*) and automation level. Via the description and modeling of objects within the production system, digital factory would be mapped to the cyber level. In addition, automation level with the existing but developed information systems, plays as a foundation and mediated role for the application of Cyber-Physical systems. Here, within the automation level, all the involved systems would be gathered and sorted as in a pyramid manner. Therefore, with the help of these structured information systems, dynamics of the physical objects can be reflected real time to the automation systems. Moreover, the changes of data within the automation systems will automatically be adapted to the digital systems. In the digital system, the status of planned and actual process can be compared via the usage of virtual technologies. Safeguard operational decisions will also be provided based on the valid and continuously update simulation model. Taken together, with the development of the synchronous production model, the real-time link between physical production and the digital factory becomes possible, and the general logic of this model can also be transferred to different industries.

3.4 Resource-cockpit for Socio-Cyber-Physical Systems

Considering the scopes of general value-added chain, the applications of cyber-physical systems can also be extent to the maintenance issue, as the scheduling of maintenance activities plays an important role for the availability and reliability of production facilities [11]. Maintenance is defined as "the combination of all technical, administrative and managerial actions during the life cycle of an item intended to retain it in, or restore it to, a state in which it can perform the required function" [21]. For the planning of maintenance, information from different sections of the production system should be taken into account. They are not only concerning to the real-time monitoring conditions of machines, but also to the scheduling of staffs, availability of other resources and so on. With existing but developed IoT technologies (e.g., sensor, RFID), facilities are equipped to be smart [10]. However, considering the dynamics of all those involved objects, challenges for the realization of smart maintenance lies on the on-time integration of all relative information. It is not just "marginal"

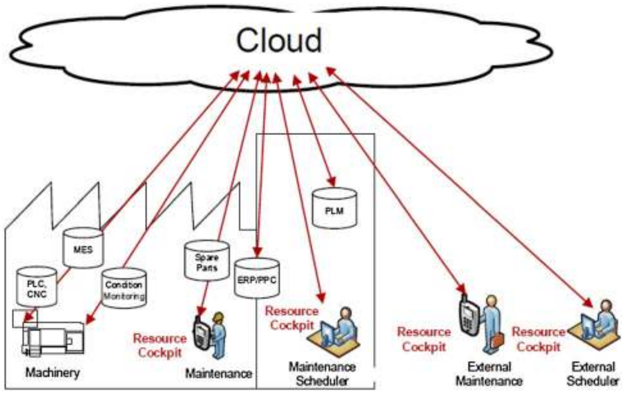

Figure 8 Scenario for the usage of resource cockpit [11, 22]

involving of decentralized data in the digital system [11], but unifying and structuring of these real-time information for the general arrangement. With this in mind, a project called "Resource-cockpit for Socio-Cyber-Physical Systems (S-CPS)" has been funded by the German Federal Ministry of Education and Research (BMBF). And the target of the project is to realize flexible integration of heterogeneous master and dynamic data. Moreover, with the combination of "socio" perspective, interaction and collaboration between human and smart objects would be focused. As a result, mobile support for internal and external maintenance personnel would be realized, so as to improve efficiency and flexibility for the on-site and off-site maintenance [11].

Based on the systematic modeling and optimization of maintenance processes, all kinds of information related to the product and production resources would be merged as in a resource cockpit (seen as in Figure 8). As the output, the cockpit will create lists of tasks, where different roles of users will be adapted [11]. Contents of the lists include not only detail tasks, but also necessary resources required, resource availability, competence required, machines states and relative schedule. Thus, with the usage of resource cockpit, efficiency and efficacy would be enhanced considering the management of the maintenance activities. General concept of this project can also be adapted and further extent to the coordination and controlling of other stages of value-added chain.

4 Conclusions and Discussions

Considered as a top priority of industrial development, Industrie 4.0 has being highlighted as the pursuit of both academic and practical sides. In this paper, based on the review of state of art and also the state of practice in different countries, shortcomings have been revealed as the lacking of applicable framework for the implementation of Industrie 4.0. Therefore, in order to shed some light on the "knowledge of the details" [14], a reference architecture has been developed, where four perspectives have been highlighted for the consideration. They are issues related to the manufacturing process, devices, software and engineering. Moreover, with a view on the importance of Cyber-Physical systems, the structure of Cyber-Physical System has been established for the in-depth analysis. Further cases with the usage of Cyber-Physical System have also been arranged, which attempts to provide some implications to match the theoretical findings together with the experience of companies. In general, results of this paper would be useful for the extending on the theoretical understanding of Industrie 4.0. Additionally, applied framework and prototypes based on the usage of Cyber-Physical Systems are also potential to help companies to design the layout of sensor nets, to achieve coordination and controlling of smart machines, to realize synchronous production with systematic structure, and to extend the usage of information and communication technologies to the maintenance processes. Similar principles concluded based on these applied cases can also be used to other industrial environment or other stages of the value-added chain. Therefore, this study would also be helpful to bridge the gap between theory and application.

In this work, the construction and operation of Cyber-Physical Systems is considered as one of the biggest challenges of Industrie 4.0 application. However, when considering as a whole, general challenges for the realization of Industrie 4.0 in the industrial environment also involve IT security issues. Detail technologies (including real-time tracking, mobile devices, human-machine collaboration, human-robot collaboration, smart digital models, distributed sensor networks and competence development) compose as another trends of further research. These are also what we will do within the laboratory "Work world 4.0" in the following steps. In order to apply Industrie 4.0 in the worldwide, horizontal and vertical collaborations should be encouraged, researches related to the development of suitable collaboration mechanism for national and international collaborations would also be a trends of study in the further.

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