Enabling Smart Workplaces by Implementing an Adaptive Software Framework

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Abstract. Today's requirements and challenges on production systems have led to an increasing importance of flexible assembly processes. At the same time, arising technologies in the context of Industry 4.0 offer the opportunity to tap previously unknown potentials. These provide both opportunities and risks for the most flexible and important resource in the production: the workers. Within the EU research project A4BLUE, Smart Workplaces are developed in order to raise productivity and quality, while sustaining and enhancing worker satisfaction. Enabled through both a software framework for adaptation management and contextual worker assistance as well as hardware solutions (e.g. automation mechanisms such as smart tools or co-operative robots) for physical support, the workplaces adapt to the workers' specific characteristics considering both process and environmental variability. The presented research work provides an overview about the Frameworks' software components and the application to a use case at the RWTH Aachen University.

Keywords: Smart Manufacturing · Smart Workplaces · Smart assembly · Worker assistance · Adaptive Automation · Software reference architecture

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1 Introduction

In course of advancing and gradually establishing Industry 4.0 technologies, nearly every industrial sector is affected or being transformed somehow. Those technologies such as Virtual Reality (VR), Augmented Reality (AR) or Collaborative Robots, can be both enablers and catalysts for the transformation towards Smart Manufacturing. Smart Manufacturing can provide a company's crucial competitive edge by shortening times for production, implementation and information processing, thus allowing faster reactions to continuously changing markets [1].

Nevertheless, the conversion to Smart Manufacturing leads to a certain amount of investment costs. In order to optimize efficiency in the manufacturing ecosystem, it is crucial that all resources are used to their full potential. This is particularly significant on the shop floor level, where humans directly interact with automated systems. Consequently, Smart Workplaces – the shop floor level subdivision of Smart Manufacturing – need to ensure the accurate application of the individual strengths of both humans and automation mechanisms.

Collaboration of humans and robots for example allows the usage of the precision, the ability of repeatability as well as the physical strength of robots combined with the humans' flexibility and capability to react to unpredictable changes. Therefore, Smart Workplaces do not primarily aim either to replace the shop floor workers (blue collar workers) with automated systems or to monitor and control the workers. Instead, the purpose of Smart Workplaces is to enable a more efficient use of the workers' strengths by assisting them with the targeted use of hardware support and real-time data processing. This will enhance the process of physical task execution with an increasing part of coordinating tasks and distributed decision making [2].

To enable Smart Workplaces, real time collection, analysis and distribution of digital information between and within the manufacturing ecosystem are required [1]. With a digital image of the production processes, adaptation measures can be executed automatically, information can be displayed to the workers and the current process efficiency can be evaluated. To manage the large amount of data generated on the shop floor, the use of key performance indicators (KPIs) could be an appropriate approach [3]. KPIs, such as process time or rework rate, are used by automated systems and can be either directly displayed to the worker or indirectly as recommendations or notifications after further analysis.

In any case, it has to be ensured that these KPIs are available in an appropriate level of detail depending on the respective addressee. This means, the workers need to be provided with the required information at the right time. Furthermore, the visualization has to be configured individually with regard to the workers' preferences and experience [4]. By doing so, experienced workers are provided with different types and information details than less experienced ones.

In a Smart Workplace, the workers are given the opportunity to check work performance by receiving individual feedback on tasks and potential errors. Having the feeling of being an irreplaceable resource in the manufacturing ecosystem and provided with the possibility of a high self-reliance degree, the workers are motivated to achieve a continuous improvement of themselves as well as of the processes [5]. It is assumed, that having committed shop floor workers, improvement in business KPIs, such as productivity or quality, will take place.

Physical world and virtual world need to be connected to enable a Smart Workplace. Therefore, a digital infrastructure for the processing and provision of data is needed, which is aligned to worker support. For those reasons, dedicated information and communication technology tools and methodologies have been developed within the EU research project A4BLUE (Adaptive Automation in Assembly For BLUE collar workers satisfaction in Evolvable context), realizing the so called A4BLUE Adaptive Framework.

2 Software Framework for Adaptive Assembly

The A4BLUE Adaptive Framework provides an open, secure, configurable, scalable and interoperable adaptation management and assistance toolkit. This allows to adjust workplace characteristics according to context information, such as dynamic production processes, environment changes and varying workers' characteristics. The Framework's concept includes elements of three existing Industry 4.0 reference architectures: Reference Architectural Model Industrie 4.0 (RAMI 4.0) [6], Industrial Internet Reference Architecture (IIRA) [7] and FIWARE Smart Industry Reference Architecture [8].

The main principles of the Framework's design are integration, virtualization, adaptation management, context aware worker assistance and monitoring. Three high-level functional domains (Shop Floor, Enterprise and Business) group those principles into a logical three-fold breakdown structure containing different components as outlined in Fig. 1.

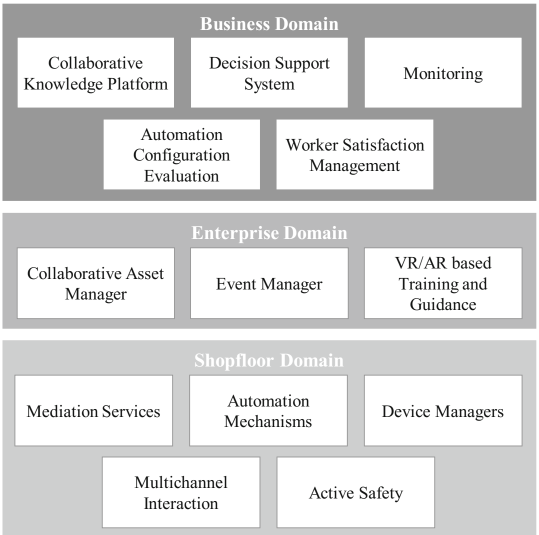

Fig. 1. Domains and components of the A4BLUE Adaptive Framework

The domains define a coarse mapping of system elements either to the factory – Shop Floor Domain - or to the broader field of corporate IT - Enterprise or Business Domain. This structure empowers the direct connection of cyber-physical systems with humans in the different areas of the production ecosystem.

The Shop Floor Domain is the bottom layer of the Framework and populated by any kind of device that is connected to the physical world on one side and to the virtual world on the other. Therefore, this domain includes functionalities supporting automated control and adaptation of physical production processes as well as the main human-machine interactions. The domain consists of the software components shortly described in Table 1.

Table 1. Components of the Shop Floor Domain

Shop Floor Domain	
Mediation Services	The Mediation Services enable the integration of existing enterprise level legacy systems (e.g. Manufacturing Execution Systems) into the Framework
Automation Mechanisms	The Automation Mechanisms component includes physical automation technology such Collaborative Robots or Smart Tools
Device Managers	The Device Managers support a plug and produce approach by enabling discovery and integration of external automation mechanisms using existing and common standards (i.e. OPC UA)
Multichannel Interaction	The Multichannel Interaction component enables the workers to interact with the automation mechanisms in an intuitive way through verbal (e.g. voice commands or natural speaking) and non-verbal (e.g. gestures) channels, as well as to receive appropriate feedback through visual (e.g. graphical user interfaces, lights) or auditory (e.g. voice messages, sounds) channels
Active Safety	The Active Safety component adapts the behavior of automation mechanisms considering the workers activity

The Enterprise Domain is the middle layer and represents the core part of the A4BLUE Adaptive Framework. To this end, this domain consists of several components in charge of managing the logic for adaptation management and the provision of assistance services using an Event Driven Architecture. The domain consists of the software components briefly described in Table 2.

Table 2. Components of the Enterprise Domain

Enterprise Domain	
Collaborative Asset Manager	The Collaborative Asset Manager provides virtualization capabilities by managing the semantic virtual asset model as a knowledge base of the ecosystem. It includes reasoning capabilities and contains static representations of both tangible assets (physical assets) and intangible assets (non-physical assets) as well as dynamic context representations
Event Manager	The Event Manager continuously captures and analyzes relevant events from the shop floor as well as the legacy system. It reacts to an event, by triggering the required adaptation or assistance actions or by enabling the information flow among the different components of the Framework
VR/AR Based Training and Guidance	The Virtual and Augmented Reality component provides off- and on- the job training and guidance for the operator. Furthermore, VR/AR interaction devices allow capturing events and data, which are used for real-time context aware reasoning in collaboration with other components of the Framework

The A4BLUE Business Domain is the upper layer, in charge of supporting the strategic decision-making process by targeting both, blue and white-collar workers. All components in this domain aim to extract and take benefits from the information basis of the production's running automation and adaptation processes. The domain consists of the software components shortly described in Table 3.

Table 3. Components of the Business Domain

Business Domain	
Collaborative Knowledge Platform	The Collaborative Knowledge Platform transfers knowledge, especially implicit and informal knowledge, from skilled to less experienced workers as well as to various departments of an organization
Decision Support System	The Decision Support System supports operators on relevant decisions (e.g. for assembly, maintenance or inspection operations) by providing insights on processed data
Monitoring	The Monitoring component enables the collection and calculation of KPIs for the assessment of production processes and performances
Automation Configuration Evaluation	The Automation Configuration Evaluation component allows the assessment of different levels of automation from a socio-technical as well as from an economical perspective to identify the most efficient Level of Automation
Worker Satisfaction Measurement	The Worker Satisfaction Measurement component assesses the workers satisfaction quantitatively in relation to human-automation systems and work environment characteristics

As outlined in the component's descriptions, every component is designed to serve a specific purpose, which differs from each other significantly. Some components enable the connection of the A4BLUE Adaptive Framework to the existing software and hardware infrastructure as well as the seamless connection of new equipment. Others are designed to manage processes and derive knowledge from information exchanged within the Framework. Finally, the actual analysis of data and information is performed to support several decision making processes.

Therefore, some of the components are operating in the background most of the time, invisible for the end user, or are seldom used for general configuration activities such as the integration of new automation mechanisms. Others have a perpetual interface to the end user for the continuous processing of input and output data in order to enable the direct worker support at the workplace.

3 Adaptive Framework Application to an Assembly Use Case

In order to test and evaluate the hardware and the software developments, two industrial as well as two laboratory use cases were set up within the A4BLUE project. The use cases' purpose is to validate the technical feasibility and functionality as well as to obtain objective feedback on the socio economic impact of the A4BLUE solutions.

One of these use cases is set in the Ramp-Up Factory of RWTH Aachen University, which has been developed in cooperation with shop floor experts of the factory. Within this use case the assembly processes of a rear light and a brake module of an electric vehicle are performed in a representative working environment. Both processes are conducted by a shop floor worker, while organizational, quality and steering operations are undertaken by a production supervisor. For the use case implementation a set of components of the A4BLUE Adaptive Framework has been selected with regard to process and production side framework conditions. Within this chapter only an extract of the overall use case is described. It provides the current status of the concept, while the technical implementation is still in progress. The entire implementation includes additional components and hardware solutions such as the Automation Configuration Evaluation or an autonomous tool trolley.

3.1 Main Components of the Adaptive Framework Applied to the Use Case

To empower the Smart Workplace within the use case, data needs to be processed according to the three steps of the data value chain: data collection, data interpretation and visualization [9].

Subsequently only those components, that interact directly or indirectly in regular operation with the shop floor worker as well as with the production supervisor are described in detail. Nevertheless, further components of the Framework such as the Event Manager or the Collaborative Asset Manager are mandatory to assure the workplaces adaptability capabilities. Within the use case three components are mainly necessary for the interaction among workplace and workers. These components are VR/AR based Training and Guidance, Monitoring and Decision Support System (DSS).

The first step (data collection) is realized with the VR/AR based Training and Guidance component. To connect this component to the physical world, the worker wears Augmented Reality glasses (Microsoft® HoloLens™). Via the device, it is possible to collect data and information from the assembly process by triggering certain actions that are proceeded as events. A back-end server application acts as a bridge between the device and the A4BLUE Adaptive Framework, where the Event Manager and the Collaborative Asset Manager provide the capabilities to exchange and process data. With this link, data (e.g. 3D-models, assembly instruction or statistics) are made available dynamically and contextually to the worker. Additionally, actions triggered by the worker (e.g. gestures or voice commands) or by external impulses (e.g. markers or a task completion event from a given work order) are captured and sent back to the Framework for further elaboration. The front-end modules are outlined in Fig. 2.

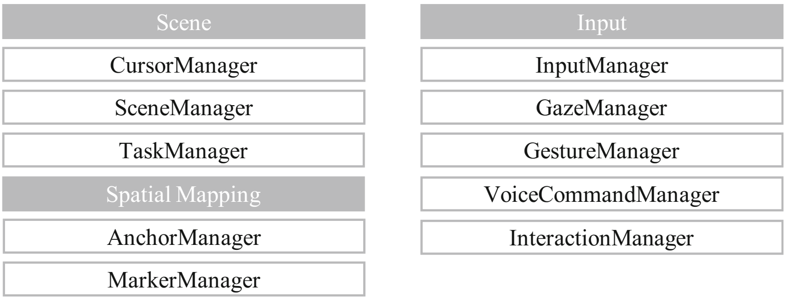

Fig. 2. Categories and modules of the front-end application

The modules are classified according to the categories Scene, Input and Spatial Mapping. Modules within Scene enable the static and dynamic visualizations of all necessary objects to create the virtual elements. The category Input contains modules for the capture, the interpretation and the management of actions via different channels. The modules of Spatial Mapping ensure correct position and size of virtual objects as well as the processing of external impulses with markers. Table 4 provides an overview of the modules.

The Monitoring and the DSS component are implemented within the second step of the data value chain (data interpretation), on basis of the Open Source Knowage Suite[1]. The purpose of the Monitoring component is to make processes and information from the production ecosystem understandable and manageable. Within this component, KPIs are calculated by using data from the production processes managed within the Framework in order create a concise representation of certain parts of the ecosystem. For example, if the worker classifies a part as scrap, further information about the quality issue can be captured with the device. This way the bare identification is enriched with additional contextual information to foster the understanding of decision makers to be alerted.

[1] https://www.knowage-suite.com/.

Table 4. Modules of the front-end application

Scene	
CursorManager	Handles cursor type and position in a scene. The cursor can be visualized in different forms for different interaction states
SceneManager	Manages consistency check, loading and unloading of all 3D objects in a scene
TaskManager	Evaluates user operations against a given work order (or task list)
Input	
InputManager	Collects all input actions (gaze, gesture, voice commands) and raises events/callbacks
GazeManager	Raycasts the 3D scene at the position the user is looking at and triggers events when capturing interactive objects
GestureManager	Adapter that interprets and translates a subset of gestures as input events
VoiceCommand Manager	Adapter for interpretation and translation of a subset of voice commands in input events
Interaction Manager	Guides the camera by using head tracking, manages the animation timing of interactive objects and translates input actions in possible events and commands
Spatial Mapping	
AnchorManager	Retrieves, clears and stores anchors (the location of physical objects in the real world) locally on the device, linking and updating an associated real transformation matrix on the scene graph
MarkerManager	Recognizes an AR marker (e.g. QR-code) in the scene, triggers an event when the marker is on line of sight and identifies if the marker is a new one or already registered

KPIs calculated in the Monitoring module are used for further analytic steps by being stored in the A4BLUE Adaptive Framework and processed by the DSS component, which is shown in Fig. 3. Input for the DSS are both historical production data and events having their root cause in the use cases assembly ecosystem. Data and information are displayed to the production supervisor through a web-based graphical user interface allowing the user to access relevant information for the support of decision making (DSS Dashboard).

In the background, the Event Manager processes events related to specific interventions, such as collaboration, maintenance or inspection intervention requests. These results are adapted by the DSS Event Adapter to translate them into notifications and to identify the correct receiver as well as the appropriate notification channel. The DSS Notification Management implements the business logic to notify the target user via an interaction device by selecting the most appropriate notification channel (e.g. graphical user interface, push notification, email).

Visualization, the third step of the considered data value chain, therefore is partly covered by the DSS components' Dashboard as described above. Furthermore, the AR device is used for the visualization as well. This involves the component VR/AR based

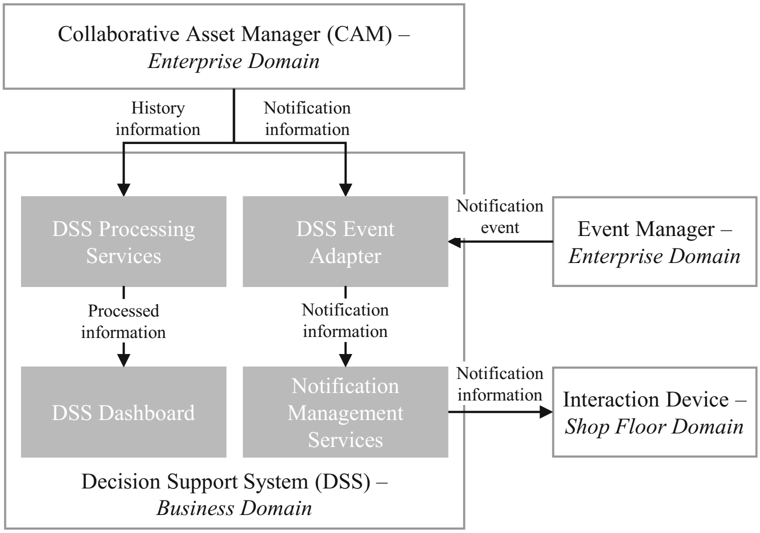

Fig. 3. Decision Support System (DSS) high-level decomposition

Training and Guidance again, which enables the display of notifications directly to the worker on the shop floor. In addition to event driven notifications the component is used to display assembly instructions with a varying level of detail depending on workers' characteristics and experiences, both stored and managed in the A4BLUE Adaptive Framework.

3.2 Exemplary User Story

Subsequently, a representative user story is described in order to outline how the information flow between workplace, worker and production supervisor is supposed to be managed for both assembly processes. The user story is visualized in Fig. 4 and shows how the worker is supported in the case of rework. This user story represents a small extract of the use cases overall capabilities under consideration of the A4BLUE solutions.

Firstly, the use case is configured by connecting the Automation Mechanisms to be used via the Devices Managers. Additionally, a complete digital image of the assembly ecosystem is generated by the production supervisor using the Collaborative Asset Manager. This image includes a semantic representation of all the tangible (e.g. tools, equipment, personnel, etc.) and intangible assets (e.g. processes, knowledge, etc.) involved in the use case to provide it throughout the Framework. In case of changes or modifications of the use case, the representation can be adapted via the Collaborative Asset Manager.

In regular shop floor operation, the worker initiates the assembly process manually, by looking at a marker, making a voice command or a gesture being captured by the AR device. This way the data and information generated in the assembly procedure is assigned to the specific process and can be stored as well as retrieved from the

Framework for further processing. The process initiation is executed manually, since the use case is designed without the involvement of a legacy system, such as a production planning and control system. If a legacy system is used, the process initiation can be executed by the system automatically. To close an operation within the assembly process the worker again uses a marker, makes a voice command or a gesture. The assembly process itself, which includes an optical and functional inspection of the assembly object, is closed automatically by the system after the last operation. After closure, a query is displayed to the worker whether rework on the product is required. The query is answered by the worker throughout a voice command or a gesture. If rework is required, the worker is requested to give further information about this specific quality issue via predefined comments. Within the Monitoring component, the rework rate, the percentage of defective products in the total number of

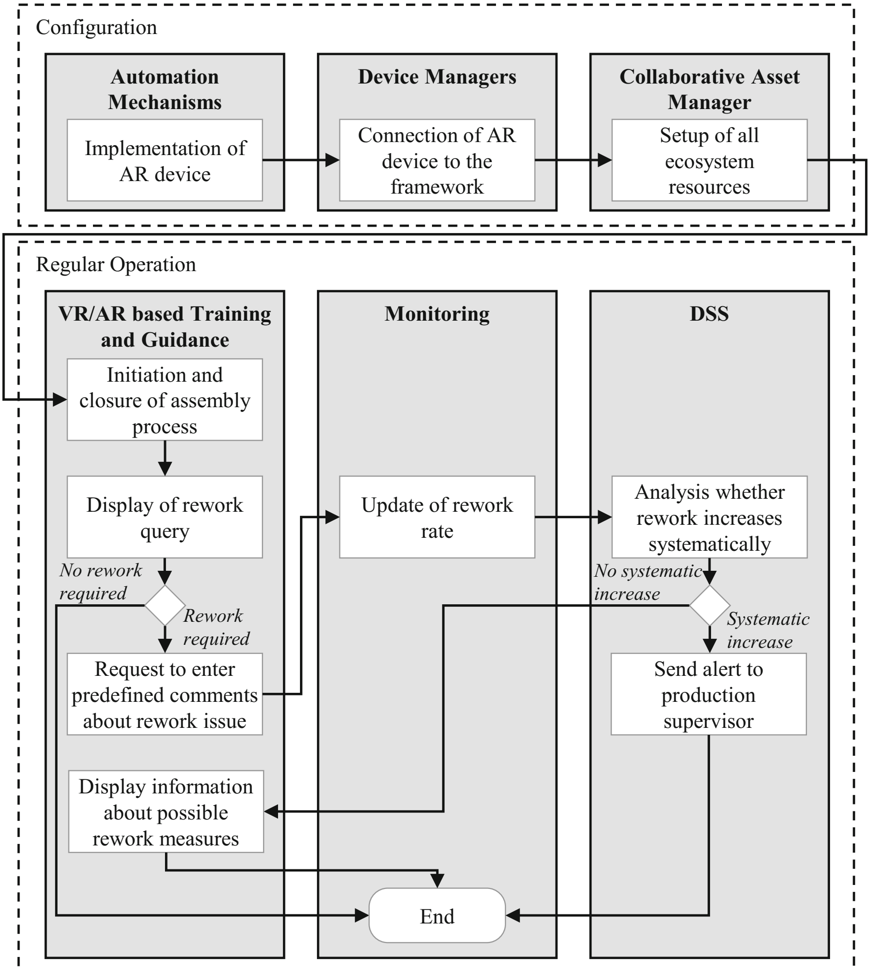

Fig. 4. Exemplary information process flow of an assembly rework process (simplified diagram)

products produced, is recalculated. Subsequently, the DSS analyses whether there has been a systematic increase of rework over the last processes.

If a systematic increase is identified, an alert notification (email or push notification) is displayed on the production supervisors smartphone to inform him to inspect the issue at the assembly object in person. Beforehand, the supervisor can retrieve the information about the issue entered by the worker that is provided by the DSS. If no systematic increase in rework was concluded, possible solutions for rework measures are provided to the worker. Afterwards the initiation of the next assembly process can be executed.

4 Conclusion

In the presented research work, concept and implementation of a digital infrastructure, the A4BLUE Adaptive Framework is presented. This Framework is the basis for the realization of Smart Workplaces as part of Smart Manufacturing. By connecting physical and virtual world, it enables the adaption of workplaces to the workers' specific profile. Additionally this empowers process as well as environmental variability. The goal is to combine the strengths of humans and automation mechanisms to achieve an increase in efficiency and to sustain worker satisfaction.

The A4BLUE Adaptive Framework contains a set of software components that are structured in three domains: Shop Floor, Enterprise and Business Domain. Each component is designed for a different purpose. Some components manage processes and databases, derive knowledge, trigger actions or analyze data, altogether realizing a Smart Workplace.

The Framework is implemented, amongst others, in an assembly use case at the Ramp-Up Factory at RWTH Aachen University. The use case provides an exemplary Smart Workplace in a real production environment using for example Augmented Reality, monitoring via key performance indicators and a system for decision support. Furthermore, hardware solutions and automation mechanisms can be connected to the Framework, while a complete digital image of the assembly ecosystem is managed and provided within the Framework.

As next steps the technical implementation will be finalized. Following experiments will be conducted to assess economic efficiency as well as worker satisfaction of the A4BLUE Adaptive Framework. To create a quantitative performance reference, the experiments in the first instance are conducted to a conventional workplace. Afterwards they are repeated with the implemented Framework. The results are expected to proof the potential of Smart Workplaces. Therefore, key performance indicators are used, being significant for a company's short- and long-term success, with a focus on economic efficiency as well as worker satisfaction.

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References

1. Lu, Y., Morris, K.C.: Current standards landscape for smart manufacturing systems. National Institute of Standards and Technology (2016)
2. Spath, D., Ganschar, O., Gerlach, S., Hämmerle, M., Krause, T., Schlund, S.: Produktionsarbeit der Zukunft. Industrie 4.0. Fraunhofer IAO, Fraunhofer Verlag (2013)
3. Lado, M.: Building a Showcase Culture: Powerful and Practical Keys for Manufacturing. Global Manufacturing Services (2018)
4. Rasmussen, J.: The role of hierarchical knowledge representation in decisionmaking and system management. IEEE Trans. Syst. Man Cybern. **SMC-15**(2), 234–243 (1985)
5. Agustiady, T.: Communication for Continuous Improvement Projects. CRC Press, Boca Raton (2014)
6. Zezulka, F., Marcon, P., Vesely, I., Sajdl, O.: Industry 4.0 – an introduction in the phenomenon. IFAC-PapersOnLine **49**(25), 8–12 (2016)
7. Lin, S.-W., Crawford, M., Mellor, S.: The Industrial Internet of Things - Volume G1: Reference Architecture. Industrial Internet Consortium. https://www.iiconsortium.org/IIC_PUB_G1_V1.80_2017-01-31.pdf
8. FIWARE: Smart Industry. Data is driving Industrie 4.0. https://www.fiware.org/community/smart-industry/
9. Gubbi, J., Buyya, R., Marusic, S., Palaniswami, M.: Internet of Things (IoT): a vision, architectural elements, and future directions. Future Gener. Comput. Syst. **29**(7), 1645–1660 (2013)