Methodological Implementation of Sensor Networks for Smart Manufacturing and Smart Factories

André Hurzig* and Egon Müller

Department of Factory Planning and Factory Management
Chemnitz University of Technology
Chemnitz, Saxony, 09112, Germany

ABSTRACT

With the transformation to "Industry 4.0", companies are faced with new challenges in the production created by intelligent networking. Flexible information gathering as well as the distribution and supply of information are needed. High economic potentials by the usage of sensor networks in factories and production systems are expected. It is necessary to standardize procedures for assessing the increased demands for sensors and their implementation in the factory. A main problem is the gap with regards to the contents of the two technical areas Factory Planning/Factory Management and Sensor Technology. This article describes procedures for the integration of sensors in production systems as well as procedures for the development of sensors and sensor networks. The significant differences between both areas are the separated consideration of the two areas out of macro perspective and micro perspective. It is essential to define interfaces in planning and development strategies of both fields to attain sensor-based factories and facilities efficiently and also to show possible benefits of those considerations. The combined design process of systems and sensor technology can help to handle the diversity of interfaces in the implementation process of sensor systems and will also lead to a higher level of system integration.

1. INTRODUCTION

The increasing market share of sensors and intelligent solutions for the design and control of sensor systems is increasingly focused. A huge potential for the smartness of processes is offered by intelligent solutions. Technical literature and magazines declare a growth of electric process automation in recent years and also for the following years as of 2014 [1]. Simultaneously a performance increase of sensor technologies will be held for years, so additional information tasks or control tasks can be implemented more efficient [1]. Improved opportunities in the development and programming of sensors [1] as well as an expansion of the areas of application of Auto-ID technologies [2] are the industrial standard for monitoring of logistics, facilities, productions and other spheres, such as gastronomy [3] or medical technology [4]. The tracing of a huge variety of parts by Auto-ID or the increasing deflection of maintenance tasks in the Auto-ID field require a consistent correlation of complex sensor systems with complex software [5]. The increasing crosslinking of different automation components, as defined in the keyword Industry 4.0, leads to increased intelligence of facilities, to more flexible and real-time monitored processes and not least to benefits in business processes and value-added processes [6]. Growing fields of activities are also machine-to-machine communication, remote maintenance [7] and object identification and tracking as well as the quality control of industrial goods. In addition to a high availability of facilities, a secure data generation and transmission take to center stage. These modern forms of automation will also lead to time savings and increased reliability [8] Therefore, it is even more necessary to combine the fields of the sensor driven data acquisition and the use of the data in the factory system.

Out of these huge amounts of opportunities for processes, facilities and also sensor applications, grows the need to view some trends and challenges to harvest the main potentials for a methodological combination in this paper.

* André Hurzig; Tel.: (+49) 371 531 39375; Fax: (+49) 371 531 8 39375; E-mail: andre.hurzig@mb.tu-chemnitz.de

Afterwards an introduction to the description of systems shall be given before sensor behaviors are treated. The goal is to combine the fields of sensor technology and factory operations in one methodological approach and to show some benefits and future tasks of this idea.

2. TRENDS AND CHALLENGES

The increasing integration of networked information technologies in processes and facilities in addition to a growing flood of information are leading to the requirements for innovative solutions in information generation, management and distribution. Technical and energetic limits of existing systems (e.g. RFID) charge for new approaches with regard to energetic self-sufficiency by the utilization of ambient energy. In response to existing challenges Factory Planning and Factory Management are encouraged to develop interdisciplinary and integrative approaches for the development of methods, procedures and solutions in information and communication technologies [9]. Higher transparency, cost savings, reduction of shrinkage, more effective inventory management and resource utilization are several goals facing the production driven by the usage of real-time information. Increasing diversity of variants and higher informational density are claiming new possibilities of real-time generation of information. It is necessary to focus information gaps in production to develop novel, real-time-based and request compliant [10] smart systems and methods. The increasing application of information technologies and wireless technologies leads to more efficiency, robustness and reliability in production and contemporary to an interface-diversity and hybridization of information technologies [11]. One resulting conflict is the energetic balance: the more information is generated the higher the energy consumption for that will be. Therefore new tools like energy harvesting methods will be provided [12]. Thus, one of the future goals of information gathering is energetic autarky.

More accurate and permanent recovered data is more useful for production systems than only the cyclical, planned acquisition of partial system parameters. The reliability of systems will be higher because of live data and better response assets. Even the monitoring usage of those data is also possible [13]. If logistical processes are not divided from transformation processes and information flows but instead considered as one unit of object-information-combination the informational needs will increase as well as the complexity. For this purpose holistic, multidisciplinary approaches are required [14]. Knowledge out of the area of Ambient Assisted Living will also effect to industrial habits as well as out of other branches of research like the home entertainment, health care or service. This means that the intelligent networking of other scientific fields will find their way into production systems – the so called Ambient Assisted Production (AAP). Requirements in the industries are clearly pointed in terms of synthesizing such systems to industrial habits [15]. Particularly, it should be investigated what information have mutual dependencies and which remain unaffected. Out of this, different methodological practices in the planning and implementation of sensors and networks are derived. This produces impacts for the transfers to the factory planning process [16] and therefore for optimization behaviors. From those considerations it is deflected, that holistic and interdisciplinary approaches have to be aspired which are needed for the design of information systems in factories, facilities and processes in early planning phases yet. One main challenge is to merge the necessary fields of sensor development (micro view) and factory operation (macro view) in an interdisciplinary way to get the global optimum.

3. APPROACHES FOR THE DESCRIPTION OF PRODUCTION SYSTEMS

3.1. SYSTEMS THEORY, SYSTEM THINKING AND OPTIMIZATION METHODS

Systems can be described in many ways. A representation that possibly can combine the use of sensor technology with the methodology of the factory operation is requested. An overview of a combination of structural and methodological description shall be given here. Production systems can be structured hierarchical and can also be characterized as flow systems. The hierarchical structure divides the system in main and peripheral segments, whereat main segments can be defined as main production processes or main transportation processes or any other main elements depending on the defined system boundary. Peripheral segments are structures influencing main segments directly or indirectly [17]. Between the single levels some interfaces, connecting each level, are given.

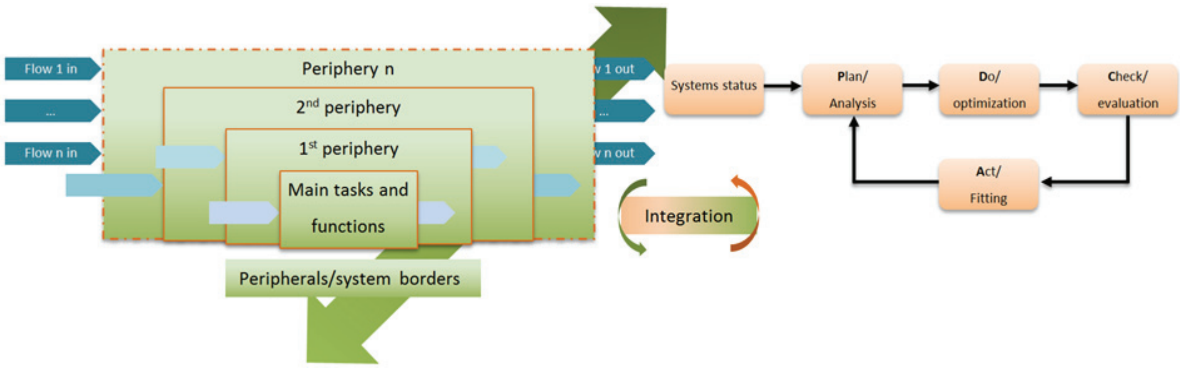

Figure 1. Hierarchical and flow model with integration of PDCA/CIP.

3.2. Methods integrated in Systemic Approach

A production system characterized as flow system shows correlations between input and output of materials, energy, workers information etc. according to the contemplated interfaces and defines the transformation processes in the production system. Each flow system can be optimized for itself or in between different levels and even each single interface can be optimized too by using optimization methods, as shown in Figure 1. One of these methods is the PDCA-cycle [17] or the Continuous Improvement Process (CIP) which leads on indicator-based assessments. Because each level can be seen as functional layer, technologies, facilities and/or (main) activities/processes can be allocated to those layers. This leads to the description of information tasks and the needs of information detailing for each level and in between the levels, which can be seen as optimization tasks. The optimization tasks have to be fulfilled by measurement technology and sensor technology. Thus a mapping of the area, the used technology and sensors/sensor grids is possible. Interferences between optimization methods and sensor networks can possibly be shown as well as the interferences between methods and each common system.

For example the method of CIP is used for specific optimization issues. It can be used in single operation or it can be used in multitude cases to improve several habits over the whole system – depending on the declared system boundaries. The Information out of the factory planning are giving nominal conditions to the future system – such as functions, facilities, technologies, subsystems, data, processes and/or information. The monitoring of these conditions in an existing system let control the system itself, the internal flows, the arrangements and settlements and leads to continuous system improvement. The monitoring itself is driven by sensor technologies, which give their information to control systems like automation control or ERP-Systems. Both – the hierarchical structure and the flow system – can be combined in a methodological way. The combination of the hierarchical and the flow system – can be combined in a methodological way. The combination of the hierarchical and themethodological model is shown in Figure 2.

4. Development of Sensor Nodes and Sensor Networks

According to the standardized procedure in the factory planning and methodical detailing in factory operation, a standard procedure for the sensor development is also provided. This can be seen as methodology, too. The basic

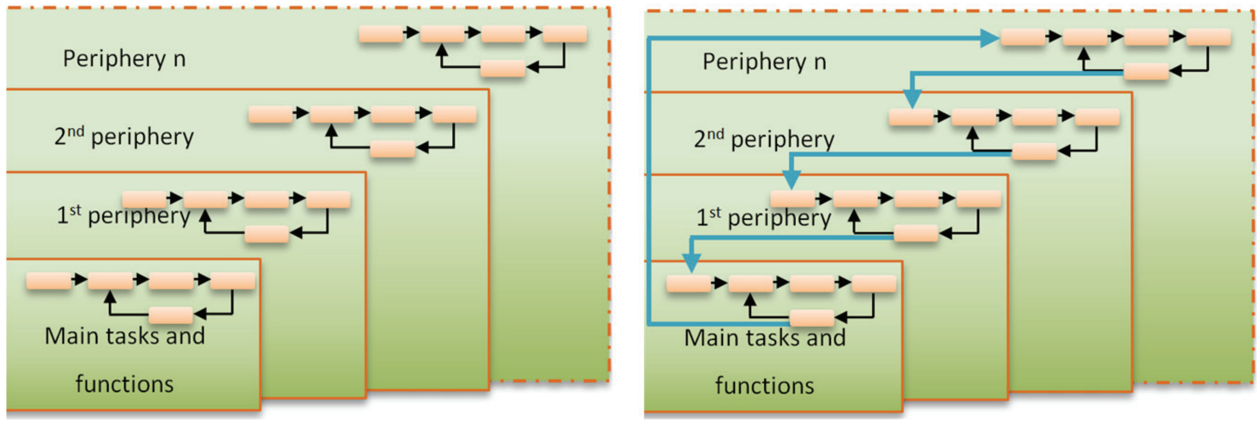

Figure 2. Example for single peripheral optimization (left) and cross-system optimization by PDCA.

steps of the process can be divided in four main phases [18]. The first phase is defined as the planning phase. Here requirements are defined, informational gaps or necessities will be detected. With this information, potential applications are identified which will influence the later usage. The second phase is the technology selection, which defines appropriate technologies and resources as well as methods for closing identified information gaps. The combination of both phases leads to economic potentials by describing the found information gaps and making suggestions for closing those gaps [16]. Phase three is the so called design phase. Functions of future sensor systems are characterized and/or recreated as well as software and hardware components are determined. In the end of the activities, the physical layer of the sensor node or sensor system will be combined with its software layer and set to the microcontroller (μC) [18]. To cope with the future goal of energy self-sufficiency (as shown in the introduction), it is necessary to expand this design phase by metrological behaviors. Before determining the final hardware and software the prevailing environmental parameters have to be measured. This identification of environmental energies is taking into account the subsequent applications defined under Phase 1 [16]. Due to the acquired amounts of ambient energy it may be confirmed if a sensor (network) can work energy self-sufficient or if an additional supply is needed. The final phase of sensor development is the implementation and the test of the sensor system respectively the sensor network. Therefore components have to be designed in two ways: components for measuring devices meeting the requirements more than before and components for the final system or network. Finally the matching, system integration and the system test must be completed [16], [18]. Figure 3 shows the information declared in the development phases for sensor networks. This procedure is now seen as the given optimization method for the main system or the systems periphery.

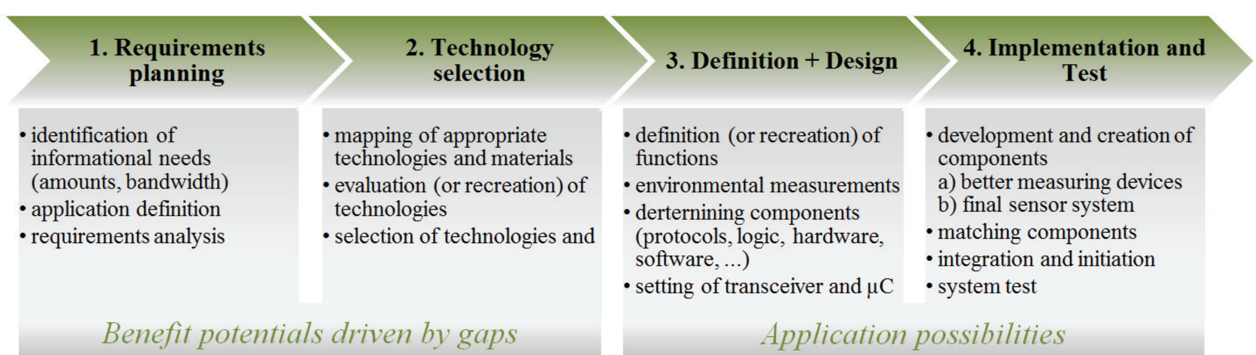

Figure 3. Combined development chain for sensor nodes and sensor networks.

5. Approach of Integration of Different Methodologies in Different Systems

5.1. Modeling

The shown instructions for factory optimization and sensor developing behaviors work each separated for itself. Though the goal is to integrate complementary and themselves influencing methods into each other, which leads to the idea of interlacing these methods. Basic of this idea gives the field of industrial automation, which separately processes several dimensions and then restores the dependencies by combining the results via a so called tandem or cascade connection [19]. The regulation variable at the output of a controller is used as an input to a downstream control element. Thereby the overall arrangement is chained or cascaded. For example this allows gentle acceleration-speed gradients of robot movements. The dependencies are geometries, coordinates and derivatives of dimensions with respect to time, which are computed separately for each axis and then are combined to smooth movement expiration by cascade computing. This is similar to the description of systems, as shown in chapter 2 but it combines system thinking and variables/restrictions with the definition of interfaces from outer to the core system. Figure clarifies this idea in a schematically way.

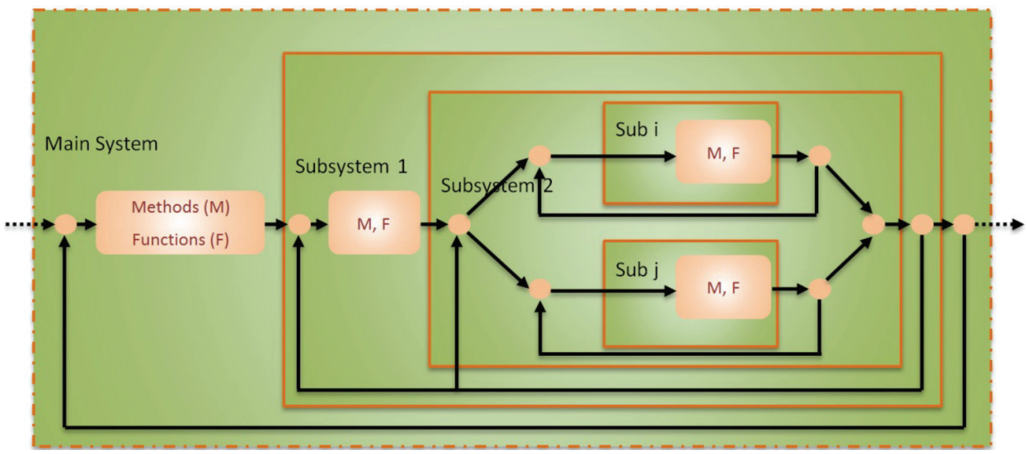

Figure 4. Combination of methodological, functional and sysmtemical models to a cascade with dependencies.

For the deployment of systems, processes and facilities with sensor based integration, this interlacing should lead to simultaneously and independently designed function modules and contents. Later, these modules are linked again. Corresponding to the previously defined dependencies factory operation can use this cascade for the dimensioning of sensor-based systems and processes. One use case is the definition of sensor-actuator relationships, which handles the circulation from informational needs. The gathering, transmission and analysis of information are followed by the response of facilities and processes with new informational needs. With these interconnections, it is possible to design processes and to configure sensor systems with specific requirements, simultaneously. Therefore the definition of system boundaries, interfaces, dependencies, flows or flow circuits is required. The assignment of information requirements to those described subsystems allows the identification and assignment of specific instruments to satisfy the information needs. Such instruments may be methods, functions or technologies, such as procedures for sensor design and sensor selection, measuring instruments or existing sensor networks. Prior condition for the correct assignment is the correct determination of the system boundaries and the correct definition of interfaces and dependencies over the system boundaries. The determination of the system boundaries and interfaces is the essential link to close this circulation to a holistic method.

5.2. Functional Principle

The application of the shown approach can be used in two directions. The first direction acts from the outer system inwards and is seen here as a top-down application. Based on the defined system boundaries, the main system with its inherent facilities and processes determines its subsystems. The main information needs and associated methods to satisfy those claims are connected. Simultaneously peripherals and subsystems are described and the facilities and processes to be committed are derived here as well. Each of these peripherals includes again a specific information need, which also has to be satisfied by technical and organizational methods. The core system shall describe the sensor technology, which finally shall serve the information generation. This makes it possible to make demands to existing sensor networks or sensor networks which have to be developed from outside to inside (top down). The conception of sensor networks for smart productions can be done systematically based on the requirements of the factory operation.

The second direction acts from the inner system outwards and is seen as a bottom-up application. A sensor network informs its parent subsystem (main or sub) on system states. Based on the performance of existing sensor networks it first defines what information to what extent and what density can be produced. If this performance is compared with existing information requirements, the degree of compliance with information requirements becomes apparent. Since every system is seen as peripheral, this chain can continue up to the main system. Thus the quality of information can be determined for each subsystem by the allocation to the implemented sensors. It is also possible to derive potential areas of application for the information gathering from existing sensors. From this, arrangements can be derived that lead to the application, to improvement, to redevelopment or further development of sensor networks.

The combination of both directions provides an integrated approach to the planning and development of sensor networks. Simultaneously it forms an assignment of areas for the sensor use in facilities and processes. Basis for this is the creation of interfaces between information generation and information needs over system boundaries. Requirement for the application of the model is that the target system is divisible to handle sensor networks as the smallest system unit. Furthermore, the effort for definition and test of the model should be economically justifiable. The systemic divisibility usually exists, since each technical system can be segmented into sub-systems. The economic cost must be balanced with appropriate methods. Discussions, respecting new or further developments of sensor networks and the use of certain sensor networks should be driven.

6. Example of Use and Practical Aplication

As an example, a logistics application is selected, in which the cargo exchanges its position over a time period and requires a special conveying technology for the accomplishment of this task. The system to be described is characterized by the transport task, its system elements and its existing information needs. The transport task is characterized in a change of location of the cargo, which has to be monitored. For monitoring the cargo needs to be identified at the same time, in order to demonstrate the accuracy of the object. The system elements are conveyor systems with specific performance (e.g., throughput) and the freight, also with specific characteristics (e. g, weight, vibration pattern). Information needs arise from the knowledge of the used technology and the object to be transported. They are referred as the measurement tasks, here. The identification of the object on the conveyor system (once per transport process) and the determination of the position of the identified object (in a permanent measurement interval) are the specific measuring tasks that arise.

6.1. Top Down Usage

To achieve this functionality, the cascade can be used by running it top-down or bottom-up (in this example, the top-down method is more evident). For the top-down use the outer system boundary is the conveyor system, to

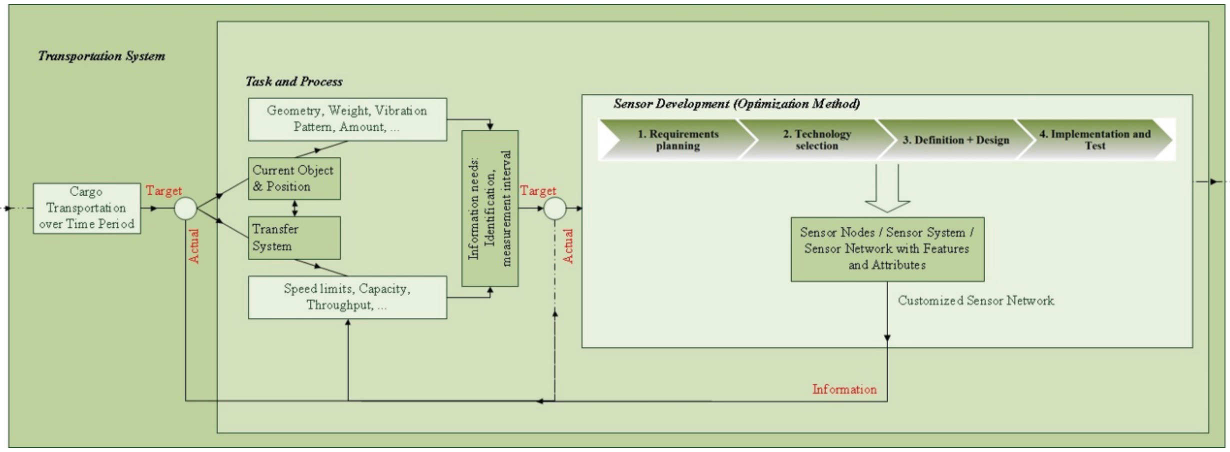

Figure 5. Example of cascade with concrete Elements and Methods in the top down usage.

which the conveyed object is subordinate. The core subsystem is the sensor network, which identifies the cargo and its movement and also receives and transmits data. Measurement tasks and the measurement frequencies define the specific field of the sensor application. A narrowing of possibilities is given here by the performance of the sensor. The interfaces between technology, objects and sensor are given by suitable process logic and get supplied by sensor development methods (Figure5).

If a static conveyor system (for example, a chain conveyor) with moving objects is used, static sensor nodes for identifying and tracking can be sufficient. Automated guided vehicles (AGV) would require dynamic sensors or other technology of locating. The wired connection to existing software system would fit in the given monitoring task. If existing sensor networks can fulfill the information task, they can be further restricted under economic considerations and finally implemented. If not, it can be tried to characterize and to develop improved sensor technologies for this application. The development and deployment of the sensors is carried out according to the methodology of Section 3 of this paper.

6.2. Bottom Up Usage

The bottom-up application requires the alignment of the application range of the sensor network with the given information tasks. The sensor is substantiated and associated with special use areas. Exactly those sensor networks are sufficiently, which can identify the conveyed good properly and which can cover the required measurement frequency. All other systems are eliminated. If a sensor network is selected, concrete work on the specific information tasks can be started. For this interfaces have to be defined that feed the obtained information in higher level systems. For example, Wi-Fi, Bluetooth or wired interfaces are suitable. The selection is made on the basis of cost-effectiveness evidence or other criteria. Then the integration of sensors into the conveyor system or process defines the outer system boundaries and thus the performance of the sensor in terms of the information task. It can be assessed to what extent existing sensors are suitable for the concrete measuring tasks.

7. Discussion and Conclusions

This paper has handled a methodological approach for the development and operation of sensor networks. The development of an appropriate methodology for a requirements-based sensor selection or the clarification of the application area from the given network performance were the tasks for modeling. One feasible approach was the combination of different process models and methods that simultaneously take into account the objectives of integrated sensor systems. With this more comprehensive model it should be possible to connect existing processes with new sensor technologies and to define meaningful applications for existing sensors. Thus, the technical fields of factory operation and sensor technology became closely linked. The procedure for defining sensors and networks was added to the processes design.

The result was a solution called “cascaded system view”, that allows the definition of every hierarchical system or subsystem in freely scalable boundaries. The conventional system view, with predetermined material, information and energy flows was added by the functionality to freely branch within the system. These flows are considered as top-down or bottom-up paths with integrated areas of responsibilities. Along the flow direction, different possibilities for additional description of the sensor networks are given. Interfaces are technical, procedural and logical elements that can link different contents and can have a direction. The running direction determines the respective input and target variables and can be expanded later by a workflow or other systematically views. Thus, the combination of sensor-linkage and process modeling can be seen as succeeded.

The approach has currently the character of an idea, is still unproven and must be subjected to a detailed analysis in terms of functionality and potential weak points: The most relevant applications in logistics and production have to be detected systematically in order to demonstrate the functionality of the method. For this purpose, technical regions should be selected first, which can be modeled by planning approaches and can be supported by sensor technology. Ideally, areas with high potential benefits for sensors should be selected. Specifically, applications that have increased information requirements and thus are increasingly demanding the sensor usage can help for that.

Weak points of the modeling can be found in the linkage to software systems. Currently it has not been provided to implement this complex modeling of a system into software yet. So modeling problems can only be supposed. A performance measurement system for the comparison with existing models is not developed yet. This leads to a deficiency in cases of evaluation of the modeling. In addition, the graphical representation of the model is only superficial. The idea of cascading is not physically visible and therefore difficult for the user to grasp. By choosing to wide spread system limits there is a risk to lose the clarity of the approach. A new model construction and a system definition have to be fulfilled for each new information task. Depending on the target range, the model complexity can sharply rise by a variety of different influences and requirements. This can lead to long lasting system reviews and implementations.

Nevertheless, some advantages and disadvantages can already be provided without testing the method. The cascade design provides a systematic segmentation of the considerate area based on the system theory. The simple description helps to narrow or to expand discretionary systems, which is essential for the combination of the fields of sensors and factory operation. By the free definition of the system boundaries, the target frame is determined properly and requirements for subsystems can be derived. Thus parameters such as environmental conditions, technical restrictions or information needs can be passed in the subordinate layer, where they are used directly as control variables. Furthermore, a more targeted forecast of the utilization of sensor networks is possible, because system interrelationships are illustrated by the definition of precise interfaces. In addition, the approach can be incorporated with more specific requirements (e.g. industries or facilities) in order to use existing sensors or for further developing. Thus, the approach is more universal and portable and leads to customized sensor networks for specific conditions. At Chemnitz University of Technology the methodology will be tested soon. Here a sensor box for live data acquisition is implemented in the laboratories, which can confirm or reject the dependencies between sensor and system technologies.

Future tasks can be the software implementation or the automated modeling (e.g. with live sensor data) and possibly the implementation of genetic algorithms. The latter can be used for spreading the won knowledge and for the analysis and optimization of the modeled system. Some further necessities for action that will underpin and enhance this idea, arise. The functionality of the approach have to be assured – suitable in a first approximation, a SWOT analysis seems useful. Furthermore, additional models should arise, which integrates economic considerations to emphasize the obviousness of use and development, for example. Currently, only a general description of the running directions to work top-down and bottom-up exists. Specific workflows that are subject to the paths of action are used to define. If the function of the approach is proven, the general graph has to be adapted modular to specific application fields later. The resulting partial models have to be automated. This creates transparency and helps to accelerate the development and deployment of sensor networks. Afterwards the approach can be enriched by precise key performance indicator systems. Thus, a possibility to evaluate the method itself but also to achieve measurability of the methods results is attained.

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