Resource-Optimized Design of Communication Networks for Flexible Production Plants

Petar Vukovic, Stephan Höme, Sven Kerschbaum and Jörg Franke

Abstract

In the context of digitalization and Industry 4.0, the flexibility within the production halls is increasing more and more. This leads to an increasingly difficult planning of the communication network. The increase in the number of different network technologies operating in parallel will make planning, commissioning and service more and more difficult. It will no longer be possible to carry out a rough layout of the network, as stable communication will become more essential for the successful operation of the plant. Thus, for example, the increasing complexity can be faced with simulation software in various areas. The use of network simulations will therefore become increasingly important in the future. Already existing simulation tools in the field of network simulation show good results, but can only be carried out very late in the life cycle of a plant, where remaining errors become expensive. In this paper we will first show already existing network and material flow simulations in an industrial environment and then introduce and prototypically implement a new co-simulation approach.

P. Vukovic (✉) · J. Franke
Institute for Factory Automation and Production Systems, Friedrich-Alexander-University of Erlangen-Nuremberg, Erlangen, Germany
e-mail: petar.vukovic@faps.fau.de; joerg.franke@faps.fau.de

S. Höme · S. Kerschbaum
Siemens AG, Nuremberg, Germany
e-mail: stephan.hoeme@siemens.com; sven.kerschbaum@siemens.com

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Co-Simulation · Industrial communication networks · Network simulation · Material flow simulation · Plant lifecycle management

1 Introduction

Since the introduction of Industry 4.0, the penetration of digitalization in the production plants has been increasing continuously. The implementation of Industry 4.0 in manufacturing is multifaceted and requires a restructuring of already existing processes. One of the fundamental ideas of Industry 4.0 is the ability to produce in batch size one. In order to implement this successfully, production must be made more flexible throughout [12]. This is the only way to implement production in batch size one effectively and efficiently [9,11]. Flexible production plants not only support the successful implementation of Industry 4.0 ideas, but also help to remain competitive in the long term. This makes it possible to react in time to changing market requirements. With the introduction of flexibility a change towards wireless communication networks in industrial environments is taking place [15]. However, it is becoming apparent that wireless communication networks are much more vulnerable to errors, both in planning and during operation [15]. In order to meet this increasing complexity and to eliminate cost-intensive errors, more and more importance is attached to simulations in various areas [5]. Thus, this paper also deals with the approach of a co-simulation framework to meet the increasing complexity and error-proneness in industrial communication networks for flexible production plants. In order to meet cost efficiency requirements, the design of such wireless communication networks must therefore be resource-optimized.

This paper is separated into five sections. After the introduction, Sect. 2 introduces the state of the art in error costs along the life cycle and the simulation usage in industrial communication networks as well as in production system planning. It motivates why current simulation software solutions cannot fulfill today's demands on a flexible production plant and why it is important to simulate as early as possible in the life cycle of a plant. In Sect. 3 a concept for the integration of network planning into FPS planning is introduced using a new co-simulation approach. Based on an exemplary use-case the current implementation is presented. Finally, a short summary and an outlook concerning future work are given.

2 State of the Art

In the context of Industry 4.0, flexibility in production continues to increase. The larger the production facilities become, the more the increase in flexibility pays off [8]. However, it is not enough here to simply make the production process as such more flexible. Rather, the plant must be viewed holistically. When it comes to the interconnectivity between different plants, at the latest, the communication aspect plays a major role. This shows that wireless communication technologies must be increasingly used in flexible production plants to meet flexibility requirements [15]. To ensure that wireless communication systems always meet the industrial requirements of flexible production plants, it is no longer sufficient to design them in the conventional way. Thus, also in the field of design and validation of industrial communication technology the share of simulation software is constantly increasing.

The following section explains why errors should be avoided, especially in early phases of the life cycle of a plant. The second part deals with different types of simulation of communication systems and which are usually used in an industrial context. In the third section, communication needs, which are important for the co-simulation approach at any early phase of the life cycle in this paper, are explained. Finally, the need for a dynamic co-simulation approach is motivated.

2.1 Error Costs Along the Life Cycle

The life cycle of a plant is divided into five categories. Thus, at the beginning of each life cycle is the planning and design. The plant is then engineered, commissioned and operated at its destination. The last step in the life cycle of a plant is service. Errors occur during every life cycle. However, it has been shown that the later an existing error is discovered in a lifecycle, the more expensive it is to correct [10]. Figure 1 shows how expensive an undetected error is. Per phase of the life cycle, the cost of the error increases by a factor of 10.

Consequently, plant manufacturers strive to remove faults from their plants as quickly and as early as possible. As plants become increasingly complex in planning and engineering, manufacturers are striving to meet this complexity. For example, the use of simulation software is a common method of detecting and eliminating errors at an early stage of the life cycle. The use of virtual commissioning already shows impressively how simulation software can be used to validate and optimize both the hardware design and the software code without requiring the real plant. This makes it possible to find the errors in time and thus reduce costs. This is the motivation to apply simulations in the field of industrial communication technology to detect and correct errors in the planning and design of such networks at an early stage.

2.2 Simulation of Industrial Communication Networks

There are many different tools to perform a network simulation. However, only some of them are effectively applied in an industrial environment. To make a short comparison, two concepts of communication simulation are discussed below. First, the tool SINETPLAN is introduced and its classification in the life cycle is described. Then a comparison to an existing co-simulation approach between OMNeT++ and SINEMA E will be made.

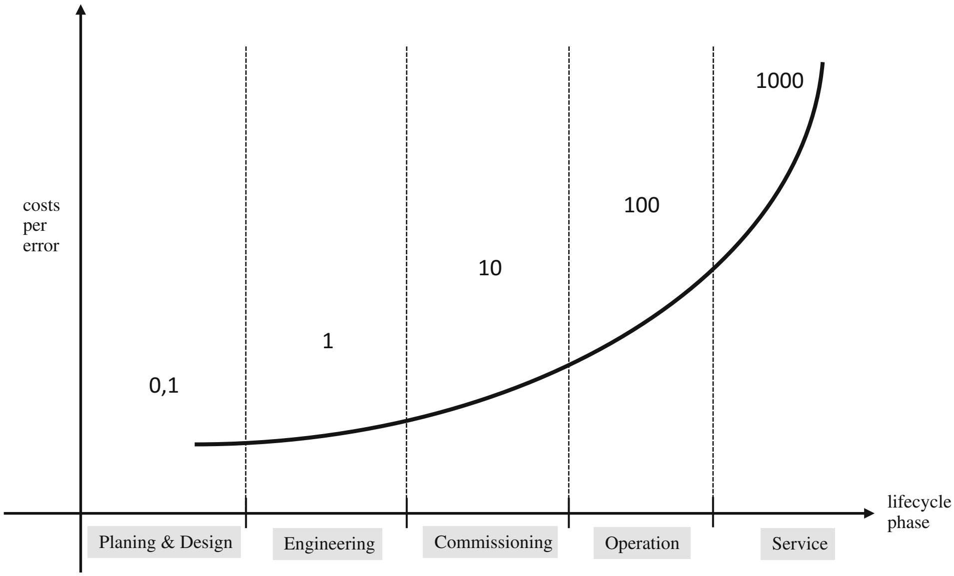

Fig. 1 According to the rule of ten, later discovered errors cause higher costs [10]

SINETPLAN is a tool developed by the industry to meet network load predictions based on the network calculus method. Thus, arrival, service curves and shapers are used to analyze these networks [3]. Furthermore, worst case scenarios can be simulated using min-plus and max-plus algebra from the system theory of computer networks [6]. To be able to measure these predictions, exact information about the hardware design and the software application is needed. SINETPLAN uses this method to analyze static network structures and is located in the field of wired communication technology [6].

The co-simulation approach between OMNeT++ and SINEMA E follows a dynamic communication structure. SINEMA E is a tool for planning, simulating and configuring WLAN networks, thus facilitating installation and commissioning. Using the SINEMA E tool, data is read out and transferred to OMNeT++ for simulation. This information exchange is a one-way connection and reduces the simulation effort by adopting certain values like topologys, devices and environments. IEEE 802.15.4 protocol is the basic idea of this approach [1].

2.3 Simulation in Production System Planning

Due to the constant increase of industry 4.0, a simulation in the area of production system planning is indispensable, as the requirements for quality and complexity continue to increase [5]. To deal with this increasing complexity, the use of simulation tools in the context of production system planning is necessary [7]. One of the most important areas is the simulation of material flow, as it reveals bottlenecks during production and thus improves efficiency [4]. In addition, the use of material flow simulation has already been successfully implemented in the industrial environment and its advantages have been demonstrated. Furthermore, the software also offers the possibility of path planning of automated guided vehicles (AGV) and thus the mapping of an important detail of flexible production plants. A simulation tool that is already frequently used in industry for such applications is Plant Simulation from Siemens. Here detailed information is provided, which is indispensable for a network simulation later on.

2.4 Communication Needs

In early stages of the life cycle of a plant, the hardware and programmed software used is often not yet known. However, the scenarios, applications, number and types of machines required for a productive plant are known. Therefore, the use of abstract communication needs, which are hardware and software independent, offers the possibility to make a rough estimation of the communication requirements that will occur later [14]. On the basis of this, the communication networks can then be designed to meet the requirements and resources.

Basically, a distinction is made between static and dynamic communication needs [14]. Static communication needs are requirements that occur regardless of the current state, location or time aspect of the machine. These may include the following points:

- Maximum reaction times to avoid collisions
- Data rate of image transmission for object recognition
- Standardized communication interfaces (e.g. PackML)
- Defined communication protocols (e.g. OPC UA)

In contrast, dynamic communication needs are, for example, local changes in AGVs or changes in the status of a machine. With the help of these dynamic changes, not only static communication scenarios can be realized during a simulation, but also changing states of the system as a whole.

2.5 Need for Action

As already described in the previous section, it is evident that error correction at a very early stage of the planning process is essential for cost reduction. In order to correct such errors in time, the use of simulation software is indispensable due to the increasing complexity of communication systems. Today’s simulation software solutions such as SINETPLAN currently only offer the possibility to map wired communication topologies. Furthermore, SINETPLAN applies at a stage of the life cycle, when the hardware selection has already been made. The shown co-simulation between SINEMA E and OMNeT++ shows reasonable basic approaches but is insufficient due to the one-sided connection and therefore missing optimization loop. Furthermore, the decision to use a single communication protocol and the no longer available SINEMA E software is not a viable solution.

Therefore, a new co-simulation approach will be introduced in the next sections, which will cover different radio technologies and enhances the simulation possibilities with wireless communication aspects. The use of generic, hardware-independent models also makes it possible to start at a very early stage of the life cycle. Furthermore, using a co-simulation offers the possibility to integrate dynamic aspects of a flexible production plant. The integration of already existing simulation tools used in the industry, such as Plant Simulation, also offers the possibility to keep the additional effort through simulation as low as possible. With the material flow simulation, Plant Simulation provides important information that has not been used in any network simulation so far. With the help of a bidirectional connection an optimization loop is made possible and thus a correction proposal of the communication network is evaluated.

3 Co-simulation Approach

In order to be able to perform a holistic view regarding an early simulation of the communication network, the above mentioned aspects must be considered correctly. These are among others the following:

- Use of existing simulation software
- Event-discrete simulation to integrate dynamic changes
- Ability to change the topology during simulation
- Combination of wired and wireless network technology
- Consideration of dynamic communication needs
- Optimization loop when designing the network topology and placing the components

For simulation in the early phase of the life cycle, a simulation tool already frequently used in industry should be used in the area of production system planning. One such tool is Plant Simulation, which supports the planning and design of a plant. Among other things, material flow simulations are carried out here, which can reveal bottlenecks in production at an early stage. The path planning of an AGV is also carried out in this software. One of the advantages of using this software is that dynamic status changes and local changes of machines are optimally represented. Furthermore, the function library of Plant Simulation can be extended with own components and thus the aspect of network planning can be integrated.

As a previous co-simulation approach has already shown, OMNeT++ is suitable for event-discrete simulation in the field of network simulation. Therefore, in combination

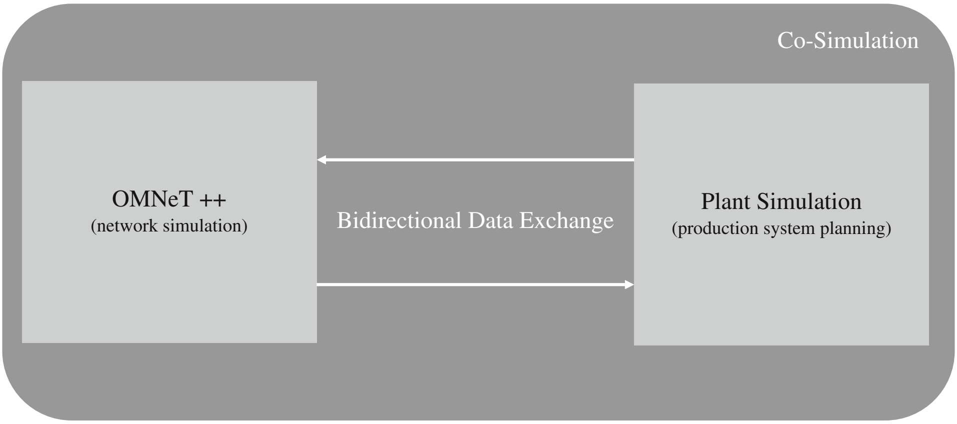

Fig. 2 Basic architecture of the co-simulation approach

with Plant Simulation, it should provide reliable predictions about upcoming network traffic. However, it is important that the new co-simulation approach has a bidirectional connection and thus allows optimization within Plant Simulation by e.g. repositioning the hardware. Figure 2 shows the architecture of a possible co-simulation between Plant Simulation and OMNeT++. In the next sections, the functions and tasks of the individual simulation tools will be described and then the connection between both tools will be explained in more detail.

3.1 Plant Simulation

The main task of Plant Simulation is the material flow simulation of a plant. The user determines the production process by placing the individual machines and configuring their status. Another feature is the path planning of AGVs. This also takes place directly in Plant Simulation and is performed by the user. In addition to the basic tasks of Plant Simulation, a new library for determining the network load is introduced. Here the user has the possibility to determine the topology of the plant by setting individual access points (AP). This is essential for the later simulation in OMNeT++, as the expected network load is simulated based on the position of the APs, machines and AGVs. Furthermore, a bidirectional connection should be created within Plant Simulation in order to exchange data for co-simulation.

3.2 OMNeT++

OMNeT++ is responsible for the network simulation based on the data received from Plant Simulation. An initial configuration is carried out on the basis of the derived hardware setup. OMNeT++ will perform a simulation of the network traffic using the configured APs and the associated topology. Since the status of the machine and the positioning of the AGVs can change at runtime, a connection will be used to react to such dynamic changes. Thus OMNeT++ connects to Plant Simulation and uses the bidirectional connection to obtain the latest data from Plant Simulation about the topology and to provide Plant Simulation with feedback about the utilization of individual APs.

3.3 Data Exchange

Since data exchange is of existential importance in co-simulation, this section describes it in detail. Beforehand, two different data exchange scenarios need to be distinguished. The first is sending data from Plant Simulation to OMNeT++ for initialization. The second scenario includes the continuous data exchange between both simulations. Table 1 contains the needed data for the initialization process. The size of the model is required so that the simulation environment can be set to the same size in OMNeT++. In the case of devices, AGVs and machines are grouped together and differentiated under fixed and mobile. Since the initialization file provides only a one-way information exchange, there is no data exchange back to Plant Simulation.

Table 2 shows the continuous data exchange during the simulation. The status is also added for APs and devices to identify their current state, as this is important for network

Table 1 Content of the initialization file

Component	Information	Description
FPS model	Size	Size (x,y) of the FPS model in meters
Access Point	Index	Index of AP in model
	Position	Position (x,y) of AP in meters
Device	Index	Index of device in model
	Position	Position (x,y) of device in meter
	Fixed/mobile	Member of fixed or mobile devices

Table 2 Continuous data exchange from Plant Simulation to OMNeT++

Component	Information	Description
Access point	Index	Index of AP in model
	Position	Position (x,y) of AP in meter
	Status	Status of AP
Device	Index	Index of device in model
	Position	Position (x,y) of device in meter
	Fixed/mobile	Member of fixed or mobile devices
	Status	Status of device
	Communication needs	Communication needs the device represents

analysis. The Communication needs of devices can change during the simulation due to their flexibility and change the communication requirements to the network. Therefore, they are also indicated in the continuous data exchange. As a result, Plant Simulation receives from OMNeT++ the index of the APs to be iterated with the respective network load.

4 Current Implementation

In order to implement the shown co-simulation approach, the first implementation will be explained in this section. Figure 3 shows a detailed implementation of the previously shown architecture and thus the complete information exchange between the individual tools. Specific details, such as necessary adaptations and adding libraries, are dealt with in more detail in the following subsections. In Fig. 3, the architecture is divided into four independent areas. On the left side OMNeT++ covers all simulations concerning network simulation, whereas Plant Simulation on the right side performs the necessary material flow simulation. For a first initial configuration the initialization file below is used. To ensure a continuous bidirectional data exchange, the TCP/IP interface between both tools

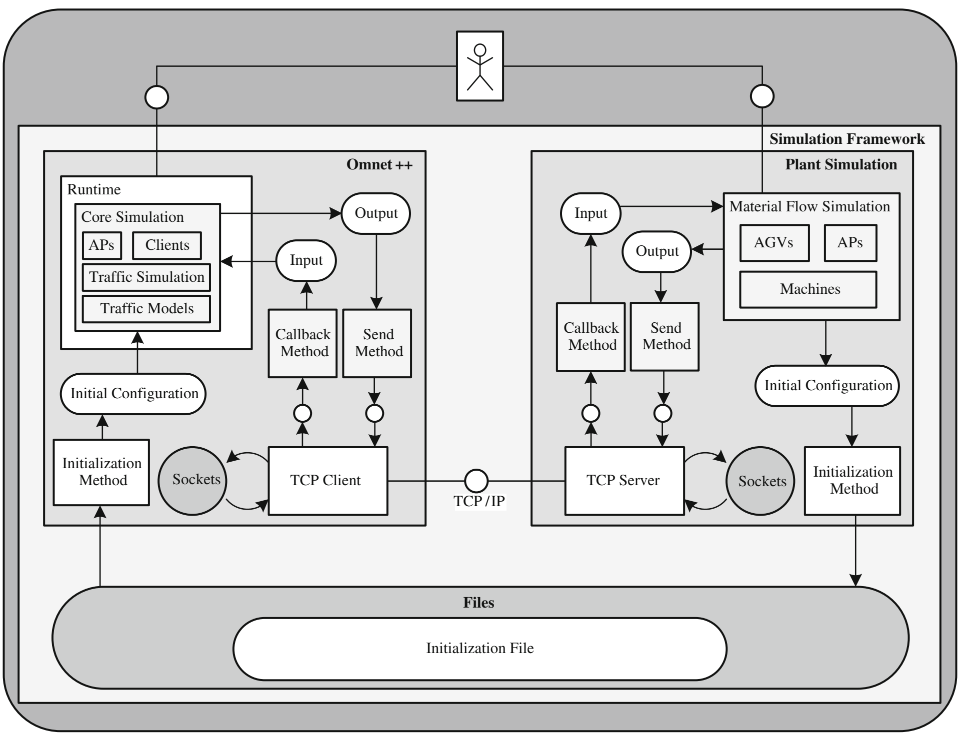

Fig. 3 Schematic of the simulation framework using Fundamental Modeling Concept [3]

provides the necessary implementation. From the outside, the user controls all inputs for the running of the co-simulation.

4.1 Plant Simulation

Within Plant Simulation some important functions are implemented to ensure that the calculation of the distance of individual APs to the respective machines works correctly. A simulation step is currently carried out with $t = 1$ s and therefore an almost complete coverage of the production can be shown. The implemented library for the placement of APs offers objects in a spherical shape for better visualization. Furthermore, these objects represent important properties for later identification in space. For example, a function calculates the current removal of machines and AGVs to the respective closest APs by means of triangulation during the material flow simulation during each simulation step.

4.2 OMNeT++

OMNeT++ currently focuses on the correct mapping of an industrial environment. Although the approach is in principle open to communication technologies, the first implementation was carried out in the IEEE 802.11 standard. Thus, meaningful values from different sources are used here and no own values are measured. This is particularly evident in the configuration of the transmission medium and the technology-dependent physical layer. According to various sources, the use of rician fading as a path loss model in industrial environments provides a very good representation of real conditions [2,13]. So the system loss is set to a realistic value of 15 dB. For the configuration of the physical layer an isotropic antenna is used as antenna model and the Ieee80211ScalarTransmitter and Ieee80211ScalarReceiver provided by OMNeT++ as transmitter and receiver models. An associated stochastic error model is also used, which best represents the technology. This modular division into transmission medium and physical layer offers the best prerequisites for the implementation of further innovative communication technologies. One of the goals here is to switch to 5G models in the long term, if they are made available in the future.

4.3 Data Exchange

This subsection is divided into two parts. The initialization file, which stops in Architecture, is used to export the coordinates and the current structure of the plant from Plant Simulation. This file can then be imported into OMNeT++ using an import function to generate the necessary .net-files. At the same time, depending on the placed objects, the .ini-file is created, which contains information about the network configuration.

A TCP interface is implemented for bidirectional communication. The TCP server is defined in Plan Simulation and the TCP client in OMNeT++. During the start of the simulation in OMNeT++ both tools are automatically coupled and the information exchange is executed with t = 1 s.

4.4 Simulation Workflow

The existing Plant Simulation model will be extended using the library for network components. The placement of APs in space is done using spheres as shown in the First planning concept in Fig. 4. Based on the placed network components and all machines the tool generates an initialization file, which is used for the initial configuration in OMNeT++. This leads to a synchronization of the topology and the structure of both models and thus to the functionality of the co-simulation. The start of the simulation triggers a coupling of the TCP connection and cyclically transfers the data from Plant Simulation to OMNeT++ and vice versa. On the basis of the most current data, the

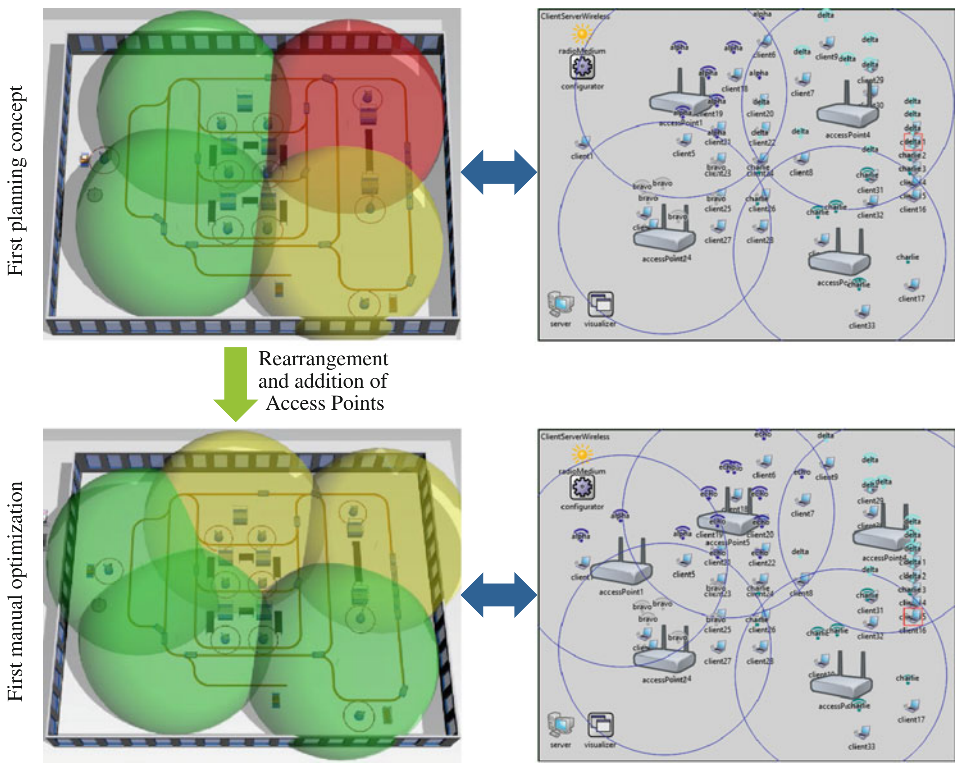

Fig. 4 Co-simulation of the FPS use case including one iteration: Plant Simulation model showing the network utilization for each AP (left), OMNeT++ model for network simulation (right)

simulation within OMNeT++ results in an utilization for the network components and returns this information to Plant Simulation for visualization. Using the visualization within Plant Simulation, the planner can see if a network component is congested and react by either rearranging or adding new APs, as shown in Fig. 4. Currently, the implementation provides for a manual optimization loop and must therefore be carried out by the planner independently.

Currently, no network simulation and thus validation of the Plant Simulation setup is performed within OMNeT++, since the main focus was initially on the co-simulation architecture and the correct mapping of the industrial infrastructure. Therefore, the current utilization information in Plant Simulation is a pure utilization display based on the number of machines and AGVs in the sphere

5 Summary and Outlook

In this paper a new co-simulation approach was introduced, which starts at a very early stage of the life cycle. Thus, errors can be eliminated early and costs can be saved. By using material flow simulations already available in industry, the additional effort is estimated as low and therefore effective.

Since the initial focus was on the design and implementation of the architecture, the next step will be the correct implementation and validation of the network simulation. Furthermore the important communication needs for individual machines will be worked out and defined. This will allow a precise statement about the expected network utilization. The extension of wired technologies is also an additional aspect in the future, as the main focus is currently on wireless technologies. The current implementation provides for a manual optimization loop in case of identified weaknesses. The implementation of an evolutionary algorithm is also conceivable here, which carries out the optimal placement of the network components.

References

1. Chen, F., German, R., Dressler, F.: Qos-oriented integrated network planning for industrial wireless sensor networks. In: 2009 6th IEEE Annual Communications Society Conference on Sensor, Mesh and Ad Hoc Communications and Networks Workshops. pp. 1–3. IEEE (2009)
2. Croonenbroeck, R., Underberg, L., Wulf, A., Kays, R.: Measurements for the development of an enhanced model for wireless channels in industrial environments. In: 2017 IEEE 13th International Conference on Wireless and Mobile Computing, Networking and Communications (WiMob). pp. 1–8. IEEE (2017)
3. Goos, G., Hartmanis, J., van Leeuwen, J., Le Boudec, J.Y., Thiran, P.: Network Calculus, vol. 2050. Springer Berlin Heidelberg, Berlin, Heidelberg (2001)
4. Gutenschwager, K., Rabe, M., Spieckermann, S., Wenzel, S.: Simulation in Produktion und Logistik: Grundlagen und Anwendungen. Springer Vieweg, Berlin (2017)

5. Jäger, J., Schöllhammer, O., Lickefett, M., Bauernhansl, T.: Advanced Complexity Management Strategic Recommendations of Handling the "Industrie 4.0" Complexity for Small and Medium Enterprises. Procedia CIRP **57**, 116–121 (2016)
6. Kerschbaum, S.: Dienstguetegarantien fuer Ethernet in der industriellen Kommunikation (2016)
7. Mourtzis, D., Papakostas, N., Mavrikios, D., Makris, S., Alexopoulos, K.: The Role of Simulation in Digital Manufacturing – Applications and Outlook. Proceedings of DET2011 7th International Conference on Digital Enterprise Technology (2011)
8. Muriel, A., Somasundaram, A., Zhang, Y.: Impact of Partial Manufacturing Flexibility on Production Variability. Manufacturing & Service Operations Management **8**(2), 192–205 (2006)
9. Panzar, J.C., Willig, R.D.: Economies of scope. The American Economic Review **71**(2), 268–272 (1981)
10. Schmidt-Kretschmer, M., Gries, B., Blessing, L.: Bug or feature? möglichkeiten und grenzen des fehlermanagements in der produktentwicklung. In: DFX 2006: Proceedings of the 17th Symposium on Design for X, Neukirchen/Erlangen, Germany, 12.-13.10. 2006 (2006)
11. Sethi, A.K., Sethi, S.P.: Flexibility in manufacturing: A survey. The International Journal of Flexible Manufacturing Systems (2), 289–328 (1990)
12. Talaysum, A.T., Hassan, M., Goldhar, J.: Scale vs. scope considerations in the cim/fms factory (1986)
13. Traßl, A., Hößler, T., Scheuvens, L., Franchi, N., Fettweis, G.P.: Deriving an empirical channel model for wireless industrial indoor communications. In: 2019 IEEE 30th Annual International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC). pp. 1–7. IEEE (2019)
14. Vukovic, P., Franke, J.: Communication needs of flexible production plants. In: 21. Leitkongress der Mess- und Automatisierungstechnik AUTOMATION 2020. pp. 843–852. VDI VDE (2020)
15. Wollschlaeger, M., Sauter, T., Jasperneite, J.: The Future of Industrial Communication: Automation Networks in the Era of the Internet of Things and Industry 4.0. IEEE Industrial Electronics Magazine **11**(1), 17–27 (2017)