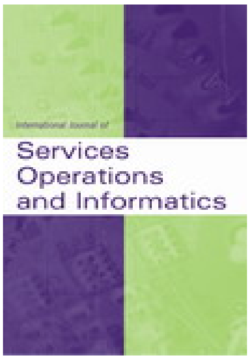

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Extending and demonstrating an engineering communication framework utilising the digital twin concept in a context of factory layouts

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Abstract: The factory layout is frequently planned in virtual environments, based on the experience of software tool users. This planning process is cumbersome and iterative to collect the necessary information, with a high risk of faulty inputs and updates. The digital twin concept has been introduced in order to speed up information sharing within a company; it relies on connectivity. However, the concept is often misunderstood as just a 3D model of a virtual object, not including connectivity. The aim of this paper is to present an extended virtual and physical engineering communication framework including four concepts: digital model, digital pre-runner, digital shadow, and digital twin. The four concepts are demonstrated and described in order to facilitate understanding how data exchange between virtual and physical objects can work in the future and having up-to date virtual environments enables simulating, analysing, and improving on more realistic and accurate datasets.

Keywords: digital model; digital pre-runner; digital shadow; digital twin; factory layout.

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1 Introduction

In the era of digitalisation there are several concepts described in the literature, such as smart factory (Tao and Zhang, 2017), smart manufacturing (Cheng et al., 2020), cyber-physical systems (Lim et al., 2020), Industry 4.0 (Leng et al., 2021), and Industry 5.0 (Nahavandi, 2019). This digitalisation revolution and the concepts just mentioned share similarities and target data exchange to a large extent between several areas and functions of a company, where information in a workshop can be sent and received by sensors, equipment, software, systems, and more.

1.1 The digital factory

The digital factory includes all the planning and design activities of manufacturing and is applied with virtual models to all planning aspects such as product descriptions, processes, resources, factory layouts, capacity, and more (Kuhn, 2006). These activities are usually performed with computer-aided technology (CAx) applications (Kuhn, 2006), such as computer-aided design (CAD), computer-aided process planning (CAPP), and computer-aided manufacturing (CAM), hence in virtual environments (Shafiq et al., 2015), in order to plan, evaluate, and visualise potential outcomes of manufacturing activities. The intention is to first design the models; the physical equipment is then built according to the blueprints and models (Mourtzis et al., 2014). The capability of the CAx applications is continuously evolving and are considered to be a crucial part in the digitalisation journey and future for reducing the development time and cost of product, manufacturing processes, and factory setups (Mourtzis et al., 2014). However, the modern IT landscape is diverse in the sense that different software applications provide different capabilities and functionalities in order to perform the various planning tasks and activities (Zadeh et al., 2017).

The current way of working and the execution of the planning task in one software is in many aspects based on experience of the software tool user, i.e., knowledge and understanding of requirements for the activity in question such as, e.g., factory layout planning. With this way of working based on experience, having little or no existing knowledge and experience of, for example, regulations and standards, easily leads to a planning process that is slow and prone to mistakes and misunderstandings. To add to this, the information generated in one software, from the experience of a user, for one activity of the digital factory planning, is often distributed manually and unsynchronised with other software applications and users that perform other planning tasks and actions (Süße and Putz, 2021). Frequently the information generated with these software applications is stored with its own native data format (Zadeh et al., 2017). This manual approach is a cumbersome iterative process with a high risk of faulty inputs and updates since the information needed by cross-discipline tasks is also created based on experience of the user and manually distributed (Süße and Putz, 2021). In the future this information from CAx applications is expected to be exchanged seamlessly between applications (Lim et al., 2020). The virtual environment allows simulation of alternative outcomes and presents knowledge and analyses of the virtual setup to reduce uncertainty in decision-making processes (De Vin et al., 2010).

This digitalisation process is an ongoing journey for many companies and there are many challenges. The general trend of Industry 4.0 is to automate and assist the manual work with digitalisation (Chromjaková and Hrušecká, 2019). One approach to automate the use of virtual tools is to convert experience and knowledge in the field in question into “smart” solutions in the software tools. The aim is that it should be easy to perform a task or an action correctly, efficiently, and objectively, and the performance should to a lesser degree depend on the background and experience of the user in the planning activity. A growing number of research papers refer to the concept of Industry 5.0. Industry 5.0 focuses, among other things, on the sustainability of the human factor inside the technologies of Industry 4.0 (Panagou et al., 2021). The major point would be to focus on the human and the environment with Industry 5.0 and assist repetitive tasks with, e.g., robots, exoskeletons, or machines to enable the human workforce to focus on more complex tasks in the future (Nahavandi, 2019). Industry 5.0 then extends from previous digitalisation concepts and continues to automate and assist humans and machines to work cooperatively with all kinds of manufacturing tasks and planning activities. From a high-level view, many research papers highlight a recurring notion that digitalisation will have a huge impact on smart industry and its connected systems (Mourtzis, 2020).

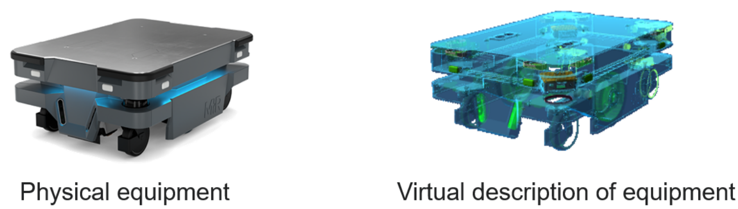
1.2 The digital twin

From a high-level view many research publications emphasise a recurring notion that the digital twin concept is a technology with a huge impact on the digitalisation journey and its connected systems (cyber-physical systems) (Mourtzis, 2020). One perceived intent of the digital twin is to have sensors and historical data available from the physical world to mirror and replicate outcomes in the virtual world in an objective manner (Qi et al., 2021). The digital twin concept is about communication and was first introduced to achieve better simulations, verification, and optimisation of equipment (Grieves and Vickers, 2017).

The digital twin requires a physical artefact and a virtual description of the artefact (Figure 1), in which the physical equipment is connected to its virtual twin representation; the concept also includes the information exchange between the physical equipment and its virtual representation (Tao et al., 2019).

This also relates to other concepts such as internet of things (IoT), which is known as things that are equipped with sensors or software technologies with the possibility of exchanging data with other things over the internet (Rajalakshmi and Shahnasser, 2017). One can interpret IoT as a communication platform (Gerrikagoitia et al., 2019) that allows exchanging information between a sender and a receiver.

Figure 1 The physical equipment and its corresponding virtual representation (see online version for colours)



A digital twin is an application that could utilise such a communication platform as a means of transmitting and receiving information (Rosen et al., 2015). Extending the concept of digital twin to include several physical artefacts and corresponding virtual descriptions, one can then with sensor technology attached to each of the physical artefacts send information, e.g., spatial position or sensor information, to each corresponding virtual description of each artefact and then create a virtual representation of the complete factory (Tran et al., 2021). Hence, representing a digital twin of the factory, this would allow for an up-to-date factory layout ready to be used for simulation, optimisation, and decisions on future outcomes.

1.3 The virtual factory layout

The virtual factory layout is one of the planning activities in the digital factory and describes the equipment setup in a factory.

This includes the spatial positions of artefacts such as resources, equipment, and products that together describe a setup of a factory (Muther and Hales, 2015). The setup of the resources, equipment, and products within a factory presents the potential of the manufacturing possibilities, meaning what and how the factory can manufacture. For example, the setup of resources within a robot cell influences what manufacturing tasks the robot cell can perform, and how the tasks of the robot cell can be carried out.

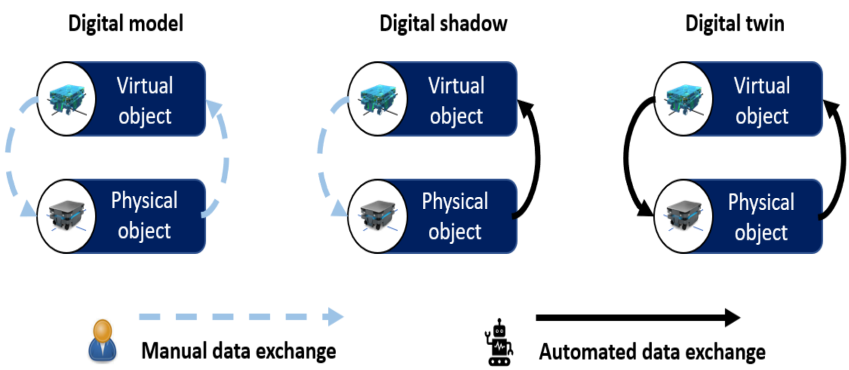
Today these virtual descriptions of factory layouts are frequently prepared and modelled with CAD environments (Shafiq et al., 2015). During the lifecycle of the manufacturing factory, the virtual factory layout is a "living" description that constantly needs to be kept up to date, so that analyses, verifications, and simulations of, e.g., new product or resource introductions can be performed (Silva et al., 2015).

Keeping the virtual factory layout constantly up to date involves updates on existing equipment (e.g., products and resources) as well as adding new equipment, but also updating the actual spatial positions of the equipment. There is no automated process or communication setup to update the virtual factory layout. Hence, each time an update of the virtual environment is required, there is a manual effort of editing and potentially measure positions in the physical factory to confirm the factory layout.

1.4 Challenges

Fuller et al. (2020) describe a framework (Figure 2) in which previous literature is used to position the digital twin concept in regard to how data can be exchanged between a physical object and a corresponding virtual object. However, in the literature and industry there are still common misconceptions of the descriptions of the digital twin and related framework. For example, often just a 3D model, a virtual environment, is described as a digital twin, but with no description on how data are to be exchange with its physical counterpart.

Figure 2 The framework of Fuller et al. (2020) (see online version for colours)



This framework (Figure 2) lists three potential distribution ways to exchange datasets between a virtual object and a physical counterpart: the digital model, the digital shadow, and the digital twin.

The Digital model describes the approach where datasets are distributed between the virtual object and physical object in no form of automatic way; when an update needs to happen across the virtual environment and the physical environment it is done manually in both directions (Figure 2).

The Digital shadow presents a one-way automated distribution of datasets from the physical environment to a virtual environment (Figure 2). The change of state of the physical object is read by the virtual environment. However, if changes are performed in the virtual environment, they need to be introduced manually on the physical object.

The Digital twin allows for a bidirectional data exchange, where a seamless distribution is to be achieved (Figure 2). When a change is made either on the virtual side or on the physical side, the data exchange is automated between the twins (the virtual object and its physical counterpart).

However, the digital shadow and digital twin concepts have not yet been implemented in a broader range in the automotive industry, nor for manufacturing factory setup, and have therefore not yet been evaluated to any large extent (Guzina et al., 2022).

Today the update of the virtual environment is frequently done manually, often calculated with laser measurements, 3D point cloud scans, or other measurements, and then manually edited and updated in the virtual environment (Nafors et al., 2020). Fuller et al. (2020) refer to this manual approach as the digital model concept. With the example of factory layout setup, exchanging information, e.g., measurements between a physical object and the corresponding virtual object's spatial position, is time-consuming and costly in the sense that the measurements often need to be made when the equipment is not in movement, hence often scheduled when production is stopped (Nafors et al., 2020). As a result, such manual measurements and updates of the virtual environment are not done frequently. The manual approach carries a risk of human errors, but also a risk of not having the virtual environment up to date. Usually, with every new product or resource introduction, there is a need to manually remeasure and update the virtual environment to have a description of how the factory is currently performing and then plan for future setup.

There is a need to clarify, exemplify, and demonstrate the digital twin concept to present its potential and realise an objective process to harmonise virtual and physical twins. With these two environments, the physical environment and the virtual environment, there are potentially two times two data exchange patterns, in total four communication possibilities. The first communication way would be no automated communication at all, as in the digital model concept. The second communication way would be automated distribution of information from the physical environment to the virtual environment, presented as the digital shadow concept. The third communication way would be automated distribution of information from the virtual environment to the physical environment, which is not described in the framework by Fuller et al. (2020). Lastly, the fourth communication way would be full automated communication integration where information can flow in both directions between the virtual environment and the physical environment, presented as the digital twin concept.

In this paper the framework described by Fuller et al. (2020) has been extended to include also the automated distribution of information from the virtual environment to the physical environment. This extended framework is referred to as the Virtual and physical engineering communication framework (VPEC framework).

The aim of this paper is to present and demonstrate the VPEC framework. This is done in order to increase awareness of what the digital twin concept is and what it could mean in the context of factory layout setups.

2 Method

The method approach of this research is inspired by the design science research concept (Hevner et al., 2004). Experiences of end users working with factory layout planning in industry together with the literature review revealed the need to clarify what a digital twin is. In order to do so, artefacts in form of demonstrators were built in line with the design science research concept where artefacts are, for example, a software or demonstrator to present a solution for the issue. Information was acquired through observations and interviews with end users, experts, and planning staff in industry, and through literature studies in the research domain.

The framework by Fuller et al. (2020) (Figure 2) was the starting point to build real-world demonstrators, in order to assess the feasibility of the concepts given in the framework. During the development it was noted that the framework can be extended. This paper presents and explains the extended framework.

2.1 The extended framework – VPEC

In this paper the framework presented by Fuller et al. (2020) has been extended to include also the concept of automated distribution of information from the virtual environment to the physical environment, denoted a digital pre-runner. Hence, the VPEC framework contains four concepts for data exchange between a virtual object and a physical counterpart: digital model, digital pre-runner, digital shadow, and digital twin (Figure 10). In order to clarify the VPEC framework and the digital twin concept, demonstrators were built and videos recorded to demonstrate the fundamental characteristics of the various concepts.

The digital pre-runner is added to facilitate a one-way automated distribution of datasets from the virtual environment to its corresponding physical object. The change of state on the virtual object can be distributed and read by the physical environment without necessarily sending data back. This means a distribution of information that is opposite in direction to that of a digital shadow (Figure 10).

The demonstrators and descriptions are presented in the context of a factory layout setup. Communication between a virtual object and its corresponding physical object has been performed with an automated mobile robot (AMR) resource. This resource, the AMR, is equipped with sensors to track its physical location and used to exemplify sending spatial information between a virtual environment and a physical environment. Extending similar approach to several physical objects with sensors and corresponding virtual objects, the sensor technology attached to each of the physical artefacts should be able to send information such as spatial position to each corresponding virtual description of each artefact and then create an up-to-date virtual representation of the complete factory layout.

2.2 The virtual object

In order to demonstrate the digital model, digital pre-runner, digital shadow, and digital twin in the context of a factory layout setup, virtual descriptions of the equipment inside a factory was retrieved. This corresponds to the existing physical setup in the real workshop. For this demonstrator a part of a factory building model was used; designed with AutoCAD Architecture software. The factory building model holds the master origin, i.e., the main reference point of (0,0,0) (Figure 3). The XY-plane is defined as the floor level with the Z-axis upwards. This is taken into account, since when positioning content such as resources and equipment, it should be harmonised so that information can be sent between the software and the physical environment. This is done to enable the transformation matrix to match the corresponding position in the virtual environment.

The virtual resource equipment used to design the virtual factory layout was either received in STEP format from the suppliers or modelled with in-house software Dassault Catia V5 and AutoCAD Architecture. In order to be able to utilise the models in several software, the models were also simplified and exported to .CGR and .DWG formats. The models shared commonalities such as orientation and insertion point/origin definition with all formats (Figure 4).

Figure 3 The building model for the demonstrator and the master origin (see online version for colours)

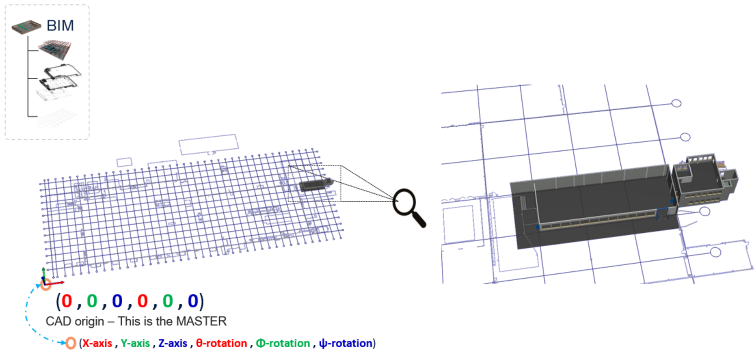
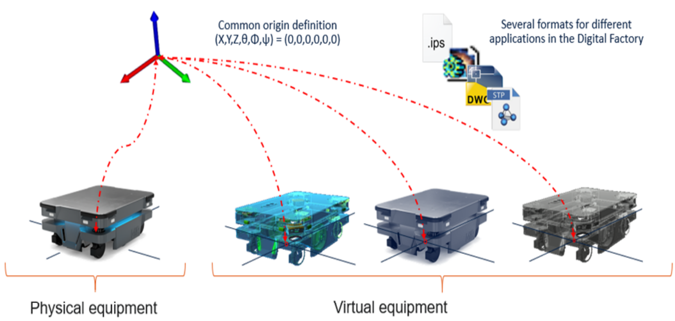
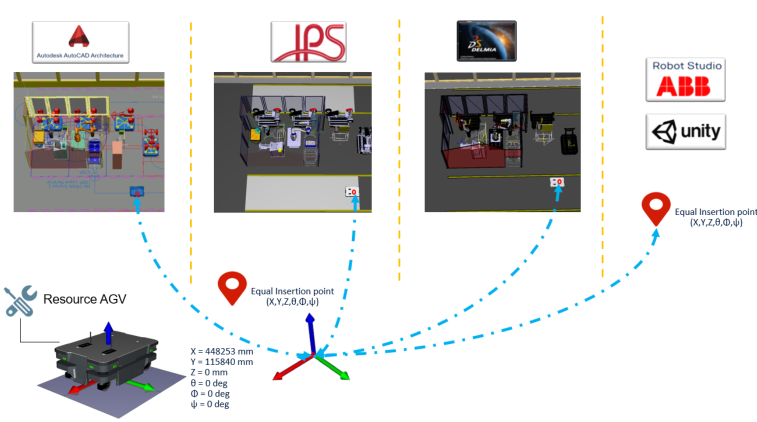


Figure 4 Example of resource description with shared insertion point/origin (see online version for colours)



With all the virtual resources of the workshop specified, the resource models were instantiated with an absolute position in regard to the building model. This describes the setup of the factory layout and could be achieved since the resource descriptions shared the insertion point/origin and orientation (Figures 4 and 5).

Figure 5 Instantiation of resources in several software with shared insertion point (see online version for colours)



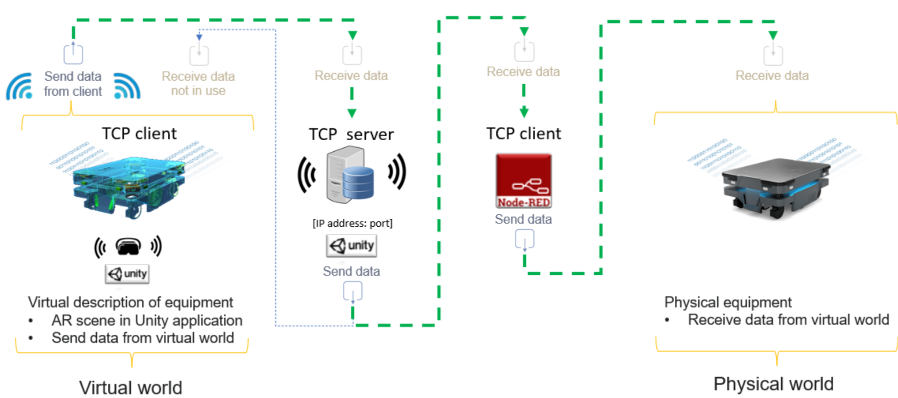
The factory layout content was also exported into .FBX format to enable the import to the software Unity where an augmented reality (AR) application was built for Oculus Quest 2 in order to present the VPEC framework. In Unity, with the AR application, the defined point of origin and world coordinates are intact in order to allow data exchange if needed between different software (Figure 5). The software tool Industrial Path Solutions (IPS) was used to visualise the VPEC framework in a desktop environment. The IPS software is a math-based tool used for simulations of virtual environments. IPS facilitates simulations with rigid body path planning and flexible components (Hermansson et al., 2013), ergonomics simulations (Hanson et al., 2019), robot simulations (Hermansson et al., 2021), and surface treatment processes (Mark et al., 2014).

2.3 *The communication layer*

There are several potential software to create a communication layer between virtual objects and physical counterparts. For the demonstrators of this paper, the software Node-RED was used to create a communication layer between the virtual object and the physical counterpart in order to exchange data. Node-RED is a flow-based programming tool, originally developed by International Business Machines Corporation (IBM) for IoT applications.

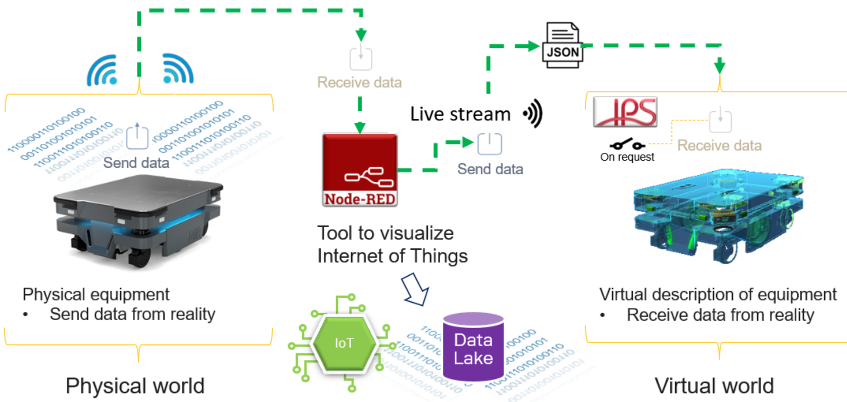
When sending data from the virtual object to its physical counterpart, the virtual environment of the workshop was imported into the software Unity, and then two applications were created to demonstrate the digital pre-runner. Unity allows for programming in C# (C Sharp); with Unity a server solution application to echo received data was created for Windows, and an application was built for an android Oculus Quest 2 device, this android application contained the virtual environment together with a client connection (WebSocket). The Oculus Quest 2 environment acted as a Transmission Control Protocol (TCP) client that sent information to a fixed Internet Protocol (IP) address, and the server solution application acted as a TCP server for the demonstrator, enabling the Node-RED software to connect to the TCP server and receive data sent to the TCP server (Figure 6). Then Node-RED sent the received data to the physical object via Representational State Transfer Application Programming Interface (REST API).

Figure 6 Schematic communication setup, sending data from the virtual object to the physical counterpart (see online version for colours)



To achieve the reversed communication setup, i.e., the sending of information from the physical object to the virtual object, the software tool IPS was connected to Node-RED. The demonstrator enables sending data between reality and a virtual environment with a one-way directed data flow. The physical equipment is connected with REST API to Node-RED and streams its spatial position via Node-RED to the virtual environment setup in IPS. Thereby the virtual environment reads and updates the corresponding virtual description (Figure 7).

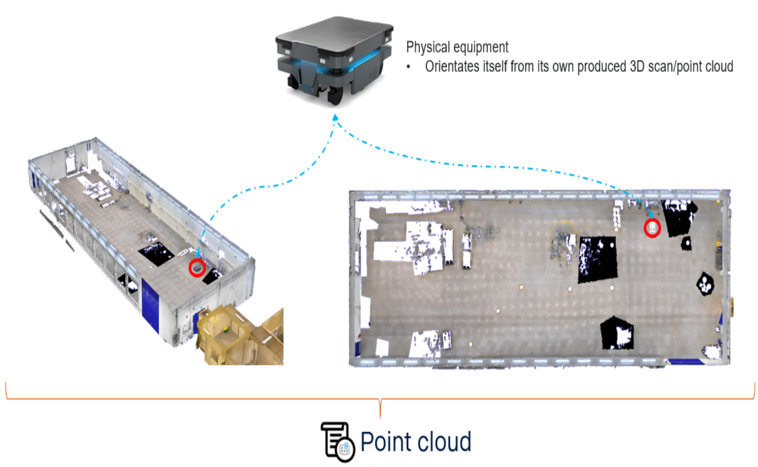
Figure 7 Schematic communication setup, sending data from the physical counterpart to the virtual object (see online version for colours)



2.4 The physical object

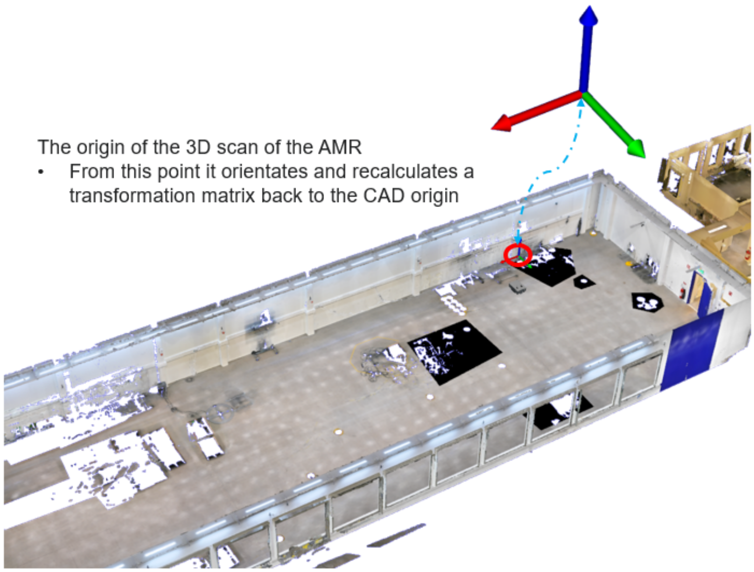
The test was performed with the factory of an industrial innovation arena. The physical object was an AMR, a MiR250 from the company Mobile Industrial Robots (MiR). The AMR has an inbuilt position handling system to track its spatial position and orientation, by the means of 3D scanning its surrounding (Figure 8).

Figure 8 The AMR 3D scans a point cloud to orientate itself (see online version for colours)



The AMR's 3D scan has a locally defined zero coordinate (Figure 9). It is from this coordinate the AMR tracks and calculates its position and orientation. The coordinate of the AMR can be continuously read by Node-RED via rest API. Also, Node-RED can set new positions for the AMR via REST API.

Figure 9 The locally defined origin of the AMR's 3D scan/point cloud (see online version for colours)



Since the virtual environment has its own defined origin (the master origin) (Figure 4), the incoming data from the physical equipment and sensors are recalculated with a transformation matrix before updating the virtual environment and vice versa.

3 Result

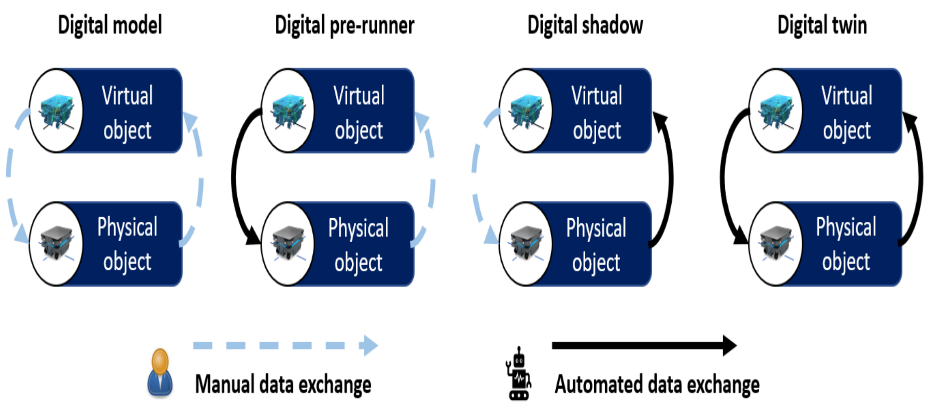
The virtual and physical engineering communication framework (VPEC), and associated examples and demonstrators, facilitates understanding how the digital twin concept could work in the future, in a context of factory layouts.

3.1 The extended VPEC framework

The framework by Fuller et al. (2020) was extended to include the digital pre-runner concept (Figure 10). The VPEC framework then includes an additional possible communication possibility.

In contrast, the digital pre-runner represents a data distribution concept where data is sent from the virtual object to the physical object in an automated manner. The argument is also that the virtual object should be designed in advance in order to be able to take decisions on future outcomes. Then one would want to be able to send such designed information to the physical object when created. If, for example, a workshop has a robot cell for manufacturing a product, the robot code could be created in advance with virtual commissioning technique, and when the physical robot cell is built, the virtual commissioned code could be sent directly to the physical counterpart. Another example would be factories with mobile equipment and resources, were one is able to send the virtually designed spatial positions and coordinates of the virtual object directly to the physical mobile equipment. Hence, automatically rearranging the physical factory identically to the setup planned in the virtual environment.

Figure 10 Extended VPEC framework including the digital pre-runner (see online version for colours)



3.1.1 *Digital model*

The digital model is exemplified with a 2D drawing (Figure 11) of the workshop. The virtual environment corresponds to its physical workshop twin but with no automated data exchange. With this approach the virtual environment is designed and the virtual description is used as decision material to proceed with the physical build-up, but there is no automated data exchange.

The virtual environment can be used for simulations of different aspects and utilised with different software e.g., it can be "awakened" by kinematics to simulate process steps such as robot and human manikin movements and more. The digital model concept also allows for several visualisation possibilities such as desktop visualisation, augmented reality (AR) or virtual reality (VR) and more.

To showcase the digital model concept, an online animation and demonstrator can be viewed at https://vimeo.com/711229609, or via the quick response code, matrix barcode (QR code) in Figure 12. The virtual layout of the factory is displayed in an AR context and positioned in the context of the physical workshop. The animation also displays the animated simulation of the path of an automatic guided vehicle (AGV) with a loaded product and a not yet implemented tightening technique cell is also shown.

The AR environment allows inspecting and presenting not yet implemented workshop installations. A key aspect of the digital model concept is that there is no automated data exchange between physical objects and virtual objects. The purpose of the virtual layout is to plan a future outcome, to test concepts and ideas. However, the actual realisation and information sharing is done manually, either with plotting material on paper, displaying content with desktop, VR (e.g., training workers for new work area setup), AR, or other functionality.

Figure 11 Factory layout setup presented in a 2D drawing (see online version for colours)

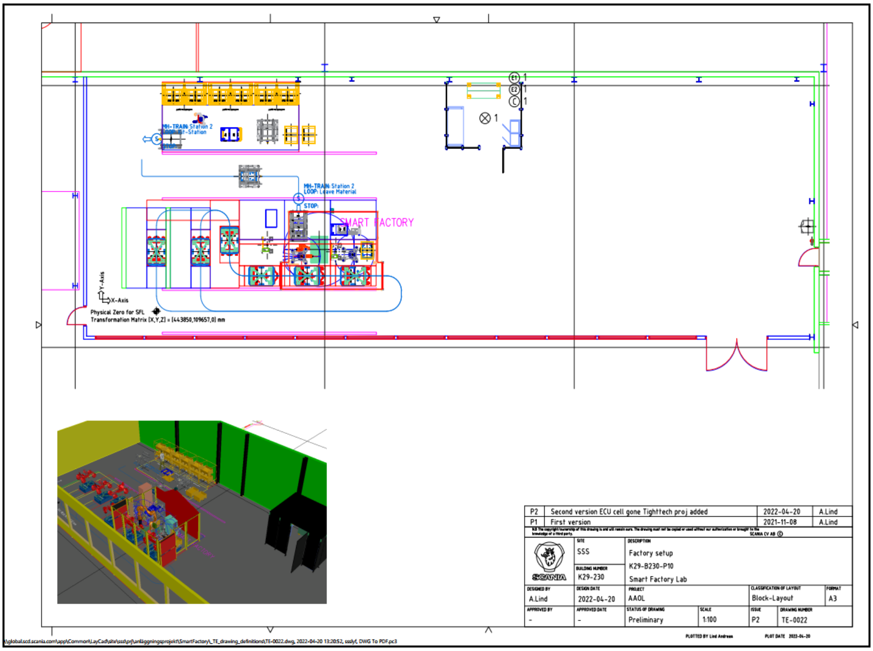
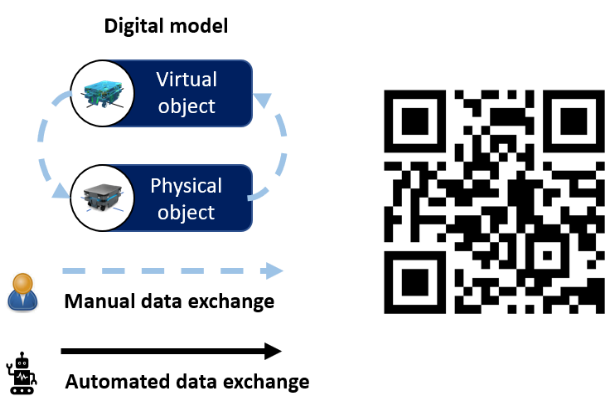


Figure 12 A digital model animation can be called up with the QR code (see online version for colours)

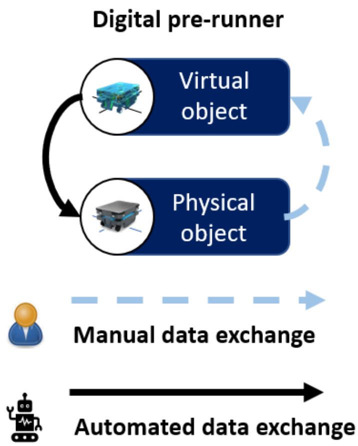


3.1.2 Digital pre-runner

The difference between the digital model and the digital pre-runner is how information is distributed between the virtual object and the physical counterpart. Information created in the virtual environment can be forwarded to the physical object in an automated way; in a sense the virtual environment can control the physical environment.

To showcase the digital pre-runner concept, an online animation and demonstrator can be viewed at https://vimeo.com/711234094, or via the QR code in Figure 13.

Figure 13 A digital pre-runner animation can be called up with the QR code (see online version for colours)



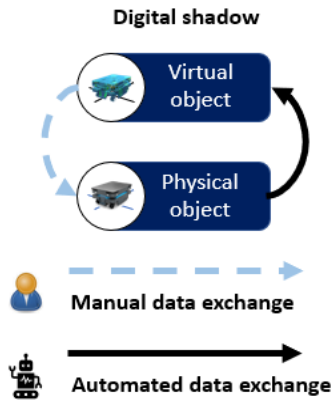
Parts of the virtual environment of the factory are displayed in an AR context, where a virtual object is operated with the controllers in the AR setup; then, when the virtual object is put in position, the virtual coordinates can be sent via Node-RED to the physical counterpart and trigger a task to go to these coordinates and new location/teach new positions.

The AMR in this case can be given new positions based on the virtual factory layout setup. Having the factory layout setup context in mind, this could be seen as similar to virtual commissioning but with actually sending and executing the physical environment based on virtual content. This could as well work for a typical robot cell setup analysed, simulated, and optimised in the virtual environment and then sent to its physical counterpart.

3.1.3 Digital shadow

The digital shadow demonstrator is implemented with a connection between the physical equipment via Node-RED and the virtual environment of IPS. The incoming data from the AMR are distributed via Node-RED and are automatically read by IPS, which updates the spatial position of the corresponding virtual description of the equipment in the virtual environment of IPS. The connection thereby updates the positions and allows an objective approach to positioning the virtual equipment since it is a value sent by the physical equipment rather than performed manually, which would involve subjectivity. Figure 14 includes a QR code that leads to an online animation of a developed demonstrator exemplifying the digital shadow concept, the animation can also be viewed at https://vimeo.com/711238375.

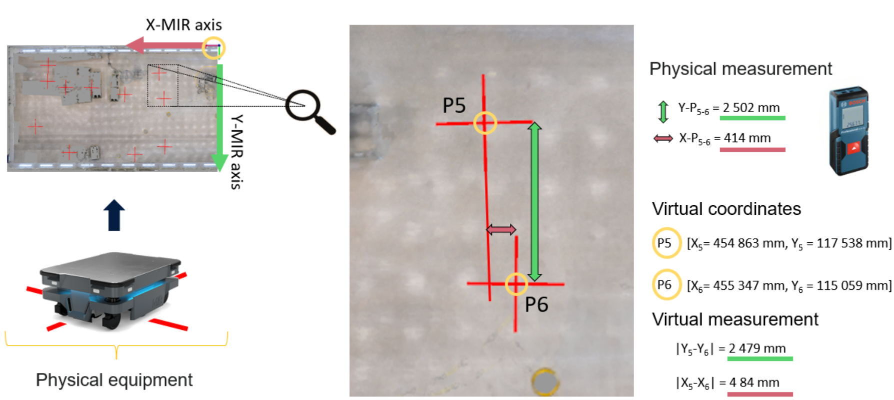
Figure 14 A digital shadow animation can be called up with the QR code (see online version for colours)



The connection between the physical equipment and sensors via Node-RED and the virtual environment of IPS is functional, but the precision of the sensors of the physical objects can be questioned. To evaluate the achieved and updated spatial positions in the virtual environment based on data sent from the physical equipment, a test was conducted, and the physical AMR resource was sent to 10 positions in the workshop. For each position the floor was physically marked with the centre point of the physical equipment (Figure 15). Then a digital laser rangefinder (model GLM30/Bosch with a stated precision of plus/minus 2 mm) was used to measure the distance travelled.

Then from the updated virtual environment, the coordinates of the virtual object were read and calculations of differences between the positions in the virtual environment were compared with the distance measured by the digital laser rangefinder in *x* direction and *y* direction.

Figure 15 Ten locations and markings of the physical object's positions (see online version for colours)



The resulting values for the 10 observed points per equipment are presented in Table 1. The results are based on the absolute value distance for each difference between physical measurements and virtual measurements.

Table 1 Results from the AMR digital shadow evaluation

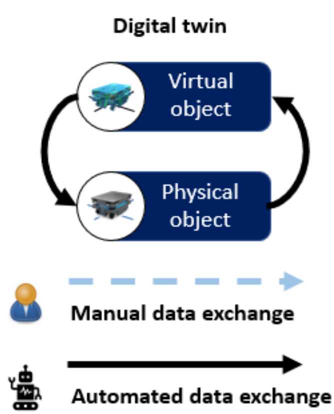
Direction	*Mean* [mm]	*Standard deviation* [mm]
X	21	19
Y	31	17

The expectation is that sensors, either inbuilt ones or potential external sensors added to or mounted on equipment, will have higher accuracy in the future. With the factory layout setup context in mind, if one were to have sensors on all equipment in the factory, with a push of a button the virtual factory layout would be up to date and available for future layout planning activities.

3.1.4 Digital twin

Combining the digital pre-runner and digital shadow concept, a bidirectional automated data exchange is enabled, i.e., representing the digital twin approach in the VPEC framework (Figure 10). This concept is showcased with an online animation and demonstrator at https://vimeo.com/711239358 and also reachable with the QR code in Figure 16. With an AR environment, the virtual environment as well as the physical environment are displayed simultaneously. The virtual object is controlled, and new positions can be set and sent to the physical counterpart; when the physical object operates, it sends the spatial positions back to the virtual environment of IPS.

Figure 16 A digital twin animation can be called up with the QR code (see online version for colours)



With this approach, a bidirectional automated data exchange is achieved. Then, extending this concept of digital twin to include several physical objects and corresponding virtual objects allows utilising the digital twin for the complete factory, based on the condition that sensor technology is accurate enough.

4 Discussion

The demonstrators exemplify the four concepts of the extended virtual and physical engineering communication framework (VPEC) (Figure 10), i.e., a digital model, a digital pre-runner, a digital shadow, and a digital twin. This paper does not claim the presented solution for the demonstrators to be the only possible solution, there are several other software that could be considered to create similar capability. Exactly which software and integration to choose is out of scope of the research, the achievement of the developed demonstrators is to showcase the capability of the extended framework. The conclusions are drawn from realising the demonstrators and referring to relevant publications. The demonstrators are presented with AR and desktop visualisation techniques, however the visualisation could also be performed with other procedures such as, virtual reality (VR), mixed reality (MR) or other means of visualisation.

Publications highlight the need for digital twins in industry and states that digital twins are part of the Industry 4.0 and Industry 5.0 concepts. However, there is a scarcity of publications that present, demonstrate, or evaluate the actual outcome of such ideas, especially in a manufacturing perspective. The digital twin is a hot topic within Industry 4.0 and Industry 5.0 and it is believed to assist and enable faster decision makings on accurate datasets. With this paper, the digital twin concept is positioned as one out of four communication possibilities, within an extended virtual and physical engineering communication (VPEC) framework for data exchange between virtual objects and physical objects. The VPEC framework, including the demonstrators built, aims to facilitate clearer comprehension of the digital twin concept. Since there are several publications that does not distinguish between 3D models and digital twins, the VPEC framework and demonstrators assist in exemplifying the digital twin concept and allows for other solution and communication possibilities to select from e.g., the digital model, digital pre-runner and digital shadow concept. The question could also be raised if it is always necessary to strive for the digital twin in industry, is there really the need to automate all communications between the virtual and physical environment. The VPEC framework presents possibilities of communication selections and there still is need to investigate further requirements both on the virtual side and on the physical side. With regards of sensor selection, accuracy requirements and more.

To have the spatial positions sent from the physical equipment to the virtual environment requires high precision, so that the virtual environment is as accurate as needed and the trust in the correctness of the virtual environment is unquestioned. When this is achieved, it should be possible to minimise manual work to keep the virtual environment of the factory layout up to date as well as to run updates in the physical factory. With an up-to-date virtual environment, more accurate simulations and optimisations of the factory setup can be achieved. Examples of such possibilities are to evaluate ergonomic conditions or to optimise robot paths for robot cells in realistic and up-to-date virtual environments. Also, one could imagine making virtual reality visits to hazardous or sensitive factory environments in a safe way or studying things that otherwise would be hard or impossible to see and reach in the real world.

The VPEC framework is expected to work not only for factory layout purposes but also for other applications in manufacturing, e.g., filling rate information in material facades were planned filling rate (virtual side) and current filling rate (physical side) could be distributed and used in between for decisions.

The main contribution of the paper is the extended virtual and physical engineering communication (VPEC) framework with four potential communication strategies available to send information between a planned environment and a physical execution environment. Together with actual demonstrator presenting these four concepts.

4.1 Consideration of results

To realise a digital twin solution, the virtual object needs to be described in such a way that it shares commonalities with its corresponding physical object. The aspect of the definition of the origin of the object would be important in data exchange in regard to spatial position (Figure 5). If the spatial position is to be sent from the physical environment and update the virtual environment and vice versa, the origin definitions on the object level need to match.

Further, an evaluation of the data being sent needs to be carried out, and the data sent from the physical sensors need to be evaluated. With the digital shadow example, it can be questioned whether this accuracy is sufficient. In some cases, such levels of accuracy might be good enough, but in other cases, for example, in a robot cell, the accuracy might rather need to be in millimetres in accordance with reachability tests and clash analyses, and simulations of such equipment need to be done with a virtual environment with high accuracy. There is a need for more development and research to increase the accuracy but also to better understand how accuracy depends on application.

In summary, today's user experience based and manual work approach to keep virtual environments up to date is cumbersome and subjective, with a high risk of faulty inputs and updates. The VPEC framework, with associated demonstrators, present ways to create connection between reality and a virtual environment in various ways, where the virtual environment can be automatically updated based on incoming real-world data. Even with the current accuracy of the demonstrator, it still offers the possibility to track changes observed in reality, which should trigger the need to understand and react on changes so that updates of the virtual factory layout are made.

It is always important to keep the factory layout planning up to date. With all phases and descriptions of the factory layout, decisions are taken to proceed with projects and how to execute manufacturing. To know where, meaning the spatial positions, the resources in a factory are actually positioned, defines the factory layout. Of course, it is not possible to connect a virtual object to the corresponding physical object until it exists but when projects are realised and connected to the virtual environment, it should be possible to verify the layout and evaluate its planning. With the up-to-date factory layout, the decisions and activities in the digital factory capabilities should have a great starting point to consider aspects for the future projects in the manufacturing factory and evaluate and plan on up-to-date information. The factory layout description is used as input for several activities for manufacturing planning.

4.2 Thoughts on the virtual object

Our literature analysis shows that the general descriptions agree on great benefits of digitalisation. However, the analysis indicates that the concepts of digital twin, Industry 4.0, Industry 5.0, and cyber-physical systems appear to be described from a high-level view in the sense that there is no real explanation as to what is required on the actual lower levels such as resource level, nor on how to enable distribution of information between applications supposed to be connected. To further explain this gap, today's commercial applications used to create, simulate, and analyse geometrical datasets in virtual planning activities share commonalities as well as have differences. For instance, the coordinate system definition differs between commercial applications. This is a vital feature to have control of, if the intention is to connect systems such as those proposed in the digital twin, Industry 4.0, Industry 5.0, or cyber-physical system concept. For example, if user A working in application B needs to collaborate and distribute information such as spatial position to user C working in application D, there needs to be an understanding on the different conditions in the applications. Potentially conversions and transformation matrices need to be dealt with, when distributing data between systems (Figure 17).

4.3 Means of communication

The extended virtual and physical communication framework presented in this paper has been showcased with a wireless setup and one AMR unit with inbuilt sensors and a Wi-Fi connection. When extending the VPEC framework and including several resources, there are several distribution possibilities such as Wi-Fi6, LORA, 5G, ethernet cables, etc. This paper used the Node-RED software as the communication layer between a virtual object (AMR) and its physical counterpart, but there are several potential software to be used to create similar communication layers as well as all kinds of equipment and resources (e.g., robot arms, turning machines, drilling machines, tables and more) to connect and exchange datasets between. There are of course other software available to visualise 3D models and content, together with several connection protocols among WebSocket's, MQTT brokers and more. The belief is that such software and connection protocols also are able to connect to similar communication layers to achieve the communication possibilities presented with the VPEC framework.

Figure 17 Software share similarities as well as have differences (see online version for colours)

Design applications Where data are created	**Simulation applications** Where data are reused	**Visualization applications** Where data are reused
Examples Part design Assembly design BIM creation Factory design	Examples Animation Simulation Commissioning	Examples Immersive (VR, AR, MR) Application viewers
Examples of applications • Autodesk AutoCAD • Dassault CATIA Both have Right-handed coordinates Z-axis up	Examples of applications • Industrial path solutions (IPS) • ABB Robot Studio Both have Right-handed coordinates Z-axis up	Example of applications • Unity Left-handed coordinates Y-axis up

There will be a mixture of these regarding how physical objects are connected and how the IT security will be handled in the future. Hence, there will be resources connected with wires as well as wireless ones, probably depending on resource type and the possibilities of the resource. There will be resources with inbuilt sensors and resources with attached exterior sensors; what solution is most applicable depends on the application.

5 Conclusion

This paper presents an extended virtual and physical engineering communication framework of data exchange between virtual objects and physical objects with examples of digital model, digital pre-runner, digital shadow, and digital twin. A successful realisation of a digital twin solution can facilitate analyses of all kinds of data from reality to virtual environments and vice versa. With data mapped correctly to the corresponding virtual model, one can use the data to simulate and optimise the virtual environment and then use it as a base to implement and improve reality. This is a step towards Industry 4.0 and Industry 5.0, i.e., to be able to reuse information from reality in virtual upstream preparation activities and make use of data.

The virtual object offers capabilities to simulate and analyse, but it can only simulate the content that is present and accessible in the virtual environment.

5.1 Future research

Factory layouts are today described and prepared with modelled virtual environments. The planning process is most often done based on experience of users, and the factory layout depends on several different inputs in separated planning tasks. The digital twin concept has not yet been implemented on a large scale in the automotive industry and for manufacturing factory setup and therefore not yet evaluated to a large extent. Frequently updates of the virtual environment are performed manually, either with laser measurements, 3D point cloud scans, or other measurements, and then manually edited and updated in the virtual environment. Although the dependencies are cross-disciplined between planning activities, the data information created in one task is often distributed manually as input to other planning activities. Therefore, the planning activities do not consider all variables simultaneously, thereby increasing the risk of sub-optimising the interests of different activities.

With this as background and with previous explanation of, for example, the importance of point of origin, standardisation of both the virtual object descriptions and physical object is needed, this area calls for future research. Further, in digital factory planning activities, the factory layout is but one of the activities concerning the spatial position of the equipment. However, there are several other planning activities and potentially other kinds of information in the future that need to be exchanged between a physical and a virtual object; it is expected that, e.g., sensor status such as open or closed fixtures, and other signals are also useful to exchange.

The benefit of having an up-to-date virtual environment is that one is then able to simulate, analyse, and improve on more realistic and accurate datasets. A future outlook would also be to find optimisation possibilities on up-to date factory layouts and the possibility to implement improvements across the virtual and physical environment in a faster manner.

Then one could imagine virtual reality visits to hazardous or sensitive factory environments in a secure virtual way to present safe ways to conduct studies of running production systems. Or indeed study things that otherwise would be hard or impossible to study in the real world. However, the sensors and position data need to have high accuracy, and evaluation is necessary. The information received from the position of the physical equipment requires higher precision if the virtual environment is to be updated automatically, since the virtual environment is a basis for decisions and simulations of the process and factory setup. When precision expectations are met, a digital twin concept can be realised, meaning an up-to-date virtual environment automatically updated for virtual commissioning and optimisation of production processes.

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