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# Procedure for creating a digital factory model in brownfield planning

## Vorgehen zur Erstellung eines digitalen Fabrikmodells in der Brownfieldplanung

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**Companies need valid models of their production and logistics systems as well as their buildings to plan and optimize their production facilities. For the most part, these models are not up-to-date, sometimes only available as PDF documents and not as CAD models, and certainly not as digital 3D models. Despite long-established technology such as laser scanning, 3D factory models are not yet widespread in the industry. A survey conducted underpins the need for a process model. This article presents a process model for creating a digital factory model to solve the problem addressed. The digital factory model is created in seven steps, starting with the definition of objectives, followed by the selection and use of suitable hardware and software. It enables stakeholders in production and logistics to plan and optimize more efficiently. The procedure is applied and evaluated in an industrial project.**

*[Keywords: Factory planning, Digital factory model, Laser scanning, Mobile mapping, Point cloud]*

**Für die Planung und Optimierung benötigen Unternehmen valide Modelle ihrer Produktions- und Logistiksysteme sowie ihrer Gebäude. Diese Modelle sind zumeist nicht aktuell, teilweise nur als PDF-Dokument und meistens nicht als 3D CAD-Modell verfügbar. Trotz etablierter Technologien wie dem Laserscanning sind 3D-Fabrikmodelle in der Industrie noch nicht weit verbreitet. Dieser Artikel stellt ein Vorgehen für die Erstellung eines digitalen Fabrikmodells vor, um das angesprochene Problem zu lösen. Der Bedarf eines solchen Vorgehen wird durch eine Umfrage bekräftigt. Das Fabrikmodell wird in sieben Schritten erstellt, beginnend mit der Definition der Ziele, gefolgt von der Auswahl und dem Einsatz geeigneter Hard- und Software. Es ermöglicht den Beteiligten in Produktion und Logistik eine effizientere und validere Planung und Optimierung durchzuführen. Das Vorgehen wird in einem Industrieprojekt angewendet und evaluiert.**

*[Schlüsselwörter: Fabrikplanung, Digitales Fabrikmodell, Laserscanning, Mobile Mapping, Punktwolke]*

## 1 INTRODUCTION

In the fast-paced world of modern industry, companies are faced with the challenge of planning and optimizing their production facilities efficiently and with an eye to the future. A central aspect of this task is the precise representation and analysis of existing building structures as well as production and logistics systems. However, this information is often only available in insufficiently updated formats, such as static PDF documents, which make holistic planning difficult. In particular, there is often a lack of digital CAD or 3D models that enable a detailed virtual representation of building structures and systems [1]. These can be 2D drawings as well as 3D models of assets, for example. One potential reason for the lack of CAD plans is that the assets is so old that no digital data is available [1]. For companies that do have factory layout data, it should be emphasized that this is often outdated layout data and no longer corresponds to reality [2]. Another challenge relevant to factory planning is the consideration of existing restrictions in factory operations, such as existing infrastructure [3]. For many companies, the recording of existing structures is time-consuming and is therefore often avoided, so that no layout data is available; this is associated with a great deal of effort, especially for SMEs [2]. Overall, redesigning a factory can be considered a complex and resource-intensive process [4]. The digital factory approach helps to meet these challenges. The digital factory helps to avoid costly adjustments during operation. Furthermore, planning tasks can run in parallel to increase the speed of the planning process [5]. The adaptability of a factory is a key characteristic, as factory planning must be agile and continuous [6]. To ensure this, digital factory models can be used to support factory conversion projects [4].

The aim of this contribution is to develop a generic process model for the creation of digital factory models, which should enable stakeholders in production and logistics to plan and optimize more efficiently and validly. The focus of the process model is on the recording and processing of data in brownfield factories.

A quantitative research survey in the form of a questionnaire according to Kurzhals [7] was used to gain a better understanding of current practice. The questionnaire was implemented using an online tool and contained both predefined response options and the opportunity to formulate your own response. In the survey, 15 experts from 13 companies, all of which belong to the manufacturing industry, answered eleven questions. Eight of them work in mechanical engineering, five in the automotive industry, one in research and one in the furniture industry. Most of the experts are employed in factory and logistics planning and industrial engineering. Managing directors, department and group managers, project managers and one master's student took part in the survey. The survey dealt with the challenges of brownfield planning, the availability of 2D and 3D data, experiences with capturing real structures, the use of software for layout planning and the potential added value of digital factory models.

The results of the research survey serve as the basis for the process model developed. Out of these results, requirements for the process model were derived. The survey also aims to underpin the necessity of the process model.

As previously mentioned, one question in the survey addressed the challenges of planning brownfield projects (Figure 1). As can be seen from the figure, the most frequent answers were outdated layout data, the consideration of existing infrastructure and the lack of 2D plans of buildings and technical building equipment. This result of the survey thus underpins the challenges listed at the beginning of this chapter.

## 2 DEFINITIONS

In this chapter, significant terms are defined to improve the understanding of this article.

### 2.1 DIGITAL FACTORY MODEL AND DIGITAL TWIN IN THE CONTEXT OF THE DIGITAL FACTORY

According to Stark [8], a digital factory model represents the overarching and unifying information and data model for holistic planning and is therefore the overall result of digital factory planning. It is important to emphasize that the digital factory model is a component of the digital factory and should not be equated with it. The term digital factory is defined in the VDI 4499 standard as "[...] the generic term for a comprehensive network of digital models, methods and tools - including simulation and 3D visualization - integrated by a continuous data management system." [9]. Accordingly, it is important to view the digital factory model in the context of the digital factory as an integral part of it.

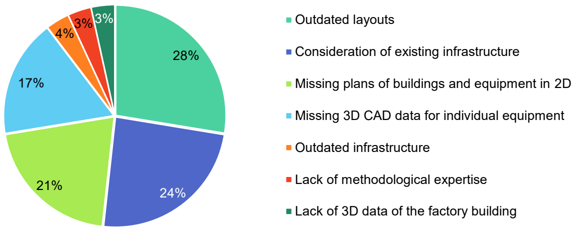


Figure 1.: *Results of the survey on challenges in brownfield planning*

Finally, the term digital factory model is used in this article for 3D models of individual pieces of assets through to entire factories for purposes such as planning, simulation, documentation and analysis.

The term digital twin is also used in the literature. This term is often interpreted and used differently in industry. The Fraunhofer-Gesellschaft [10] defines the digital twin as a "[...] concept with which products, machines and their components are modeled with the help of digital tools, including all geometry, kinematics and logic data. A digital twin is the image of the physical asset in the real factory and allows it to be simulated, controlled, and improved" [10]. In addition, a digital twin is a realistic representation of a physical space through actual data in real time, enabling simulations and predictions with a digital twin [11].

Overall, it can be deduced from the above-mentioned literature that a digital twin represents a more comprehensive image than a digital factory model. In the context of the present work, digital factory models can ultimately serve as the basis for the creation of a digital twin.

### 2.2 LEVEL OF DETAIL (LOD) VS. LEVEL OF DEVELOPMENT

The Level of Detail (LOD) contains information about the geometric level of detail of a model from a visualization perspective and indicates how detailed the model element is. There is also the Level of Development, which includes associated alphanumeric information in addition to the specification of geometric details and is mostly applied in Building Information Modelling (BIM). These are attributes that are assigned to the model [12, 13]. According to the American Institute of Architects (AIA) and the BIM Forum, six Level of Development are defined [14, 15]. Level of Development 100 represents the least detailed level and Level of Development 500 the most detailed level, the so-called “as built”.

As this article does not focus on a BIM project in which the Level of Development is important, but rather contains a procedure for creating digital factory models in which the geometric details of models are decisive and information-related details about the models can be neglected, the Level of Detail (LOD) is used in this work. In addition, the LOD is used in this paper as an important criterion for the quality of a factory model.

## 3 STATE OF THE ART

The following section provides an overview of the state of the art relevant to this paper. It covers hardware technologies for real structure detection, processing of point clouds, simplification of 3D CAD models and meshes, and automatic segmentation of objects from point clouds.

### 3.1 CAPTURING STRUCTURES USING HARDWARE

This chapter contains the capturing of structures using different hardware technologies.

### 3.1.1 3D LASER SCANNING

Two laser scanning methods are of importance for this article. The first is terrestrial laser scanning (TLS) and the second is mobile mapping systems (MMS). TLS have been in use for a long time. In their study, Liu et al. [16] examined 58 articles published between 2012 and 2022. It was found that 50 terrestrial laser scanners from five brands were mentioned in the articles, with the companies FARO Technologies, Inc. and Leica Geosystems AG being the most frequently represented with their laser scanners.

In addition to TLS, portable mobile mapping systems have established themselves in recent years as a fast and efficient technology for data acquisition [17]. Furthermore, these systems are designed to be handy, easy to carry and lightweight, which facilitates their use and data collection in confined and hard-to-reach areas. These mobile mapping systems can, for example, be carried as a backpack or by hand [18]. One example is the NavVis VLX, which is a mobile mapping system widely used in digital factory planning [19]. Another examples is the FARO® Orbis™ Mobile Scanner, which offers the functions of a stationary and mobile scanner [20].

### 3.1.2 UAV-PHOTOGRAMMETRY

In addition to laser scanners, unmanned aerial vehicles (UAVs) are increasingly being used in factory planning to record buildings and facilities [21]. A distinction is made between UAVs that take off vertically and those that take off horizontally. In the case of vertical take-off UAVs, multicopter, as a type of drone, are proven hardware that is characterized by high flexibility and stability when flying [22]. The main advantages are the short data acquisition time and flexibility [23]. Disadvantages include possible permits for a flight authorization and the limitation to indoor areas in case of poor weather conditions outdoors [21].

Finally, the EU-wide AIMS5.0 research project should be mentioned, which aims to create a digital twin of a factory by capturing data with an autonomously flying drone [24]. The drone to be developed is to be equipped with cameras and sensors and should fly through a factory from BMW Group. The factory is to be scanned by the drone every night so that a daily updated digital model is available. The aim is to achieve a measurement accuracy of at least 2 mm. The challenge lies in the technical feasibility, as the drone should autonomously recognize obstacles and plan the route independently [24].

### 3.2 FURTHER PROCESSING OF POINT CLOUDS

The result of data acquisition using the hardware technologies described above (3D laser scanning or UAV photogrammetry) is a point cloud or a photo. The following chapter describes how these can be further processed. Modeling and the creation of 3D meshes are presented as possible further processing steps of a point cloud.

### 3.2.1 MODELING FROM POINT CLOUDS

One way of further processing a point cloud is modeling. An example for a comprehensive software application for state-of-the-art modeling is As-Built™ for Autodesk Revit®, which was developed by FARO Europe GmbH for modeling building models and point cloud data in a 3D environment [25]. A model can be created from a point cloud in an "as-built" state. The application of this technology allows for semi-automated modeling as the software enables the recognition of objects and provides suggestions for footprints, walls, doors, windows, columns, beams, pillars, roofs, and piping that can be selected and precisely aligned. In addition to Autodesk Revit®, suitable software programs for modeling from point clouds include MicroStation® from Bentley Systems and the software from Halocline GmbH & Co. KG, for example.

### 3.2.2 CREATING MESHES FROM POINT CLOUDS

Another way of processing point clouds is to create meshes. Poux [26] emphasizes in his dissertation that meshes are one of the most common forms of representation of 3D models. A three-dimensional mesh consists of many triangular faces, which are referred to as polygons and are connected to each other by vertices [26]. A mesh can therefore be described as a polygon mesh, which is used for the geometric description of surfaces.

### 3.3 METHODS OF SIMPLIFYING 3D CAD MODELS AND MESHES

This chapter presents methods for simplifying 3D CAD models and meshes.

### 3.3.1 METHODS FOR SIMPLIFYING 3D CAD MODELS

As part of the research survey, the experts were also asked about the data available in the companies. The results (Figure 2) show that four experts state that 3D CAD models of individual items of equipment are partially available at in their company. Ten experts respond they are fully available. Only one person stated that no 3D CAD models were available. Based on the results, it can be assumed that 3D CAD models are available in many manufacturing companies, which is why they will be discussed in this chapter.

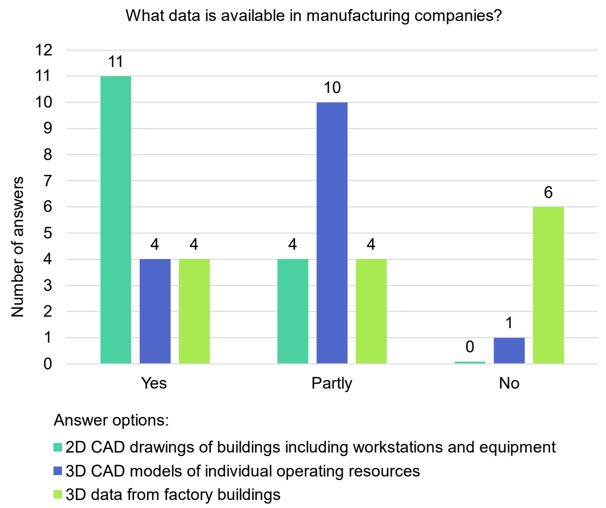


Figure 2.: *Evaluation of existing data in manufacturing companies*

In contrast to meshes, 3D CAD models are defined as a type of 3D models that are not based on point clouds, but are created according to Douglass [27], e.g. by direct or parametric modeling. According to the VDI guideline 3633 [28], a data reduction of 3D models is often necessary to harmonize the performance of a computer with the optical quality of the representation of a model. Suriyababu et al. [29] also point out that CAD models often have complex geometries and contain complicated components and holes. For these reasons, model simplification is an important factor. 3D CAD models can be simplified in suitable software by removing complex internal geometries from a model. Autodesk Inventor® design software offers extensive tools for simplifying 3D CAD models. For example, components such as holes, curves or chamfers can be removed by manual selection. It is also possible to exclude components after a defined maximum size. Furthermore, entire models or individual components can be replaced by shrink wrapping for strong simplifications [30].

### 3.3.2 METHODS FOR SIMPLIFYING MESHES

A common method for simplifying meshes is shrinkwrapping. Suriyababu et al. [29] have developed an algorithm that uses mathematical morphology to simplify the surface of 3D models consisting of triangular surfaces so that a geometry of a shrink wrap is generated. With this method, the internal geometries of closed bodies can be removed [28].

In addition, the decimation algorithm by Schroeder et al. [31] is a method for simplifying meshes. The algorithm removes vertices in several iterations according to defined criteria so that a new triangle is formed by the resulting holes. This reduces the number of polygons [30].

Another algorithm, by Garland and Heckbert [32], uses quadric error metrics. The error metric determines the importance of a point in the mesh. The algorithm is used to identify and remove unimportant points, thereby reducing the number of polygons [32].

There are many other methods for simplifying meshes, which will not be discussed further in this paper.

### 3.4 AUTOMATIC SEGMENTATION OF OBJECTS FROM POINT CLOUDS

Melcher et al. [33] describe in a study how automatic point cloud segmentation can be used to plan the layout directly in a scanned factory. The basis is a point cloud of a factory hall. The processes described below are carried out in MATLAB® software. The basis for the segmentation is formed by so-called labels, which correspond to an attribute of each point in the point cloud to be able to assign the points to objects. The label makes it possible to identify individual objects in the matrix, whereby the geometry remains identical when an object is reoriented. Furthermore, a voxel model is required for segmentation, which divides the overall model into uniform cuboids. This creates a matrix in which individual voxel elements can be analyzed and connected. Each cuboid is checked to see whether it contains points. If points are contained, the point is marked as occupied. This forms the basis for the region growing algorithm, which starts with an occupied cuboid and searches for other neighboring cuboids with occupied points. All neighboring cuboids with an occupied point are given a common label. The process is repeated until all occupied cuboids in the immediate vicinity have been assigned a label. In addition, the watershed algorithm is used for objects that are physically connected but should be given separate labels. The process starts at the lowest layer of cuboids, whereby labels are generated for all cuboids that touch the ground. Further layers are then checked until different labels meet, for example on pipes. At these points, a boundary is defined to separate the objects, even if they are physically connected.

In summary, all objects can be individually edited, repositioned, exported, and hidden using the labels. However, it is important to emphasize that automatic segmentation requires sufficient point cloud quality. Segmentation can only be performed roughly if the point cloud quality is poor and the boundaries between objects are unclear.

In an article published in 2022, Hülsewede et al. [34] presented two methods for material classification in point clouds using machine learning, which is a subfield of artificial intelligence (AI). According to Plaue [35], machine learning uses algorithms that can output correct results from given input data. This teaches the algorithm with data and allows predictions to be made for new, unknown data.

In the studies by Hülsewede et al. [34], a terrestrial laser scanner is used to capture the facades of a building. The first method is a point-based approach in which each point of a point cloud is given attributes for intensity, roughness, and color information. The Support Vector Machine (SVM) is used as a machine learning method. The attributes of the points are combined into a feature vector and introduced into a training model in MATLAB® software to perform a material-specific classification. Another approach by Hülsewede et al. [34] is image-based, in which deep learning, a sub-method of machine learning, is applied in the form of Convolutional Neural Networks (CNN).

The same features are calculated for each point as in the method described above. However, here the point cloud is transferred into 2D image sections, and the results are transferred back into the point cloud. The classification of the data and transfer of the image data to the point cloud is carried out in MATLAB®. According to the authors, satisfactory results are achieved with both methods presented. However, as incorrect classifications sometimes occur, it is emphasized that optimizations are necessary in further investigations.

## 4 REQUIREMENTS AND SELECTION OF A PROCESS MODEL AS A REFERENCE MODEL

The process model should fulfill general requirements. In particular, the requirements of clarity and comprehensibility, general validity and repeatability are important for the process model described in this article [36, 37].

In addition to general requirements, five specific requirements are formulated which the process model must fulfill, and which arise from the survey results.

1. Identification of the challenges in brownfield planning
2. Necessity of data understanding
3. Enumeration of the possible applications of a digital factory model
4. Need to develop a method for selecting hardware
5. Selection of suitable software for layout planning

Methods from various specialist areas are taken into consideration when selecting a reference model. The process model should be able to process large volumes of data. Therefore, the Cross Industry Standard Process for Data Mining (CRISP-DM) according to Shearer [38], a standard procedure model from data mining, is taken into consideration. Furthermore, the creation of digital factory models takes place in the context of production and logistics and simulations are potentially carried out. Therefore, the process model of VDI 3633 is examined [39]. In addition, the creation of digital factory models takes place in the context of the digital factory, which is why the introduction process of the digital factory is considered [9]. Finally, a recently published process model is used as a possible reference model, which shows the creation of digital models with possible hardware technologies for data acquisition and software applications for data processing and model development [16].

After a comprehensive literature review and an evaluation of the process model based on the general requirements, it can be stated that CRISP-DM is suitable as a reference model. The defined requirements of clarity and comprehensibility, general validity and repeatability are fully met by this process model. Finally, it must be made clear that CRISP-DM must be adapted as a process model for the creation of digital factory models in brownfield planning.

## 5 PROCEDURE FOR CREATING A DIGITAL FACTORY MODEL IN BROWNFIELD PLANNING

The following chapter describes the process model for creating digital factory models in brownfield planning, which is divided into seven steps, which in turn consist of several sub-steps. The structure of the procedure follows the CRISP-DM process according to Shearer [38], whereby the process is supplemented by data acquisition in step three. The outer circle with the four arrows symbolizes that the process model is cyclical to ensure that the process is repeated regularly to keep layouts and the factory model up to date. It can also be a one-off project depending on the target definition. The links between the individual phases are symbolized by visual arrows, which are described in the corresponding sub-chapters.

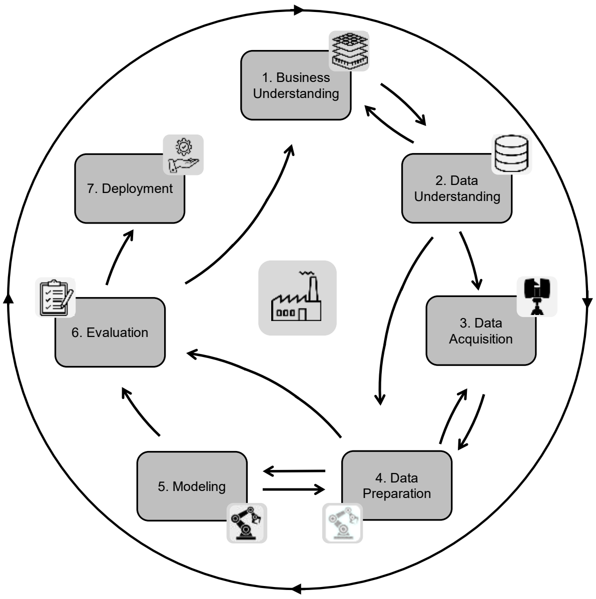


Figure 3.: *Procedure for creating a digital factory model in brownfield planning*

### 5.1 STEP 1: BUSINESS UNDERSTANDING

The first step is to identify the challenges that arise in brownfield planning. Possible challenges have already been mentioned in chapter 1. After identifying the stakeholders involved in the project, which may include factory and logistics planners, suppliers, management, architects and BIM Engineers, the project objectives are subsequently delineated. Consequently, five alternative objectives are discussed that are pursued with the creation of a digital factory model. The list below is not exhaustive:

- Creation of a 2D or 3D block layout using rectangular blocks as a rough layout.
- Creation of a detailed layout in 3D as a result of detailed planning.
- Simulations, e.g. for optimizing the material flow or checking for possible collisions with the building.
- The evaluation of ergonomics at the workplace or the training and further education of employees in production using virtual reality (VR).
- Creating the basis for developing a digital twin of the factory.

The tasks and objectives are defined and recorded in a document in the form of the project assignment [40].

The next step in understanding the business involves determining the planning level, which results from the previously defined objective. Planning levels can, for example, be divided into the production network, plant, building, segment, and workplace levels [41]. In the next step, the requirements that a digital factory model should fulfill are defined and documented in a specification sheet. The requirements are derived from the objectives and define what is to be achieved with the project. Examples of requirements are the level of detail (LOD), flexibility during the development of a digital factory model due to possible changes, simplicity in the form of easy understanding and simple application, visualization and storage in file formats that are compatible with the software programs used. In the next step, it is important to determine the appropriate software programs for the task at hand. These include programs for point cloud processing, modeling, mesh creation, model simplification, layout planning and virtual reality applications. This is followed by the step of economic evaluation of the project. In line with Shearer [38], a risk analysis must first be carried out to identify potential risks associated with the project and derive possible solutions. Furthermore, a business case must be created to analyze and compare the costs and benefits. For a specific practical application, the costs and benefits must be quantified to be able to make a well-founded decision on the profitability of the project. In particular, the benefits of the respective project objective must be comprehensively analyzed and evaluated. The first step of the process model, the business understanding, concludes with the development of a project plan in which all defined aspects are recorded.

### 5.2 STEP 2: DATA UNDERSTANDING

In the second step of the procedure, the aim is to gain an understanding of the data. Depending on the defined project objective, it is necessary to check which data is required or already available. The data can be divided into three categories. 2D data from CAD drawings, 3D data from CAD models of individual pieces of assets and 3D data from entire factory buildings. When analyzing the data, a distinction is made as to whether all, some or no data is available in the company.

Firstly, there is the possibility that all data is already available. If this is the case, the data is first checked for quality. Checking the quality of models involves a comparison with the specifications by defining the required level of detail. In addition to the LOD, the file size, which refers to the size of a single file or model, the data volume, which is the total size of several files or models, and the correct file format are important quality characteristics that must be considered when processing models in software programs. If the quality is poor, there are two possible procedures. On the one hand, data acquisition is necessary if the existing models do not correspond to the LOD from the requirements and more detailed models are required. Secondly, a model simplification (see section 5.4.2) should be carried out in the event of excessive data volumes or file sizes or an incorrect file format. If the quality is sufficient, the data acquisition and preparation can be skipped and the preparation of the models for modeling can continue directly in step 5. Preparation refers to the structured storage of the files in folders or in document management software. It should be emphasized that the sufficient quality of the existing data is a special case in the context of this work and is therefore not considered in the process model (see Figure 3).

Secondly, if part of the data is available, the data must be separated. Two paths are then possible. Firstly, the quality of the existing data must be checked. The further process steps are carried out in the same way as if all the data is available. Secondly, the remaining missing data must be captured (step 3) after the data has been separated.

Thirdly, if no data is available, you must also proceed directly to data capturing in step 3.

### 5.3 STEP 3: DATA ACQUISITION

Step 3 of the process model is an optional step that only takes place if the decision to record data was previously made during data understanding. In the first sub-step (see Figure 4), the requirements resulting from step 1 are evaluated as part of the specifications in order to check the necessary conditions that must be met for the inclusion of a factory building or area.

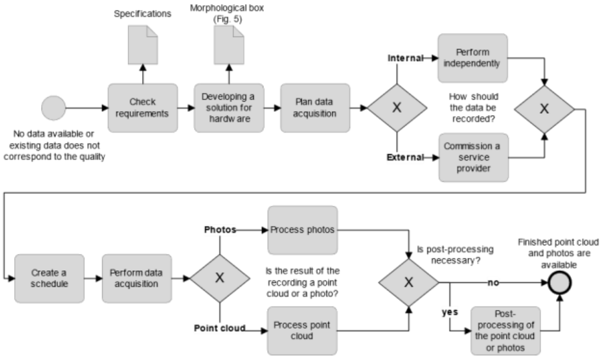
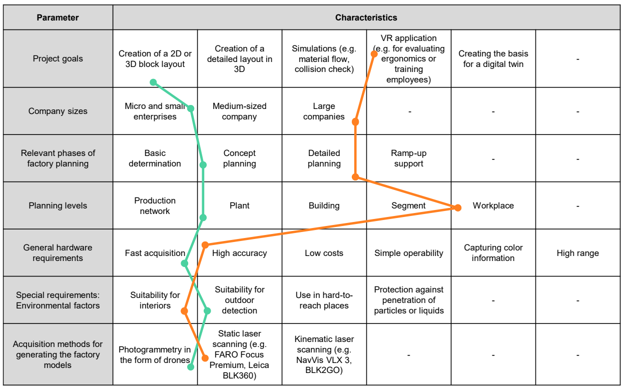


Figure 4.: *Sub-steps of data acquisition*

Step 3 of the process model is an optional step that only takes place if the decision to record data was previously made during data understanding. In the first sub-step (see Figure 4), the requirements resulting from step 1 are evaluated as part of the specifications in order to check the necessary conditions that must be met for the inclusion of a factory building or area. Once these have been compared, the sequence for the next step, in which a hardware solution is developed, can be initiated. The morphological box (see Figure 5) is used to select a suitable solution for the generation of factory models. Various parameters are determined, with each parameter containing several characteristics. By combining the characteristics, a wide range of potential solutions is generated in a multidimensional matrix [42]. Figure 5.: shows this morphological box with the various possibilities. Two exemplary solutions are visualized in the form of colored lines, but these are not to be interpreted as binding recommendations.



| Parameter | Characteristics | | | | | |
|---|---|---|---|---|---|---|
| Project goals | Creation of a 2D or 3D block layout | Creation of a detailed layout in 3D | Simulations (e.g. material flow, collision check) | VR application (e.g. for evaluating ergonomics or training employees) | Creating the basis for a digital twin | - |
| Company sizes | Micro and small enterprises | Medium-sized company | Large companies | - | - | - |
| Relevant phases of factory planning | Basic determination | Concept planning | Detailed planning | Ramp-up support | - | - |
| Planning levels | Production network | Plant | Building | Segment | Workplace | - |
| General hardware requirements | Fast acquisition | High accuracy | Low costs | Simple operability | Capturing color information | High range |
| Special requirements: Environmental factors | Suitability for interiors | Suitability for outdoor detection | Use in hard-to-reach places | Protection against penetration of particles or liquids | - | - |
| Acquisition methods for generating the factory models | Photogrammetry in the form of drones | Static laser scanning (e.g. FARO Focus Premium, Leica BLK360) | Kinematic laser scanning (e.g. NavVis VLX 3, BLK2GO) | - | - | - |

Figure 5.: *Morphological box for the development of a hardware solution*

Once the hardware has been selected, the data acquisition must be planned. The first decision to be made is whether it is economical to commission a service provider to record buildings or whether, alternatively, the hardware should be purchased to carry out data recording independently. The decision depends on various factors and must be made individually. A schedule with project phases should then be drawn up, setting out when the data acquisition should be carried out. Once all preparations have been completed, the data acquisition can begin. It should be noted that the duration of data collection can vary depending on the technology and covers different time frames. As soon as the data acquisition has been completed, the photos or point clouds created can be processed in the next step. Processing includes the conversion of collected raw data into point cloud files in a software program and the subsequent linking of the point cloud files from individual viewpoints into an overall point cloud. Examples of software programs for processing point clouds are NavVis IVION, FARO® SCENE or Autodesk ReCap® Pro. Alternatively, photogrammetry technology can be used to create and process photos without generating a point cloud. Examples include the hardware technologies from HottScan GmbH and immersight®, which can be used to create 3D models from images. The software programs ReCap® Photo or Agisoft Metashape, for example, are suitable for processing digital images and creating 3D spatial data.

The final step in data acquisition is to check whether post-processing is required for the point cloud or the photos. If so, this may mean removing noise or increasing the point density for the point cloud, for example. For the photos, this may mean, for example, changing the sharpness settings of the image or cropping to a smaller area. If post-processing is not required, the processed point clouds or photos are ready for the next step.

## 5.4 STEP 4: DATA PREPARATION

The following chapter deals with data preparation and is subdivided into the further processing of a point cloud or photos (chapter 5.4.1) and a subsequent optional simplification of 3D models (chapter 5.4.2).

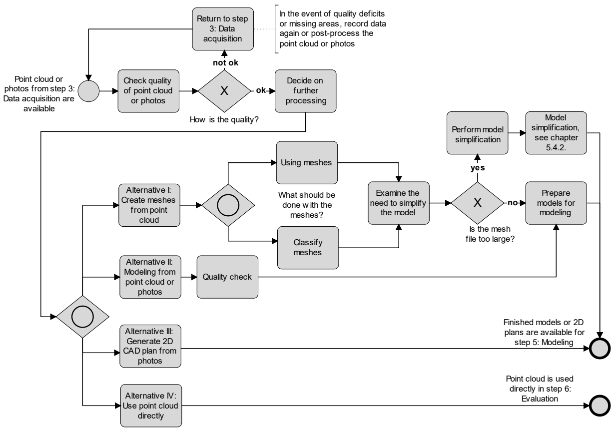


Figure 6.: *Sub-steps of data preparation for point clouds or photos*

### 5.4.1 PREPARATION OF POINT CLOUDS OR PHOTOS

First, it is necessary to check the quality of the point clouds or photos. Four quality criteria are defined for the quality of the point clouds:

- *The reduction of noise*
- *Color information is available*

- *Sufficient point density of the point cloud*
- *The point cloud is available in the required file format*

As an alternative to point clouds, photos may have been created for which a quality check is also required. The quality of the photos is satisfactory if all desired areas of the photographed object have been captured and the image is sufficiently sharp. If the quality is deemed satisfactory, there are several options for further processing, which may vary depending on the planning task and application of the factory model.

One option is the creation of meshes from point clouds (Alternative I, see Figure 6). The two options of direct use of the mesh and classification are discussed in this process model. When using the meshes directly for later modeling in step 5, it is important to note that they must be available in the correct file format so that they can be imported into suitable modeling software. The second option is to classify individual objects, such as assets or machines, after a mesh has been created. On the one hand, classification can be carried out manually. This is possible in the software PointFuse®, for example. After classification, it is possible to export individual objects as a mesh so that they can be used later, e.g. for layout planning. On the other hand, the mesh can be classified automatically using artificial intelligence, such as deep learning algorithms, in a suitable software environment (see chapter 3.4).

In addition to meshes, modeling from point clouds or photos can also represent suitable further processing, as visualized in figure 6 (Alternative II). The point cloud can be modeled in different software e.g. As Built™ plug-in for Autodesk Revit® from FARO®, Halocline and MicroStation®. However, this only represents a selection of possible tools. Once the modeling of the point cloud has been completed, a final quality check is carried out in the form of a collision check. The point cloud can be compared with the created factory model and checked for interference. A well-known software is Navisworks® from Autodesk Inc., which can be used to identify interferences by means of so-called conflict tests between the point cloud and the modeled representation [43]. As an alternative to a point cloud, modeling can also be carried out from several photos. Possible software tools are offered by Hottscan GmbH and immersight®, as already mentioned in Chapter 5.3. This allows 3D modeling of building structures to be carried out. Once the quality of the modeling has been ensured, the models are prepared for modeling. This is done by storing the models in folders in a structured manner.

Another alternative is to create 2D CAD plans from the photos taken (Alternative III). Orthophotos are generated in software such as Agisoft Metashape. Orthophotos serve as a basis for planning and enable the manual creation of true-to-scale 2D CAD plans, which can be exported in the DWG file format, for example.

A final option for data preparation is the direct use of the point cloud, e.g. for measuring distances between objects or for height measurements in software tools like NavVis IVION oder FARO® SCENE (Alternative IV). Modeling in step 5 is not necessary in this case, as no merging of models is required. It is therefore possible to proceed directly to step 6: Evaluation.

### 5.4.2 SIMPLIFICATION OF 3D MODELS

Companies are increasingly working with large volumes of data that are processed in various systems and exchanged between customers and suppliers. Large models can lead to performance problems and long loading times in the software systems, which in the worst case cannot be opened. To counteract these problems, there is the option of simplifying the 3D models in order to be able to work successfully in heterogeneous software environments and downstream process steps [44]. A distinction is made between two different types of 3D models. Either an existing 3D CAD model from step 2 or a mesh created in step 4 is simplified. The existing 3D data may be data that is available in standard CAD formats, such as STEP or DWG, and was not originally intended for use in factory planning but for product development. If the aim is to integrate the CAD models into a factory layout, the CAD data needs to be comprehensively simplified.

When creating meshes, it may be necessary to reduce the number of polygons to reduce the complexity and ultimately the file size. The right software must be selected for decimate the 3D mesh size. Before selecting suitable software, a cost-benefit analysis must be carried out to evaluate the economic viability of the model simplification process. For example, the software programs Teamcenter® Visualization Mockup from Siemens, RapidCompact by Darmstadt Graphics Group GmbH, or Autodesk Inventor® can be used to simplify models. However, after having tested the programs, it should be noted that it is not always guaranteed that the color of the models will be retained, and the degree of simplification may not be sufficient to meet the requirements. The process of model simplification is an iterative process that is carried out until the polygons have been reduced to meet the requirements. Once the simplification has been completed in the software, the number of polygons must be checked. The simplified model must be saved in a 3D file format that is compatible with the software used in step 5: Modeling. It should be noted that, depending on the different software used for modeling in step 5 of the process model, there may be different requirements for importing the models, such as a different number of polygons or specific file formats. Once the models have been simplified and saved in a suitable file format, they are ready for the next step in the process.

## 5.5 STEP 5: MODELLING

Modeling is an essential and extensive part of the process. In this context, modeling means integrating the previously created models, a modeled point cloud, a 3D mesh, a

2D CAD plan or a CAD model already available in the company into a coherent overall model in software designed for this purpose. The result should be a digital factory model that meets the requirements of the operational understanding and ensures that the defined objectives are achieved. First, a test data set is generated, whereby an exemplary model is used to check whether the quality of the models is satisfactory, which means that the models meet the requirements for importing the modeling software used. The import criteria depend on the software used. Suitable software programs are, for example, visTABLE®, Visual Components or ipolog.

Once the quality is satisfactory, the modeling process can continue with the creation of a structure for layers or libraries. Layers or planning levels are logical layers in the layout model to which resource elements such as buildings, facilities, machines, or plants can be assigned on one level each [8]. The libraries, on the other hand, are used to categorize the created factory models, which can be sorted according to "assets" or "logistics means of transport", for example. The individual models are then imported into the software. In addition to the import of specially created 3D models, the software environments usually also offer internal libraries, whereby the scope of available models can vary depending on the software. Depending on the level of detail and scope of the self-created factory model, the internal model library can be viewed as a supplement. The result is a complete 3D model of the factory.

### 5.6 STEP 6: EVALUATION

For an evaluation, both the overall model, which is available after step 5, and a point cloud or a mesh classified by artificial intelligence can be available as input. In the first step of the evaluation, the results are assessed to determine the extent to which the generated factory model meets the project objectives. The results are measured against the requirements for project success defined in step 1: Business understanding and are evaluated based on the benefits achieved. If the quality is not satisfactory, the conditions in step 1 must be checked again. If the quality is satisfactory, the next step is to review the processes. Shearer [38] emphasizes the importance of checking whether important factors have been forgotten throughout the process. As part of quality assurance, the question of whether the model was created correctly is answered in particular. At the end of the evaluation, the project manager must decide whether the project can proceed to application or whether iterative steps are necessary to continuously improve the model [38].

### 5.7 STEP 7: DEPLOYMENT

The final step in the procedure is the deployment of the digital factory model. It is important to emphasize that the application phase can vary in length and depends on which requirements and objectives were defined at the beginning [38]. In the survey conducted, the experts interviewed named a total of eleven added values for a digital factory model (see Figure 7).

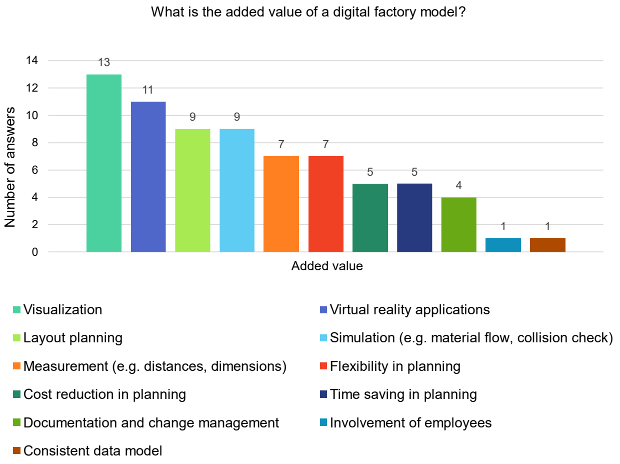


Figure 7.: *Results of the survey on the added value of digital factory models*

Six of the listed added values can be understood as application options, which are described below.

Visualization represents a major added value of a digital factory model, which, according to Stark [8], is used, for example, to display transport flows in a static 3D block layout and to provide a general insight into the spatial dimensions of a factory.

In addition to visualization, the use of Virtual Reality (VR) is a suitable means of using the digital factory model. The software environments Halocline, XR Easy® and Visual Components Experience, which is an integrated VR environment of the Visual Components software, can be used for the VR application. For example, a workstation in a VR environment can be used as part of a training course for production employees for the future design of workstations to optimally prepare employees for their new workplace [45]. Another potential use of VR is the ergonomic evaluation of workstations, e.g. in assembly or production. Al-Jundi et al. [5] explain that VR technology can be used to identify unfavorable assembly workstations at an early stage. In factory planning projects, it is also common to carry out virtual inspections to check how the planned factory building and assets will look spatially and how future workstations will be designed.

Another important use case is simulation. To counteract the challenges, simulation using digital factory models can support the factory planner in the early planning phases [39]. For example, material flows can be simulated and optimized. It is also possible to check the function and efficiency of newly planned systems before they are implemented. For example, the factors of throughput time or dimensioning of systems can be considered [39].

Layout planning is another possible deployment. Planning can be simplified, and flexibility increased using digital factory models. In layout planning, a distinction is made between rough layouts and detailed layouts, which are created in different planning phases. The LOD is higher for detailed layouts than for rough layouts. Consequently, detailed layouts enable a detailed representation of the virtual factory.

Furthermore, a digital factory model can be used for documentation to enable communication and collaboration of uniform data across several departments. In addition to documentation, a virtual image of a factory is essential for successful change management in brownfield planning. The task of change management is to ensure that changes are recorded in the planning and that all those involved are informed.

A final deployment which was mentioned in the survey is the performance of various measurements, such as the distance between machines, the dimensions of individual pieces of assets or the height of a hall. This is possible in a previously generated point cloud (see Alternative IV in chapter 5.4.1). Furthermore, virtual inspections of buildings or plants can be realized in the point cloud.

In addition to the results of the survey, there is also the option of integrating a created factory model into an Industrial Metaverse platform. Depending on the application, the software used and the available project budget, this can be the final step in integrating a virtual image of the existing brownfield factory into the metaverse and thus carrying out analyses in real time, for example. The company NVIDIA corporation offers an exemplary metaverse platform with Omniverse™ [46].

The process model concludes with the creation of a final report and a project review in the form of interviews with the project core team or a lesson learned workshop.

## 6 VALIDATION, DISCUSSION AND CONCLUSION

In this chapter, the procedure is validated based on the application in an industrial project. Finally, a conclusion is drawn.

### 6.1 VALIDATION OF THE PROCESS MODEL IN AN INDUSTRIAL PROJECT

The application took place at a manufacturer of commercial vehicles for agriculture. The project objectives were first defined as part of the business understanding. The main objectives were to lay the foundation for an upcoming factory planning project so that layout planning could be carried out using a digital factory model and to create a basis for virtual cardboard engineering in VR software. On the one hand, the factory was defined as the planning level, as a block layout was to be generated for all areas, and on the other hand, the workplace, to create detailed models for layout planning and use in a VR environment. The requirement for the models was defined as achieving a quality with a LOD 300.

The result of understanding the data was that some of the data was already available in the form of 3D CAD models of individual pieces of assets. The missing 2D and 3D data was to be captured using hardware technology. The company decided to use UAV photogrammetry with a drone to record the external dimensions of the factory buildings. In addition, the 3D laser scanning technology of a terrestrial laser scanner was used to capture data inside the plant.

During data preparation, a distinction was made between existing models and point clouds generated in the previous step 3. Two methods were tested for the further processing of point clouds, which are described in more detail below.

#### First method: Digital factory models as meshes from point clouds

In the first step, for example, a high-lift truck was clipped from the point cloud of an entire hall using a clipping box in FARO® SCENE. The separated point cloud was then loaded into PointFuse® in E57 format. When creating a mesh, the scanner type and several LOD levels can be selected in the software. The LOD levels in PointFuse® are not the same as the Levels of Detail (LOD) from chapter 2.2. This is a software-specific definition of the LOD. Figure 8 shows a point cloud in the FARO® SCENE software and the 3D meshes of the high-lift truck created from it in PointFuse®. The meshes are shown in the three LOD levels "low", "medium" and "high". The mesh with the highest LOD was used, which consists of around 11,600 polygons and has a file size of 3 MB in OBJ format.

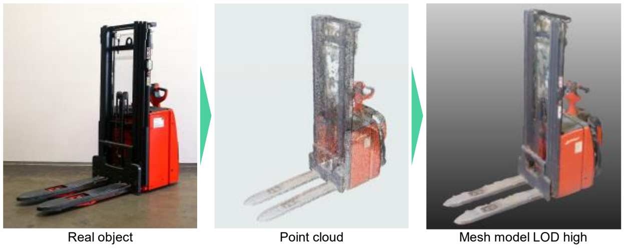


Figure 8.: *From the real object via the point cloud to the mesh model*

In addition to generating 3D meshes of assets such as the high-lift truck, the aim was to find out to what extent it is possible to classify the meshes from an entire factory hall in PointFuse® and what quality can be achieved. In Figure 9, a hall is visualized in which the classification can be recognized by the different colors. The following classes have been generated: Floor (light red), wall (green), pallet cages (dark red), a workstation with lathe (dark blue), a workbench (purple), trusses (yellow) and other assets (light blue).

The approach of manually classifying meshes is a time-consuming process because the classification must be carried out manually by selecting individual surfaces. Due to the complexity and many surfaces to be selected, the classification is prone to errors. Some reworking was necessary and new classifications of models had to be made. As can be seen in Figure 9, for example, on the green wall with occasional blue surfaces, assigning the surfaces to the objects was a challenging task that did not allow for a completely accurate classification. After classifying the meshes, the individual classes could be shown and hidden in the software and then exported separately in one of the possible file formats (e.g. OBJ, STEP or IFC).

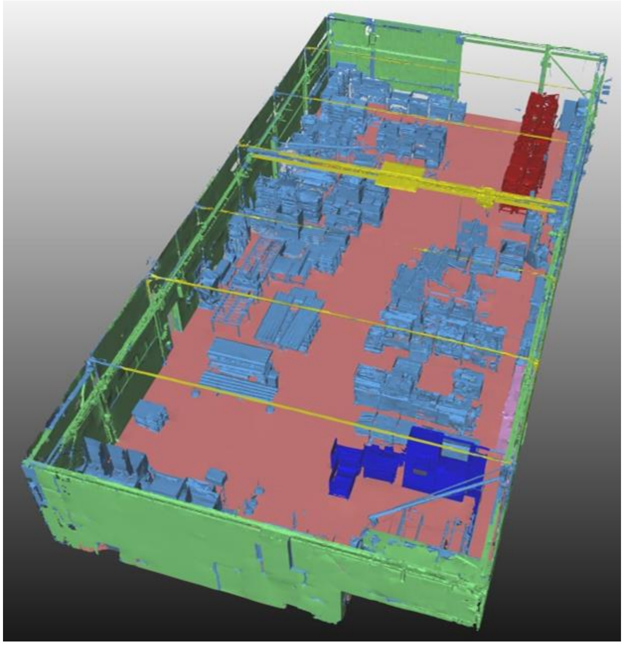


Figure 9.: *Factory hall as mesh with manual classification*

### Second method: Digital factory models through modeling from point clouds

Another way of data preparation was the modeling of the assets from point clouds, which was carried out in MicroStation®. The quality check after successful modeling took place in the Navisworks® software from Autodesk in the form of a collision check. Figure 10 shows an example of a high-lift truck as a STEP file created in MicroStation®.

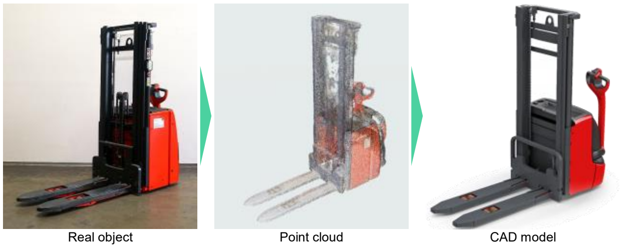


Figure 10.: *From the real object via the point cloud to the CAD model*

## 6.2 CONCLUSION AND DISCUSSION OF THE RESULTS

In conclusion, it can be stated that the developed process model can be applied to practical industrial projects, as was successfully validated in the project described above. The present work has demonstrated a comprehensive generic procedure for the creation of digital factory models in brownfield planning that can be used for various applications.

In the industrial project, the external dimensions of the factory buildings were successfully captured using a drone, which provided a 2D CAD plan as the basis for layout planning. In addition, the FARO® Focus Premium laser scanner proved to be suitable hardware, as its high accuracy made it possible to create high-quality point clouds.

During data preparation, it became clear that modeling from point clouds in MicroStation proved to be a better alternative for the company than creating meshes in PointFuse®. This is because an LOD 300 could be achieved for the CAD models. In addition, the file size of the models in the STEP and JT formats in MicroStation® was much smaller than that of the meshes created. The most CAD models were in the kilobyte range, while the mesh files were several megabytes in size.

Nevertheless, meshes can be a suitable alternative if only a 3D model of an area of a factory or of an asset is required, and a larger file size is acceptable.

Furthermore, the manual classification of meshes, as is possible in PointFuse®, is a valuable tool that can provide significant benefits. However, this process is also time consuming.

## 7 OUTLOOK

It can be concluded from the work that many different software programs are required in the process. Data preparation in particular is a time-consuming process step, as modeling from point clouds and creating meshes can take a lot of time. If model simplifications are necessary, additional effort is required. The existence of an integrated software solution that can potentially be used for all process steps would potentially lead to significant time and cost savings. In addition to the extensive range of software, the market offers a wide selection of 3D laser scanners and drones. Comprehensive cost-benefit analyses are therefore necessary for a well-founded decision. It is also important to analyze which buildings, segments, or workplaces of a factory a digital factory model provides added value for, as not every application will benefit from the entire factory as a digital model.

The procedure in this work offers potential for further investigations into the use of digital factory models in the industrial metaverse. The Omniverse platform from the NVIDIA Corporation already offers interfaces to various software programs so that it is possible to work in a digital twin of a factory in real time. The process model developed in this contribution can be further developed to focus on integration and working in the model in the industrial metaverse.

In addition, software environments that work with artificial intelligence could play a significant role in future projects, as the automatic segmentation of objects using AI can lead to considerable savings. The reason for this is that AI-based layout planning methods could make step 5, modeling, in the process model superfluous. This would potentially lead to cost and time savings. Finally, the use of AI in the brownfield planning of factories offers considerable potential, which is why further research in this area makes sense.

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