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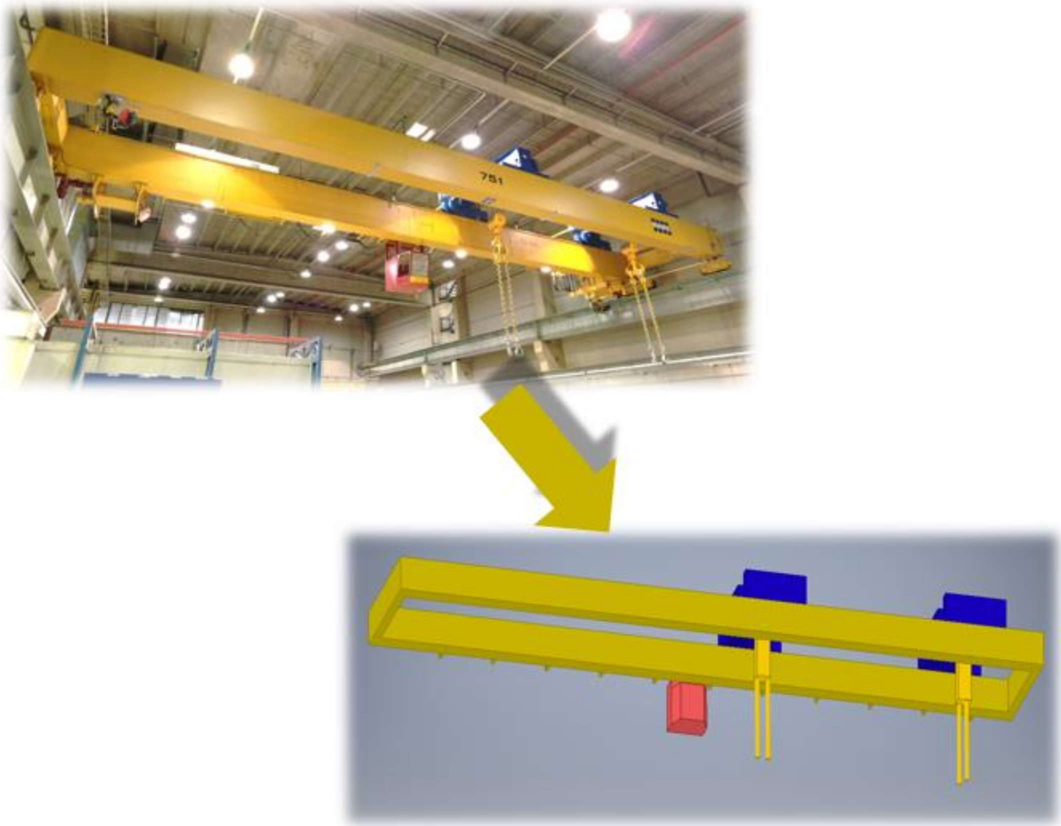

Factory layouts from 3D scanned data

A method supporting establishment of virtual factory layouts for production development

Master's thesis in Production Engineering

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Cover: Illustration of a typical transformation to virtual objects, showing a traverse as is in an factory environment and the recognizable solid modeler representation of the same object.

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Abstract

The increased demands for offline evaluation of change management projects puts requirements on virtual factory layouts. The company studied in this thesis, Virtual Manufacturing AB, provides the service of establishing virtual factory layouts. Yet, the current process is costly, time-consuming and highly dependent on skill of engineers available for these projects. By investigating current process at the company, theory on the subject and how other industries handle reverse engineering, this thesis will examine how time-consumption and costs for creating a virtual factory layout can be reduced without compromising quality of the deliveries

Flaws identified in the current state process are defined and further investigated upon potential solutions. A best practise workflow is then presented, containing solutions for these flaws as well as logical steps for conducting reverse engineering of a factory layout project. Steps covered are; how time can be estimated for such a project and how 3D scanned data is processed and then translated to deliverable format. The thesis also covers how standardized delivery packages can be arranged with customer values in focus, as well as how a practical approach to define requirements, in form of development and detail of models within these packages. All the proposed results support a more time- and cost-efficient workflow with increased quality assurance of deliveries. Also, it improves the communication between supplier and customer since the framework for model-definition describes how much the supplier should develop the factory layout, which also contributes to that the customer gets a view of what to expect from the model.

Acknowledgement

We would like to thank Björn Johansson and Jonatan Berglund at Chalmers for making this thesis possible, especially Jonatan for all your supervising, providing us with both knowledge and support. We would also like to thank Virtual Manufacturing AB, and their employees, whom given us the possibility to examining this subject in real work environment, as well as providing us with both hardware and case material needed for performing this thesis. Last but not least, we would like to thank our families and friends for supporting us in the ups and downs we have experienced during the efforts conducting this project.

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Abbreviations and Symbols

CAD	Computer Aided Design
LoD	Level of Development
DoR	Degree of Recognizability
LoA	Level of Accuracy
BIM	Building Information Model
VM	Virtual Manufacturing AB
VR	Virtual Reality
BOM	Bill of Materials

1 Introduction

This master thesis was performed at Virtual Manufacturing AB (VM), a company that provides the service of scanning production areas and transforming it into editable Computer Aided Design (CAD)-models to help customers with production layout planning. Following paragraphs will provide a brief background to the project as well as purposes, delimitations and problem definition.

1.1 Background

In the strive to be as competitive and lean as possible, manufacturing companies do their best to improve their processes and decrease losses. One field of interest is how to get the best possible factory layout, both to create optimal product flows as well as fully utilise available space (Shariatzadeh, Sivard, & Chen, 2012). To decrease downtime in production and avoid design mistakes, evaluation of current facility and conceptual new layouts should preferably be performed virtually (Lindskog, Vallhagen, & Johansson, 2016). Measuring could be done physically and machine footprint can be illustrated on 2D blueprints of the factory. Yet, this is extremely time-consuming and with risk of human errors (Klein, Li, & Becerik-Gerber, 2012). Another way to tackle the issue is to 3D scan the factory, register into point clouds and evaluate concepts in a software handling 3D objects (Lindskog et al., 2016). By using this procedure, it is possible to decrease time-consumption and risk for human errors. Furthermore, by adding this third-dimension illustrations as well as evaluation of concept analysis can be improved.

Working with point clouds is a useful method to reverse engineer factory layouts into 3D models (Lindskog et al., 2016). The process has been used in the studied company for several years and factory layout projects are a common service sold to manufacturing companies. VM handles the scanned data from their 3D scanner in a point cloud registration software, where each project has a coordinator who is supposed to register, process and divide the full factory scan to work packages for CAD designers. These packages will then be modelled manually in a simple CAD software, before the models are put together as one assembly-model in which it is possible to move single objects. Since the technique in these kind of processes is constantly improving, the process has several flaws that has to be improved in terms of time, quality and cost to bring more value both to customers and the supplier VM. Therefore, it is of interest to evaluate if work methods and alternative technologies can decrease lead-time and cost as well as increase quality for factory layout projects.

1.2 Purpose

The aim of the thesis is to find the processes of highest improvement potential, in the process going from raw point cloud data to deliverable factory layout, and try to find potential ways of improving these processes. By creating methods to make the workflow more efficient and predictable in terms of time-consumption, quality of deliverable and cost of a project. The project will study an existing process at the consultancy firm VM, map the current process flaws and try to improve them. By providing an improved process, VM should be able to increase profitability and predictability as well as added value in relation to customers. By introducing a structured workflow and clearly defined modelling methods as well as detail levels of output, the thesis will try to provide a foundation for handling the processes from scanned data to deliverable data. Implementation of well-defined guidelines for modelling and output requirements for delivery packages, would strive to minimize required initial knowledge or training time for designers, which should lead to a more constant quality of deliveries as well as lead-time.

Apart from creating a useful workflow, the project should also offer delivery packages based on customer value. Clearly defined customer needs and work methods to obtain them has to be presented to increase the competitiveness of the process, and therefore VMs' offerings. The purposes of factory layouts have to be examined from a customer perspective and complements to solid models is an issue that needs to be evaluated to give customers the best possible offers.

1.3 Delimitations

In order to come up with valuable findings during the initially set project time frame, delimitations have been made. These limitations consider both process areas as well as depth and range of evaluation.

- Simulation and analysis of factory layouts are excluded from the project.
- Initial planning and scanning are excluded from the project. Therefore, the project only considers the steps from already scanned data to modelled factory layouts.
- The project only fully evaluates the final method and software combination versus the current process at VM
- Data handling of the project is benchmarked against a factory of 10000 m^2 which means that there is no guarantee that larger factories can be modelled using proposed solution.
- The project does not perform a full layout project, evaluations are therefore only based on sub processes and do not provide a full project comparison to the current method at VM.

1.4 Research questions

1. Which processes within the current method at Virtual Manufacturing has the largest impact on lead time, quality and cost?
2. How can these processes be improved?
3. How can detail-level of delivery packages be arranged to bring value to both customer and supplier?
4. How can duration of factory layout projects be estimated?

2 Theory

This chapter aims to give a theoretical background of the terms and technologies that this project is built upon. It will cover some knowledge in factory layout planning as such, combined with in-going parts of the process like scanning and modelling. The chapter will also handle support for definition of required quality of factory layouts, with sections including Level of Development (LoD), Level of Accuracy (LoA) and drawing techniques.

2.1 Factory layout planning

Factory layout planning has become a fundamental part for manufacturing companies due to the change in customer demand, with requirements of being able to produce high quantities as well as large variations of products (Shariatzadeh et al., 2012) A virtual factory layout can be defined as a virtual model representing the real factory in terms of buildings, machinery, equipment, etc.

One advantage of having a virtual factory layout is because visualization can be used to simplify communication, making it easier to transfer information in a short amount of time (Ebert, 2005; Rohrer, 2000). The last two decades it has been of great importance for scientists to share complex information with high pace. For instance, computer-graphics of manufacturing systems and processes has been used frequently since it increases understanding amongst people in an organization.

According to Azevedo & Almeida (2011), the aim with virtual factory layouts is to interact with the real factory to make time and cost savings. Therefore, companies want virtual models of their factories that support the whole factory life-cycle, starting with designing the factory and ending with being able to simulate factory operations to make manufacturing improvements. This is also supported by Shariatzadeh et al. (2012), who claims that the goal of using 3D digital factory layouts is to shorten time for making changes in an existing factory, or while designing a new factory, by giving the design team the possibility of using layout designs and simulation. According to Schuh et al. (2011) a virtual production system can be used in product planning, factory planning, technology planning, process simulation and control simulation to be able to perform product and process development in parallel.

When redesigning a factory or production system, it is of high importance to design correct from the beginning and avoid design mistakes, such as insufficient space for machines, due to the costs such a design mistake would bring (Lindskog et al., 2016). A way to support a correctly executed redesign of a facility is to virtually evaluate the changes before they are applied to the real environment. However, there is still a risk using virtual evaluation due to measurement or modelling inaccuracies. Yet, it is possible to get accurate virtual representations by capturing the as-built data with 3D scanning and model with the 3D scanned data as reference.

2.2 3D Laser scanning

3D laser scanning is a technology that supports accurate planning and redesign of existing production facilities (Lindskog et al., 2016). It enables the use of realistic virtual representations which helps a human to gain better understanding of an environment.

A 3D laser scanner operates by emitting laser beams and measures the distance when a laser beam reflects back from an object (Klein et al., 2012). Normally, as seen in figure 2.1, a 3D laser scanner can rotate around its horizontal (360 degrees) and vertical (300-320 degrees) axes to get a large field of view (Dassot, Constant, & Fournier, 2011). This makes it possible to obtain information from millions of measurements around the position of the laser scanner. These measurements are stored as points with xyz-coordinates relative to the scanner-position which creates a point cloud that accurately represents the real environment (Klein et al., 2012). How dense the point clouds are depends on the performance of the laser scanner as well as user settings such as resolution, that describes the interval between points (Dassot et al., 2011).

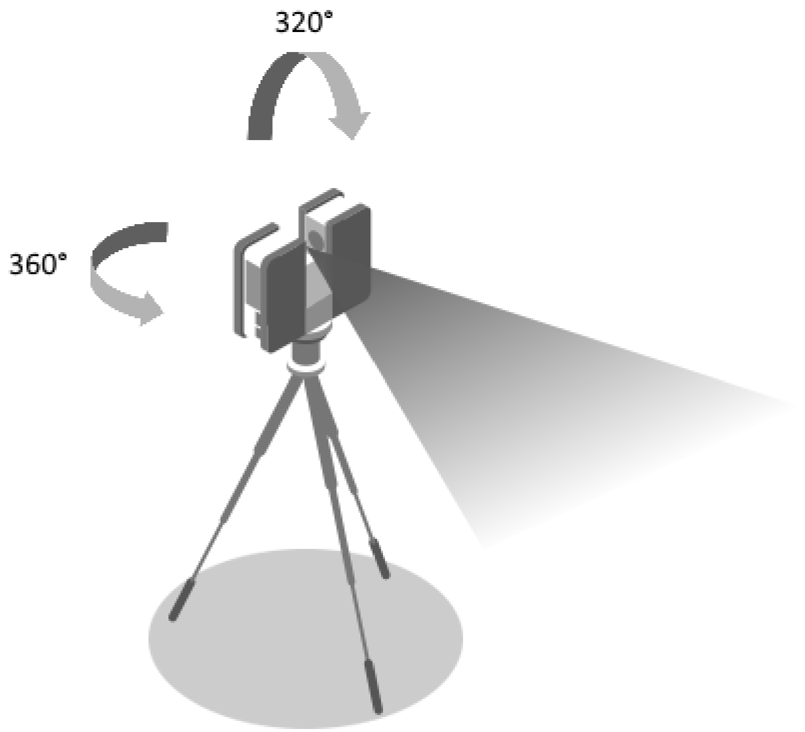


Figure 2.1 - A 3D laser scanner can rotate around its horizontal axis with 360 degrees and 300-320 degrees around its vertical axis. Adapted from Dassot et al. (2011).

Furthermore, there are several 3D laser scanners equipped with digital single-lens reflex cameras (Dassot et al., 2011). These cameras capture images and maps them to the point cloud so that each point is assigned a colour. This gives an even more realistic view of the real environment.

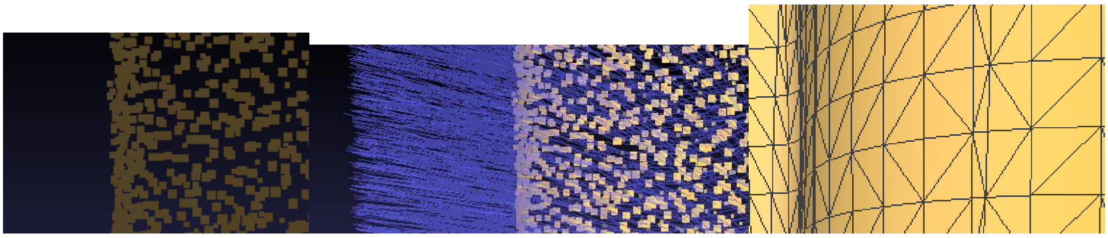
2.3 Registration and processing of point clouds

To capture larger areas or all sides of an object, several scans must be performed and merged together as one in a registration (Becerik-Gerber, Jazizadeh, Kavulya, & Calis, 2011). This is done by using laser scanning softwares in which it is possible to reference scans to each other. Referencing is made by identifying common targets between the scans. Typically, spheres are added to the scan-environment because its geometry has the same representation regardless line of sight. These targets can then be either found automatically by the software or marked manually to indicate common geometries between different scans.

Because of reflections from reflective objects and partially captured moving objects when performing a 3D laser scan, the point cloud will consist of unwanted points (Lindskog et al., 2016). These points can be removed by processing the point cloud so that the data becomes usable for reverse engineering. Also, to make a point cloud more easily managed in terms of data-size, it is possible to thin out the point cloud by removing points that are situated inside a specified range to each other. This gives a lighter point cloud with longer distances between the points.

2.4 Mesh generation

Meshing is a technique for creating surfaces from laser scanned data (Remondino, 2003). While generating a mesh, a net of polygons, triangles or quadrilaterals, are created from the points in the point cloud as seen in figure 2.2. A polygon consists of three or more corners, i.e. points, and a normal vector perpendicular to the surface created between these corners. Therefore, the mesh result is affected by how the normal vectors are defined for the point cloud-points.



a) ***b)*** ***c)***

Figure 2.2 - a) Point cloud. b) Point cloud with point set normals. c) Mesh made up by several polygons.

Meshes are created by different mathematical algorithms that defines how to look for neighbouring points (Kazhdan & Hoppe, 2013). One way to reconstruct surfaces from point clouds is to use poisson surface reconstruction. It is an efficient way to create watertight meshes with low respect to noise and artefacts. There are several softwares designed for this purpose. Examples of functions that are possible for the user to define are normal vector direction, number of triangles and how triangles are distributed (adaptively or uniformly).

2.5 Solid modelling

In order to provide a volume, solid models are used. These can be represented by using different internal representations. A good way is to use the Constructive Solid Geometry (CSG), a technique based on primitive shapes and boolean operators (T.-C. Chang, Wysk, & Wang, 2006). The primitive shapes are built upon several parameters and with the use of boolean operators they can then be combined to more complex shapes. Boolean operators such as AND, OR and NOT can be used to describe how these primitive shapes will relate to each other, enabling functionalities such as intersection, addition (union) or removal (difference) of material (K.-H. Chang, 2016). An illustration of how these boolean operators function in a solid modelling environment is found in figure 2.3.

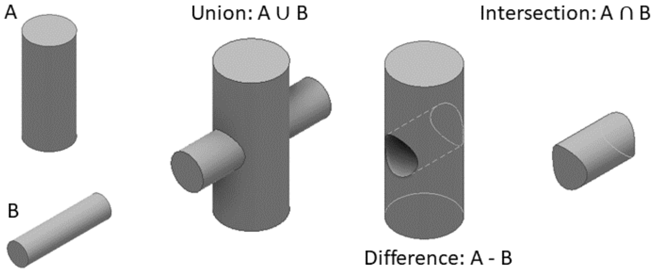


Figure 2.3 - Boolean operators in solid modelling. Adapted from K.-H. Chang (2016).

2.5.1 Working standards

In order to acquire controlled manual labour output regarding quality and quantity, standards are important since they enable measurability and setting of expectations (Zandin, 2004). Creating 3D models, consist of several manual tasks such as moving the mouse and clicking or holding of certain buttons and even though the object geometries may differ, the methods can be reused (Stroud & Nagy, 2011). With standardised work, tasks can be more clearly defined, enabling more accurate resource scheduling, cost control and supporting pricing of services (Zandin, 2004). Also, being aware of what is expected, can have a stress relieving effect on personnel.

Ikerd et al. (2013) describes the importance of clearly defining what a model can be relied for. By having a standardised way of showing output validity it is possible to provide the receiver with knowledge of a model's validity. Nowadays standards for naming of features and building structure of a model is present in most larger firms, with the purpose to help this understanding of model properties as well as its reliability and validity (Middlebrook, 2000).

2.5.2 Handling, movement, rotation etc.

CAD softwares locate points and parts by using a coordinate system (T.-C. Chang et al., 2006). The Cartesian coordinate system is based on X, Y and Z translations to describe a point, whilst a polar coordinate system defines it by a distance and an angle. A modelling software uses two coordinate systems, one for placement of the object being modelled and one to decide viewing perspective. The second decide from which direction an object will be viewed. Both systems are illustrated in figure 2.4 below.

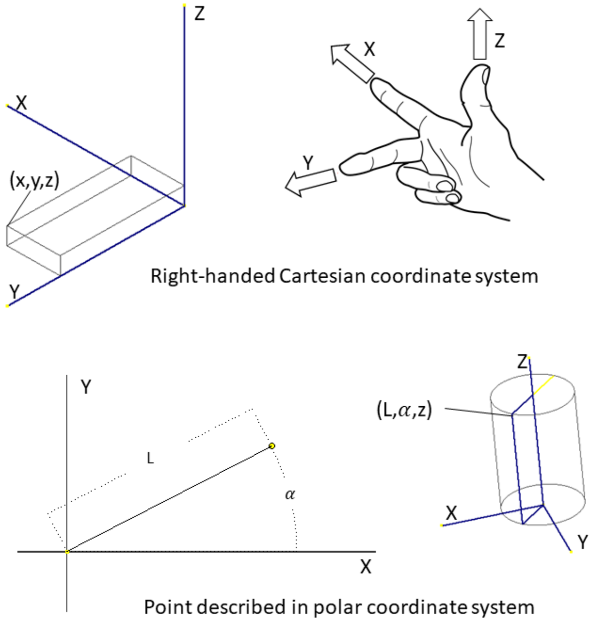


Figure 2.4 - Cartesian and polar coordinate system. Adapted from T.-C. Chang et al. (2006).

There are two general ways of moving an object, either by translation or rotations (T.-C. Chang et al., 2006). Translation is obtained by a point to point movement, setting a delta value for X, Y and Z movements. Definition of rotation on the other hand, requires a rotation axis that the part will rotate around as well as the angle of the rotation. With the use of these two moving operations, CAD-softwares enables the user to define position and orientation of an object.

When, in an assembly, positioning objects in relation to each other, mates and assembly constraints are used (Trigui, BenHadj, & Aifaoui, 2015). Constraints such as coincidence or coaxiality can be used to describe a relation between two objects, for example by two intersecting surfaces or a common centre axis of a hole and a cylinder. When an object is fully constrained, it is positioned in a specific point within the global coordination system and with a certain rotation.

2.5.3 Parameterized models

As mentioned in section *2.5.2 Handling, movement, rotation etc.*, models are defined in polar and Cartesian coordinate systems. For instance, a block will be defined with x, y and z vectors from origin in the Cartesian coordinate system and with its width, height and depth. Reusability and adaptability of the box will be dependent of the models parametric design quality (Bodein, Rose, & Caillaud, 2013; Camba, Contero, & Company, 2016) where a well parameterised model will keep intended relations. By defining a hole, intended to be placed in the centre of a rectangular surface with its centre positioned half the width and half the length from a corner of the surface, both length and width can be changed still keeping the hole centred (T.-C. Chang et al., 2006).

Ability to alter and reuse existing models is identified as an essential factor within product development, which can accelerate the development process (Camba et al., 2016). By using parameters properly, reusability as well as adaptability can be simplified. However, with dependencies defined improperly, these dependencies can cause unwanted relations and complexity. Correctly parameterised models could therefore quickly be reused by just changing a couple of parameters to fit its new purpose. Although, incorrectly set relations could make unwanted changes when editing a parameter.

2.6 Reverse engineering

The traditional forward engineering process includes designing a 3D-model of a part, with drawings and details about the part as support (Raja, V., & Fernandes, 2008). However, in some cases, specification of a part does not exist, which makes it necessary to "reverse engineer" the part. The process of Reverse Engineering often starts with capturing the object using 3D laser scanning, to be able to create a representative 3D-model with drawings and specifications in a CAD-software. A general definition of Reverse Engineering can therefore be described as the design of a computer 3D-model from a physical part (Svirsky, 2001).

Reverse Engineering is used for several different purposes such as product design, production design and Building Information Models (BIMs) (Raja, V., & Fernandes, 2008; Mikael Viklund Tallgren, personal communication, June 8, 2017). According to the research engineer within architecture and construction, Mikael Viklund Tallgren, reverse engineering of buildings, i.e. creation of BIMs, are used to capture the design of buildings to be able to reconstruct or make changes to them.

According to the BIM Coordinator Hugo Hammarstrand (personal communication, June 13, 2017), reverse engineering is also used in the infrastructure business, where they 3D scan an environment and mesh it to get information about topology to know e.g. how much land that has to be eliminated in a project. It is also used to visualise how a new solution, e.g. construction of a new road, is going to look like while finished.

2.7 Level of Development

When inheriting information in terms of a model, the receiver needs to know the limitations of the model in order to use it properly, LoD is designed to support the author in how to define what their models can be relied for (Ikerd et al., 2013). Different LoDs serve different purposes where a lower LoD can be used for obtaining space, whilst a higher level can be required for human-machine interaction. With the purpose of estimating number of possible desk locations in an office, it would be enough to get 2D space of furniture's and restriction areas for moveable objects. Whilst planning a desk layout requires 3D perspective, illustrating distances, available space on the desk, in drawers and in cabins.

LoD might easily be misinterpreted as Level of Detail or, as defined in this report LoA, whilst the latter two focuses on deviation from nominal model to actual model. Instead, LoD focuses on what the reliable output of the model is (Ikerd et al., 2013).

2.8 Level of Accuracy

As stated in section 2*.7 Level of Development*, the LoA targets the deviations from measured object to finalized replica model, which includes the combination of deviation accumulated from scanning tolerances and modelling tolerances. It is of importance to adapt the LoA to comply with the purpose that drives the LoD, since different LoD might require different accuracy levels to be fulfilled (U.S. Institute of Building Documentation, 2016). U.S. Institute of Building Documentation has defined five levels of LoA with each one consisting of a upper and lower tolerance levels, representing the specified deviation at the 95th percent confidence level.

2.9 Drawing technique

The purpose of a drawing is to describe the shape and function of an object, it is of importance that the drawing is clear (Lilja, Olsson, & Wickström, 2010). In order to clearly describe an object, there are several tools and standards available. From how to define the roughness of a surface to fitting of an axle and a hole.

A tool to define an object is to use the standard for Geometrical tolerances, ISO 1101, combined with Datums- and datum system, ISO 5459 (Lilja et al., 2010). Tools from ISO 1101, which can be found in figure 2.5, is put in relation to references described with tools from ISO 5459. For example, datum features A, B and C in combination with the form tolerance and control of the orientation fully describes the position of every point in the surface of figure 2.6. A sphere with the diameter of 2 defines all acceptable positions of a point on the surface in relation to its nominal position, resulting in two parallel surfaces where the actual surface should be placed within (see figure 2.6).

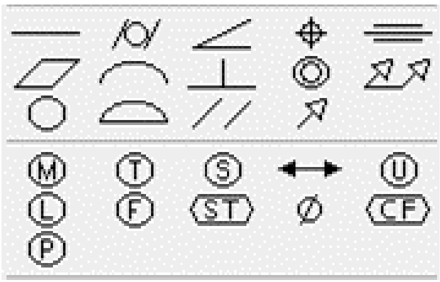


Figure 2.5 - ISO 1101 features. Adapted from Humienny & Berta (2015).

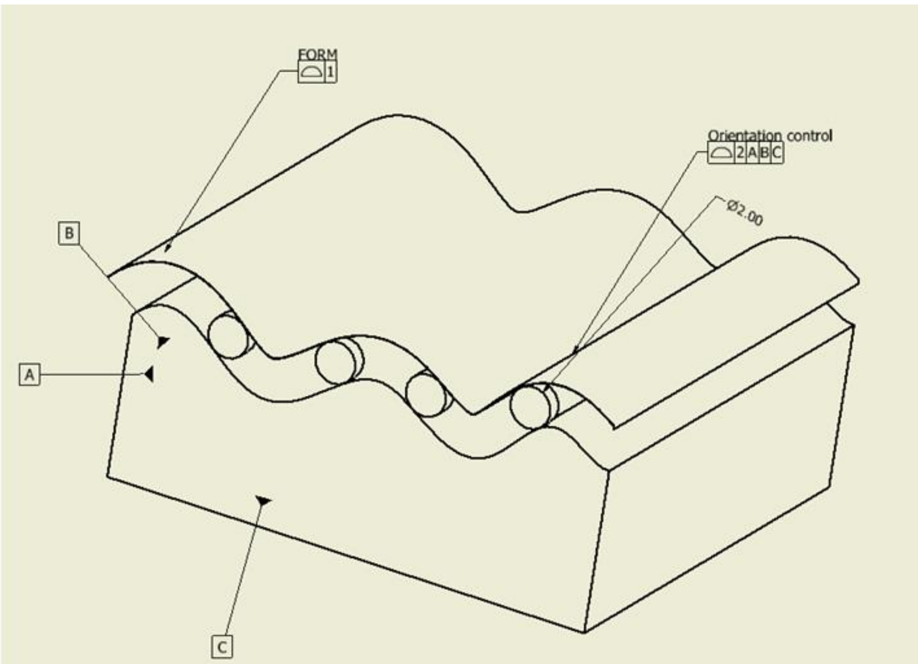


Figure 2.6 - Surface profile tolerance. Adapted from Chiabert, Lombardi, & Orlando (1998).

Another tool provided from drawing standards is the ISO 2768 which allows the user to define a general tolerance class instead of tolerancing every single measure. Measures will then depend of length and class to get a general tolerance. For measures with higher or lower requirements, a specific measure can be set to override the general tolerance. There are tables for linear measurements, see table 2.1, as well as other tables covering e.g. straightness and flatness (Henzold, 2006).

Table 2.1 - ISO 2768 -1 table for Tolerances of linear measurements. Data extracted from ISO Certificate Online (2017).

Tolerances for linear measurements								
Class of Tolerance	**Limits (mm) for nominal sizes (mm)**							
	0.5 up to 3	Exceeding 3 up to 6	Exceeding 6 up to 30	Exceeding 30 up to 120	Exceeding 120 up to 400	Exceeding 400 up to 1000	Exceeding 400 up to 2000	Exceeding 2000 up to 4000
f (fine)	± 0.05	± 0.05	± 0.1	± 0.15	± 0.2	± 0.3	± 0.5	-
m (medium)	± 0.1	± 0.1	± 0.2	± 0.3	± 0.5	± 0.8	± 1.2	± 2
c (coarse)	± 0.15	± 0.2	± 0.5	± 0.8	± 1.2	± 2	± 3	± 4
v (very coarse)	-	± 0.5	± 1	± 1.5	± 2.5	±4	± 6	± 8

2.10 File formats

To be able to use information from 3D scanned data, meshes and 3D-solids, different information is necessary. This is because different file formats contain different information and/or present it in different ways. Below, point cloud, mesh and CAD-formats are described briefly.

An issue in today's management of point clouds is that different developers use their own proprietary file formats (Huber, 2011). This makes it difficult to switch between softwares and makes it advantageous to use softwares from the same developer. Although, Huber (2011) describes a 3D file format, E57, that aims to be open so that users must not rely on one single software developer. The E57-format works with most softwares and can contain information such as coordinates and colours of laser-measured points.

CAD softwares have their own file formats and in order to translate information between them, lightweight formats such as STEP and IGES are often used (Stroud & Nagy, 2011). Issues with translating appears when the receiver of the model wants to review the construction history and adapt it since in many cases the construction history gets lost, leaving the receiver with a model without the construction history. Although, conversions are necessary for the receiver to be able to open the models unless the sender and receiver works in compatible file formats. Efforts are being made regarding lightweight formats handling construction history where some features used in several softwares are able to be detected from the lightweight format.

While meshing an object, it is most often saved as a STereo Lithography(STL)-file which is a standard 3D file format that contains information about planar triangles, described as three unique vertices and a normal direction out from the triangles surfaces (Kumar & Dutta, 1997). The file format is commonly used in reverse engineering and rapid prototyping (Wang & Chang, 2008). This is due to the simplicity of converting a STL-file as well as the ability to import it into several different softwares. Kumar & Dutta (1997) refers to STL as a "specific neutral exchange format" because it only has the ability to store one kind of representation (planar triangles). This can be compared to e.g. STEP and IGES, that can store several kinds of representations.

3 Methodology

This project was performed at Virtual Manufacturing AB, with the aim to improve their current methodology of working with factory layout projects in terms of cost, quality and time as well as improving their way of estimating time for these projects. Therefore, the work of this project has touched upon details such as modelling techniques and working steps in different softwares to fulfil the company’s wishes. The overall method, shown in figure 3.1, was designed to support the generation of a final concept, with both theoretical foundation and validation. The method was divided into three main areas; pre-study, concept generation and implementation & validation. All these areas are described further below, explaining how and why the included steps were performed.

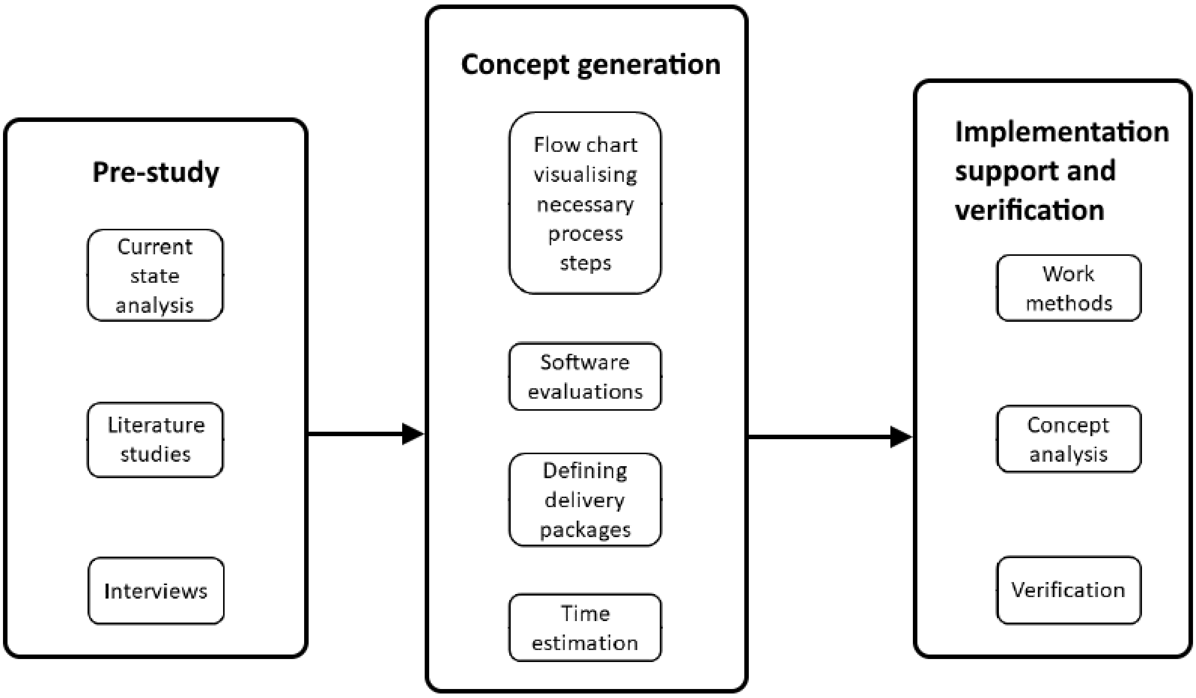


Figure 3.1 - Flow chart of project methodology.

3.1 Pre-study

To get a good knowledge-base in the area of transformation from point cloud to 3D objects it was of high importance to scour for information from several different sources. The pre-study was divided into three main steps; current state analysis, literature studies and interviews, where each of the three steps gave information from different angles about generating factory layouts from point clouds.

3.1.1 Current state analysis

Analysis of the current working methodology, of transforming point clouds to factory layouts, at VM was used to get knowledge of how factory layout projects were performed. This knowledge was supposed to give the project members better understanding of how VM worked with factory layout projects.

The current state analysis was performed by scanning a room from 5 positions, properly referenced with sphere-targets. These scans were then processed and registered according to VMs existing working methods, before they were divided into smaller point cloud-pieces and imported to the CAD-software that VM used. In the CAD-software, a few objects were modelled to understand how modelling was performed. During this process, going from 3D-scanned data to solid objects, all steps, from technical functions to method structures, were analysed in terms of how they affected quality, time and cost of the deliverable. With the purpose to find out where the main flaws were so that the process as such could be improved. The found flaws, or improvement potentials, are presented in section *5.1 Improvement potentials*.

3.1.2 Literature studies

Because virtual factory layout planning is a quite new and immature area, most work within this area could be found in articles from academia research. These literature studies were performed to gain information regarding, for the subject, interesting theory as well as to identify ways that other researchers have worked with reverse engineering and especially creation of factory layouts from 3D scans. Typical search-terms were "reverse engineering", "factory layout" and "digital factory". However, other work areas were also analysed in terms of used technologies and factors that can help reduce project-time, to gain inspiration about how to make a project as time- and cost-efficient as possible. Several articles regarding creating Building Information Models (BIMs) were e.g. used to find out how they reverse engineer buildings in the construction-business, both by looking at their way of structuring a project and by getting inspiration of the technologies they use to model from point clouds.

3.1.3 Interviews

Generally, interviews are used to find out qualitative information, such as facts or opinions (Rowley, 2012). Depending on what the interviewer wants to find out, it is possible to steer the interview to go in a direction that the project benefits from. Therefore, interviews can be structured, semi-structured or unstructured, depending on the purpose of the interview. A structured interview includes specific questions and is quite similar to a questionnaire, with the difference that the interviewer is present when the interviewee answers. An unstructured interview on the other hand is performed by asking general questions so that the interviewee is free to elaborate about the area.

In this project, the pre-study included interviews with engineers with experience from current scanning method. These interviews were made to straighten out what requirements there were on deliveries and to get information regarding the process as such. The format of these interviews was a discussion regarding the factory layout process, with a few questions directed towards specific areas such as what areas the employees thought was most time-consuming, if they knew how much detail-level they should include while modelling an object and their general view of how the process was performed (See *Appendix A* for interview guide). The aim of these interviews was to get a view of what the employees thought was important to consider while improving the process.

Also, engineers from the businesses of construction and infrastructure were interviewed due to their knowledge of reverse engineering for larger sites. The hope of these interviews was to get a hint of what techniques they used for creating BIMs that would be possible to implement in factory layout projects. Therefore, the interviews were structured with questions directed towards the area of modelling from 3D scanned data (See *Appendix A* for interview guide).

3.2 Concept generation

In order to find the best possible solution, concepts were generated and evaluated for the separate process steps. With good knowledge in the area of transforming from point cloud to deliverable 3D objects, it was possible to generate concepts based on current state, available methodologies on the market and own knowledge about the subject.

3.2.1 Flow chart visualising necessary process steps

To get a general overview of which processes to improve, a flow chart was constructed. The workflow chart consisted of all process steps that were necessary to perform to go from 3D scanned data to deliverable factory layout and different concepts were generated for different steps of the process. E.g. two concepts were generated for registration and division of point clouds, while several other concepts were generated for solid modelling, before narrowing down to one final workflow concept.

3.2.2 Software evaluations

To know which softwares that could best support the factory layout process, software evaluations were made. In these evaluations, different important factors were analysed to find the most suitable softwares for creating factory layouts from 3D scanned data. The factors were analysed either quantitatively or qualitatively.

Quantitative data is defined as data that is statistically collected, where relationships between different variables can be analysed to see how they affect each other (Kuada, 2012). In other words, quantitative data can be measured and analysed without impact of opinions or feelings. Qualitative data on the other hand, is data that is not collected from statistical procedures and therefore cannot be quantified (Kuada, 2012). It may include feelings or opinions from the participants that has to be taken into consideration while using the information. The aim with this project's software evaluations was to analyse the factors in a quantitative manner with measurable units. Although, due to difficulties in quantifying human perception, some of the factors had to be qualitatively evaluated with the customers view as basis.

3.2.2.1 Registration software evaluation

The registration, processing and point cloud management softwares were evaluated by factors that had impact on the time and quality of the final result as well as how well they supported the CAD-modelling procedure. This was to find a registration-software that could fulfil the requirements of this project's specific work procedure. The factors contributing to choice of software were:

- If the software could register scans with the required quality. [Yes/No]
- Time for processing and registration. [Minutes]
- Simplicity of workflow.
- The software's ability to divide and clean point clouds.
- Available tools for point cloud management.
- If the software could export files useful for the modelling procedure. [Yes/No]

3.2.2.2 CAD-software evaluation

The modelling phase was identified as a major contributor to time-consumption for a layout project already in the project initiation. Finding the most suitable software for layout modelling was therefore considered crucial. With hundreds of different CAD softwares available at the time of the evaluation, the project decided to perform the evaluation in several steps, with more depth in the latter steps of the evaluation.

The first evaluation step focused on limiting all softwares out there to a more manageable amount of softwares, trying to include merely softwares of potential interest. This evaluation step put emphasis on gathering softwares frequently used in industry, as well as softwares with focus on reverse engineering. The sources for this evaluation came from:

- Knowledge shared from studied company
- CAD advanced course (project initial knowledge)
- Search hits on "reverse engineering" and "point cloud modelling"

In the second step, these softwares were evaluated upon criteria accessible without installing the software. Technical specifications, YouTube videos and interviews was the basis for these evaluations and focus lied on the following criteria:

- Accessibility - If it was possible to receive a license within the software evaluation period
- Appearance in industry today

- Available import and export formats
- Available knowledge
- Price

The third step focused on decimating the remaining softwares to one final software to use in the layout process methods. This evaluation step included test scenarios within the softwares and also put some emphasis on the interest from the studied company. Due to time limitation, the evaluation had to be based on qualitative judgement of the perceived potential of the software rather than actual capability. Although, a test form was created to support a quantitative evaluation, which can be found in *Appendix C*. This limited the evaluation to perceived best solution within available time. Potential found to be inaccessible within the project-time was therefore not considered as available potential. The test focused on following criteria:

- Reference creation features
- Point cloud handling and illustration properties
- Stability
- Assembly features
- Hybrid handling
- Collaborative advantages

3.2.2.3 Mesh software evaluation

There were a lot of different softwares able to produce meshes of different quality. Therefore, the mesh softwares had to be evaluated according to a couple of factors that affected the end-result.

- If normals are not automatically generated from the 3D scans. Is it possible for the user to control how normals are generated? [Yes/No]
- Depending on the normal-creation, can the mesh get a shape that fulfil the customer values of a meshed object (See section *5.3 Define delivery packages from customer values*)? [Yes/No]
- Can the software be used to achieve a watertight mesh? [Yes/No]
- Can the software be used for any other task of the reverse engineering-process? E.g. registration, solid modelling etc. so that new licences are not required. [Yes/No]
- Cost of a license. [SEK]
- Can the software import the point cloud file format that the registration/cleaning software can export? [Yes/No]
- Can the software export the file format required for import to chosen CAD-software? [Yes/No]
- How large point clouds can the software handle without lag or termination? [File size]
- Can the software reduce number of polygons of a mesh without causing an adverse shape-modification of the object? [Yes/No]

3.2.3 Defining delivery packages

To handle the issue with varying output and time-consumption, an investigation of the current system, or lack of system, of deciding how developed a model should be, was performed. In order to provide customers with useful delivery packages, yet keeping number of packages manageable, focus was put on the most selling layouts and the ability to clarify the requirements of them. The investigation was made in 5 steps that is shown in figure 3.2:

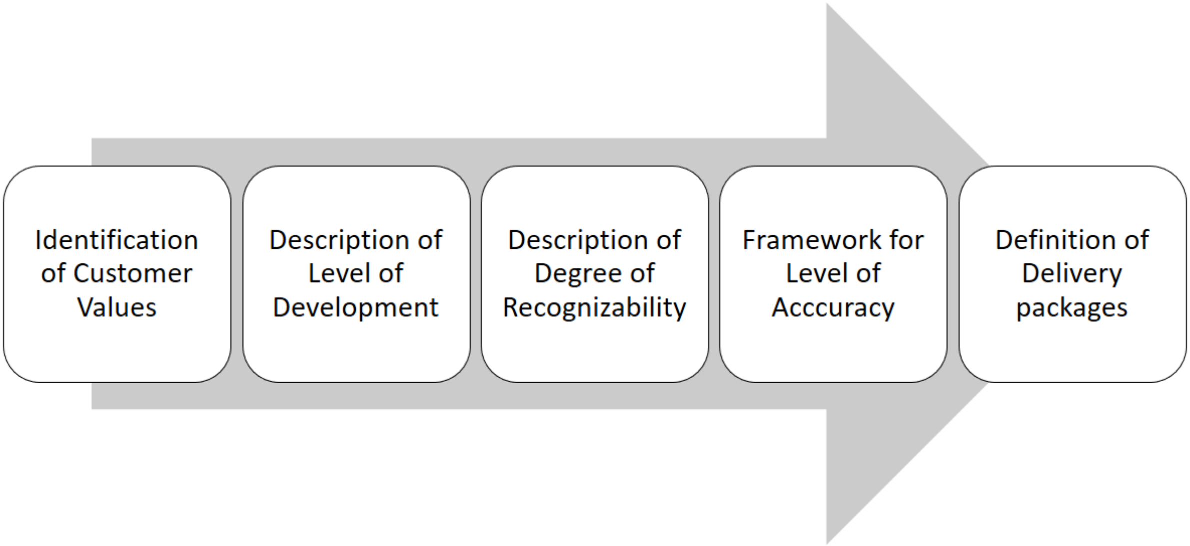


Figure 3.2 - The way to define delivery packages with respect to customer values.

1. Customer values were identified by studying purposes of VMs former factory layout deliverables as well as using scientific literature to identify for what other purposes factory layouts could be used for. See section *2.1 Factory layout planning* for purposes of using factory layouts.
2. Each customer value was connected to a LoD that described needed functions/features to fulfil the customer value. In other words, the LoDs were set to specify what kind of analysis a model should be able to be used for.
3. The Degree of Recognizability (DoR) was described as visual features that could be included while modelling an object. This was to give the modeller, and customer, a basis for what to include while modelling an object.
4. For the modeller and customer to know what accuracy an object was supposed to be modelled with, a framework for working with LoA was created. It was created in two sections; a theoretical proposition and a practical approach, where the theoretical solution was supposed to define LoA and the practical approach supposed to simplify use in reality.
5. Delivery packages were defined to fulfil the customer values. Each delivery package was connected to both the LoDs it should satisfy and the DoRs needed to fulfil the LoDs and customer values.

3.2.4 Time estimation

In order to support cost and lead-time estimations, a time-estimation method was created by following the procedure in figure 3.3. Efforts were made to find a structured way of combining factors to get an accurate estimation of required resource hours, without requiring too large efforts of getting the estimation.

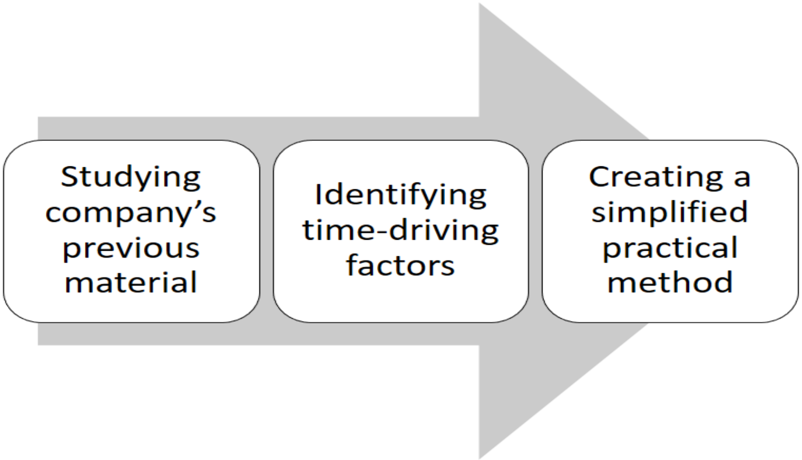


Figure 3.3 - The method used for creating a framework for time-estimation of factory layout projects.

First of all, previous work at VM was studied to get a base of what findings that were already made. The study of the previous work focused mainly on finding factors that VM had found to be time-drivers, but also on analysing the simplicity of these models to understand if they were too difficult to use or too simple to get a good time-estimation.

Secondly, factors were identified from experience of the project members and assigned to the process steps where they had an impact. The experience came from analysis of the current state factory layout process as well as experiments in the proposed final solution of this project.

Lastly, for the time-estimation method to be usable in factory layout projects without taking too much time to understand or fill in, the identified factors were divided into measurable sub steps. E.g. some factors were seen to not affect time-consumption as much as others and could therefore be set to standard times. Also, some factors could be estimated by an experienced engineer who could assign objects to different time-consumption-groups.

3.3 Implementation support and Verification

To support implementation of the proposed solution, actions were taken to simplify understanding for new users and to verify that the proposed solution actually worked as intended. The implementation and validation process was divided into three steps; work methods, concept analysis and verification.

3.3.1 Work methods

To simplify implementation of the proposed factory layout process a power-point presentation, consisting all process steps together with associated step-by-step instructions, was created. A description of the factory layout process power-point presentation is found in *Appendix D* and an example of a step-by-step instruction can be seen in *Appendix E.*

3.3.2 Concept analysis

In the concept analysis phase, the final concept was evaluated in terms of analysing how it affected the identified improvement potentials that can be found in section *5.1 Improvement potentials.* This was to get a view of what factors that had improved with the proposed solution, making it safe to say whether the solution was an improvement and in which ways it was an improvement. The analysis was made by identifying if the found improvement potentials were quality, time or cost issues, which made it possible to measure if the studied improvement potential was improved in relation to its identified factor. E.g. if an improvement potential was found to be a quality-issue, the proposed solution was studied by considering if it improved the quality with its solution for the specific improvement potential.

3.3.3 Verification

To prove that the final solution actually worked and to compare it to the current state process, tests were made. The first test was about comparing the registration process in terms of time, quality and usable tools to show the differences between current state and the proposed solution. Secondly, division and cleaning of point clouds were compared between the two processes. Factors that were of interest in this test was time and usable tools. Further, the solid modelling procedures were compared in terms of tools that could simplify for the user, point cloud handling and briefly time for modelling a standard object. Also, the mesh-procedure was compared to the current state solid modelling procedure in terms of time, quality and required input to show the differences in results by using mesh instead of conventional CAD-modelling to create a factory layout.

4 Current state at Virtual Manufacturing AB

This chapter provides a description of the current state procedures of transforming raw point cloud data to customer deliverables. The description includes process steps, general methods as well as specific tools in current softwares. The following description of the current state working procedure at VM is based upon personnel interviews with a manager, a coordinator and a modelling resource at the firm together with tests made by the project members.

4.1 Working procedure

The process for factory layout projects performed by Virtual Manufacturing Sweden AB is described below, from managing 3D laser scans and modelling deliverable factory layouts. The process had three main steps, convert raw point cloud data to point cloud regions, model from these point clouds and compile the top-level assembly from modelled objects before the final model could be delivered (See figure 4.1 for general work procedure). How sub-steps were arranged was less clear, methods for some of the sub-steps were already created such as for the processing and registration process. However, these sub steps lacked a clear flow to follow. This resulted in a time-consuming process of locating methods or finding out that the desired method did not exist.

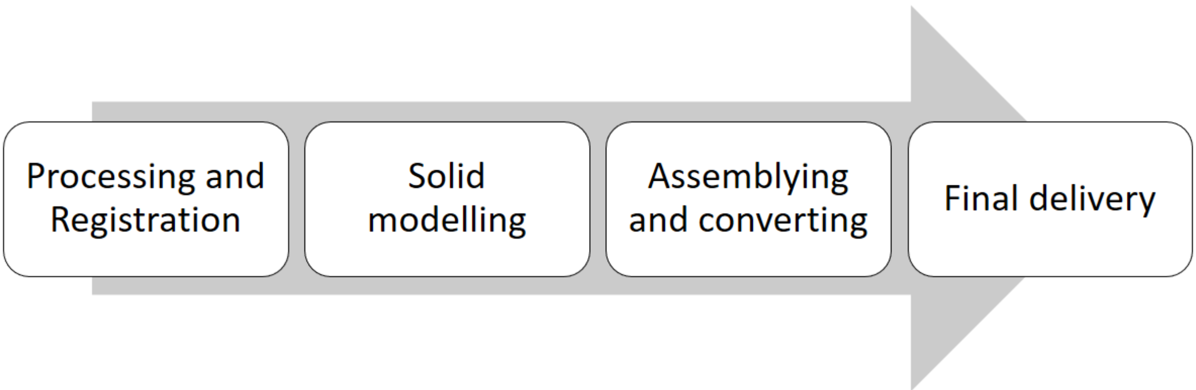


Figure 4.1 - The overall current process for creating a factory layout from point cloud.

4.1.1 Processing and registration of point cloud

The process of preparing a point cloud for modelling was identified to consist of 8 steps that are shown in figure 4.2.

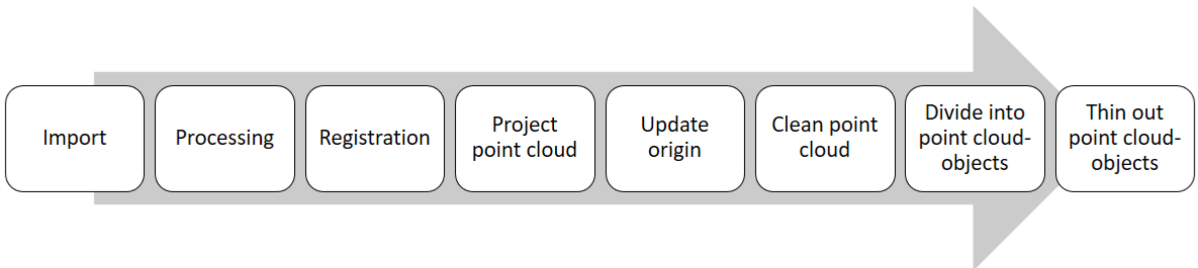


Figure 4.2 - The current process of point cloud management.

When all factory scan data was gathered, it had to be processed and registered, merging scans into one single point cloud. First of all, the 3D laser scans were imported from an SD-card, that contained both raw scan data and pictures of the scanned factory, to the registration software currently in use at VM. Secondly, the scans had to be pre-processed to enable registration.

Further, the scans were registered, mainly using the automatic registration tool in the registration software. However, according to the project coordinator Gustav Svensson (personal communication, June 15, 2017), manual registration had to be made in about 10-20% of the cases because of bad referencing in scan planning. Manual registration was done by marking 3 common targets between two scans. This locked the scans to each other in x-, y- and z-directions so that the scans only could be merged together in one possible way. The combined point cloud was then arranged with a global coordinate system based on user defined settings.

Lastly, the merged point cloud visualising the whole factory had to be cleaned of unwanted points and then divided into manageable pieces with just one, or a few, objects represented in each piece. This was done to support the CAD-software used in the following procedure, which had complications when handling point clouds larger than roughly 30 MB, depending on hardware. The point cloud-pieces were then exported to PTS-files, since this format was possible to import into the modelling software. Furthermore, in most cases, the point cloud-piece had to be thinned out in a separate software to comply with mentioned size limitations.

4.1.2 Generation of 3D objects

The point cloud was imported and automatically localized, in relation to the inherited factory origin, with coordinates provided from the PTS-files. This would position the cloud in correct place in the final assembly. Models were then created with drag and drop functions, compared to a more general sketch and extrusion technique. The point cloud was used as “up to” reference, in combination with constraints connected to the tribal tool. This was where the power in the method were, the tribal tool, since the different functions of the tool could lock rotation axes or directions.

A typical scenario started off by placing a cube in contact with a point placed on the floor, with its Z-direction in parallel with the global Z-direction of the whole part that would be approximately the same as the floor normal. The floor box was then expanded to cover the floor area of the whole object.

The part modelling procedure from the point cloud continued by inserting more boxes on the currently created floor. This was made by choosing tribal rotation centre, setting which properties that should be fixed, how dimensions should be chosen and then selecting point cloud points as reference for the operation. The operations required a user well-familiarised with the functions of the tribal as well as concentration, since mistakes such as setting the wrong relation or picking wrong points would relocate the part. The wrong relations created by these mistakes sometimes made it easier to start over, by replacing the current box with a new one, than fixing it. Successfully mastering the tribal- tool was time-consuming to learn. Yet, even when mastered, choosing points would continue to be tricky.

When hovering over points in the graphics window area it was difficult to get a depth perspective. Some users had problems importing colour with the point cloud, which made it even more difficult to distinguish which surfaces points belonged to. For example, the user could easily choose the floor located behind the leg of a table, snapping the box to unintended points, instead of picking the intended point on the table. Also, without a tool for hiding parts of the point cloud, users had to rotate the part trying to find a view where it was most unlikely to choose an unintended point.

The process then repeated itself until the modeller was of the impression that his or her model was according to the requirements. However, definition of requirements was considerably subject, even though some efforts had been made to define different model levels. This resulted in that detail-level of models could differ significantly even within the same delivery package level. It was therefore difficult for users to get a picture of how a correctly modelled object would look like, which made it very difficult to know when the model was good enough. With the combination of subjective view of when a model was finished as well as a process highly dependent of the modellers software-skills, it could differ a lot in modelling time for modelling two identical objects. This caused problems when estimating a price for the customer. Since the modellers in general focused too much on quality, the projects tended to be less predictable in terms of time-consumption and most often more expensive than necessary.

4.1.3 Part library

Combined with the process of modelling objects from point clouds, a modeller could also reuse already modelled objects in a library. With this library, VM had an intention to reuse already modelled objects instead of redoing the work. Although, the size of the library made it difficult to find the sought models and with lack of information gathered from the scanning occasion, the point cloud alone did not help enough with providing search terms. These difficulties led to that reusing through the library was used rather seldom. Furthermore, in order to reuse for objects, the knowledge of how to position them in the assembly was needed. With lack of standards for working in their CAD-software, positioning became unnecessarily difficult. Also, there were no way of differentiating the library models into clearly defined package levels which led to that the modeller did not know which library models that could be used to fulfil specific delivery requirements. Due to these reasons, the modellers often tended to create new models instead of spending time looking for models that did not exist or were difficult to insert.

4.1.4 Assemble layout

When a model was finished, it was put in the part structure within the folder structure, organised in categories such as buildings or equipment and tools, provided within each project folder. The modeller then made a note to the responsible project coordinator, who was responsible of creating an assembly model which would include all the parts assigned to the specific project. Depending on the project size, the assembly could be made in either the same CAD-software used by the modellers or, if too big, converted to a more stable one. The complications related to that larger file sizes often required assemblies to be made in a separate CAD-software, because the one used for modelling was not stable enough. The conversion process made parts lose their building history, making them less editable. It also contributed to unnecessary time and added the risk of conversion failure.

Since all parts were modelled in accordance to the global coordination system, the coordinator could import the models with an option to inherit coordinates, placing them correctly in relation to each other in the final assembly. The coordinator was then responsible of ensuring that all models were imported as well as making the layout presentable in the, by the customer, requested delivery format.

5 Results

The results are divided into five main sections. The first section is an analysis of the current state where improvement potentials has been found. This is followed by a description of the preferred work procedure for performing factory layout projects. Further, the third section presents a framework for how factory layouts can be delivered in different packages that fulfils different customer values and the fourth section proposes a method for how duration of factory layout projects can be estimated. Lastly, the proposed final solution is compared to the current state process.

5.1 Improvement potentials

The analysis of the current state led to identification of a few improvement potentials, which are listed below. These improvement potentials are factors that either affects quality of workflow or delivery, time-consumption and/or cost.

Evaluation of final factory layout model
The current state do not consist of a way to evaluate if the modelled factory layout actually represents the real factory layout. This is a flaw that could contribute to delivery of incorrectly modelled factory layouts and can therefore be seen as an issue of quality-assurance. The modelled layout can for example be compared to a point cloud of the full factory to evaluate the result and assure that every factory layout is delivered with the right quality.

Connection between parts
When different CAD-modellers create 3D representations of different objects for the factory layout, there are no connection between the modelled pieces so that the project-coordinator easily can follow the progress throughout the project. Instead, all objects/pieces are modelled separately and in the end put together as a factory layout by the project-coordinator. A solution for this would bring value in the continuous customer dialogue as well as to find and correct faults in an early state. This can be solved by connecting all parts/pieces in an assembly. However, it requires a more powerful software than the one used today.

Level of detail
The guidelines for how detailed an object should be modelled are not clear enough, which makes it difficult for a modeller to know when he/she is finished with modelling an object. This ambiguity contributes to modelling of details that are unnecessary for the purpose of a factory layout. This flaw was supported by the research engineer Mikael Viklund Tallgren (personal communication, June 8, 2017) who said that the best way to reduce lead-time for reverse engineering of buildings is to know the purpose of the building-model and model just enough detail for that purpose.

Modeller competence
The modelling technique used in the current process is unconventional and new to most of the modellers entering their first layout project. With a high degree of staff exchange in these projects, a lot of time is spent on learning the processes. Even when the modeller learns how it is done, it can still differ quite a lot how easily the modeller chooses the intended points.

CAD software
The software that was used for modelling has several limitations which have an impact on the modelling process in terms of both quality and time. The main software for modelling of objects, used for layout projects at VM, is restricted to point cloud sizes of approximately 30 Mb, otherwise there is a high risk of unwanted termination of the software and/or significant lagging. Other drawbacks are the lack in possibilities to hide and show parts of the cloud separately, as well as lack of simple ways to define reference geometry.

Process flow and methods
There are both work methods and flow examples found on the company server, although it is difficult to find them. All methods are supposed to be gathered within the same folder regardless if they are related to layout projects or something completely else. Naming of methods or folder structure lacks function in finding what is sought in a structured way, since names are descriptive but chosen subjectively apart from the sequence number connected to each method. There are also several methods placed in folders elsewhere, which increases confusion and searching time. The lack of possibility to find methods related to certain process steps, are especially missed.

5.2 Work procedure

The proposed factory layout process is shown in figure 5.1 and includes point cloud management, CAD-coordination, Solid modelling or Mesh modelling and visualisation of final delivery. This chapter includes evaluation of different available functions to support the workflow as well as a proposed course of action for factory layout projects. The course of action uses the most suitable functions, regardless of unsuitable software limitations. Therefore, trade-offs have to be made in order to find the best overall process. Also, methods are provided in a workflow PowerPoint where the user easily can browse to areas of interest. This is to support implementation of the proposed solution.

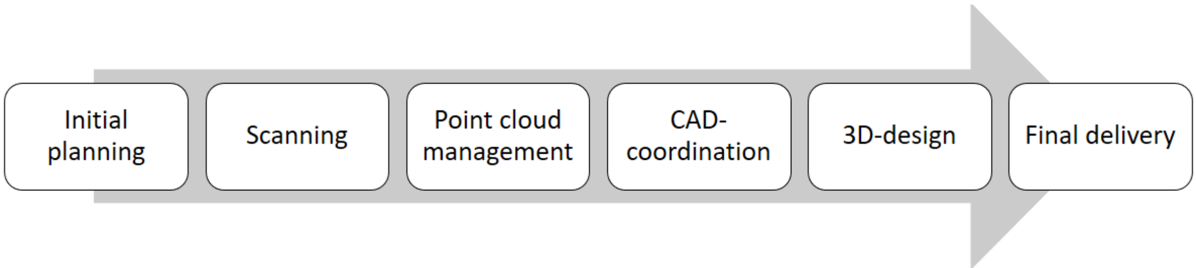


Figure 5.1 - The full factory layout process divided into 6 steps. However, the scope of this project only considers the steps from point cloud management and forward.

5.2.1 Point cloud management

Management of 3D scanned data includes import of scans, processing, registration, indexing of scans, setting origin, cleaning of point clouds, division into regions and export of manageable point clouds as can be seen in figure 5.2. Below, each of these steps are described more thoroughly to describe how point cloud management can be performed and what factors to think about. Preferably, this procedure is performed by one single resource, acting as project-coordinator.

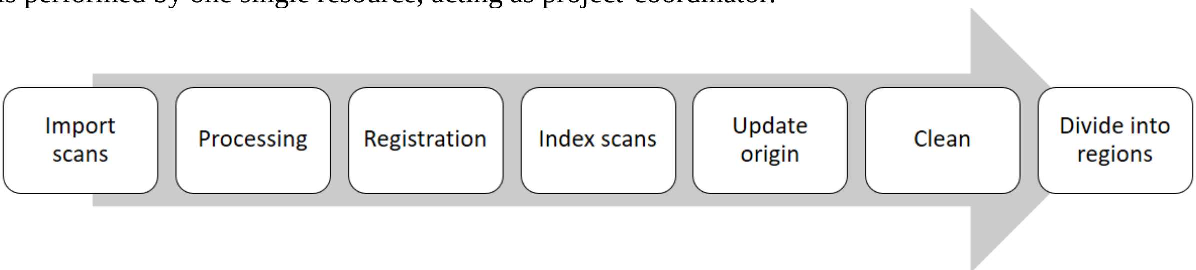


Figure 5.2 - Process steps included in point cloud management.

5.2.1.1 Process and register scans

To achieve a single full factory point cloud from the captured 3D scanned data, the data has to be imported, processed and registered. The purpose of these tasks is to decimate the scans and merge them together so that the 3D scanned data can be used for further tasks such as modelling or visualisation. There are several different tools available to handle this purpose automatically. First of all, importing the scans aims to choose which scans that are going to be included in the full factory point cloud. Secondly, the processing includes using automatic filters depending on how the scans should be decimated.

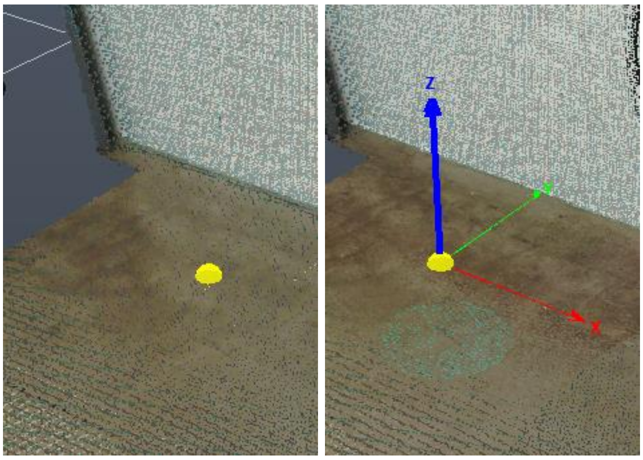
Further, the registration part is about merging the different scans together so that they are situated with the same relation to each other as the real factory looks like. This operation can be made using automatic registration tools looking for common targets, such as spheres and checkerboards, or cloud-to-cloud registration where the algorithm looks for common planes etc. However, an inadequate referenced scan-environment will most likely leave the user with the need to manually register the scans together. This is made by manually marking common targets, i.e. spheres and/or checkerboards, between the scans. Marking three common objects between two scans will lock them in x-, y- and z-directions and only give one possible way to merge these two scans together. If the scans cannot be automatically registered, this procedure has to be performed until all scans are correctly merged together as one single point cloud. Due to the time-consuming task of manually registering scans it is preferable to reference the scanned environment carefully and use automatic target based registration to be able to register the scans as fast as possible with adequate accuracy.

The output required from import, processing and registration is a single explorable point cloud that represents the scanned environment. To support both visualisation and modelling purposes, it is beneficial if the points in the point cloud, beyond their XYZ-coordinates, consist of colour described as RGB.

The work procedure of importing, processing and registering the 3D scanned data is not time-consuming in terms of manual work, however it requires hours of processing time depending on the number of scans and points. One resource should be responsible for the whole procedure as a project-coordinator.

5.2.1.2 Update origin

The origins position and orientation are not, directly after registration, situated to best support cleaning and modelling purposes. Therefore, updating or changing the origin of the registered factory point cloud is of high necessity. This can be made by picking a point somewhere in the point cloud, preferably in an outer corner of the factory, and choose direction of each axis by either defining planes and their orientation as ground, north and east or by choosing a smaller amount of points that forms a plane and assign that an axis should be normal to these points (See figure 5.3).



a) **b)**

Figure 5.3 - a) A point is defined to be the new origin. b) The direction of the coordinate system is set by defining a number of points that the axes are going to be normal to.

Assigning larger planes gives a more accurate estimation of the orientation of the factory. Yet, it is a much more time-consuming task since finding all points that defines a plane can take hours. Depending on how modelling from point clouds is performed, i.e. if modelling is performed by creating planes or by using the point clouds coordinate system, the requirements of the updated coordinate system shift. If, while modelling, a ground plane is created for each part, then the origins orientation is not of high importance. However, if modelling is performed using the point cloud coordinate system, then the origins orientation is of high importance.

Since this proposed workflow consist of modelling with planes (more of this in section *5.2.3 Solid modelling*), it is preferable to use the most time-efficient solution, still with an acceptable result, of updating the origin since the accuracy of the origins orientation does not affect the end-result.

Moreover, updating the origin is advantageous in cleaning, division of point cloud and modelling purposes too. This is because the point cloud is oriented correctly so that top view is the roof of the factory, bottom view is from the factory floor perspective, etc.

5.2.1.3 Clean, divide into regions and export

In most cases, the registered point cloud consists of unwanted points such as environment captured through windows etc. These unwanted points are irritating when handling the point cloud and makes the file size of the point cloud larger than necessary. Therefore, these unwanted points should be removed. This can easily be made using selection-tools, making it possible for the user to capture points within a specific area and simply delete them.

To support modelling purposes, the full point cloud should be divided into regions, where each region should consist of single objects, e.g. one machine. This is to give the modeller the possibility to only work with the points that regards the machine he/she is going to model. If the object is going to be modelled in a CAD-software, the point cloud object has to include a small area of the floor to support creation of ground plane. However, if the object is going to be meshed, the floor should not be present. To perform region-division, selection-tools can be used in the same way as they are used for cleaning of the point cloud, but instead of deleting the points, the points are assigned to a region.

To be able to mesh or model the point cloud objects/regions, the files have to be exported to a file format that is supported by the mesh or modelling software. There are different ways of doing this, depending on what modelling software that is used. Some softwares can handle larger point clouds and have the possibility to hide and show the regions. In that case, the point cloud can be exported as one single project-file. However, most CAD- or mesh-softwares do not have the ability to handle point clouds with a size of a factory, which makes it necessary to export each region as its own point cloud-file.

The less time-consuming task is to just save one file with the whole factory point cloud, but it is important to consider that the CAD- or mesh-software need to support this kind of file. Otherwise, there are no choice but to export every single point cloud-object. In any case, the requirement of the output is to be a point cloud in a size and file format that the CAD- or mesh-software can handle.

5.2.2 CAD-coordination

The CAD-coordinator is supposed to have control of the final delivery, both assuring quality and that the delivery is finished in time. The coordinator is responsible of creating the final assembly file, keeping modellers busy and having a dialogue with the customer. In order to do this in a sufficient way, there are some steps of greater importance and features found to be more useful. The working steps included in CAD-coordination is shown in figure 5.4.

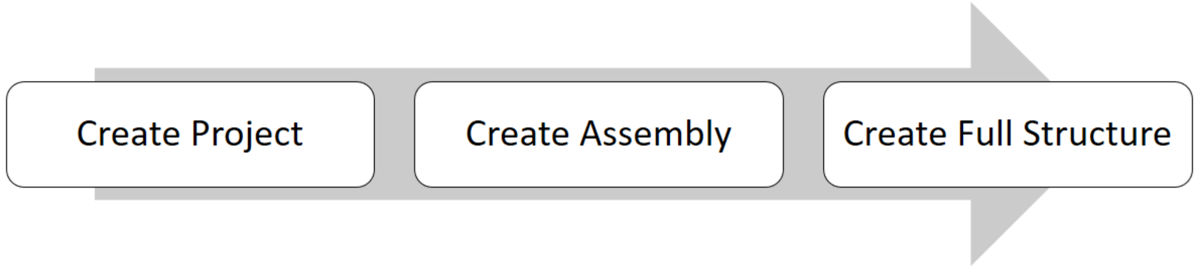


Figure 5.4 - Process steps included in CAD-coordination.

5.2.2.1 Preparing for CAD modelling

In order to ensure that goals will be met in time, the coordinator needs to provide the resources with expectations. The modelling resources might have different levels of experience within the procedure of modelling, which requires the coordinator to elaborately assign appropriate tasks for each modeller. The coordinator also needs to make sure that they are aware of where to place files, that they work in correct units, that they can access part libraries and that they know how detailed or developed models needs to be to reach the delivery expectations.

By providing the resources with model templates, assigned working folders, guidelines for model expectations and method guidelines, the coordinator can minimize the risk of modellers not delivering as intended. One way of achieving this can be by creating a specific project file including company templates, shortcuts to working folders and access to the part library. By opening the file, users will inherit these settings into their part-files. Also, to ensure that modellers deliver in accordance with expectations, the workflow document should be shared. Since it includes methods for all steps of a layout project illustrated as a clickable workflow chart, the users should easily find the information they need instead of spending lots of time in searching for the right method.

5.2.2.2 Keeping control over process

During the time of the project it is important that the coordinator keeps a dialogue with the customer to ensure that the output is according to the customer expectations. Modellers need to be provided with new tasks and models need to be internally controlled, to minimize the risk of getting in an inconvenient situation when presenting material to the customer.

By initially creating a top-level assembly with connections to work-in-progress-parts, the coordinator do not have to set up specific customer review assemblies. If some parts are not ready for presentation they can easily be hidden. With instant access of this assembly, containing the latest saved version of ingoing parts, modelled parts can be reviewed by just opening one file. Also, with the possibility to include the full point cloud in the assembly file, it helps both the dialogue with the customer and insurance of model quality.

5.2.3 3D design

In the generation of 3D design, point cloud objects provided in point cloud management and distributed in the CAD-coordination process, are supposed to be translated into CAD-parts. The output can be presented in three different ways, as point cloud objects, surface/mesh objects and solid model objects. How these objects preferably can be generated, or in part library inherited, are further described in following paragraphs.

5.2.3.1 Solid modelling

In the solid modelling step, several modellers are supposed to convert point clouds received from the coordinator into deliverable models of requested accuracy and development. Regardless of previous experience, modellers should be able to fulfil these quality expectations in requested time. It is crucial that output formats match assembly format, in order to inherit correct global coordinates, which will position objects correctly within the assembly. The process steps of the solid modelling procedure can be seen in figure 5.5.

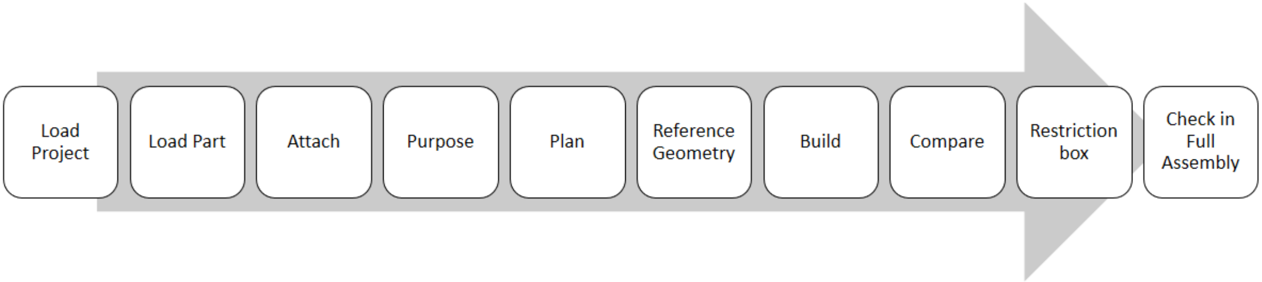


Figure 5.5 - Process steps included in solid modelling.

5.2.3.1.1 Supporting functions for successful modelling

In order to create the models requested by the customer according to expectations, it is crucial that the modellers know what is expected of them regarding accuracy and development of models. It is also important that the same structured method of modelling is used by all modelling resources, to provide the adopter of the model with better understanding of the model, what it is valid for and where to find reference objects.

By using clearly defined delivery packages, it is possible for the modeller to know what is expected. These definitions should include which kind of features that is necessary to receive a certain level, as well as tolerances needed to fulfil. With a modelling standard describing model steps and ways of thinking, it is possible to guide modellers into using the same way of working. By knowing how a colleague's model is built, less time is required to take over an unfinished model or referring to a finished one.

5.2.3.1.2 Start-up

The first steps a modeller need to do before modelling can be begin is to figure out model requirements, i.e. how this specific model should be modelled to fulfil demands, and which file settings to work with. This should be handled with guidelines described in previous paragraph, delivery package levels and part templates achieved from coordinator.

When requirements and settings are set, it is time to import files. Preferably the modeller can be assigned to open a part file, already placed correctly within the assembly structure, point clouds should easily be accessed and logically named, e.g. with the same name as the part file. Point clouds should be imported from a format that provide colours and is easily managed by the CAD software. Also, it should be possible to automatically inherit cloud position to place it correctly in relation to part origin.

5.2.3.1.3 Planning

Before modelling starts, it is important to review the model and form a strategy. Depending on the shape of the object, it can be attacked in different ways. The modeller should try to find out which references from the point cloud that fits best with chosen strategy and modelling standard at the company.

Having an initial plan and taking some time to reconsider thoughts, can have a significant positive impact on the modelling time. It can also provide a more logical approach than an ad-hoc technique, which therefore will provide more value for the receiver. Important factors to consider in the process are to find good references, find out from which directions sketches can provide most use and how each specific model should be handled to fit the delivery package level.

5.2.3.1.4 Point cloud handling

Working with point clouds can be quite messy since depths are difficult to illustrate with only points which can make it hard for the modeller to refer to intended points. However, there are different tools that can simplify this task. Another important aspect is how much information that can be loaded from a point cloud without causing the CAD-software to run slow and risk unwanted termination.

Regarding handling of point cloud data, amount of manageable data depends on hardware, file format of point cloud and the CAD-software. Different softwares handle the points differently making the data more or less hardware demanding.

When it comes to hide and show properties of points in a point cloud, there are several ways of handling it. Depending on user and modelling technique, this function is more or less useful. Some point handling features uses model references, such as planes, to select which points to show and not. While others place boxes freely in modelling space, using drag and drop functions and then setting if either outside or inside of boxes should be shown/hidden.

By supporting the use of modelling features when selecting points to show and hide, such as planes and surfaces, the user gets greater variability when choosing points, and potentially ability to use already defined features without need for adaption of references. A common scenario is when trying to sketch object contours, since the modeller then would like to capture the contours of the point cloud-object, seen from the sketch view, and exclude the rest of the points. By using plane offsets from the sketch plane, the visibility can quickly and accurately be chosen and a section of desired depth, including desired points, can be set visible whilst the rest are hidden.

5.2.3.1.5 Modelling technique and features

Different CAD-softwares provide different features and also different ways of using these features. Which techniques to use depends on company strategy, available tools, modeller knowledge and the purpose of the model. Generally, 2D contours are sketched and then extruded normal to the sketch to produce a 3D geometry, but some tools also provide the possibility of dragging objects into the model and adapting them on place. These adaptations could be made by dragging in corners, setting constraints or adapting feature parents.

There are pros and cons with both techniques. In order to make a sketch, a plane is required, whilst a box could be dragged into place instantly if there are some sort of reference. On the other hand, defining exact position of a plane might be easier and more visible how it is placed. Sketching provides more accurate 2D contours than standard objects. E.g. adapting a parent sketch of a standard object requires the object to be aligned with the sketch in the intended direction, whilst direction is obvious when sketching on a plane.

There are different tools for adding and removing material which are more or less useful when modelling. With a sketch-extrusion technique, boolean operators such as add, remove and intersect are very useful. Also, the ability to separate extrusions into own solids or bodies can be made using boolean operators. Having an extrusion in its own solid makes it easy to define colours to a certain subpart.

As mentioned, there are both pros and cons with these techniques. Although, given the task to reverse engineer objects from point clouds, the sketch and extrusion technique combined with the boolean intersection operator, provides best output quality combined with shortest modelling time. This is apart from number of operation done also supported by the test case provided in *Appendix C*.

5.2.3.1.6 Model output

Depending on how models are intended to be used, the desired output can look different. In some cases, additional information is needed, whilst in others the additional information is confusing. Once again, it is important to have clear instructions of what is expected from the final model. Things to consider are whether the model should be repositioned by plane to plane constraints, if material flows should be visible and if area restrictions should be added for doors and operator space.

The output does not only consider which features that are included in the model, but also how these are presented. Things that has to be taken into account are:

- Should features be placed in certain sub-folders, with explanatory name, in the model tree to ease access?
- Which features should be set to visible and which should be set to hidden?
- How do features need to be constructed in order to not be lost in translation when converting models to a delivery format that differs from working format?

The preferred method should be able to categorise and visualize these features or elements in a simple and structured way for the receiver. Features such as sub-folders will therefore provide support in presenting these elements in a clear way.

5.2.3.2 Part library

An alternative to modelling similar parts over and over again, which still consist of solid models, is to create a part library of reusable models. When a scanned object already exists in the part library, the modeller should locate and insert the existing model. For such a process to work successfully, information provided to the modeller should be enough to locate and insert reusable parts correctly.

5.2.3.2.1 Library structure

A common issue with reusing knowledge or information is to find the sought information. This is an issue that appears when reusing for models. With millions of different machines, racks, tables and other equipment it gets difficult to create a structure making objects easily found. With the limitations in what information that is available to extract from a point cloud, the available search terms get limited.

By providing models with searchable tags and having a logical categorising, models will be more easily found. Adding manufacturing article number or model name to parts, whilst always collecting it from new scans, can both confirm a search and provide an easy search method. Models will still have to be compared to the point cloud to ensure customer specifications are captured. For standard parts such as tables and racks, some general models can be made and provided with adaptable measures, which will be further described in section *5.2.4.3 Parameterised library models*.

5.2.3.2.2 Library model references

Inserting parts in an assembly or sub-assembly can be made in different ways. Either part coordinates can be edited, translations features can be used or constraints can snap parts to references. Without a clear structure of which references that should be provided in a model, the modeller inheriting the model will have to use occasion specific methods which can be complicated, inaccurate and time-consuming.

By having a modelling standard which includes creation of certain references, these references can be used to ease the locating procedure. Within the drawing creation of parts to be manufactured, a 3-2-1 system is used that locks the model to a plane (with three points), along a line (with two points) and fixes translation along the line (with one point). This way of attacking fixation of a model can be applied to placement of models in an assembly. A common plane to use is the floor, other references can then be found from properties in the feature, such as material direction and flat surfaces.

A way of using this system can be to create three perpendicular planes where these planes will not only define placement of the model but also help rearranging. The planes can be used when moving the object in a change management process, referring to other objects or object reference planes and using offset values to set distances between objects.

5.2.3.2.3 Parameterised library models

Parameterised models include a set of parameters named and adaptable that can support editing of frequently adapted measures. For example, a certain table model might always have four legs and a 20mm thick tops, but comes in variable height of legs and length and width of the top. Instead of remodelling all possible variations, the leg height and top length and width can be parameterised.

By providing some frequent standard objects, such as tables, bins and racks, with adaptable parameters for frequently changed measures, the modeller can just change these parameters instead of remodel the parts. This would decrease number of library parts and difficulties of finding a perfect match since a suitable match could be found and adapted easily instead.

5.2.3.3 Mesh-modelling

Under this section it is described how modelling of solids and surfaces can be made using mesh. Depending on the purpose of the factory layout model, mesh can be a way to reduce time for modelling. The mesh workflow can potentially replace the solid modelling flow. The workflow for creating a mesh and importing it to the 3D environment consists of 6 steps that can be seen in figure 5.6.

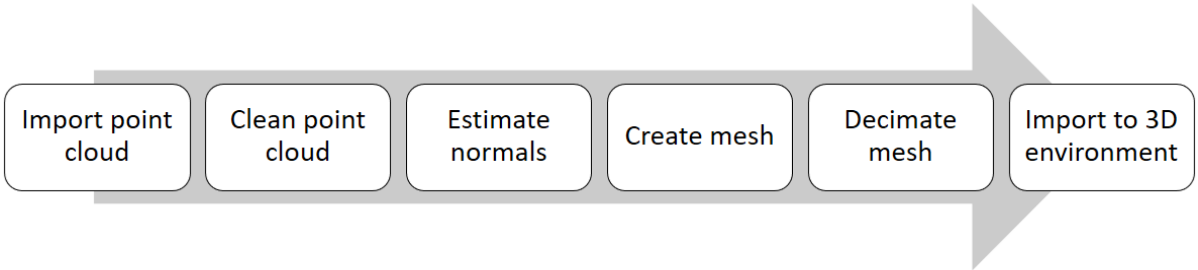


Figure 5.6 - Process steps included in mesh-modelling.

5.2.3.3.1 Import point cloud

Using mesh as modelling method requires high quality of the point cloud in terms of two factors. First of all, the object that is going to be modelled needs to be scanned so that points cover the whole area of the object without larger holes (This is described further in section *5.3.1 Requirements on 3D scanned data*). Secondly, the point cloud can only be of a size that is able to import and manage in the mesh-software. Also, the power of used hardware has a great impact on the size of which the point cloud can be. However, the aim of importing a point cloud is just to support the mesh-function. Therefore, the output requirement is to get the point cloud object into the mesh-software in a manageable state. Also, it is of high importance that the point cloud object keeps its world coordinates while imported.

5.2.3.3.2 Create normals

Normal direction of point sets lies as basis for how a mesh is created since a mesh-algorithm looks for neighbouring points depending on how the point normals are directed. Therefore, the normal direction is crucial for the shape of the created mesh. Several registration-softwares gives each point a normal direction towards the position from where the points were captured. This gives a normal direction of the point sets that represents the scanned environment and the mesh is therefore more likely to imitate the real environment.

Another possible way to create normals is to estimate the normals with respect to a point or direction. This gives a quite good normal estimation, but with inferior result than if the normals are created directly from the scans. Therefore, it is preferable to use the point normals from the registered point cloud if the purpose only is to mimic the reality with normals. Yet, there are other factors that affect the end-result of the mesh (See *5.2.3.3.3 Create and export mesh*).

In conclusion, the required output is point sets with normals. However, how these normals are created will affect the quality of the mesh. How a point cloud with normals looks is shown in figure 5.7.

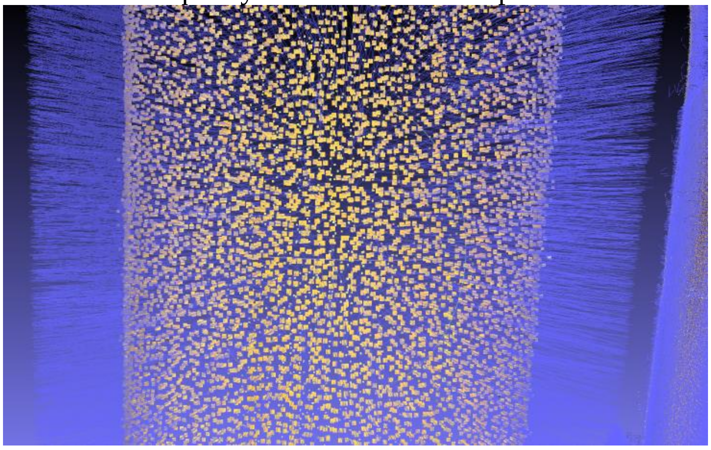


Figure 5.7 - The blue lines describes the normal direction for each point (yellow dots).

5.2.3.3.3 Create and export mesh

The purpose of creating a mesh is to, with high pace, create surfaces from a point cloud that represents an object. This can be made using Poisson Surface Reconstruction, which is an algorithm that is good at compensating for noise and artefacts. Creating a mesh with Poisson Surface Reconstruction gives a watertight mesh with a shape that depends on the normal direction of the point set and of number of polygons. However, in most cases, the Poisson Surface Reconstruction creates bulges on the surface because it cannot understand how to search for neighbouring points in all cases. Therefore, there is a need for eliminating these bulges which can be made by e.g. removing edges with a distance longer than a specific length. Yet, the most important thing is that the debaucheries are eliminated from the mesh to imitate the real object in a better way. Further, to support import into a 3D environment, the mesh has to be decimated to fewer number of polygons to make the file smaller and more manageable.

Moreover, the mesh has to be exported. The aim with exporting a mesh is to export a file format that can be handled by used CAD-software. Thereby, the required output of creating and exporting meshes is a mesh, visually representing the real object and that is in a file size and file format that can be managed by used CAD-software.

5.2.3.3.4 Import mesh to 3D environment

A mesh can be used in a 3D environment in different ways. Depending on the purpose of the factory layout, the mesh can either be used as it is to support measuring and movements of objects, or it can be transformed into a solid or surface to be editable.

Regardless the end-purpose of the mesh, it has to be imported into the 3D-environment as a mesh-file that can be exported from used mesh-software and imported by used CAD-software. Each meshed object should be imported to a Part that in its case is created from the Full assembly to get the same origin of the Part as for the Assembly (See section *5.2.2.1 preparing for CAD modelling*). When the meshed object has been imported, it has the right world coordinates in relation to the rest of the objects (if the requirements in *5.2.5.1 Import point cloud* has been considered), which only makes it necessary to save the Part to get the meshed object in its right position in the Assembly. If the purpose is to use the mesh in the same way as standard solid models are used, the mesh must be converted to a solid. However, this requires that the mesh is watertight so that the closed surface can be filled. Further, each part has to be assigned a colour to make it easier to recognize the meshed object.

The required output is therefore a recognizable meshed object, situated in its original location in the factory layout. However, the output-requirement differs with the purpose of the factory layout depending on if it is going to be used as a meshed object or transformed to a solid or surface.

5.2.3.4 Point cloud objects

A possible way to visualise factory assets as 3D objects, is to include point cloud objects in the 3D environment. Depending on the purpose of the factory layout, it might be beneficial to present objects as point clouds since it does not require any time for modelling. The only thing that has to be made is to prepare the point cloud object for positioning and import it into the CAD-software. Point cloud objects fulfil visualisation purposes and are possible to move inside the factory layout. Yet, point cloud objects lack in how they are presented, surfaces and solid models provide some improved properties and information.

As described in *5.3.1 Requirements on 3D scanned data*, using point cloud objects requires higher efforts when capturing 3D scanned data. This is because the object has to be covered in points from all directions so that the user can understand how the real object looks.

When preparing point cloud objects for use in a factory layout there are three steps that has to be performed:

1. The point cloud objects received from point cloud management has to be cleaned to exclude unwanted points.
2. The cleaned point cloud object has to be imported to a CAD-software as one part.
3. The modeller has to created 3 perpendicular reference planes so that the point cloud object easily can be moved and rotated while positioning it in the factory layout. Preferably, one plane is created along the floor and two are created parallel with the object's vertical axis and perpendicular to each other.

Hence, the required output when preparing a point cloud object is a well-scanned, cleaned point cloud object that is put in its own CAD-part. Also, it needs three reference planes to support positioning in the factory layout.

5.2.4 Final delivery

Depending on customer requirements, the final delivery needs to be arranged in certain ways, both when it comes to what information the delivery includes and in which format. Delivery packages can be everything from a registered point cloud to complex 3D models including kinematics and programming codes.

5.2.4.1 Delivery responsibility

As responsible for the delivery, the coordinator should briefly review the final delivery assembly, convert models to the agreed format and arrange a presentation. Depending on customer, there might be a need for viewers and instructions of how to handle these files. In some cases, the layout-creation is followed by another project which might require certain deliveries and instructions.

By providing the customer with material able to analyse in a free software, number of potential customers will increase. Being able to visualise the final layout in ways adapted to customer needs can increase the perceived value and customer satisfaction. With the already created top level assembly file, there is no time needed for compilation of the final delivery, apart from converting to desired format.

5.2.4.2 Delivery packages

To fulfil customer demands, but still keep a standardised workflow, a couple of standard delivery packages should be arranged. In order to create a standardised workflow and methods to support it, it was found that number of delivery packages needs to be limited. Too many packages results in complex guidelines and difficult workflow structures. The more detailed the project is, the more likely it is to be customer specific, which indicates that the predefined customer packages should be comparably simple.

In section *5.3 Define delivery packages from customer values*, delivery packages are arranged to comply with found customer values that could initiate layout projects. It is important to follow up project initiating sales meetings with current state customer meetings by sharing finalized models, to ensure that the customer is aware of what is included in the ordered delivery package. This dialogue can minimize misunderstanding and potential customer dissatisfaction when receiving final delivery.

5.3 Define delivery packages from customer values

The factor that was found to be the main contributor to lead-time of factory layout projects, is how much an object should be developed and with what accuracy this object should be modelled. In this section, a framework is proposed for how to translate customer values into Level of Development (LoD) and Degree of Recognizability (DoR), which in its case can be connected to Level of Accuracy (LoA).

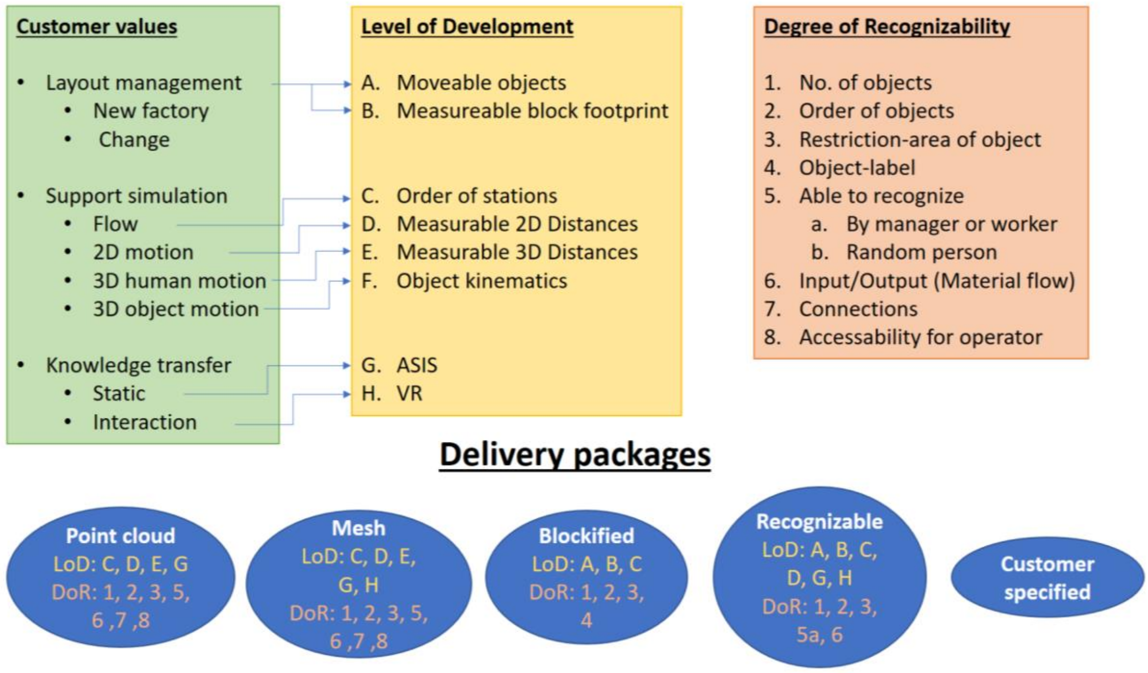
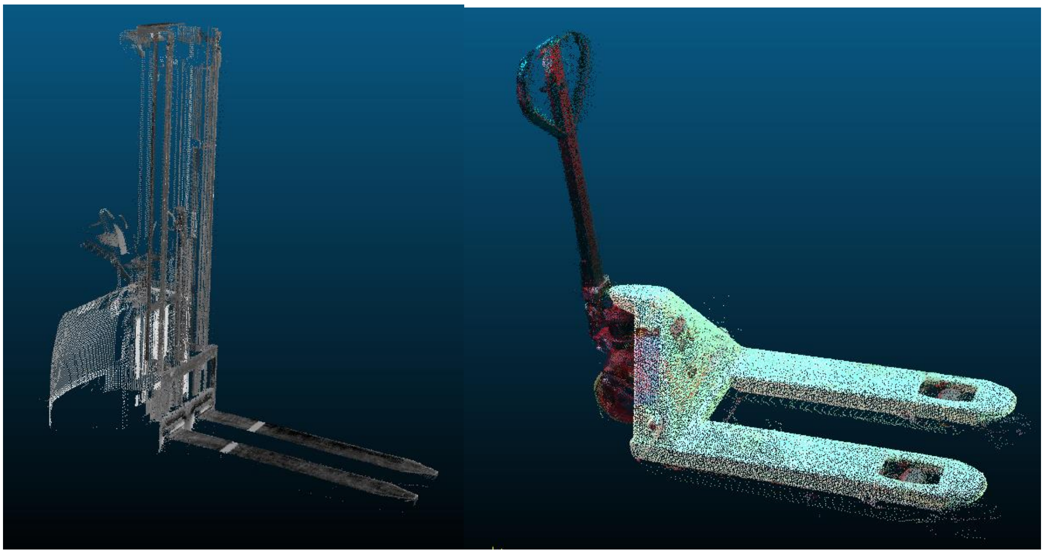


Figure 5.8 - Customer values, of using factory layout models, described as LoD and DoR to know how detailed a factory layout model has to be.

Each customer has a purpose to why they want a factory layout model. The three main customer values was identified to be layout management, simulation and knowledge transfer. Figure 5.8 describes how these customer values can be connected to LoD and DoR and which type of deliverable that is suitable to achieve certain LoDs and DoRs.

5.3.1 Requirements on 3D scanned data

To be able to build the different deliverables in Figure 5.8, the 3D scanned data has to be of separate quality. For the deliverables point cloud, blockified solids and recognizable solids, the 3D scanned data is required to cover all wanted features so that the modeller can determine size and shape of the specific objects. However, for creation of a meshed factory or point cloud objects (added in a customer specified, hybrid model), the requirements for point coverage of the 3D scanned objects are higher. In this case, an object has to be scanned from at least three different angles depending on its shape, so that points can be captured all along the object's surface without leaving any "holes". In Figure 5.9a a 3D scanned object, enough for modelling, is shown. However, there are "scan-holes" in its surface which unable the possibility to create a mesh, with acceptable accuracy, from it. Instead, the object has to be fully covered with points as shown in Figure 5.9b.



a) **b)**

Figure 5.9 - a) Point cloud-object with enough points for modelling since it is possible to, with minor industrial knowledge, decide how to model the object manually. Yet, there are "scan-holes" in the point cloud-object which makes it insufficient to automatically generate the surface using mesh.
b) Point cloud-object where the object's surface is fully covered with points, which can be used for automatic surface generation.

5.3.2 Customer values as Level of Development and Degree of Recognizability

Layout management consists of placing equipment in a new factory, or of moving equipment in an already existing layout. To support this purpose, it is required that the factory layout include objects that are moveable as well as the possibility to measure distances between the objects. The LoD can thereby be described as "moveable and measurable objects".

Furthermore, the customer value layout management can be connected to DoR depending on the customer needs and wants. A customer that are familiar with their factory and the machines/objects in it, e.g. production managers, can perhaps perform layout management with a model that visualise number of objects, order of objects and restriction-area of objects with each object labelled with a number or name. However, if the factory layout model is to be understood by several employees throughout the organization, or by a consultant, the objects have to be modelled with more detail to be recognizable. A model fulfilling this purpose would have to, in addition to number, order and restriction-area of objects, consider being visually recognizable (See *5.3.3.2 Definition: Level of Accuracy*) and show input/output of material flow.

Regarding using factory layouts for simulation, the LoD depends on what kind of simulation that is desirable to perform. Performing a 3D object simulation (e.g. robot simulation) requires that the objects are kinematically defined, 3D human simulation demands that 3D distances can be measured, 2D motion analysis requires accurately measurable 2D distances and flow simulation demands correct order of stations to follow workflow. Therefore, the customer value of performing simulation is connected to four different LoDs (object kinematics, measurable 3D distances, measurable 2D distances and order of stations), depending on the purpose of the model.

A factory layout with the purpose to perform 3D simulation (object and/or human), i.e. consist of object kinematics and tight tolerances and/or measurable 3D distances, is considered too progressive to assign to a delivery package. Instead, a factory layout model with this complexity should be planned and designed in co-operation with the customer to be able to fulfil the customer needs. However, it is possible to use the framework in Figure 5.8 as basis for a customer specified factory layout and then add features that are necessary for the specific purpose.

Regarding simulation of 2D motions, the factory layout model has to consist of the functionality to see how humans and machine can move in relation to each other in a 2D perspective. To measure 2D distances, it is required a DoR that visualise number, order and restriction-area of objects as well as recognizability (See *5.3.3.2 Definition: Level of Accuracy*) which can be translated into the deliverable "recognizable" factory layout.

When performing a flow simulation, there are less value in being able to recognize the objects in the factory layout since a flow simulation is about predicting system behaviours like throughput, breakdowns etc. (Taylor & Robinson, 2006). Therefore, a factory layout model designed for flow simulation, would in most cases be designed with "blockified" objects with information of number, order and restriction-area of objects as well as labels specifying which object is which.

Transferring knowledge using a factory layout model requires most of the DoRs which includes visualising number, order and restriction-area of objects as well as recognizable objects, input/output of material flow, connections and accessibility. However, there are two different approaches of transferring knowledge which leads to two different LoDs; static and interactive. A static factory layout, used for knowledge transfer, do not need any functionality more than visualisation. Therefore, this LoD can be satisfied using a factory layout point cloud. However, because of loading issues, a point cloud is not the most adequate solution for human interaction even if it is possible, with a little patience, to use point clouds in a VR-environment. Therefore, a meshed factory layout can be more suitable for this purpose if the customer are willing to pay for the extra performance that a meshed layout has compared to a point cloud factory.

5.3.3 Definition: Level of Accuracy

The LoA is supposed to describe how well a model correlates to the actual object scanned, which can be described as a profile surface tolerance described in section *2.9 Drawing technique*. Since the point cloud is what is available to refer to, the scanning tolerances needs to be included when setting the LoA requirements. As the name states, LoA only defines how well the models correlates to reality in terms of accuracy. Yet, for best use it should be combined with LoD in order to set an accuracy level that correlates with the requirements of each feature.

5.3.3.1 Represented Accuracy

Because of the diffuse factor "Able to recognize" of DoR, a framework has been constructed to theoretically define it. This framework is built on the same principles as profile tolerances described in section *2.9 Drawing technique*, but instead of translation from drawing to reality, it considers modelling from point clouds, i.e. scanned reality to solid model. Further, the framework was inspired by LoD for BIM (Ikerd et al. 2013).

The basic idea is to find a way of defining which parts of an object that has to be modelled for a specific purpose. Consequently, the result ended up in using upper and lower tolerances, where shapes inside these tolerances can be ignored, i.e. do not have to be modelled.

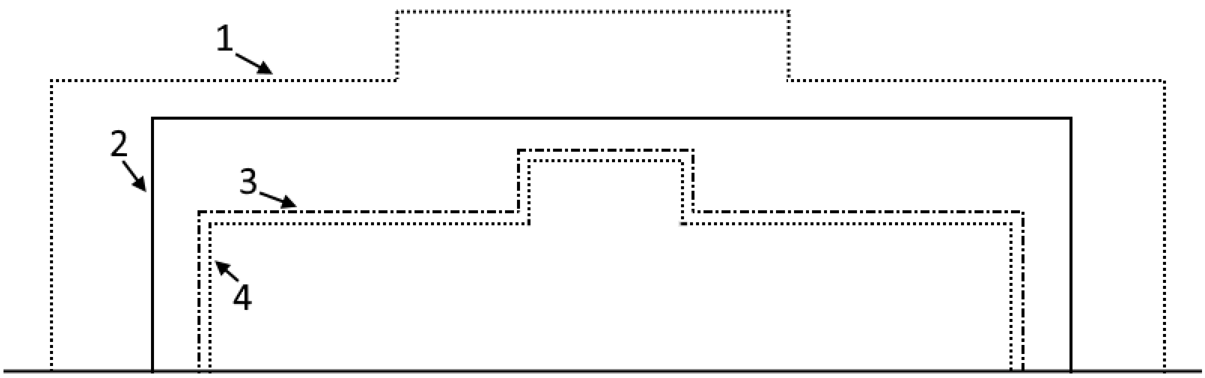


Figure 5.10 - Describing how upper and lower tolerances are meant to be used to know which parts to ignore while modelling.

Figure 5.10 show how the Level of Represented Accuracy is designed. The dotted line (3) represents the outer boundary of a 3D scanned object, while (1) is the upper tolerance and (4) is the lower tolerance. It is possible to see that the 3D scanned object (3) consist of a bulge that is difficult for the modeller to know if necessary to model or not. Since the upper tolerance (1) in Figure 5.10 is set to be larger than the bulge, it is possible to draw a straight line (2) without trespassing the tolerances. Therefore, the bulge does not have to be modelled. Instead, if the upper tolerance were to be smaller than the bulge, the bulge would have to be modelled.

Due to the end purpose of supporting change management in layout planning, the lower tolerance is set to always be narrower than the upper tolerance. It is considered to be more vital to allocate at least enough space, to minimize risk conflicts when installing new machines. Since not being able to fit an already bought machine is considered to be combined with a higher cost, than to re-investigate a small area more thoroughly if the machine is just slightly too big.

The LoA tolerances are combined with different LoD or DoR requirements, depending on purpose different accuracy requirement might be needed. For instance, it is in general of importance to consider how machines connect with each other, where input power and connectors would fit and the most outer dimensions, which should result in higher accuracy requirement on these features than others. This is basically due to supporting issues of aligning machines, making sure input and outputs are accessible and that critical space requirements are as correct as needed to support the customer sufficiently.

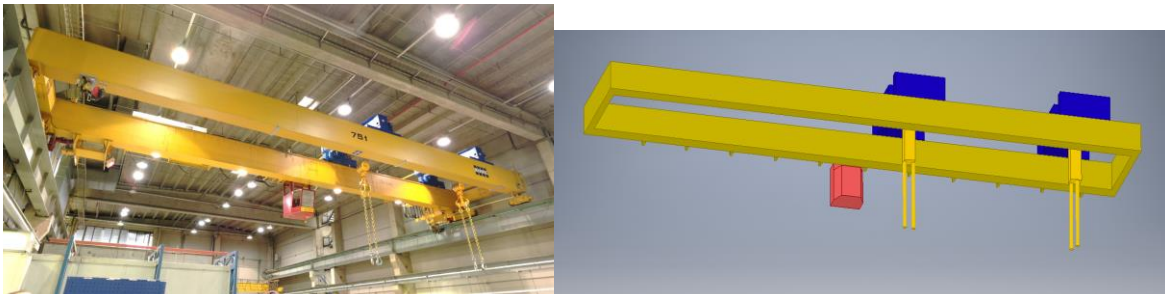
U.S. Institute of Building Documentation (2016) provides a number of LoA for BIM that would allow the customer to choose a standard LoA. A company providing reverse engineering of Factory Layouts should either sell a package defining a standard LoA or have a customer specified LoA. The provided levels described by U.S. Institute of Building Documentation are difficult to applicate in the proposed layout project workflow since they do not provide different positive and negative tolerances. Another feature that is found useful and that is not supported by U.S. Institute of Building Documentations LoA framework, is different accuracy levels depending on the size of an object. Such a feature would decrease modelling time due to decreased amounts of panning and zooming as well as part size, due to fewer surfaces. A way of handling size specific tolerances is found in the ISO-2768 standard, described in *2.9 Drawing technique,* which is frequently used in drawings to define general tolerances.

With large differences in required LoA depending on shape of objects, it is difficult to set standard levels that both ensure recognizability of objects as well as provides useful tolerances for important measures. Apart from the difficulties of setting a useful LoA, there are also issues with translating the standard to modeller knowledge since it has to be within the limited time the modellers get before they have to perform the task. LoA is therefore a more suitable tool for customer specific projects where accuracy levels can be set to comply with customer needs. Yet, for general purposes, it is not found applicable in a satisfying way.

5.3.3.2 Approach to simplify use in reality

Because of the theoretical complexity of LoA for factory layouts, an approach for user-friendly application is provided. This approach is based on creation of reference objects, visually aiding the modeller towards the requested “recognizability” (LoA). Below, examples of a few reference objects of the recognizable level are shown, as well as a clarification of their validity. Commonly for the reference objects are that their parts are assigned with colours. This is due to that colorizing the different parts greatly simplifies the understanding of the object and its parts. Therefore, it should be done for all recognizable objects.

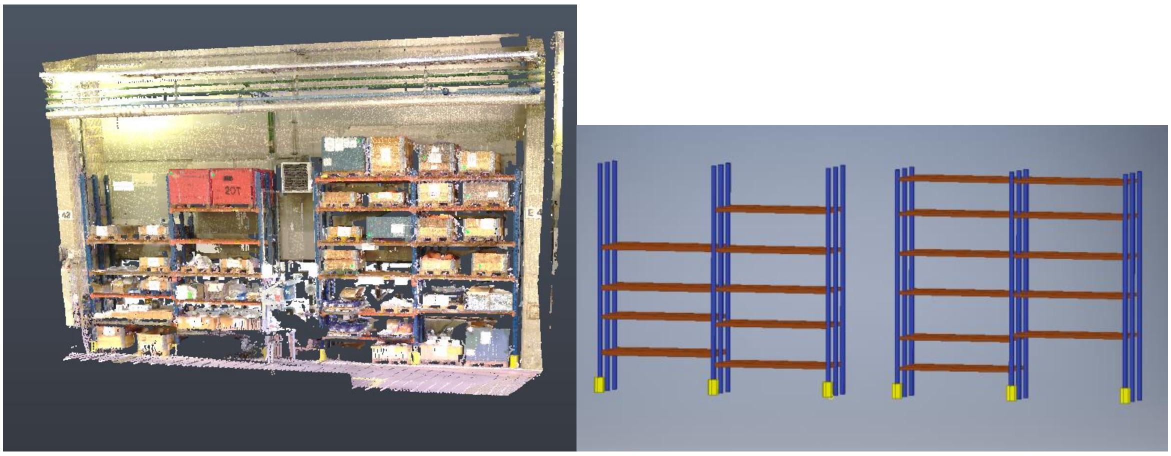
In figure 5.11a and 5.11b below, a traverse is presented in the form of a picture and a screenshot of the deliverable CAD model. Features such as the red cabin, lifting chains and bottom of the frame has higher focus on accuracy, due to their higher risk of conflict with interior equipment standing in the factory. The context, size and placement of the traverse within the final assembly, makes it easier for the receiver to recognize the object, which put less requirements on the detail of the traverse itself.



a) ***b)***

Figure 5.11 - a) shows a picture of a real traverse and b) shows the modelled reference traverse.

Figures 5.12a and 5.12b presents a point cloud and CAD model screenshot of a pallet rack. The model captures legs, shelves height and leg protectors. This provides enough information to easily recognize it as a rack and also space requirements and shelve heights which supports planning of available pallet slots and needed space. Material on the shelves and fixtures/tubes combining the front section with the middle and the rear section should not be modelled. The fixtures are ignored due to recognizability and space allocating reasons since it was judged that the rack is recognizable without these features. Also, the fixtures fall within the space behind the legs, seen from the angle one would access material in the racks.



a) ***b)***

Figure 6.12 - a) A point cloud of two racks. b) The modelled reference racks.

5.4 Time setting sheet

In order to provide customers with an accurate estimation of the final cost and lead-time of a layout project, it is important to know how different factors contribute to the cost of performing such a project. The main cost driver is the cost of project personnel, but costs of overhead personnel, software licenses and having appropriate hardware for performing the tasks should also be compensated for. It was therefore requested by VM to find a way to predict the total time consumption of a factory layout project, starting with the steps from point cloud management and ending with final deliverable models. The proposed time estimation sheet can be found in *Appendix F*.

5.4.1 Point cloud management

The first step to consider is the registration of raw point cloud data. This process include steps from importing raw data to exporting point cloud regions ready to be modelled.

5.4.1.1 Found factors and contribution

The factors found to be most influential on time-consumption for processing and registration of 3D scanned data are:

- Number of scans
- Number of points (Depending on quality, resolution and colour)
- Number of objects to divide point cloud into

The number of scans as well as the size of each scan, in terms of number of points, are the major contributors to the duration of registration and processing steps. Another factor is the time for manual registration, however, this time-estimation framework assumes that referencing is properly made during the scanning-phase, which enables all registration to be performed automatically and manual registration can therefore be excluded.

Number of objects to divide point cloud into is synonym with number of objects to be modelled. Since each object is modelled individually, it requires an individual point cloud region supporting this work. Using selection-tools to divide each object into its own region takes a small amount of time, but with several objects to assign to different regions, this is a factor that has to be accounted for.

5.4.1.2 Practical approach

Since number of scans is planned in the beginning of a project, it is simple to account for this factor. However, the number of points of each scan can differ because of quality-, resolution- and colour-settings. Yet, in most projects, the same quality, resolution and colour are used, resulting in the use of a standard time for processing and registering one scan.

Regarding division of point cloud into regions, the amount of time can differ between objects. However, with use of the simple selection-tools, assigning an object into a region combined with time of saving or exporting will result in a time factor linked to number of objects. Although, to set a proper value for this factor, a method and a number of test cases needs to be arranged. The total time-consumption for point cloud management can then be estimated to number of scans times a scan factor and number of objects times an object factor.

5.4.2 CAD-coordination

The CAD coordinator has the overall responsibility of the CAD data, collaborating with modellers trying to make the project run as smooth and successful as possible.

5.4.2.1 Found factors and contribution

- No. of modellers - how many modellers to keep busy and to support

- No. of objects - parts needed to be created in assembly
- Time required to support modellers
- Customer dialogue

5.4.2.2 Practical approach

Estimating the time consumption of the CAD coordination is rather difficult, factors such as supporting modellers and customer dialogue is highly dependent on each case. With a number of inexperienced modellers, it could be difficult to estimate work division and require a lot of support, whilst experienced resources are easier to predict and require less support.

The time it takes for creating the assembly model structure is comparably short. There are some specific project files needed to be created for every project and the assembly structure needs to be created. Creating standard documents will take the same time in every project and depends upon what to include in a standard project. Adding parts in the assembly structure then adds about 20 seconds per insertion, of either part or sub-assembly. The file preparation is therefore roughly the same for all projects unless they contain a really complicated Bill of Materials (BOM).

The standard time for creating files should be added to some kind of expert judgement made by the coordinator, which include the factors of available modellers competence and required dialogue with customer.

5.4.3 Solid modelling

The process of creating CAD models was told to be most time consuming in the initiation of the project and this is supported by the project findings. The task of a modeller is to convert the point cloud received from the coordinator to a solid 3D-model, in the standard delivery format.

5.4.3.1 Found factors and contribution

Found factors can be categorised in general modelling objects and building objects. Factors found for modelling of the general objects are:

- No. of items to be CAD'ed
- Complexity of object, shape and size
- Level of Development
- Degree of recognizability
- Level of Accuracy

Factors contributing to modelling time of buildings are:

- No. of rooms
- No. of walls
- Floors on same or different levels, no. of floor levels
- No. differently shaped pillars, as well as total amount of pillars
- No. of doors and windows

5.4.3.2 Practical approach

Described in section *5.3 Define delivery packages from customer values*, there are a lot of different factors affecting how to make a model, several features and different accuracy requirements can be used. In order to make an estimation approach useful, these factors are combined to certain delivery packages. The project puts focus on the delivery package used in the majority of orders, the recognizable level. For blockified objects, the process can be simplified by just decreasing modelling time for objects and giving all objects the same time, whilst more detailed delivery packages require a case specific approach.

With support of the model definitions proposed to be set by VM, an experienced coordinator should be able to estimate time consumptions for the ingoing objects. The upper time limit is based on the current recommendation at VM, that objects should not take more than 120 min, and the intervals are judged to be easily defined yet fairly accurate. The project propose that a model could fall into following time categories:

- 0-30 min: allocate 30 min
- 30-60 min: allocate 60 min
- 60-120 min: allocate 120 min
- More than 120 min: running cost

For the time estimation of buildings, mentioned factors should be used to estimate the time needed to model the building, this estimation should be presented in the same way as specific object but with an additional interval of 120-240 min, allocating 240 min. The sum of time allocations, for all ingoing objects and the building, result in the final time estimation for modelling. If either building or objects does not fit in the intervals generating time allocations, these objects could be offered separately.

5.4.4 Mesh modelling

Using mesh as modelling technique changes the equation of allocated time for scanning compared to modelling. With traditional modelling, there are lower requirements on scan data, but high requirements on manual modelling which contributes to manual modelling being a large part of the total time consumption for a factory layout project. Instead, using mesh for modelling increases number of scans and therefore time-consumption for scanning, but reduces time for modelling since the modelling is made mainly automatically.

5.4.4.1 Found factors and contribution

In this section, factors that affects the time for modelling with mesh is considered. The increased time for scanning has to be considered while planning scan-execution and accounted for in scanning-time estimation. Yet, it is important to remember that increased number of scans has a large impact on the total time for creating a meshed factory layout.

In general, the factors that affects time-consumption of mesh modelling are mentioned below. However, software-specific factors may also have an impact on the time-consumption.

- How noisy the point cloud is
- Size of point cloud (number of points)
- Number of polygons per unit area
- Reduction of polygons

Each of these factors contribute to the time-consumption in different ways. Point cloud-noise affects time by forcing the modeller to clean up the point cloud before meshing. Size of point cloud impacts the total number of polygons that has to be created to get a mesh that represents the object. Also, the size of the polygons affects time-consumption, since it takes more time the more polygons that has to be created. Lastly, it takes time to reduce number of polygons that has to be accounted for.

5.4.4.2 Practical approach

Since it is difficult to assume how much time to allocate for a point clouds noisiness, the impact of this factor can be estimated with a standard time allocated for this purpose. This standard time has to be set from experience of how long time cleaning of noise normally takes.

The size of a point cloud impacts how many polygons that has to be created. However, it is difficult to know how many polygons that has to be created for an object. Also, the time-difference for meshing objects of different sizes are so small, that the most suitable practical approach is to set standard times for meshing an object, including estimation of normals.

Further, to be able to make manageable meshes that can be used in a 3D-environment, the mesh has to be reduced. This is a procedure that is almost independent of other factors and is therefore accounted for by a standard time.

5.5 Process comparison

The comparison is performed between the current state and the solution, by the project found, most equivalent to the preferred solution described in *5.2 Work procedure*. Due to software limitations, it was not possible to create a workflow completely in line with the preferred workflow since different softwares contain different properties described in preferred solution. However, while doing the process comparison, the softwares found to best suited for the overall process was used.

5.5.1 Processing and registration

The registration process as such was not found to be a flaw in terms of time, quality and cost even if there were possible improvement potentials. However, to support improved modelling purposes, the registration software had to be changed from current state to proposed solution. Therefore, a comparison between these two processes had to be performed to make sure that the proposed solution can deliver point clouds in approximately the same pace and quality as the old one. Also, the simplicity of working with each process is compared in terms of available methods and interface.

Tests made in the project indicates that both softwares can register scans with the same accuracy, both giving a full factory point cloud using automatic registration. Furthermore, they include the ability to perform manual target based registration if needed, as well as the functionality to change/update origin.

Regarding processing time, the proposed solution is a little bit slower in processing and registering scans, but with a, for the purpose, more suitable way to update origin, time can be saved at this operation instead. See this comparison in *Appendix B.*

Furthermore, the given workflow, including structured, easy-to-find methods as well as the simplicity of the interface of the proposed solution, is an advantage of using this instead of the current state method.

Thereby, the conclusion is that the proposed solution with its belonging methods fulfils the requirements for processing, registering and updating origin of 3D scanned data, without decreasing the performance of projecting factory point clouds, compared to the current state. Instead, it is a more user-friendly procedure that will simplify for new users.

5.5.2 Division and cleaning of point clouds

Since the proposed solution includes a workflow consisting of methods for each step, it simplifies for the user even in division and cleaning of point clouds compared to the current state procedure. Also, the proposed solution has the functionality to divide the full factory point cloud into regions, that can be shown or hidden in the CAD-software. Therefore, there is no need for exporting every single point cloud object since the full factory point cloud, including regions, can be saved as one project-file. This will save time and open up the possibility to compare the final factory layout against the full factory point cloud.

In the current state process, the point cloud objects exported from the registration software has to be thinned out in an external freeware due to limitations in the used CAD-software. In the proposed solution, the CAD-software is more powerful, which gives the possibility to handle full factory point clouds. Therefore, the process-step of thinning out the point cloud objects in an external software can be eliminated which also will contribute to saving time.

5.5.3 Proposed modelling versus Current state modelling

Modelling time was found to be the major contributor to the amount of resource hours required for a layout project, therefore the major focus was put on this process. The proposed method and software offer solutions to several of the found improvement potentials, where tools and interface of the software, combined with an improved and clarified way of working, provides support for found flaws.

With the internal clarification, combined with modelling guidelines and a more structured and conventional way of modelling, issues with varying modelling quality and time is addressed in the proposed solution. Having the reference model guide easily found in the process workflow should provide support for the difficulties of deciding when a model fulfils the demands of a certain delivery level. In the current workflow at the company this is not stated in any guiding document. Therefore, modellers will guess their way and often overdo their modelling.

The current modelling technique is rather unconventional, which in general would require further adaptation-time for new users. Functions described in solutions such as using boxes to crop away points that is not of interest in current feature, combined with the more common sketch extrude modelling technique, provides simplifications for capturing contours of objects. This procedure requires less steps and more certain model quality, which outperforms the current method. This is shown in a test case, see *Appendix C*. A fair comparison would require several modellers, modelling several objects of different shapes to exclude biases. Without access to a random set of modellers, focus of the comparison would rather be on available features and settings of them than time measures.

Both the current and the proposed modelling software has support for several of the tools mentioned in solutions, although, not equally user-friendly. The proposed software has easier ways to define the features and it generally requires less steps. Another main difference is the stability of them, with the proposed software being able to handle files more than ten times the size of the current software, with less noticeable lagging and fewer unwanted terminations. Not only does this limit the need of reducing point clouds for objects being modelled, it also provides possibility to handle modelling and assemblies in the same software. Not only can the proposed software handle more objects with higher complexity, it can also include a simplified point cloud of the full scan for the test cases. By doing so, it simplifies evaluation of the final delivery and also provides the customer with the information of both point cloud and solid models within the same file.

By performing both models and assemblies in the same software, it is possible to have the top-level assembly fully updatable. If the coordinator creates the project structure within the top-level assembly prior to modelling, the modellers can then use the part files for their models. By creating their objects from parts within the assembly structure, all parts will be displayed in the assembly in the latest saved status. This helps both the coordinator to keep track of the status of the modellers and also simplifies preparation for customer meetings, since a presentable assembly always is accessible.

5.5.4 Model with mesh versus Current state modelling

Using mesh requires higher accuracy of input data which is shown in section *5.3.1 Requirements on 3D scanned data*. However, how much more time that has to be put on scanning depends on shape of objects and placement of objects which is specific for each case. Therefore, due to differences from case to case, an adequate comparison is not possible to perform. Instead, this matter is further discussed in *6.3 Modelling with mesh in factory layout projects*.

Yet, replacing traditional CAD-modelling with modelling using mesh is a way to reduce time for modelling as well as the modellers plan of which parts to model to make an object recognizable.

However, the quality of a mesh, in terms of tolerances of outer boundaries of an object, will reduce, or at least be less controllable, while using mesh instead of CAD-modelling since the mesh-algorithm automatically estimates how to create the surface of an object.

6 Discussion

In this chapter some project findings will be analysed, trying to give a critical view of the results and look upon potential areas of further interest. The key findings discussed in this chapter will cover the comparison of the proposed solution to the current, some aspects of using compatible softwares as well as the proposed modelling techniques, definition of output requirements and time estimation.

6.1 Current state versus Proposed solution

This section covers the comparison between the current state versus proposed solution. How well do the proposed solution with its methods and related softwares stand against the current process at VM, how can a fair comparison be made and are there bias and risk for subjectivity in the results. The comparison discussion covers the major steps and findings.

6.1.1 Point cloud management

In the project start-up the point cloud management was not found as an area of high improvement potential since the process is highly automatic with only need for human work in some parts. The main flaws found in the current method is the lack of clear guidelines and especially how to locate the guidelines that exists. There are several methods, although, they are difficult to find which makes the users experience the process as difficult.

The proposed solution has its advantages in being more user-friendly, which is especially beneficial for unexperienced users, whilst the software related to the current state process seems to be more robust. However, it does not show any support for further purposes, such as increased functionality when working with point clouds or output quality, compared to the proposed solution. Therefore, even if both solutions work well, the proposed solution, with belonging methods and added support for following processes, is found beneficial to use.

6.1.2 CAD Coordination

Just as with the point cloud management, CAD coordination was not seen as an area of big improvement potential by VM. One probable reason for this is that the resource responsible for this process, is required to be more familiar with the process, than for example a modelling resource. The coordinators have had earlier projects, helping them to learn the ropes and giving possibility to make small adaptations in their own project processes. This makes them less harmed by lack of accessible methods, since they already master the processes in a factory layout project. Although, there are some areas where the project found potential flaws and managed to make improvement proposals.

In the current method, the top-level assembly is not put together prior to finalization of models. In the proposed procedure the top-level assembly is created in the initial stages. The full BOM structure should be created, with parts and assemblies, in the CAD-software and a simplified cloud of the full factory should then be inserted to the top level of the assembly. By preparing this in the initial stages of a project, the coordinator will be able to follow modelling progress, with direct access in top level assembly to the latest saved models. This will help the coordinator in project planning as well as communication with the customer and will also give better control of the resources which could prevent the modellers from continuing with making models of deviating quality. With updated models and a software that can handle a reference point cloud in the assembly, it is believed that the coordinator will get means to run a smoother and more accurate project.

6.1.3 CAD Modelling

The CAD modelling procedure was initially seen as the area of highest improvement potential, mainly due to the amount of resource hours spent within it. Apart from the fact that it is the most resource intensive process, it is also the process of highest variation between different projects, when it comes to both time and quality. It was found that output is highly dependent of the modelling resources that are assigned for each specific project. With diffuse definition of detail levels, different modelling techniques and lack of guidelines for modelling, it is obvious why this variation in output occurs so frequently. Furthermore, with the lack of defined work methods for the modelling procedure, the perception is rather that modellers make up their own way of working which results in several different model structures, with uncertainty of both output quality and lead times of modellers.

The current state result indicates that a rather unconventional modelling technique is used, whether it is due to software limitations, or if it is seen as superior to the conventional technique is not obvious and difficult to judge objectively. Some tests have been made, where time comparisons indicates that the conventional modelling technique within a common CAD software is superior to the asis methods in the present software at the company. Whether it is due to the skills of the modellers, if the objects are more suitable for either method or actually are representative of the differences between them is hard to say. Rather than just comparing time consumption, a better comparison could be to look upon number of steps in the model tree and available functions to simplify the modelling.

It is possible to allocate some features that is highly useful for reverse engineering from point clouds, supporting modellers in reaching solid models both rapidly and accurately. Mentioned in the result are point handling features such as ability to handle many points, coloured points, tools to reference to points and also abilities to hide and show parts of the point cloud. Another feature, which is found to be crucial for adopting a conventional modelling technique, is the creation of reference planes for sketches. The feature is available in most CAD-softwares, but how it is accessible differs and planes can be defined in several ways. By providing useful defining options for planes, CAD-softwares makes the conventional modelling technique truly powerful.

This conventional modelling technique is based on capturing 2D contours of objects, in sketches from different angles, from created planes, which then with extrusion and boolean operations defines the final solid objects. With creation of planes, from angles capturing the most important contours of the object, combined with the possibility of hiding points, which makes the contours less obvious, this technique can be fully utilized. Complex 3D shapes can be accurately defined by combining extrusions with boolean operators from just a couple of sketches. By such a modelling procedure, the modeller is able to use a modelling technique less object specific than the current drag and drop technique used at VM. The proposed method is believed to minimize required time for complex models, without increasing time for simple objects, creating a more predictable and standardised modelling technique.

By providing methods in a well-known work procedure, combined with more clearly defined model requirements, it is believed that the output would be not only faster, but also more consistent in both quality and lead time. This would e.g. simplify cost estimations of layout projects. By being able to accurately estimate time consumption, smaller safety margins are required which provides the company with the possibility of giving a more competitive offer without jeopardising profitability.

6.2 Advantages of using softwares from one developer

The current method at VM includes several file format conversions, a process combined with both time consumption and information losses. In the proposed procedure, the project processes consists of steps performed in softwares from a single developer, with the purpose of reducing file conversion issues. The developer has built their softwares to enable transfer of files between its different softwares without the need of conversion to lightweight formats. This minimizes the risk of conversion errors when working in multiple softwares. By importing file formats used by earlier processes, there is an assurance that the data is the same. It also gives the possibility to go back, update an ingoing model and save it without the need of replacing references. Furthermore, benefits such as similar interfaces, package discounts, one supplier and invoice as well as one support forum comes with using softwares from one developer.

Since conversion to lightweight formats is used frequently in customer deliveries, both in factory layout projects as well as many other projects, it is justified to question the risks of using lightweight formats. Although, questioning the significance of the conversion risk does not take away the other benefits, still perceiving softwares from one developer as beneficial. Furthermore, by providing a free viewer supporting the native model file format, the risk of conversion errors can be excluded for the viewing purpose, even for customers modelling in different softwares.

6.3 Modelling with mesh in factory layout projects

As mentioned in *5.5.3 Model with mesh Versus Current state modelling*, meshing an object will in general reduce modelling time, especially for complex objects. However, even if mesh reduces time for modelling it may not reduce total lead-time because the procedures put higher requirements on the scanning and the necessity to perform more scans. Depending on the shape of objects and how they are placed in relation to each other, different number of scans have to be made. Therefore, the time required for increased number of scans has to be compared to decreased time for modelling, to know if it is worth using mesh instead of solid modelling. Also, mesh provides less quality control of the modelled object compared to modelling in a CAD-software. Therefore, the cons of using mesh seems to drown the advantage of reduced modelling-time, which advocates that mesh is not a way to replace solid modelling, at least not for general purposes. Although, it can be a way to complement the solid modelling, so that hybrid factory layouts consisting of solids, meshed and point cloud objects can be delivered. Also, it might be possible to use mesh for visualisation purposes when accurate tolerances are not of high necessity.

Further, it is of high importance to consider what mesh-software to use in factory layout projects. Some softwares consist of a lot of functionality, which makes it possible to edit the mesh in several possible ways. However, increased amount of possibilities can also increase the difficulties of understanding how to use the added functionality. Other softwares, with fewer options for the user to decide from, might provide better results for the inexperienced user. Yet, some softwares lack in fundamental functionalities such as keeping world coordinates or reducing number of polygons. With this said, a mesh-software chosen for a factory layout project, have to consist of the functionality of maintaining global coordinates of a point cloud, as well as the function of reducing number of polygons. Other functionalities should be judged based on how they support the user to fulfil the specific end-purpose.

A function to search for in the future is to find a way to export point cloud-files including normals for point sets from a registration software. Since the points has a normal-direction towards the position where it was captured, this would simplify the workflow of meshing and make it possible to create more accurate representations of the reality using external mesh-softwares. Although, the registration-softwares might also improve their included mesh-functions so that they can be used for editing meshes (reducing number of polygons etc.).

Important to know is that it is not only the software that limits the possibilities of creating a mesh. Depending on how powerful the hardware is, it is possible to import point clouds of different sizes as well as mesh objects with different amounts of polygons. The hardware used in this project could e.g. create a mesh of approximately 500 000 polygons. Yet, with a more powerful computer it would be possible to create even larger meshes. Because of the low performance of the hardware used in this project, it was not possible to judge how large meshes that can be created before the software's performance is too low. Therefore, while considering using meshed objects in a factory layout, the performance of chosen software combined with invested hardware should be tested.

6.4 Defining output Level of Development and Level of Accuracy

A major issue in reverse engineering, or almost any engineering, is to decide at which level something is developed enough to fulfil its purposes. By over-developing models of a layout, resource hours are spent on creating details not requested by the customer. In the end, the customer will have to pay for these extra resource hours, making them pay for features they did not request. The process of defining LoD and LoA, could very well be compared to the process of creating drawings for models to be manufactured. In both cases an object conversion from one format to another, model to reality or in this case the opposite, is supposed to be defined in what properties and accuracies the model requires to fulfil.

LoD can be compared to drawing information such as material property, tool directions and infusion marks, whilst LoA focus on tolerances of measures and surfaces. Furthermore, a combination of these two is relevant to look upon, setting accuracy differently for certain features of the model. This is similar to e.g. setting flatness and roughness of connecting surfaces to decrease resistance in an electrical connector.

The combination of surface profile tolerances and size specific tolerances, is an interesting subject for further investigation. Surface profile is probably the easiest, as well as clearest, way of describing accuracy of a surface. Depending on the size of an object, accuracy or time of sketching the contours of it will be affected. Fitting the whole object in the graphics window area, will minimize panning and zooming when modelling and depending on the size of the object, the ratio between reality and graphics will differ. A tolerance deviation of two millimetres while choosing a point on the screen, could in reality be a deviation of a couple of micrometres to several decimetres, or even more. In order to keep up modelling speed, consideration of size of models and number of surfaces can be included by different requirements for large versus small objects. An example worth investigating when setting such a standard could be the ISO-2768 (Henzold, 2006), which is frequently used in setting general drawing tolerances.

The complexity of creating a standard definition of LoD and LoA, that is applicable and useful for all possible layout projects, can be compared to making a standard document replacing all drawings. It is just not possible which increases the necessity of making trade-offs, putting focus on creating standards where they are useful. Which components of projects are frequently occurring and are possible to clarify, how can these be standardised and easily understood in a limited amount of time. A practical approach to this, is to use reference objects combined with LoD and DoR descriptions, which should provide modellers with a quick and general view of anticipated development and recognizability of models. Although, even with a number of reference objects, there will be several occasions where the modeller is left without clear references, having to base development level on own judgement.

What might be simpler to describe, but even more difficult to apply is LoA. A general profile surface tolerance can be set for a whole project or on ingoing objects, offsetting surfaces from the finished model and comparing to the point cloud can assure its validity. However, having a general LoA would put requirement on so many unnecessary surfaces, e.g. should objects within racks be modelled and should they be modelled with the same accuracy as other parts. Should the plastic bag of a trash bin be modelled with the same accuracy as the matching surfaces of two conveyor belts. It is quite quickly found that there are so many different accuracy requirements, that having a standard LoA requires so many exceptions that it would be, if not impossible, at least impractical to use.

Although, one way of applying LoA in a practical way, providing a clear purpose, could be to use it for a 2D space requirement. Capturing outer dimensions viewed from a blueprint perspective, could set 2D space requirements of objects with clear tolerances. In many cases machines will be placed according to 2D space coverage, which will make this approach useful and able to define validity from.

6.5 Time estimation simplification

Accurately estimating required time is crucial in order to provide customers of a factory layout project, as well as any project, with a precise due date and cost assumption. With different customers, different demands and changes in modelling resources, it is difficult to correctly estimate the final time consumption of a project. With an extremely detailed time estimation, the number of factors to gather and judge gets both complex and time consuming to define. By setting some standard data and use the acquired knowledge from previous projects, it is assumed that more general data can be gathered in combination with estimations, to provide a fairly accurate time estimation in a fraction of the time required to investigate and evaluate all contributing factors.

The proposed way of estimating time, focuses on key factors in each one of the process steps, from scan processing to 3D generation. The key factors cover number of scans, with the predefined settings, and number of objects to create regions from point cloud management. Number of objects as well as customer dialogue and CAD support are the factors for project coordination. The factors for 3D generation are for the manual modelling number of objects and estimated complexity of them, whilst meshing only covers number of objects. Combined with the standard data, covering other factors, and an experienced coordinators judgement, it should be possible to estimate time fairly accurately.

With the implementation of methods describing general steps for the different processes, combined with clearly defined delivery requirements, the human factor of the assets should be less influential on the final time estimation. Deviation still remaining from the human factor, should be captured as CAD-support, which rather focuses on how to learn the resources to follow the standard procedure, than how they distinguish from each other in modelling time.

7 Conclusions

RQ1 Which processes within the current method at Virtual Manufacturing has the largest impact on lead time, quality and cost?

The most time-consuming task in factory layout projects are CAD-modelling, especially regarding labour hours. Since it is performed manually and without a clear structure, both of how detailed an object should be and how to perform the modelling, it has a significant impact on quality as well. Regarding the cost of factory layout projects, the main cost-driver was told to be personnel-time. Therefore, the cost is affected by the same flaws as time.

Furthermore, the development and detail levels of models are the major contributors to time consumed in the CAD-modelling phase. Lack of structure for how detailed an object should be modelled, as well as how this modelling should be done, are therefore seen as the factors which have the major impact on lead time, quality and cost. Not only does these factors have the highest impact on the output, they are also contributing to the high degree of variation in time consumption of similar projects.

However, apart from not having a clear modelling structure and technique, the few guidelines that could be captured through dialogue with modellers, indicated an unconventional technique with limitations. The modelling technique combined with the flaws in modelling software, is very time consuming when objects get too complicated. The software is limited in how big point clouds that can be imported, as well as in how it handles point clouds, while the modelling technique requires a lot of time when objects has many edges and difficult shapes.

Another factor found, especially contributing to the quality level, is the lack of comparison of the final assembly model and the point cloud of the scanned factory. By only comparing clouds of objects to the modelled object, it is not possible to ensure that the object is correctly located within the assembly model, nor is it clearly shown if some models are missing or if it is just an open space in the factory. This lack of comparison does not only affect internal quality control, it also makes it more difficult for the customer to follow and comment during work in progress reviews.

RQ2 How can these processes be improved?

The main time-, quality- and cost-driver was found to be the inconsistent Level of Development (LoD) and Level of Accuracy (LoA) of the finalised models, mainly due to the lack of defined detail-level for deliveries. Therefore, a framework describing how different customer values can be translated into LoD, i.e. included functions, and Degree of Recognizability (DoR), i.e. features to include, is proposed to decrease duration of a project and secure the quality of the delivery. Regarding LoA, the presented theoretical approaches are too complex to applicate in factory layout projects.

To improve the quality of the deliveries, the final factory layout should always be compared to the 3D scanned point cloud to secure that every object conforms with reality. Also, by introducing a project structure where the project-coordinator connects all parts to an assembly before modelling starts, the project progress can be followed and flaws can be discovered early in the process. Another improvement that can secure quality of the workflow is the new software proposed. The proposed software is more reliable than the current one which will decrease unwanted duration such as termination and lag.

Furthermore, a structured process flow with belonging methods has been created to simplify for the modellers, making sure that each asset knows what to do, when to do it and how to do it. This will decrease time for looking for methods, giving the modeller a framework that is easily found and can be relied upon.

RQ3 How can detail-level of delivery packages be arranged to bring value to both customer and supplier?

With respect to customer values such as layout management, simulation (robot, human/machine and flow) and knowledge transfer, LoD and DoR can be defined differently to satisfy the customer needs and wants. The proposed delivery packages are: point cloud, mesh, block, recognizable and customer specified, where each package fulfil different customer values. Using this framework for definition of delivery packages supports the modeller by describing how developed the model should be, as well as gives the customer a view of what to expect from the model. Also, it assures that the model includes features that fulfils the customer needs.

RQ4 How can duration of factory layout projects be estimated?

By extracting well-chosen time drivers from the process, time estimations can be based on fewer measures, yet be able to give an accurate time estimation. With a standardised method and more clearly described model requirements for each package level, time estimations can be less resource specific and more general.

Focused on using coordinator experience, rather than combining endless of factors, estimations can be made fairly accurate and in a fraction of the time needed to gather the information for a theoretical judgement. The presented proposal requires adaptations of an experienced coordinator to be tailored to fit VM in the best possible way.

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Appendix A - Interview guides

Two interview guides were created to have a framework for how to perform the different interviews. One of the interview guides were unstructured to give the interviewee possibilities to speak freely about the area of factory layout projects. The other interview guide was used when interviewing people from other business areas. Therefore, it was semi-structured with questions that directed them into areas that was of interest for the project.

Unstructured interview guide

Standard questions:

- Can you describe the process and your view on how factory layout projects are performed today?
    - What would you want to try if you had the time?
    - Which process-steps are the most frustrating?
- What do you think about the current delivery packages?
    - Do you know how much that is required from your modelling by looking at these packages?
    - Do customer values correspond to what is included in the delivery packages?

These questions were followed by presentation of our thoughts which led to discussions regarding several areas within factory layout projects.

Semi-structured interview guide

As a start we told the interviewee about our project and the purpose why we were performing this project to give him/her understanding on how to direct the answers.

Standard questions:

- For what is 3D-scanning used in your business?
    - What is the expected delivery?
    - Which technology/technique is used the most for this kind of projects?
    - Which technology/technique is the most innovative for performing this kind of projects?
    - Do you see any steps/techniques that we can embrace in our project?
    - What is your view on the process for transforming point clouds into solid models?
        - Where is the highest improvement potentials?
- Are there any alternative techniques to the one you use now that you see can be used?
- What softwares do you use?
    - What are their major pros and cons?
- What is the tolerances on your 3D-scanning projects?
- Is there any definition of Level of Detail in your projects?
- What companies are interesting to study within the area of 3D-scanning to 3D-model?

Naturally, each question was followed by supplementary questions to find out as much as possible.

Appendix B - Point cloud management comparison

Both procedures consist mainly of automatic processing. Therefore, the users' competence is only relevant for the manual parts. For automatic processing, the time depends on hardware, number of scans and size of scans. This test case consists of 23 scans, scanned with VMs standard quality, resolution and colour settings.

Division into regions is not measured in this test. This is due to that the proposed solution and the current state uses the same tools for this manual operation and therefore should take the same amount of time.

Proposed solution

Process step	Type of work	Time
Import scans	Manual	Approx. 1 min
	Automatic processing	59 min
Registration	Automatic processing	14 min
Index scans	Automatic processing	1 h 7 min
Setting origin	Manual	Approx. 5 min
Clean	Manual	Approx. 5 min
Divide into regions	Manual	-
total		2 h 31 min (11 min manual)

Current state

Process step	Type of work	Time
Import scans and change settings	Manual	Approx. 2 min

Processing	Manual	Approx. 1 min
	Automatic processing	1 h 14 min
Registration	Automatic processing	Approx. 1 min
Project Point cloud	Automatic processing	22 min
Setting origin	Manual	Approx. 3 min
	Automatic processing	2 h
Clean	Manual	Approx. 5 min
Divide into regions	Manual	-
total		3 h 48 min (11 min manual)

Appendix C – Solid modelling time evaluation

Time estimation
Solid Modelling

Resource:	Resource 1	Resource 2
Quality: Aimed delivery package:		
Achieved quality - Does not fulfil delivery package requirements, fulfils or more than fulfils the requirements:		
Experience: Time in CAD software - round to nearest quarter of a year:		
CAD experience overall - round to nearest quarter of a year:		
Time in factory layout projects - round to nearest quarter of a year:		
Method: CAD-software:		
Modelling technique:		
Result: Expected time (mm) - According to coordinator expectations:		
Time (mm:ss) - From CAD software home page with no model opened, to model saved in correct folder:		
Comments:		

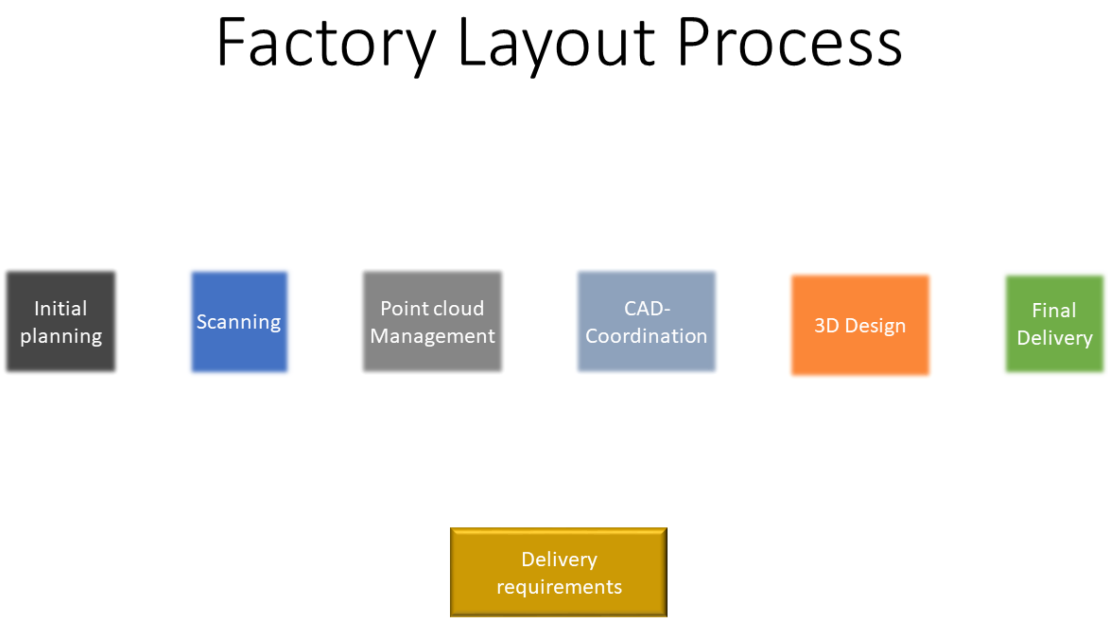
Time estimation solid modelling example description

In order to try out the Time estimation for Solid Modelling template, a test case was formed. An ongoing project at Virtual Manufacturing AB was used, a modeller from the project remodelled one of the objects in the project according to the techniques currently used at Virtual Manufacturing. The same object was modelled by one of the authors of the report, in the proposed method and software. Data gathered from modelling, the modellers experience and the final model was extracted and inserted to the document. This test was supposed to evaluate the time estimation template and give an example of how to use it. The result is target for biases, from authors being part of the test to model being chosen by the Virtual Manufacturing employee. For a reliable evaluation, a broader set of modellers and objects needs to be investigated, which was not available at the time of the project.

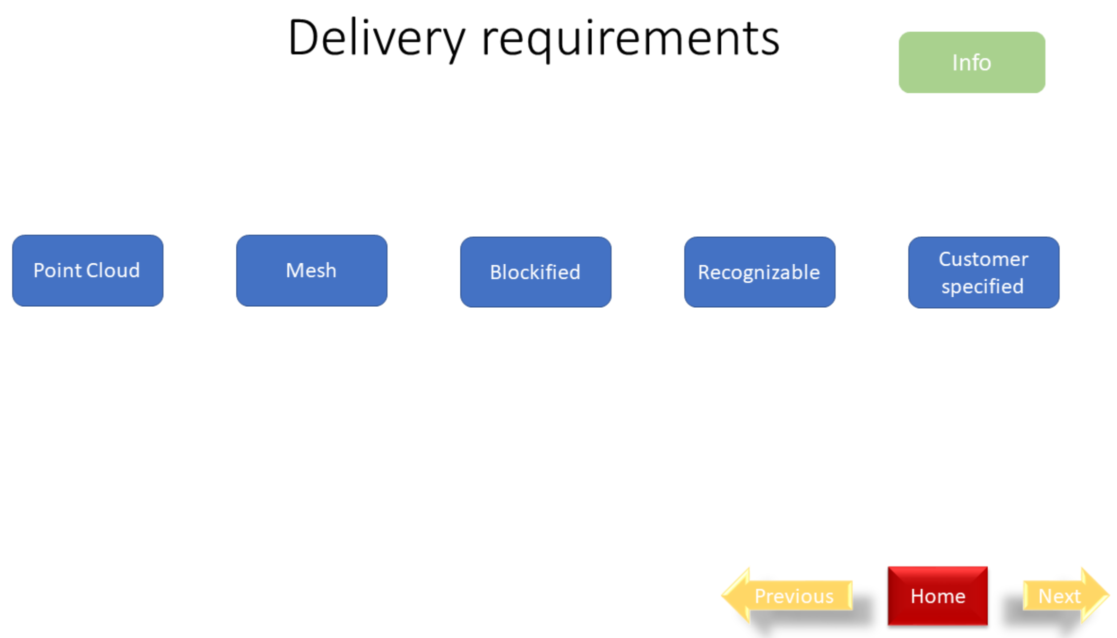
Time estimation
Solid Modelling

Resource:	Resource 1	Resource 2
Quality: Aimed delivery package:	Recognizable	Recognizable
Achieved quality - Does not fulfil delivery package requirements, fulfils or more than fulfils the requirements:	Fulfils	Fulfils
Experience: Time in CAD software - round to nearest quarter of a year:	0,5 Years	0,25 Years
CAD experience overall - round to nearest quarter of a year:	0,5 Years	3,5 Years
Time in factory layout projects - round to nearest quarter of a year:	0,5 Years	0,25 Years
Method: CAD-software:	IronCad Innovate	Autodesk Inventor
Modelling technique:	Drag/Drop boxes	Sketch/extrusion
Result: Expected time (mm) - According to coordinator expectations:	30 min	30 min
Time (mm:ss) - From CAD software home page with no model opened, to model saved in correct folder:	09:47	05:39
Comments:	Planning time not included, 2:nd time modelling	

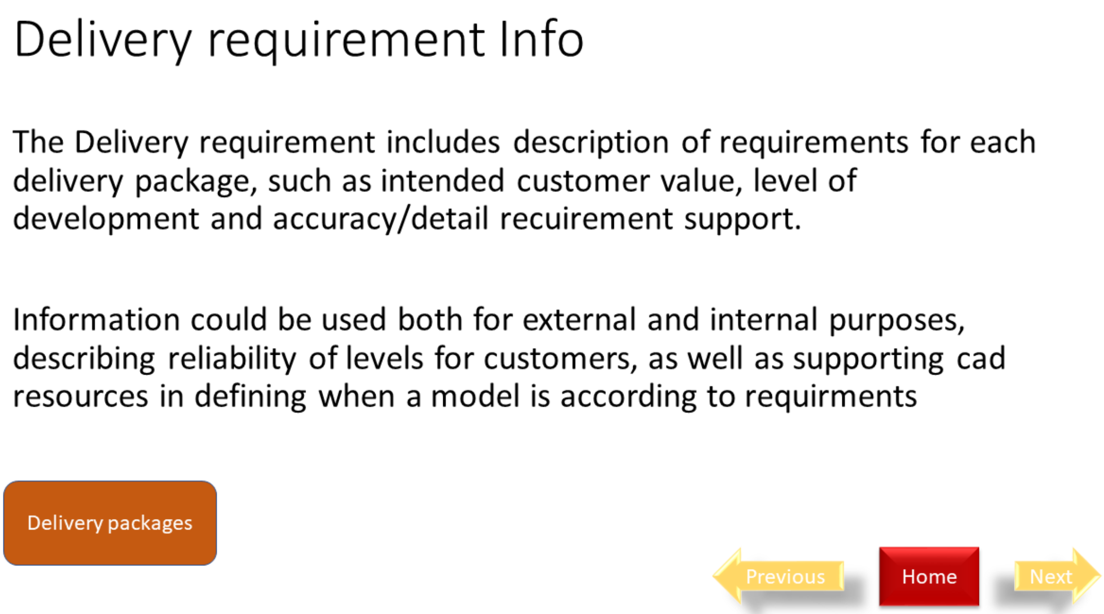
Appendix D - factory layout process



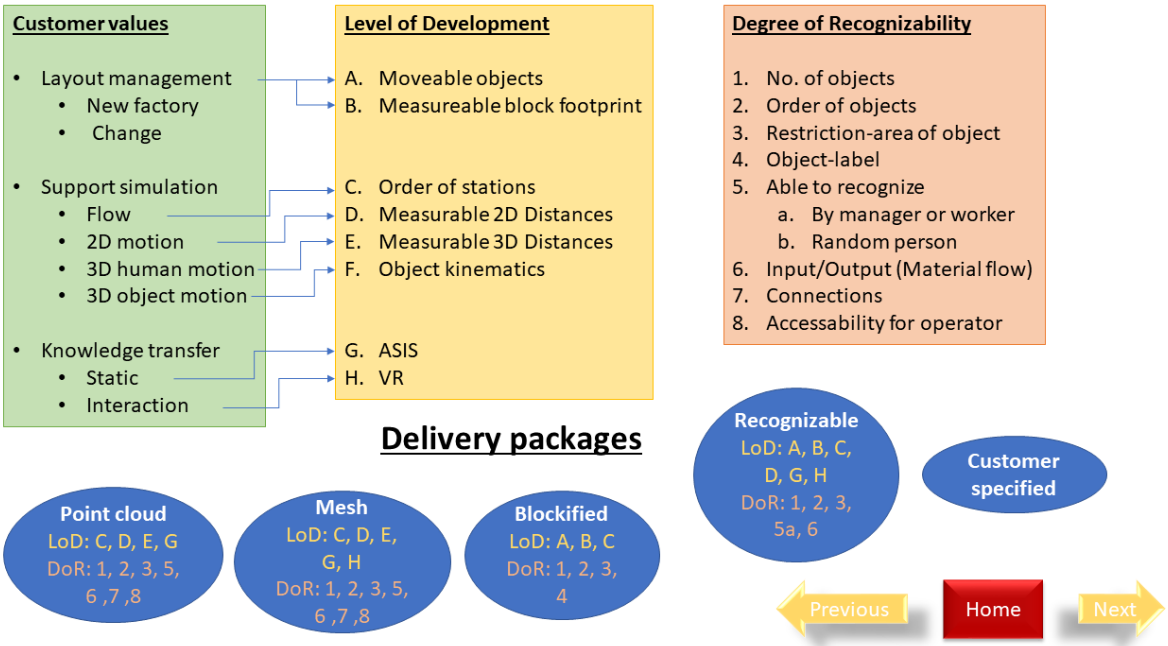
The FrontPage of the workflow document for Factory Layout Process consists of the six steps of the process as clickable objects and the Delivery requirements box, clickable as well. These seven objects work as links to these sub processes and the Delivery requirements.



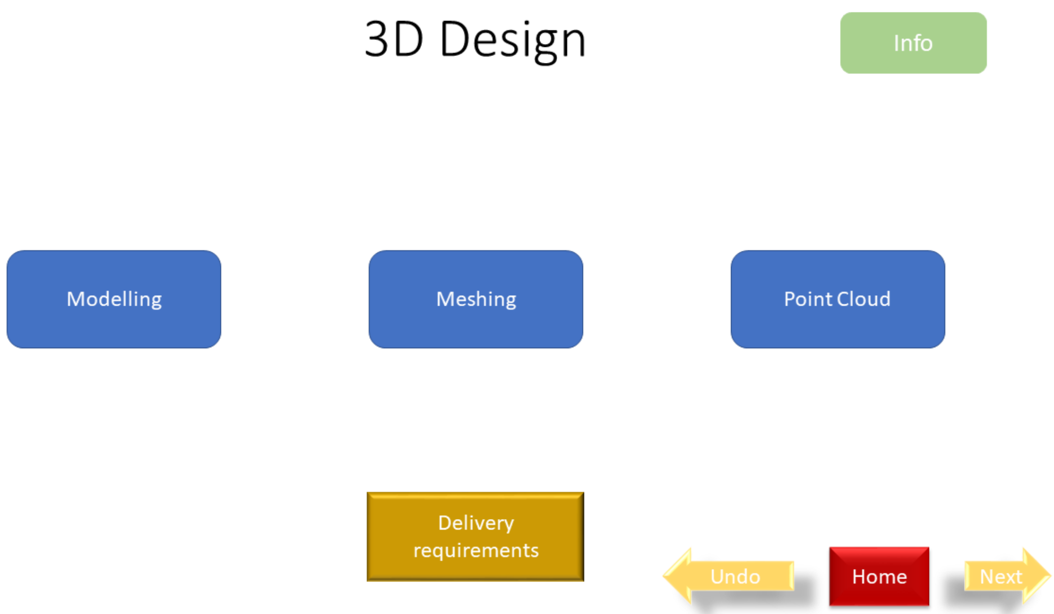
The Delivery requirement chapter is built up of a page with the different delivery packages accessible, a general Info box and as all pages (except the FrontPage), with links to previous shown page, the FrontPage and following slide in the order they come in the presentation tree.
Each one of these 5 delivery packages are further described with requirements, examples etcetera if the user click on them. The Info box will be further described in following picture.



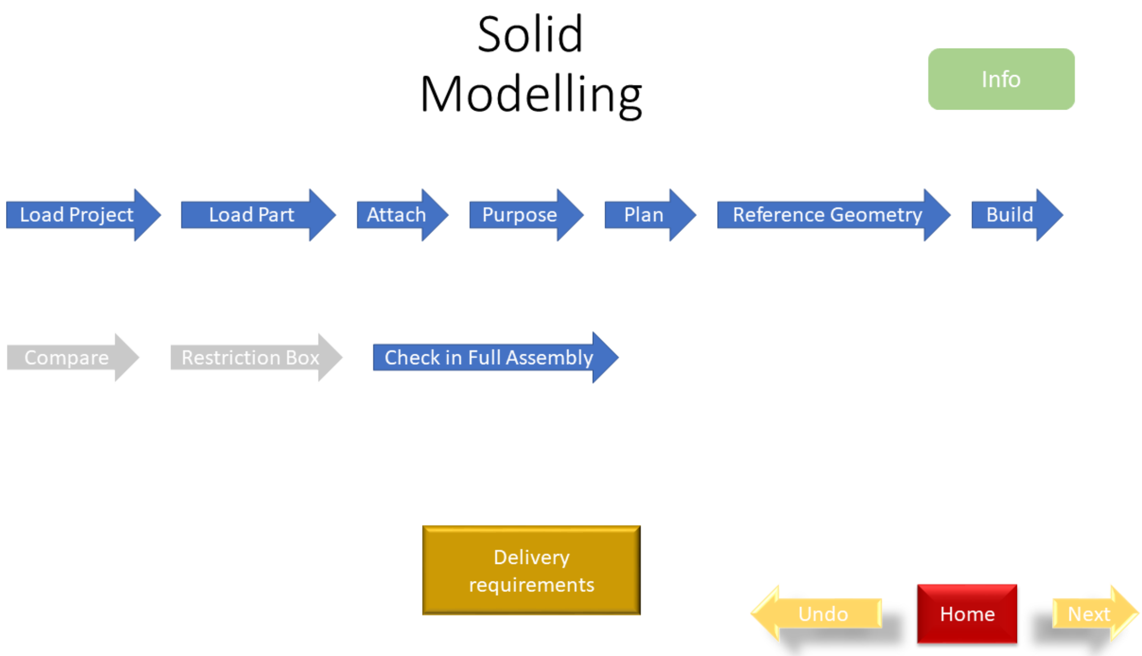
When pressing the Info box in any of the pages providing such an option, the user are directed to some general information. For the other chapters this box contains what should be expected as input for the process as well as what is expected to be delivered by the process. They also provide a short description of the process, just as the Delivery Requirement Info provides info of what to be found in that part of the work flow document. The Delivery Requirement Info also provides a link to the Delivery packages, which are shown in the following slide.



The Delivery packages page contains the packages, combined with which Customer Values they serve, and whit which Level of Developments as well as Degree of Recognizability they serve them.



The six process steps consist of clickable sub processes, a link to the Delivery requirements doc, and an Info box. They work pretty similar to the Delivery requirements slide.



The sub-process of the six main processes contain a workflow with blue standard procedures and grey optional. The Delivery requirements are accessible in several of these sub processes as well, if it is seen useful in the specific process

Solid Modelling - Info

Indata

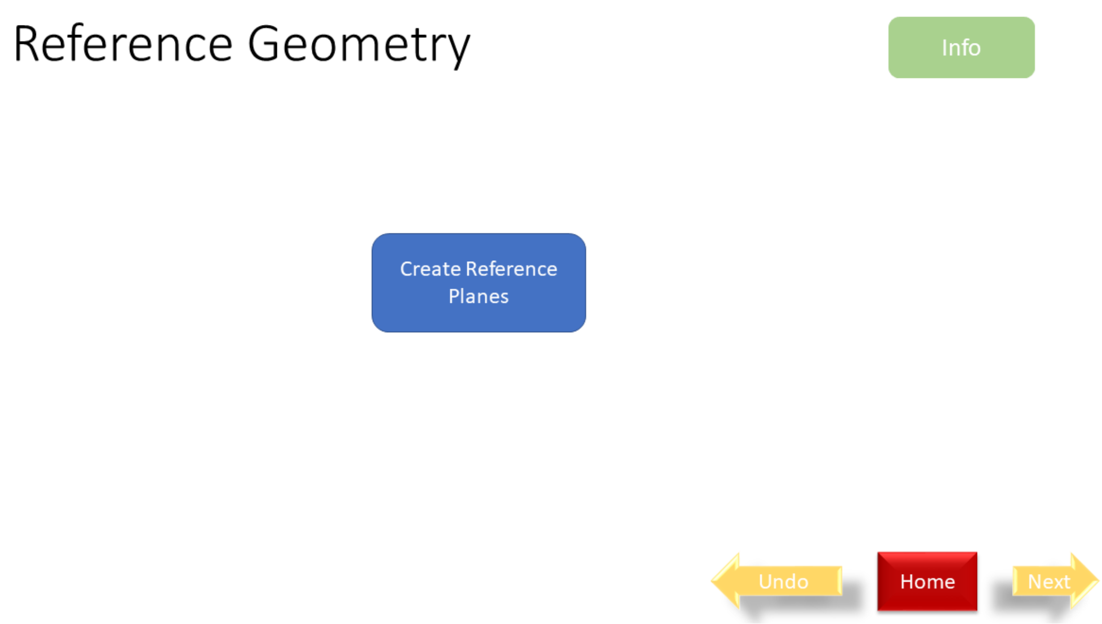
- Point cloud regions assigned
- Project spec

Output

- Solid models of object or buildings according to spec (time and quality level) saved as part file
- Reference planes and axis
- Notify coordinator

Undo Home Next

The info box in the Solid Modelling sub process, or any sub process of this level, contains input and output requirements.



The arrows in the workflows of the sub processes lead to a page containing the Info box as well as a method box, in this case “Create Reference Planes”, which leads to a separate doc containing a step by step method in either video or PowerPoint format.

Appendix E – Method example

MET_XXX
Create Reference Geometry

Change Log		
Datum	**Utfärdat av**	**Specifikation**
2017-07-12	Alexander Eriksson	Skapad

Brings Value in Production.

VIRTUAL manufacturing.

Summary

- Syfte
  - Make a standard for reference creation
- Mål
  - Support factory layout modellers in reference creaction

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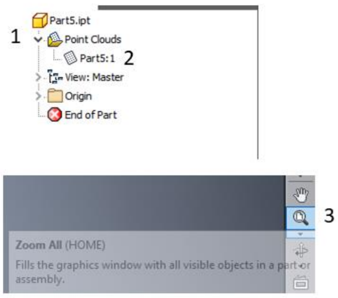
Required Input

- Correctly imported point cloud to Part file

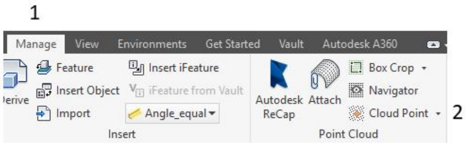
Zoom to fit

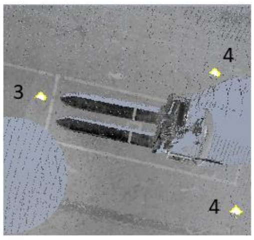
1. Expand Point Clouds
2. Press on Point Cloud
3. Press Zoom All



Choose Points for Ground plane

1. Press Manage tab
2. Press Cloude Point
3. Click on a cloud point of your choice
4. Redo step 2-3 twice





3 points should be chosen, far away from each other yet close to the detail to be modelled and on the floor

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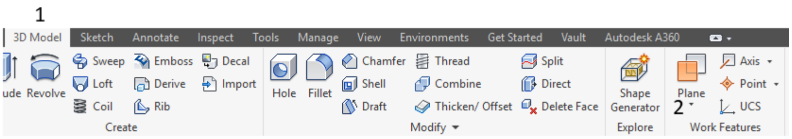
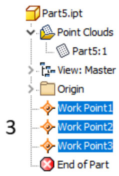
Create Floor Plane from Work Points

1. Press 3D Model tab
2. Press Plane
3. Click on the three recently created points





Make sure you choose the points intended for the floor plane

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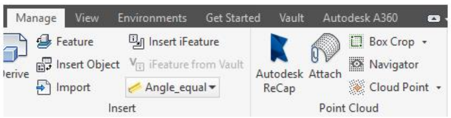
Choose Points for Second plane

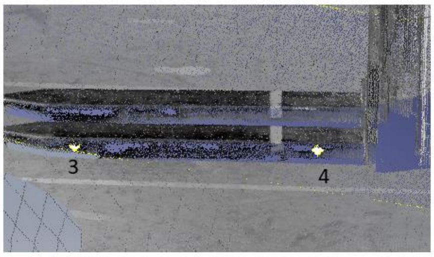
1. Press Manage tab
2. Press Cloude Point
3. Click on a cloud point of your choice
4. Redo step 2-3

The 2 points should be chosen, far away from each other yet close on a well defined planar surface

1



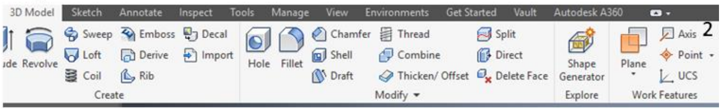
2

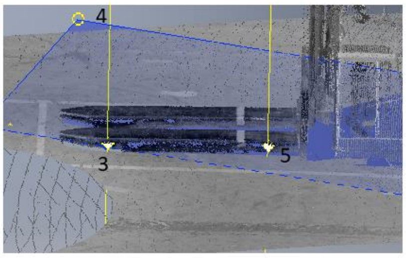


Create axis from Work Points

1. Press 3D Model Tab
2. Press Axis
3. Choose recently created point
4. Choose the ground plane
5. Redo 2-4 for the second point

1

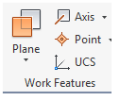




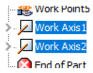
Create second plane from two axis

1. Press Plane
2. Click on the two recently created Axises

1



2



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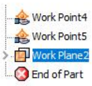
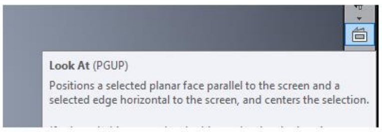
Relocate plane illustration

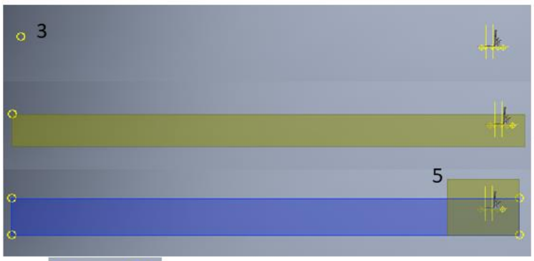
1. Press the recently created Work Plane
2. Press Look At
3. Press and hold "corner" of plane illustration, an expand arrow (↖↘) will appear beside the pointer when hoovering over plane illustration
4. Drag to fit the whole detail (point cloud)
5. Redo 3-4 with another corner to fit the detail only

1

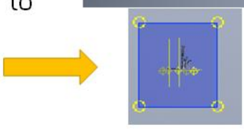




2



4



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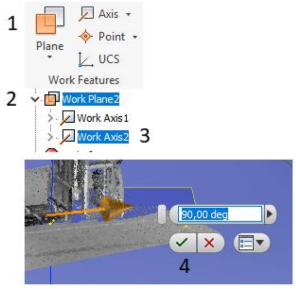
Create Plane to offset Plane three from

1. Press Plane
2. Press the recently created Plane
3. Press one of the axis used to create that plane
4. Press ✓ (If it says 90,00 deg)



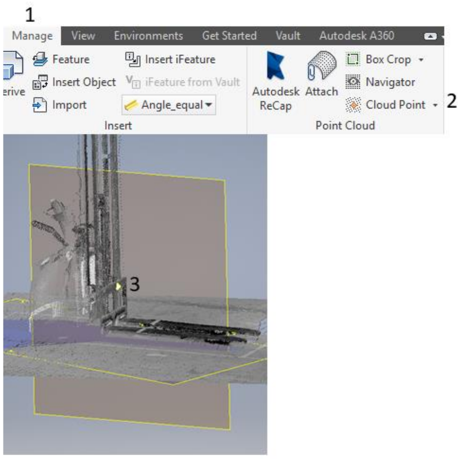
VIRTUAL manufacturing.

Brings Value in Production.

Create point for third reference plane offset

1. Press Manage tab
2. Press Cloud Point
3. Choose a desired point for third reference plane

Point should preferably be located on a planar surface almost perpendicular to the second reference plane. If such a point does not exist, choose a point on the detail as far away from the recently created plane

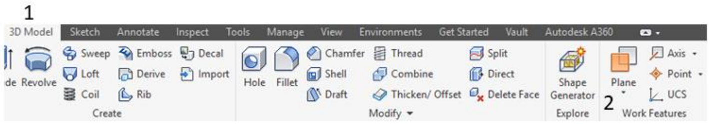


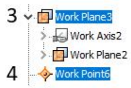
VIRTUAL manufacturing.

Brings Value in Production.

Create third reference Plane

1. Press 3D Model Tab
2. Press Plane
3. Press recently created plane
4. Press recently created point





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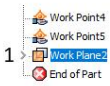
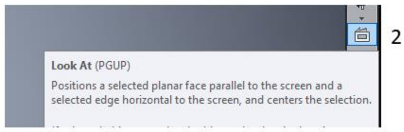
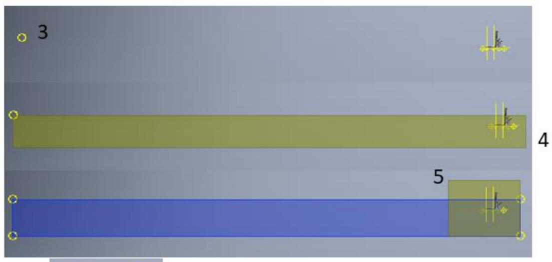
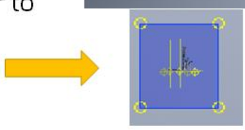
Relocate plane illustration

1. Press the recently created Work Plane
2. Press Look At
3. Press and hold "corner" of plane illustration, an expand arrow (↖↘) will appear beside the pointer when hoovering over plane illustration
4. Drag to fit the whole detail (point cloud)
5. Redo 3-4 with another corner to fit the detail only









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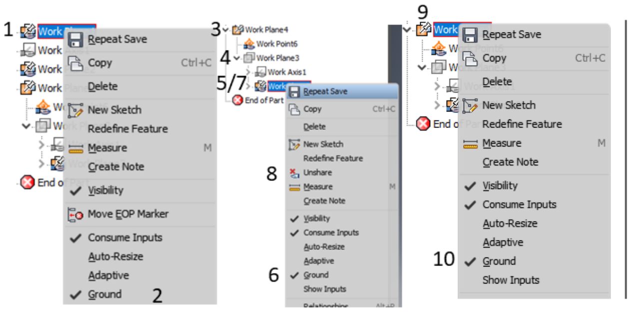
Ground and share reference Planes

1. Right Click the first Work Plane
2. Click Ground
3. Expand the final Work Plane
4. Expand the help Work Plane for the final Work Plane
5. Right Click the second Work Plane
6. Click Ground
7. Right Click the second Work Plane
8. Click Share
9. Right Click the final Work Plane
10. Click Ground



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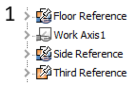
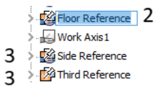
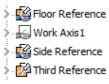
Name reference planes

1. Click first reference plane twice (do not double click)
2. Rename
3. Redo 1-2 for the second and third reference plane





Name the planes appropriately so that persons reusing or moving the model knows where the planes are located when constraining to them



All three reference planes should be visible under the part in the tree structure without need for expanding, with chosen name and a needle indicating they are Grounded

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Appendix F- Time estimating sheet

Factors	Indata	Standard times	Unit
Point cloud management			
Number of scans	(From scan-planning)		
Standard time for processing etc.	(Specify from experience) Affected by resolution(no. of points), colour and hardware	TBD	
Update origin	(Specify from experience)	TBD	
Time for processing/registration/indexing	#VÄRDEFEL!		
Number of objects to divide point cloud into	(From customer spec.)		
Standard time for dividing one object	(Specify from experience) Needs more testing	TBD	
Total time point cloud management	#VÄRDEFEL!		
CAD Coordination			
No. Of objects	(From customer spec.)		
Creating standard documents	(Standard time set from experience)		
Time for adding parts (min)	#VÄRDEFEL!	0.5	min
No. Of customer meetings	(From customer spec.)	45	min
Cad modeller support	(From experience)		
Total time CAD coordination	#VÄRDEFEL!		
CAD Modeling			
Equipment			
No. 0-30 min objects	(From scan-planning)	30	min/object
No. 30-60 min objects	(From scan-planning)	60	min/object
No. 60-120 min objects	(From scan-planning)	120	min/object
Running cost (more than 120 min)	(From work. Set time for how long this takes)		
Total time for equipment-modeling	#VÄRDEFEL!		
Building			
No. 0-30 min objects	(From scan-planning)	30	min/object
No. 30-60 min objects	(From scan-planning)	60	min/object
No. 60-120 min objects	(From scan-planning)	120	min/object
No. 120-240 min objects	(From scan-planning)	240	min/object
Running cost (more than 240 min)	(From work. Set time for how long this takes)		
Total time for building-modeling	#VÄRDEFEL!		
Mesh modeling			
No. Mesh objects	(From scan-planning)	TBD	min/object
Total time meshing	#VÄRDEFEL!		
Total time 3D scanned data to factory layout	**#VÄRDEFEL!**		
Indata - to be filled in	Standard data		
Code - do not change	Section output - do not change		
Final output			