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3-D MEASURING FOR AN ENGINEER-TO-ORDER SECONDARY WOOD PROCESSING INDUSTRY

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ABSTRACT: The construction industry has been criticized for not keeping up with other production industries in terms of cost efficiency, innovation and production methods. Supplying Engineer-to-Order (ETO) joinery products to the construction industry is a novel research area within the secondary wood-processing industry. This involves processing wood into highly refined one-of-a-kind products that are engineered to fit specific needs. Before these products are manufactured, there is a need for the supplier to verify the as-built spatial information of the products adjacent environment. This is due to differences in the tolerances of the production methods in general construction and the ETO joinery products. This verification is not always sufficiently accurate or easy to perform with current methods. Further, suppliers often lack sufficient 3-D information to eliminate spatial uncertainties that affect the level of prefabrication off the construction site. Therefore, adjustments are left to be performed during assembly, and often the time required for assembly on the construction site is equal to the time required for designing and processing the products in the production plant. This work shows that current available 3-D measuring techniques, such as 3-D laser scanning equipment, coordinate measurement machines and photogrammetry techniques, have potential to improve the quality of measurements on the construction site and add spatial information that can be used in the production, planning, and assembly of neatly fitted wooden products.

KEYWORDS: 3-D measuring techniques, ETO joinery production, Supplying to construction

1 INTRODUCTION

One of two models for the distribution of joinery products is the one supplying the construction industry with tailored, one-of-a-kind products that are fitted into a given building object. This value chain is adapted to the culture in the construction industry and is still craftwork intensive and has not been able to fully utilize industrialized processes in terms of cost efficiency, innovation and production methods. Thus, this resembles the situation in the construction industry.

In media as well as in the research community, the current state of construction is under debate. The construction industry has been criticized for not keeping up with other production industries in terms of cost efficiency, innovation and production methods [1, 2]. Innovations that decrease the cost of building production and alterations have gained considerable attention in the research community and media due to their effect on the prices of the living and working environments. Increased industrialization and higher levels of prefabrication are seen as focus areas for innovation in construction. In [3] it is shown that higher predictability in the planning of construction projects is essential in incorporating Lean principles in building construction.

Engineer-to-order (ETO) joinery products are products that are prefabricated in industrialized production plants. For suppliers of joinery products, there is a need to verify spatial as-built information, since general tolerances in construction do not provide precision in parallel with their products. Despite current efforts to verify spatial as-built information, their methods cannot eliminate the spatial uncertainties, and they need to work with methods to handle spatial uncertainty, which decreases efficiency in production as well as in assembly. Thus the level, or degree, of prefabrication is restricted by the presence of spatial uncertainties. Therefore, cost-effective methods and technology for eliminating spatial uncertainty are highly interesting for this type of industry.

Manual measurements are time consuming, and the spatial information obtained from the construction site is

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limited. Currently available 3-D digitizing equipment, such as laser scanners, coordinate measurement machines, photogrammetry solutions, *et cetera*, could be used to gather more of the spatial information (in 3-D) from the joinery products' adjacent environment. This information would then provide a basis for producing neatly fitting ETO joinery products.

Building Information Models (BIM) is today an accepted and widely used method for storing and sharing knowledge of a facility [4]. However, the information in the models, which often are based on CAD models, does not normally provide the supplier with as-built information; rather they show the as-planned information, and in alteration projects, this information can be based on old as-planned information. The joinery-product suppliers need as-built information as opposed to the as-planned information of BIMs.

This paper will address two research objectives: with 3-D measuring techniques such as laser scanning, coordinate measuring machines and photogrammetry to reduce the spatial as-built building uncertainties and increase the level of prefabrication and quality of the products; provide joineries with enough information to plan, produce and assemble the products efficiently.

With this background, the purpose of this paper is to evaluate laser scanner, coordinate measurement machine, and photogrammetry technology in terms of retrieving spatial 3-D as-built information in a "real world case" [5] of supplying ETO joinery products to construction. Here the objective is to identify best performing technology for this purpose and to identify areas for further studies.

2 Method

The supplying of ETO joinery products has been followed in a case study. Current routines and practices have been studied, and in parallel the use of 3-D measuring technology has been evaluated in the same environment as the real joinery-product supply process has been working. The surveyors' work on the site was documented by notes, photos, through asking questions about the work being performed and by studying the documentation they created during their work.

In parallel with the manual measurements performed by the joinery-product supplier, three different 3-D measuring technologies were used to capture the joinery-products' adjacent environment at the construction site. The three products used were 1) a Proliner 8 coordinate measuring machine (CMM) from Prodim[4], 2) a photogrammetry setup with a Nikon D50 DSLR camera and Photosynth software[5] and 3) a Leica Scan Station C10 laser scanning apparatus[6]. The laser scan was carried out by the company Mättjänst AB[7], and the CMM measurements and single camera photogrammetry were carried out by the authors.

The Swedish construction project was an alteration project in which an entire floor in an office building in Solna, Stockholm, was altered to fit a new tenant. At the entrance of that floor, a reception area, a visitor zone and a cloakroom were designed by the Irish architects, and the Swedish joinery-products supplier provided the interior products for the project as well as the assembly of them on the construction site. In Figure 1, the ichnography of this area this is presented. The area within the red line represents the area that was surveyed.

Figure 1: *Construction area under survey*

2.1 PROLINER 8 CMM DATA CAPTURING

The Proliner 8 CMM consists of a main unit and a measuring stylus probe connected by a 7.5 meter long steel wire. The Proliner 8 CMM measurements were done using two different strategies (Middle and upper part in Figure 5). The first one is similar to manual measuring where the stylus probe of the Proliner 8 acquired coordinate registrations in the beginning and at the end of each straight line to represent the location of each wall segments. This type of measurement is easy to perform and gives a representation of the ichnography. However, it gives no information about the vertical alignment of the walls or if there is some curvature in the wall surface. On curved walls, the stylus probe was swept along the wall and the Proliner 8 made continuous coordinate registrations.

A second Proliner 8 CMM measurement was performed using the second strategy for acquiring the as-built information. Here the Proliner 8 stylus probe was swept all over each wall segment with continuous registration of the coordinate positions in order to have a representation of the wall plane. This second measuring strategy also gives information about the walls' vertical alignment.

To cover all required surfaces, the limitations in the range of the Proliner 8 required moving the CMM and reconnecting to the previous measurements. This reconnection is a function of the Proliner 8 that is called leap—four markers are measured in the first position of the Proliner 8 and then again from the new position after relocation so as to reconnect to the initial measurement.

[4] http://prodim.eu/
[5] http://photosynth.net/
[6] http://hds.leica-geosystems.com/en/Leica-ScanStation-C10_79411.htm
[7] http://www.mattjanst.se/

The data captured with the Proliner 8 was exported in DXF format to Solid Works and Siemens NX CAD software. A 3-D model was created to represent the dimensions captured in the manual measurement performed by the joinery-products supplier (Figure 5). To create 3-D geometries, walls/planes were extruded from the lines.

2.2 SINGLE CAMERA PHOTOGRAMMETRY

Photographs were taken with a Nikon D50 DSLR camera from the middle and at the corners of the room. Each picture was taken so that it overlapped the previous one by approximately 50%. Close-up pictures of the walls were also taken. To cover the area of interest, the environment was captured with a total of 113 photos. The photos were uploaded to a photosynth.net webpage, resulting in both a 3-D panorama and a point cloud. The Photosynth software does not require targets or a calibrated camera.

2.3 LASER SCANNING

The laser scanning with the Leica Scan Station C10 was performed by the company Mätjänst AB. The survey was performed from four positions in the reception, visitors' zone and the cloakroom and then merged into a single point cloud of measured coordinates (Figure 8). Three circular targets were placed in line of sight from all scan positions. The targets were used for merging and aligning the subscans.

After performing the scanning, the measuring company supplied the authors with the raw data of the coordinate point cloud and contracted a third party, Astacus[8], to create 3-D CAD models that were later delivered to the authors. The authors also processed the raw data into useful information that was processed into measurable models to be compared with the models from the measuring company.

3 RESULTS AND DISCUSSION

In construction, there seem to be no customary practices to verify that the building really reflects the prescribing documents according to given dimensions in construction drawings. For this reason, there is a need for the joinery-product supplier to verify that the ordered joinery products adjacent environment in the prescribing documents reflects the as-built reality before producing the joinery products.

3.1 MANUAL MEASURING

Currently, the ETO joinery-products supplier uses manual measuring techniques in which folding rulers, tape measures and laser distance meters are used to obtain the as-built information (Figure 2).

Figure 2: *Manual measuring*

From the architectural drawings, important measurements were predetermined by the production preprocessor before surveying. From the predetermined list of measurements, the surveyor worked to capture wall placements, diagonals in the rooms and doorways. Measurements were noted on printouts of the architect drawings (Figure 3). The measurement were done at floor level, which means that the data is limited to a 2D representation of the site with no concern for angle between walls and floor, waviness and slope of walls and floors, *et cetera*. Some of the results of the manual measuring can be seen in Figure 3, where the dimensions 6900, 9190, 9400 mm, and an arc length of 2950 (mm) can be read out and compared with the results from the other measuring techniques.

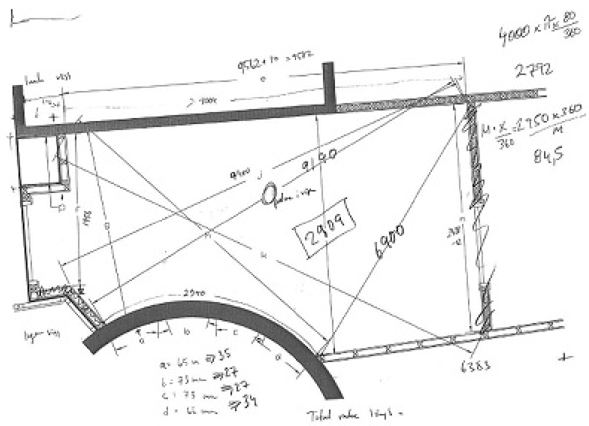

Figure 3*: Notes from manual measuring*

These methods can be seen to have a number of error sources, and their accuracy can be questioned. For example errors can be introduced when trying to measure the center position of a pillar (left picture in Figure 2) due to the difficulty of positioning tape measures or rulers correctly, or by rounding off when reading the tape measure.

To perform the measurements, personnel from the supplier needed to travel more than 800 km to perform measurements for half a day. Still this work was not fully coordinated with the construction project, and there were walls that had not yet been built that would need to be measured. Therefore, not all the necessary spatial information could be retrieved. Further, the producer had to do complementary measurements later when it was found that some important dimensions had not been defined.

[8] http://www.astacus.se/

The notes from the measurements were done on paper printouts of the architectural drawings that were physically transported to the production preprocessor. The joinery-products supplier in this study spends about 1700–2000 hours annually on geometrical measurements on the adjacent environments for their products, which is equivalent to one full time employee specialized in performing spatial measurements, but this is not how they have chosen to work. Their measurements are mainly performed on a 2-D basis, thus leaving out much of the 3-D information that could be useful when modeling during the production preprocessing. This has consequences for assembly, since the components of the ETO joinery products need on-site adjustments to fit the products' adjacent environment. The assembly work becomes more unpredictable in time and resource need due to spatial uncertainties. Therefore the level of prefabrication and predictability could be enhanced by eliminating spatial uncertainties.

3.2 PROLINER CMM

The measurements with the Proliner 8 CMM were performed in one hour for each of the two measuring strategies described in the method. In Figure 4, the Proliner 8 CMM measurements of the walls from the reception, visitor zone, and cloakroom are shown. To the left in the figure the method of sweeping the stylus probe over the wall surfaces is visible, and on the right the method of using only few coordinates to represent the wall position except on curved walls where the stylus probe is swept along the wall's length. These lines and curves were the basis for the creation of a 3-D geometry CAD model that was produced in about one hour. Thus in two hours a 3-D CAD model could be produced and delivered electronically to the joinery-products supplier.

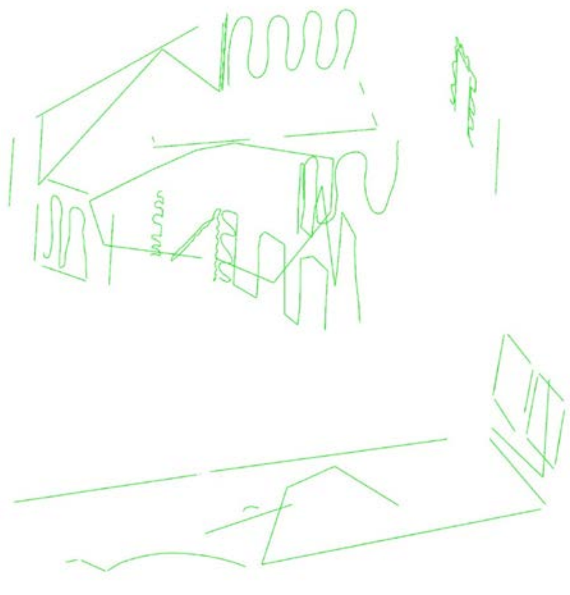

Figure 4: Measuring information from Proliner CMM

In the modeling of the Proliner Data, a DXF (Drawing Exchange Format) file was exported from the Proliner to Siemens NX, and 3-D solids where created. The process is illustrated in Figure 5. In the upper part of the figure, each plane in the DXF file represented a wall plane. Further, a combination of information about construction method and measurement information was provided to create the 3-D model representing the wall that at the time of measurement had not yet been built. In the middle part of Figure 5, the cloakroom there is a curved wall that has several different radii, and here the wall extrusion is made by several connected lines. In the lower part of Figure 5, the two separate measurements are put together in an assembly to illustrate how the two are aligned to each other.

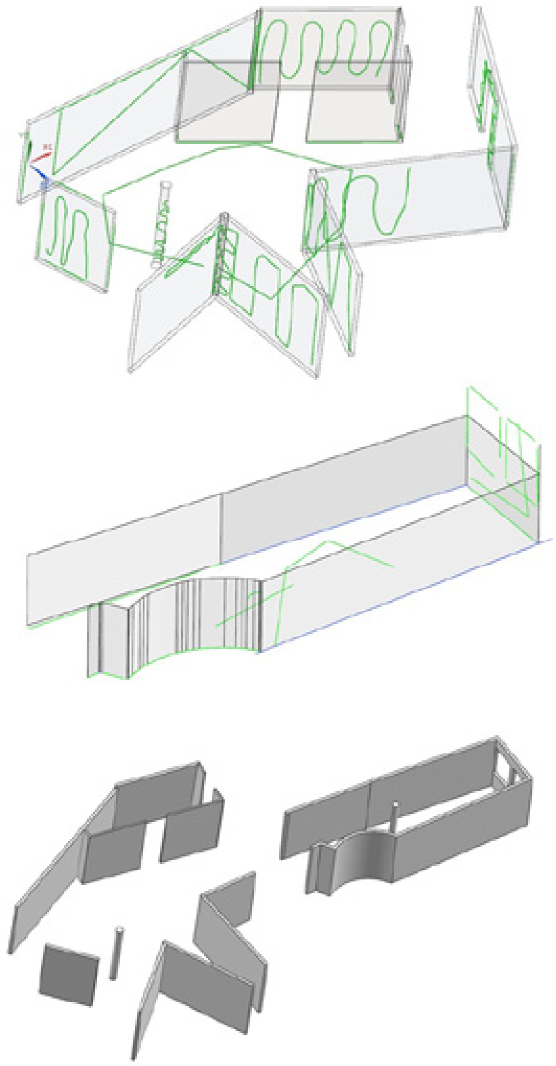

Figure 5: Model creation from Proliner data

3.3 SINGLE-CAMERA PHOTOGRAMMETRY

The 113 photographs of the construction site were captured during approximately 30 minutes. Uploading and creating the Photosynth model took about 20 minutes with a wireless network with an 80-Mbit/s capacity. In the Photosynth software, the pictures were stitched together to form a 3-D panorama (Figure 6) and a point cloud (Figure 7).

Figure 6: *Photos stitched to a 3-D panorama*

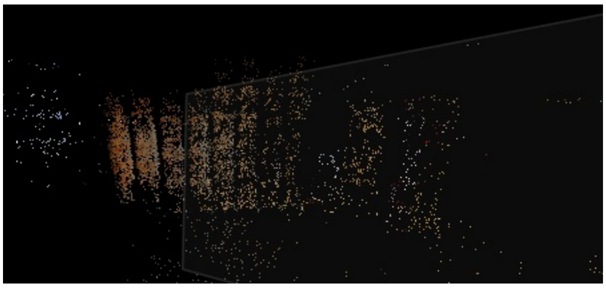

Figure 7: *The Photosynth-generated point cloud*

However the point cloud from the view in Figure 6 and shown in Figure 7 was from the highest concentration of captured coordinates and not representative for the entire area being surveyed. For most of that area, the Photosynth-generated point cloud made from these photographs was not adequate to make any representative 3-D CAD models of the surveyed area.

3.4 LASER SCANNING

The scanning of the part of the construction site of interest was performed in approximately one hour in a mode with high density of scan coordinates. The resulting point cloud gave approximately 45 million coordinates. To increase visibility, data reduction of the point cloud was performed; the result is shown in Figure 8. The scanning is easy to perform and results in a large amount of information. However, to create representative 3-D CAD models from this information requires appropriate software tools, skill and time.

Figure 8: *Point cloud from laser scanning*

The laser scan produces a good deal of information that is not needed; *e.g.*, there are free standing objects, such as toolboxes and other equipment pertaining to the construction work, that are not part of the room of interest (Figure 9). Therefore, the relevant information needs to be selected when processing the data, making experience of on-site measurement in combination with understanding of the planned products highly useful.

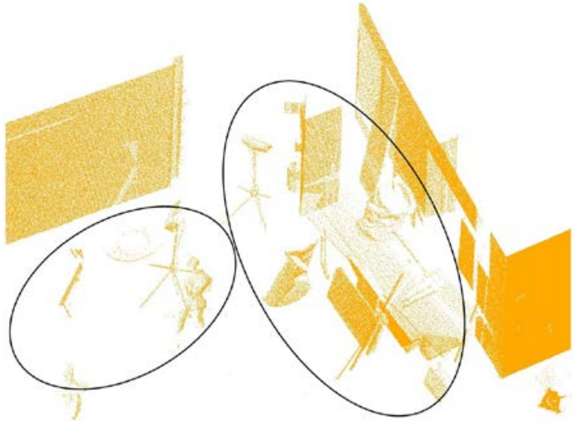

Figure 9: *Example* of clutter disturbing 3-D model creation

The models produced by the Astacus Company were supplied in three different formats: STL format (Standard Tessellation Language), the WRL or VRML (Virtual Reality Modeling Language) and in DWG (drawing) format (Figure 10). These three formats hold different types of information that can be used in the production preprocessing. Among Swedish ETO joinery-products suppliers, the DWG is the format most commonly used.

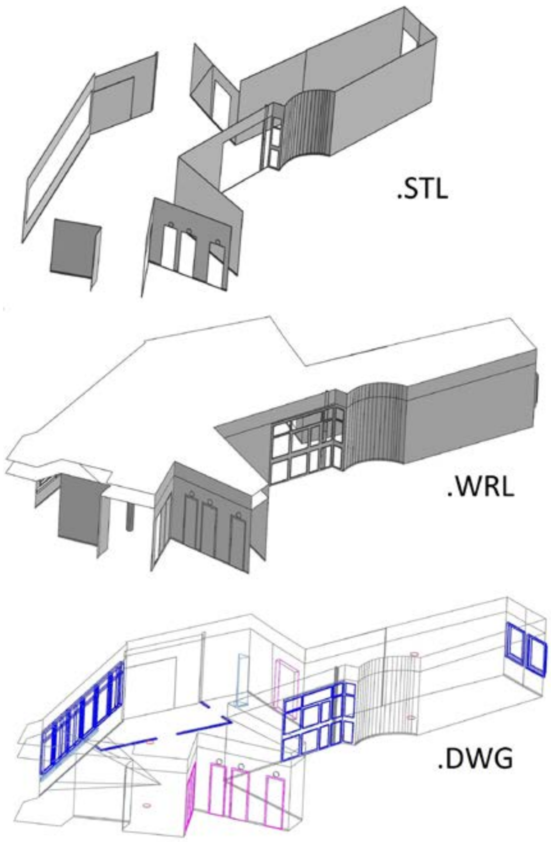

Figure 10: *Three model formats: STL; WRL; DWG*

To compare the different measuring techniques against each other, four dimensions (A, B, C, and D) that were seen as important by the production preprocessor are retrieved from the manual measurement, the Proliner measurement and the laser scanning (Figure 11). From the laser scanning, measurements are taken from the three models that where supplied by the Astacus company.

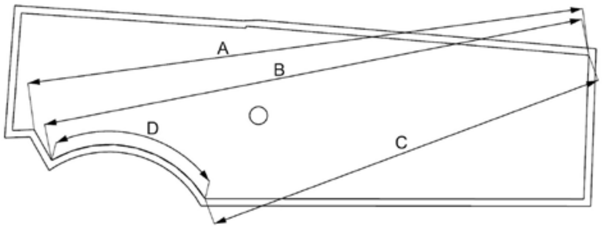

Figure 11: *Defined dimension in Cloakroom*

In Table 1, the resulting dimensions from Figure 11 are presented for the measuring techniques tested in this paper. Note that from the photogrammetry set up no measurements could be taken. From the laser scanning, measurements were done in the three CAD models. From Table 2 one can see that there are some differences despite the fact that they came from the same raw data. Both the laser scan and the Proliner CMM show differences in the dimensions compared to the manual measurement as well as compared to each other.

Table 1: *Measures of defined dimensions*

Measuring Method	A (mm)	B (mm)	C (mm)	D (mm)
Manual	9400	9190	6900	2950
STL (Scan)	9412,3	9211,3	6896,7	2923,1
WRL (Scan)	9413,2	9212,3	6897,1	2923,5
DWG (Scan)	9412,4	9211,4	6896,7	2923,2
PRT (CMM)	9431,5	9224,8	6897,2	2931,9

Table 2: *Measure differences of defined dimensions*

Method Comparison	A (mm)	B (mm)	C (mm)	D (mm)
Manual vs. Scan Average	-12,63	-21,7	3,17	26,73
Manual vs. CMM	-31,5	-34,8	2,8	18,10
Scan (Max-Min)	0,9	1,0	0,4	0,4
Scan vs. CMM	-18,7	-13,13	-0,37	-8,63

4 DISCUSSION

Currently, ETO joinery-products suppliers need to perform spatial measurements on the construction site before starting the production of the ordered products. These measurements are used to calibrate the architectural drawings against the as-built reality. In the studied case, this was done in a 2-D sense rather than a true 3-D representation of the construction scene, thus leaving a high degree of uncertainty that limits the level of prefabrication of the joinery products. Further, manual measuring shows high risk for mistakes and that the captured data might not be accurate; in this case, complementary measurement was required. These are problems that also are discussed in other research; *e.g.*, [6] and [7].

The three 3-D measuring techniques used in this work have somewhat different conditions for how to use the information and on the limitations in precision. The Proliner CMM show rather high accuracy in each measured coordinate, but the number of coordinates usually retrieved is limited, which restricts the amount of information it can provide. Further, the Proliner CMM is wire bound, which causes problems with obstacles. It is also limited in range; therefore there is a need use a leap functionality to connect measures when moving the device, and this affects accuracy.

The photogrammetry method has the strength of being useable at limited cost by using an SLR camera on a tripod. Many of the surfaces at the construction site were gypsum boards that had few or no gradients in color or textures, and windows where the exterior surfaces of the windows also gave measurement coordinates. Therefore, the number of trustworthy coordinates in the point cloud calculated by Photosynth was limited. Still the idea of using photogrammetry seems interesting if it's possible to achieve more measuring coordinates.

The laser scanning with the Leica C10 performed by "Mättjänst AB" was the technique that gave the greatest amount of information. The supplier of the measuring service provided the researchers with the point-cloud data (Figure 8). The process of transforming the scan information into 3-D CAD models is a service that seems limited in Sweden. The Astacus company used staff in India to make the point-cloud–to–CAD transformation. What can be seen in the provided 3-D CAD model is that it seems to be simplified; for example, information about wall–floor angles other than 90° is missing. Further, measured objects such as a sheet metal sleeper on the floor whose edges are about 1 mm are represented as 5-mm-thick material in the provided 3-D CAD model from the laser scanning.

There are dimensional differences between the manual measurements and the models created from the Proliner 8 CMM and the Leica ScanStation C10 laser scanner. There are several reasons for the dimensional differences between models in Table 1 and Table 2. The equipment used to capture the environment, modeling software, methodological approach, *et cetera*, affect the result of the CAD model. In the modeling of the laser-scan data, WRL, STL and DWG models are created through best-fit method from the coordinates in the point cloud. The best-fit method approximates planes to the point cloud and does not follow the topography of the geometry very well. The point cloud consists of four scans that were merged into one, which introduces accuracy errors in the point cloud.

Similarly, the data from the Proliner 8 CMM approximate curves, lines or even planes through best-fit methods. Even if the accuracy in each coordinate is high, it's not certain that the position of the stylus probe is representative for the curve, line or plane that is being measured, and the limited number of coordinates being registered affects the accuracy in the models from the Proliner 8 CMM. For example, a "straight" and "flat" wall at a construction site often have some horizontal and vertical curvature, and the plane often deviates from being truly vertical. This is a wall that is difficult to measure with the Proliner 8 CMM to create a representative model.

Assuming that laser scanning provides the best accuracy of the tested methods in this paper, the comparison between the manual measurement and laser scanning shows differences of 27 mm. These errors are quite worrying when the joinery-product supplier works with tolerances of less than 1 millimeter.

5 CONCLUSIONS

The three evaluated 3-D measuring techniques show that they all have potential to enhance the process of acquiring as-built information by comparison with currently used methods as regards the amount of information and 3-D relations.

In the work presented, it is shown that the traditional methods of measuring as-built dimensions differ quite considerably from CMM and laser-scan data. Spatial deviations of walls and floors are not considered at all with the methods used today. By reducing the spatial uncertainties for the ETO product, the need to perform on-site adjustments will decrease, leading to more predictable assembly work and a reduction in time and cost for assembly.

All three methods tested provide simplifications in the transformation to a 3-D model, but the reliability of the virtual reality based on the measurements leaves something to be desired. To achieve an accuracy of 1 mm in all aspects still seems difficult using the technology tested in this paper.

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