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Use of 3D Scanning for Manufacturing Layout Redesigns

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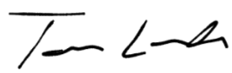
Preface

This thesis represents the work needed to complete the Master of Science degree in Global Manufacturing Management in the Department of Mechanical and Industrial Engineering at NTNU. The thesis a continuation of the fall 2019 semester project and was written remotely during the spring of 2020. The topic of the thesis stems from the Logistics 4.0 laboratory at NTNU, where digital technologies are merged with traditional production and logistic systems.

St. Petersburg, Florida – 22 July 2020



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Acknowledgments

I would like to thank my supervisor Professor Fabio Sgarbossa and co-supervisor Guiseppe Fragapane, for their support and understanding. They gave me the opportunity to write about a topic of interest and the freedom to make this thesis my own. Their collected experience, knowledge, and guidance was greatly appreciated.

I would also like to thank Brad Ahlm and Kevin Kachmarek of Conductive Containers Inc. They approved the use of their manufacturing facility for the case study and were supportive throughout the whole process.

A final thanks to my family, friends, and girlfriend for the constant support throughout this journey to complete my master's degree. The encouragement and motivation helped me finish this thesis.

Abstract

Manufacturing companies are constantly looking for ways to improve profit margins and stay competitive, and a common solution is the redesign of the manufacturing layout. During the process of designing a layout, visual tools, such as drawings or 2D CAD, are used to present visual data and analyses. However, there are many drawbacks to these traditional visual tools. This thesis researches the use of an emerging digital technology, 3D scanning, to create visual tools to be used for the redesign of a manufacturing layout using a simplified version systematic layout planning (SLP).

The objective of this thesis is to understand the capabilities of 3D scanning and how the respective visual tools can be used to support the manufacturing layout redesign using the SLP pattern of procedures. The goal is to improve the layout design process for an operations manager by reducing the overall time and increasing visual understanding and quality of the layout design and analyses.

The research of this thesis is structured around the following three research questions.

1. What is the state-of-the-art for the use of 3D scanning for manufacturing facility layouts?
2. How do 3D scanning types, photogrammetry and structured light compare when used for manufacturing facility layouts?
3. How do 3D scanned visual tools support the process of redesigning a manufacturing layout using the SLP pattern of procedures?

A state-of-the-art literature review explored recent research on the use of 3D scanning for manufacturing facility layout designs. The literature review found that laser scanning was the most used type of 3D scanning. Moreover, most of the research was based on the layout of one production system and not the overall layout. Hence, a gap in research was discovered, which led to the formulation of research questions two and three.

An empirical case study is used to examine the remaining research questions. First, an experiment is used to create a visual tool of the current manufacturing layout design using structured light and photogrammetry 3D scanning. The scanning process and visual tools of each are then compared on specific quantitative and qualitative performance metrics.

The better visual solution from the experiment is used to create a new layout using a simplified version of the SLP pattern of procedures. Qualitative observations on how the 3D scanned visual tools support the pattern of procedures are made throughout the process.

The results suggest structured light as the better overall scanning type for manufacturing layout redesigns. Additionally, the visual tools produced by structured light can support and improve the SLP process.

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Abbreviations

2D Two-dimensional

3D Three-dimensional

CAD Computer-aided design

FPS Frames per second

HD High definition

PNG Portable network graphics

SLP Systematic layout planning

Chapter 1
Introduction

1.1 Background

The design of the facility layout is considered to be one of the most important aspects to the success of a manufacturing company. According to Tompkins (2010), a well-designed manufacturing facility layout can reduce operating expenses by 50%. Various research and practice have been devoted to improving facility layout design (Gong et al., 2019). Among the existing approaches, systematic layout planning (SLP) was found to be the most suitable approach for solving facility layout designs. Additionally, it is by far the most popular approach used in practice (Heragu, 2008) A simplified version of SLP is used to understand how 3D scanned visual s can be used to support the design of a manufacturing facility layout.

Common traditional visual tools used for the design of the facility layout, in particular a 2D CAD drawing, often come from previous layout models or hand measurements, which can correlate to inaccurate measurements or information that is not present. These types of errors can often go unforeseen and lead to costly future errors after equipment installation. Another drawback of traditional visual tools is the lack of visual realism. Important looked-for information in the facility environment is regularly missed, which leads to misunderstandings and often visual misrepresentations of new layout designs. Thus, an accurate and realistic visualization of the manufacturing facility environment is needed.

3D scanning is a fast, accurate, and visually realistic way to collect spatial data of existing environmental surfaces to create a 3D model. There are many types of 3D scanning, each with different costs and performance metrics. No matter the 3D scan type used, the resulting data is a 3D visual in the form of a point cloud, which is a set of point coordinates in 3D space, typically numbering in the tens to hundreds of million data points (Berglund et al., 2014). Point clouds are useful for realistic visualization and accurate measurement data. Additionally, a point cloud can be modified to create a new layout.

1.2 Problem Definition, Objective, and Goal

The layout is the visual presentation of the arrangement of all equipment, machinery, and furnishings within a building envelope (Tompkins, 2010). Traditional visual layout tools exist, but most often lack essential visual information and are quite time-consuming. For SLP, the layout is considered one of the most important documents.

The objective of this thesis is to understand the capabilities of 3D scanning and how the respective visual tools can be used to support manufacturing layout redesigns using the SLP pattern of procedures. The goal is to improve the layout design process for an operations manager by reducing the overall time and increasing visual understanding and quality of the layout design and analyses.

The thesis will shed light on the capabilities, challenges, and limitations for the use of 3D scanning for manufacturing layout redesigns and the visual tools produced.

1.3 Related Research

Similar academic research relating to the use of 3D scanning for manufacturing facility layouts is presented in the literature review in chapter 4. The related research is summarized, analyzed, and then any gaps in the research are presented.

1.4 Scope

The scope of this thesis is limited to the use of photogrammetry and structured light 3D scanning in an existing manufacturing facility to create visual layout tools to be used for the redesign of the general overall layout using SLP.

1.5 Research Questions

The purpose of the thesis is achieved by addressing the following research questions:

1. What is the state-of-the-art for the use of 3D scanning for manufacturing facility layouts?

This question is designed to investigate and understand the latest research on the scoped down topic. The question is answered in the literature review in chapter 4 and then later recapped in the discussion in chapter 7.

2. How do 3D scanning types, photogrammetry and structured light compare when used for manufacturing facility layouts?

This question is aimed at highlighting the pros and cons of each scanning type and the respective 3D visuals produced based on specific performance metrics. The objective of this question is to understand which scanning type is better suited for creating a 3D visual tool of a manufacturing facility layout. The answer to this question is answered in the discussion in chapter 7.

3. How do 3D scanned visual tools support the process of redesigning a manufacturing layout using the SLP pattern of procedures?

This question is intended to uncover the effectiveness of using 3D scanned visual tools in a simplified version SLP pattern of procedures. The objective is to highlight the value-adding capabilities of the visual tools. This question is answered in the discussion in chapter 7.

1.6 Contributions

The main contributions of this thesis include a literature review and a case study. The literature review investigates and analyzes the latest research on the topic to find a gap in research that can be explored in the rest of the thesis. The case study involves empirical research. First, an experiment used to create visual tools of the current manufacturing layout design using structured light and photogrammetry 3D scanning. The scanning process and visual tools of each are compared on qualitative and quantitative performance metrics. The better visual solution from the experiment is used to create a new layout using a simplified version of the SLP pattern of procedures. Qualitative observations of how the 3D scanned visual tools support the pattern of procedures are made throughout the process

1.7 Thesis Summary

The remainder of the thesis is organized in the following way:

Chapter 2 - Research Methods

This chapter includes an explanation of the scientific methods used and how the methods answer the research questions.

Chapter 3 – Theoretical Background

This chapter consists of theory relevant to the research.

Chapter 4 – Literature Review

This chapter presents the literature review and the research gap.

Chapter 5 – Case Study Setup

This chapter describes the case study and how the case is structured.

Chapter 6 – Results

This chapter presents the case study results.

Chapter 7 – Discussion

The chapter includes a reflection of the research questions, the research validity, and the limitations of the research.

Chapter 8 – Conclusion

The chapter concludes the research and presents further research recommendations.

Chapter 2

Research Methods

2.1 Outline

The research began with a literature review to find gaps in previous studies on the topic and also define the research questions. The literature review then established the core topics that needed to be introduced in the theoretical background to give the reader a fundamental understanding of the theory related to the thesis research. Lastly, a case study is used to investigate the remaining research questions. The outline of the research methods used in relation to the research questions is shown in figure 1. The literature review, theoretical background, and case study are described further in detail in the remaining parts of this chapter.

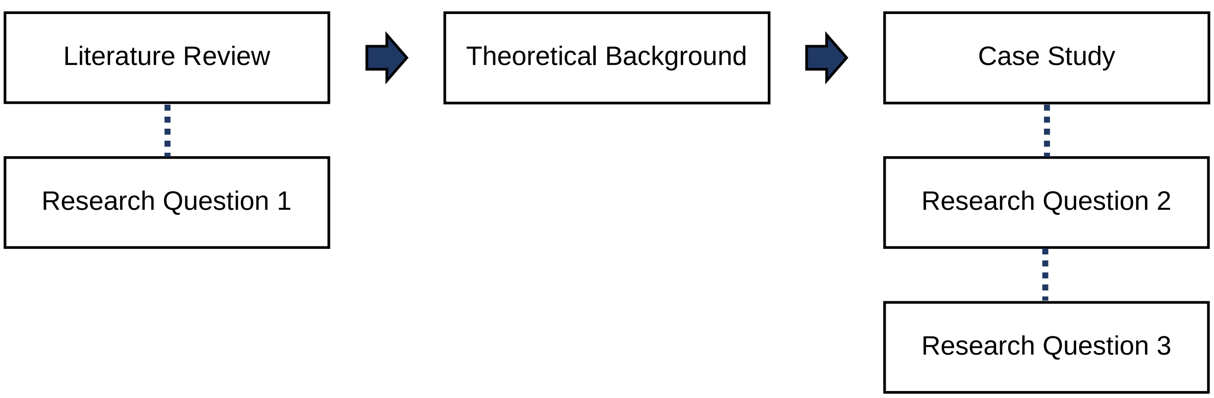

Figure 1. Outline of the research methods used related to the research questions.

2.2 Literature Review

A literature review is an account of what has been published on a topic by accredited scholars and researchers (Taylor, 2020). The review should enumerate, describe, summarize, objectively evaluate, and clarify the previous research (Coffta, 2015). The purpose is to provide context for the research, enable the researcher to learn from previous theory on the subject, and outline gaps in previous research to ensure that the thesis research is adding to the knowledge in the field.

The literature review in this thesis is based on a modified version of the PRISMA approach adapted from Liberati et al. (2009). The search was conducted through academic databases Scopus, ProQuest, and Web of Science. The search terms were divided into two categories, the first category was based on 3D scanning types, and the second was based on layout design phrases. The search terms are listed in table 1.

Table 1. Database search terms.

Category 1		**Category 2**
Scanning		"Facility layout"
or		or
Imaging		"Factory layout"
or	and	or
Photogrammetry		"Plant layout"
or		or
"Structured light"		"Layout planning"

Inclusion and exclusion were used during the database searches to filter out irrelevant articles. This comprised of including only English peer-reviewed journal articles, conference articles, and book chapters dating from May 2010 to May 2020. After completing the filtered search results of each database, duplicate articles between the databases were removed. The remaining articles were then screened by reading the abstract. Those that did not relate to manufacturing operations management were excluded. The remaining articles were screened again by reading the full text of the articles. The articles that were only vaguely related to the thesis topic were excluded. Finally, to add to the sample of the remaining articles, the cited sources and authors' previous work were viewed and screened for eligibility. In total, 12 articles make up the literature review. The inclusion and exclusion criteria are shown in table 2.

Table 2. Inclusion and exclusion criteria.

Included	Document type: Journal article, conference article, or book chapter	Database search filtering
Excluded	Non-English	
	Not peer-reviewed academic literature	
	Documents older than 2009	
	Not related to manufacturing or production (NR)	Screening 1
	Vaguely related to semester project topic (VR)	Screening 2

2.3 Theoretical Background

A theoretical background considers and discusses theory relevant to the research problem. Key concepts, theory, models, and assumptions are explained to guide and ground the thesis (Vinz, 2015).

The topics of the theoretical background in this thesis are devised from concepts and theories associated with the literature review. The information originates from prominent scholarly articles and books related to the theoretical background topics. The theoretical background is necessary to increase the understanding of the research problem.

2.4 Case Study

A case study is an empirical inquiry that investigates a contemporary phenomenon within its real-life context (Yin, 2003). A case study makes it possible to gather rich empirical data and thereby gain a deep understanding of the phenomenon in question (Kähkönen, 2011).

The case study in this thesis involves a single exploratory case involving a small manufacturing company. The advantage of having a single case allows for a more in-depth study. The data for the case study are collected through an experiment and observations. The experiment is a qualitative and quantitative research method to answer research question 2. The observations are a qualitative research method to answer question 3. The experiment, observations, and the setup of the case study are explained in detail in chapter 5. The outline of the case study is shown below in figure 2.

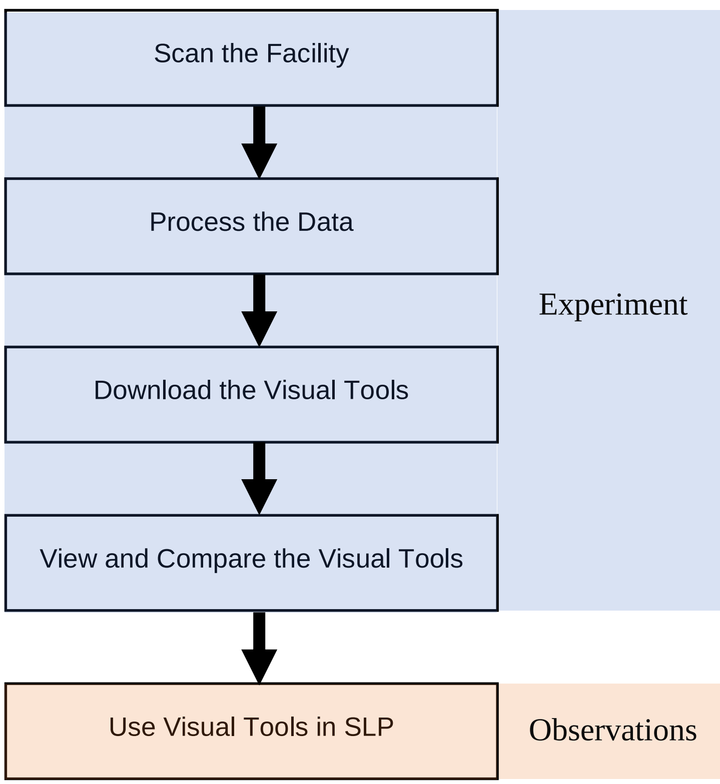

Figure 2. Case study outline.

Chapter 3

Theoretical Background

3.1 Facility Layout Design

3.1.1 Overview

Facility layout design is the arrangement of all equipment, machinery, and furnishings within a building envelope after considering the various objectives of the facility (Tompkins, 2010). It consists of two stages the general overall layout, also referred to as the block layout, and the detailed layout (Tompkins, 2010): The general overall layout shows the location shape and size of each planning department. The detailed layout shows the exact location of all equipment workbenches and storage areas within each department.

In order for the facility layout design to be complete, both the general overall and detailed layouts need to be developed and evaluated (Tompkins, 2010).

3.1.2 Objectives

The generation of a facility layout requires defining one or more objectives. The objectives can either be translated in terms of an objective function or in terms of qualitative and quantitative layout evaluation criteria (Marcoux et al., 2005). Refer to Marcoux et al. (2005) for a detailed list of objectives quoted from several previous authors. Of the listed objectives, the most popular include:

- Optimize capital investment (initial investment, installation fixed costs, start-up costs, annual operating costs, maintenance costs, return on investment, payback period)
- Optimize space utilization
- Optimize flow (materials, personnel, and information)
- Optimize handling (e.g., minimize the cost of materials handling)
- Optimize the use of equipment

According to Heragu (2008), the most commonly used quantitative criterion for evaluating a manufacturing facility layout is the minimization of the total cost of material flow.

3.1.3 Influencing Factors

Facility layout design is a multifaceted process, influenced by numerous factors and variables which are not always necessarily linked and, at times, may even have a contradictory impact on the decision-making process (Stephens and Project, 2019). Nevertheless, it is important to account for all influencing factors to maximize the benefits of the layout. A detailed list of facility layout factors can be found in Marcoux et al. (2005).

3.1.4 Systematic Layout Planning (SLP)

SLP is a procedural approach that allows users to identify, visualize, and rate the various activities, relationships, and alternatives involved in layout design planning (Tak, 2012). It uses both qualitative and quantitative information to create a re-layout or new layout. The main drawback of a procedural approach is that it is quite time-consuming, often lasting several months, according to Stephens and Project (2019).

Phases of SLP

The structure of SLP is divided into four phases: location, general overall layout, detailed layout plans, and installation. Phase II and III are most important as they are the focus of the SLP pattern of procedures.

Phase I: Location

The goal of this stage is to determine the location of the area to be laid out (Muther and Hales, 2015). This can be a re-layout of a current facility or a layout of a new facility or addition to a facility.

Phase II: General Overall Layout

After addressing the location, a general overall layout should be established. The focus of this phase is on the block layout. The basic flow patterns and areas or departments are brought together in a way that the general size, relationships, and configuration of each major area are roughly established (Muther and Hales, 2015).

Phase III: Detailed Layout Plans

The focus of this phase is on the detailed layout. Detailed layout plans involve the actual placement of each specific physical feature, such as machines and equipment in the areas or departments to be laid out (Muther and Hales, 2015).

Phase IV: Installation

The main job of this stage is to plan the installation, seek the approval of the plan, and then finally install based on the necessary physical moves (Muther and Hales, 2015).

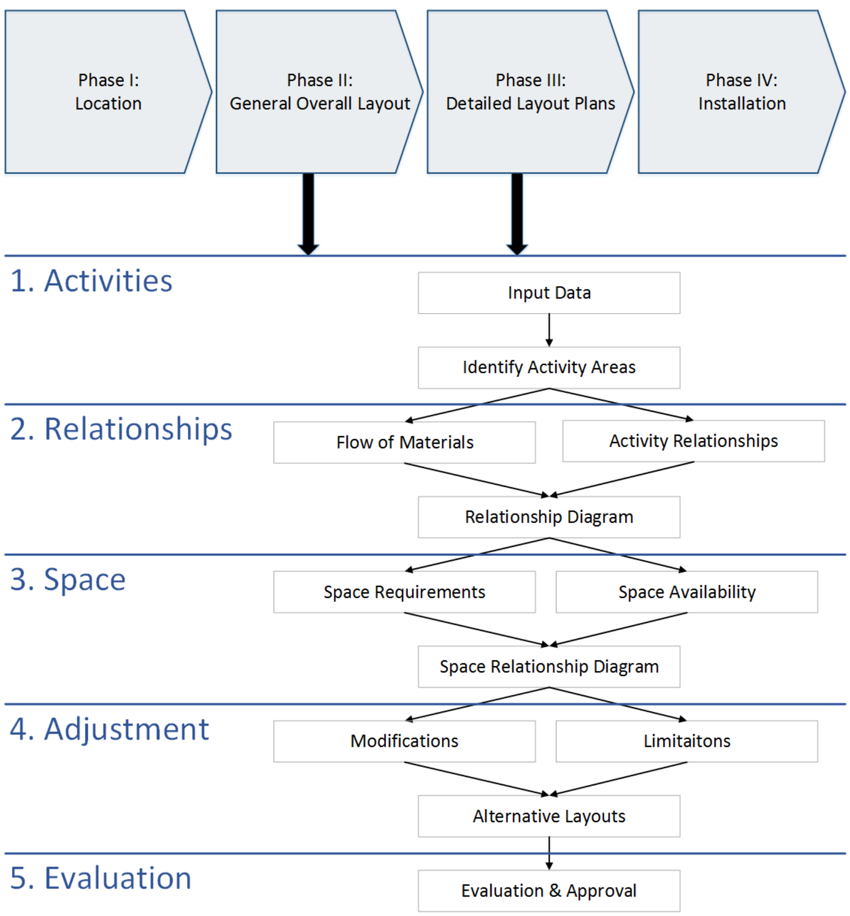

Figure 3: SLP phases and pattern of procedures.

Pattern of Procedures

The pattern of procedures are the steps taken to complete the general overall layout and detailed layout of SLP. The SLP pattern of procedures is shown in figure 3.

STEP 1 - Activities

The activities step consists of input data and identifying activity areas to create a foundation for the layout plan and design. The following five elements that should be examined include:

P - Product (What): The product element includes the raw materials, purchased parts, formed or treated parts, the finished goods, and or service items supplied or processed (Muther and Hales, 2015). This element is the key factor that affects the composition and relationship of all facilities, equipment categories, and material handling (Tak, 2012).

Q - Quantity (How Much): The quantity element indicates the number of goods or services produced, supplied, or used. (Muther and Hales, 2015). All the information is provided by production statistics such as piece, weight, volume, and price (Shekhar Tak, 2012). This element affects the layout scale, equipment amount, handling workload, and construction area (Tak, 2012).

R - Route (How): The route element relates to the process, its equipment, its operations, and its sequence (Muther and Hales, 2015). It affects the relationship among every work unit, material handling route, and storage location (Tak, 2012).

S - Supporting Service (With What): The supporting service element includes things such as maintenance, machine repair, tool room, toilets, locker rooms, cafeteria, first aid, offices, and shipping and receiving (Muther and Hales, 2015). The service department supports the production system and somehow reinforces the production efficiency (Tak, 2012). The supporting service often use more floor area than the producing departments themselves (Muther and Hales, 2015).

T - Time (When): The element of time refers to when, how long, how often, how soon the products will be produced (Muther and Hales, 2015). According to the time required, the amount of equipment, the required area, and the number of staff can be estimated (Tak, 2012).

In addition to PQRST, analysis of the activities or activity-areas included in the layout need to be identified. An activity or activity area can also be referred to as equipment or departments.

Step 2 - Relationships

The relationships step consists of the flow of materials, activity relationships, and the relationship diagram.

The goal of the material flow analysis is to find the most effective sequences of moving materials through the system. Process or flow charts can be used to analyze the material movement within the layout. A from-to-chart can be used to show quantitative data such as distance and frequency of movement between departments (Tak, 2012).

Other than the flow of materials, qualitative relationships should be considered for best practice (Muther and Hales, 2015). The activity relationship chart considers these qualitative factors by showing the degree of importance of having each department located adjacent to every other (Tak, 2012). This analysis is usually performed through stakeholder consultations.

The relationship diagram takes the information from the flow of materials analysis and or the activity relationship chart and turns it into a graphic visualization of desired closeness among activity-areas.

Step 3 - Space

The space step considers the space requirements, space availability, and the space relationship diagram.

The space requirements are focused on the necessary production parameters such as staff, equipment, and other factors from theoretical analysis (Tak, 2012).

Space availability is about the actual facility and where the different work units should be placed (Tak, 2012).

The space relationship diagram is an extension of the relationship chart in which the nodes are now represented as blocks proportional to the calculated space of the departments. It is perhaps the single most effective aid to layout planning (Muther and Hales, 2015).

Step 4 - Adjustments

The adjustments step includes modifications, limitations, and the designs of the alternate layouts.

Regarding modifications, certain factors that might affect the following implementation of the layout should be considered. Such factors include site conditions and surroundings, building features, safety, and personnel requirements.

Limitations are factors that impose constraints on planning (Muther and Hales, 2015). For each idea, there is a set of practical limitations that must be weighed (Muther and Hales, 2015). One of the most important limitations is the question of cost-saving and available investment money (Muther and Hales, 2015).

After the modifications and limitations, the planner should end up with about two to five alternative layout plans (Muther and Hales, 2015).

Step 5 - Evaluation and Approval

Evaluation and subsequent approval involve three basic methods (Muther and Hales, 2015):

- Balancing advantages against disadvantages.
- Factor analysis rating.
- Cost comparison and justification.

When approval is given for the general overall layout, the SLP pattern of procedures for phase II is complete. The next step is to move onto the detailed layout plan, phase III. An overview of the documents used in the pattern of procedures for both the general overall layout and detailed layout can be found in appendix A.

Detailed Layout Procedures

The detailed layout procedure is just like the general layout procedure, but it is more focused at the department level. The flow of materials and activity relations become those within each department. The space requirements become the space required for each specific machinery and equipment in each department. The space relationship diagram becomes a rough arrangement of templates or other replicas of machinery and equipment (Muther and Hales, 2015).

3.1.5 Visualization Tools for Layout Designs

The layout is the visual presentation of the data and the subsequent analyses by the facilities planner (Stephens and Project, 2019). When the layout is presented to management, it will be regularly referred to in order to show how the products flow through the facility (Stephens and Project, 2019). The following visual tools can be used to develop and present layout designs.

Drawings

Drawings can either be done by hand or by computer-aided design (CAD). With today's increased use of computers and computer software, manual hand drawings are becoming obsolete because it is time-consuming to make, and they must be redrawn whenever changes are made to the layout (Heragu, 2008).

Template and Tape

The template and tape method is a layout made of transparent templates and rolls of various tapes placed on a grid base (Stephens and Project, 2019). The templates indicate the positions of machines, workstations, and equipment, while the tapes indicate the flow of materials and show aisles (Heragu, 2008). According to Stephens and Project (2019), the template and tape method was the preferred method for facility designers before the introduction of CAD.

Three-Dimensional (3D) Physical Models

3D physical models are 3D versions of the template and tape method (Heragu, 2008). The big advantage of 3D models is that it illustrates and highlights the height issues (Stephens and Project, 2019). On the other hand, 3D models are more expensive, difficult to copy, and require more storage space, which makes them less desirable (Stephens and Project, 2019).

Computer-Aided Design (CAD)

CAD is the use of computers to aid in the creation, modification, analysis, or optimization of a design (Narayan et al., 2008). For facility layouts, CAD systems are mainly used to create 2D drawings and 3D models. The disadvantages include the initial cost of the software and the necessity of trained operators (Stephens and Project, 2019). The most impressive aspects are its continuous efficiency and cost-effectiveness (Stephens and Project, 2019).

Virtual Reality

According to (Stephens and Project, 2019), this technology will revolutionize facilities design by assisting layout designers and design evaluators. Recent research on the use of virtual reality for layout design shows promising results, and some of the results can be found in the literature review.

3.2 3D Scanning

3.2.1 Overview

A 3D scanner is a device that analyses a real-world object or environment to collect data on its shape and possibly its appearance (Ebrahim, 2014). The following data is then used to create a model of the object or environment in the form of a point cloud.

3D scanning has countless applications in various fields including, media and entertainment, automotive, aerospace, healthcare, manufacturing, architecture, and construction. For manufacturing, it is commonly used for reverse engineering, quality control, virtual simulation, and facility management.

3.2.2 Indoor Scanning Types

There are several different ways to scan an object or environment, and each comes with its advantages, limitations, and costs. Laser scanning, photogrammetry, and structured light were known to be the most suitable scanning types for indoor environments. The three indoor scanning types are introduced and compared in the following.

Laser Scanning

Laser scanning, also known as light detection and ranging or LiDAR, is an advanced imaging technology that acquires 3D coordinates from a target object that is visible from the viewpoint of the laser scanner (Turkan, Laflamme & tan 2016).

3D laser scanners can be generalized into three main categories, time-of-flight, phase shift, and triangulation. Time-of-flight scanners use a laser to emit a pulse of light to probe the surface of an object while the laser rangefinder detects the reflected light and finds the distance to the surface of the object by timing the round-trip time of the pulse of light. It is typical for time-of-flight scanners to measure 10,000 – 100,0000 points per second (Ebrahim, 2014). This method has the longest range of scanning, around 200 – 300 m. Phase shift scanners compare the phase shift of a specific wavelength between the sent and the received signals, where the distance is computed depending on the phase shift. Phase shift scanning speed is faster than the time-of-flight but has less range, around 70 – 80 m. Triangulation scanners shine a laser on the surface of an object while a camera looks for the location of the dot or stripe, and depending on how the dot or stripe appears in the camera's field of view, the distance can be calculated using triangulation. The triangulation works because the distance between the camera and the laser is known, the angle of laser emitted is known, and the angle of the camera can be determined to find the laser dot or stripe in the camera's field of view. This scanning method is highly accurate but has minimal range, just a few meters.

The process of capturing the laser scanned data indoors can be accomplished from a static position using terrestrial laser scanning, or on the go using mobile laser scanning. Terrestrial provides better quality point clouds but is much more time-consuming compared to mobile. Careful preplanning of scanning locations is required for terrestrial to get quality data. The planning includes location and number of scans, resolution, occlusions, and reference systems. On the other hand, mobile uses simultaneous localization and mapping (SLAM) to understand its location; therefore, no preplanning is needed.

The raw data generated from laser scanning are point clouds with known 3D coordinates. The point clouds can be colorized, but a camera needs to be integrated into the laser scanning system. The points then need to be processed in computer software such as Autodesk to be used for the objective at hand.

Photogrammetry

Photogrammetry is a 3D reconstruction technique based on conventional 2D images. Photogrammetry uses triangulation by finding the same points in different images to calculate the intersection of the projection line and to obtain the 3D position (Pérez et al., 2016).

Generally, high contrast physical marks, such as stickers or laser points, are necessary over and around the objects to ensure detection. However, software-based feature tracking algorithms have automated the detection process by finding, extracting, and matching intrinsic characteristics of the objects between similar or consecutive images.

The process of capturing photogrammetry images indoors can either be done stationary or on-the-go. An example of using a drone can be found in Li et al. (2018). Preplanning is needed to ensure the desired coverage and overlapping of images containing the common feature points. Otherwise, the software cannot align the images and create the point cloud. It is recommended that the images have at least a 60% overlap. Thus, a photo should be captured every 10 – 15 degrees horizontally and vertically. As a rule of thumb, it is always better to take more than required photos and remove the not needed photos before processing than not having enough photos. For indoor environments, a reference distance is also needed to scale the model to real-world dimensions.

The raw data, in the form of 2D images, is loaded into a reconstruction software such as RealityCapture, where the photos are aligned to create the point cloud.

Structured Light

Structured light scanning works by projecting a known pattern of light onto the surface of an object or space, while one or more cameras look at the deformation of the known pattern (Ebrahim, 2014). The distance of each point in the field of view can then be calculated using triangulation.

The light projected can either be visible or invisible (infrared or high frame rate) and come in a variety of patterns or sequences. In general, there are two main types of structured light, time multiplexing, and one-shot. Time multiplexing project a sequence of binary or grey scaled patterns while one-shot project a unique pattern (Pérez et al., 2016).

The process of capturing structured light scanned data is highly automated. Every scan, the cameras send the visual data to computer software, where algorithms perform the triangulation calculations to calculate the object's depth and surface information and display the 3D information on a computer screen in real-time. This allows the user to see what visual data has been captured, what is missing, and where to scan next. The result is typically in the form of a point cloud.

Comparison of the Indoor 3D Scanning Types

A comparison of the indoor 3D scanning types in terms of accuracy, range, cost, and processing time adapted from Pérez et al. (2016) is presented below. By understanding the capabilities of each, a layout planner or operations manager can select the most applicable scanning type to fulfill their needs.

Table 3. Comparison of indoor scanning types.

Scanning Type	Sub Type	Accuracy	Range	Cost	Processing Time
Laser Scanning	Time of Flight	+	+	-	-
	Phase Shift	+	+	-	-
	Triangulation	+	-	-	+
Structured Light	Time Multiplexing	+	-	-	+
	One-shot	-	-	+ **(Light coding)**	+
Photogrammetry		-	+	+	-

3.2.3 Resulting Characteristics

Regardless of the scanning type used, the result includes a point cloud. The quality and accuracy of the point cloud are dependent on the scan type used. Another possible result is 360-degree images from the perspective of each scanning location, but this is contingent on the scanning type and software used.

Realistic Visualization

As shown in figure 4, the point cloud and 360-degree image visuals enable the planner to make decisions based on accurate data. Objects can be easily identified because the data is so comprehensive. The characteristic of realistic visualization has been shown to give stakeholders a better understanding during evaluation and avoid costly mistakes. Additional benefits of realistic visualization include increasing the planning speed, decreasing planning costs, and increasing planning quality (Lindskog et al., 2013).

Figure 4. Point cloud view (top) vs. 360-degree image view (bottom).

Measurements

Point clouds are beneficial for measuring accurate dimensions. This characteristic helps individuals understand the spatial relation of objects throughout the facility. Consequently, it diminishes the need to be at the facility to measure dimensions by hand. The accuracy of the measurements is subject to the scanning technique used.

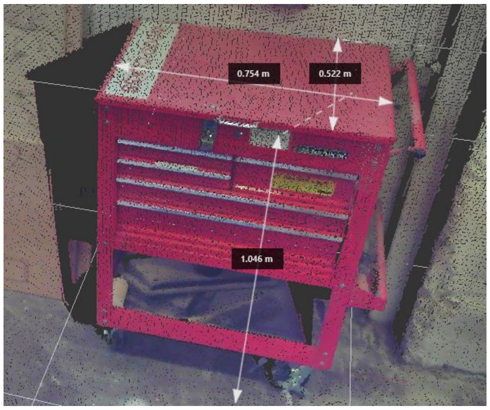

Figure 5. Point cloud measurement tool.

Modifiable

A point cloud can be edited and modified to serve many purposes. Newly created point clouds can be cleaned up by removing unwanted points or visual information through automatic filtering and manual editing. Most software designed to work with point cloud data also has the capability of rendering and editing CAD data in parallel, which is useful for several applications (Lindskog et al., 2013). Point clouds can also be converted to a polygon meshed surface. This is referred to as surface reconstruction. A meshed surface, or mesh, satisfies the high modeling and visualization demands of different graphic applications, like virtual reality (Yoon, 2006). Given the polygonal surface, various techniques such as smoothing and texturing can be used for post-processing operations and better visualization of the 3D model (Yoon, 2006).

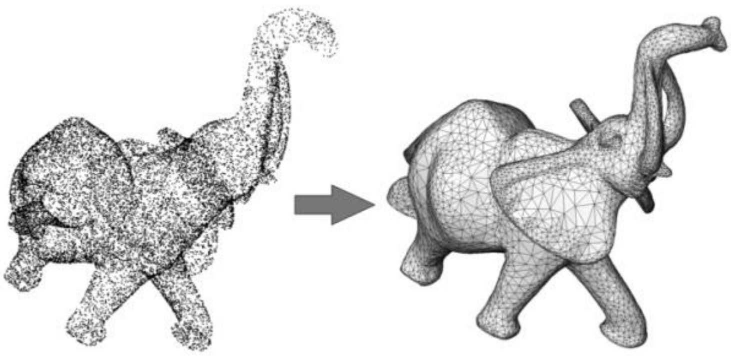

Figure 6. Surface reconstruction of a point cloud to a polygon meshed surface, taken from (Alliez et al., 2019).

Chapter 4
Literature Review

4.1 Literature Review

Although a significant amount of research has been done on the use of 3D scanning in a manufacturing environment, particularly reverse engineering and quality control, there has been little focus on the use of 3D scanning for facility layout design. Therefore, this literature review is focused on discussing what has already been researched relating to the use of 3D scanning for facility layout design. Then it will recognize gaps in the previous research that can be filled with further research on the topic.

Lindskog et al. (2013) evaluate the type of problems that can be solved with better visualization during manufacturing layout. The visualization tool combines 3D CAD models with a 3D laser scanned as-built point cloud of a facility. The evaluation consists of two case studies where one evaluates the potential of technology, and the other considers a new machine and its attached equipment before the start of an installation. A cross-functional team of people in the case company was used to evaluate the visualization from a projector. The team found the visualization to be useful, but the authors believe an interactive approach would have been a more suitable solution and suggested it as further research.

Lindskog et al. (2014) offer a structured approach to how realistic visualizations can be used to solve problems that are identified while planning the redesign of a production system. A 3D laser scanner was used to create a point cloud of a manufacturing facility and combined it with 3D CAD models. Three industrial studies were used for evaluating the required space for machines and material handling processes in cross-functional groups. The result of the studies influenced the creation of a five-step problem-solving approach based on the lean based LAMDA learning approach. LAMDA, an acronym, means Look, Ask, Model, Discuss, Act. The authors state that the proposed approach increases common understanding and better decision support for the redesigning of the production system

Lindskog et al. (2016a) evaluate how 3D laser scanning can support layout planning and geometry analysis when redesigning production systems. Five industrial studies were carried out, each tasked to plan and install new production systems in existing shop floors. A 3D laser scanner was used to scan the existing shop floors to create a point cloud for each industrial study. The observations and outcomes from the five industrial studies indicate 3D laser scanning as an important technology for supporting the redesign process of production systems, specifically layout planning. Benefits of the point clouds include accuracy and verification, which can reduce the necessary time for planning and discussions, as well as risk mitigation and the ability to reduce design errors. Furthermore, the ability to combine CAD models with the point cloud provides for a 3D visualization of future production systems and has shown to be easier to understand than traditional 2D CAD layout models. For further development, the authors suggested the use of a more systematic method for layout planning in combination with visualization, simulation, and spatial design requirements.

In Lindskog et al. (2016b), the authors evaluate a method for the systematic use of realistic visualization to support the design process of production systems. The realistic visualization was created with 3D laser scanned data of a current shop floor area in combination with 3D CAD models of new equipment. The research included three workshops where the general task was to establish a final detailed layout, identify the hardware, and verify the process sequence and operator tasks. The most important aspect of the workshops was to identify the risks and eliminate the possible problems before starting the installation of the equipment. The research found realistic visualization as valuable to the support of the design process of production systems. The visualizations created a clear view of the planned system and increased the quality of discussions during project meetings. Lastly, the systematic method resulted in the early elimination of risks and problems in the design process.

Nåfors et al. (2017) investigate and evaluate the usefulness of realistic 3D layout models in the layout planning process. An industrial study was used to address how existing methods for visualization and layout evaluation can be applied in a real industrialization project. A 3D laser scanner was used to create a point cloud of the shop floor area. The resulting point cloud was then combined with 3D CAD models to create a realistic 3D layout model of the planned layout. An identical model was also made for use in immersive virtual reality. Both models were used in workshops to evaluate the planned layout. The results show that a realistic 3D layout model can be used to support productive discussions during layout planning. The authors state that working systematically with the realistic 3D layout models allowed for quick implementation and accurate evaluation changes.

In Berglund et al. (2017), the authors develop and evaluate methods and tools to support organizational collaboration to achieve the planning and design of a new production system. 3D laser scanning and immersive virtual reality were combined to create the virtual decision support models. Evaluation of the virtual models required the participants from different organizational backgrounds to wear the virtual reality gear and conduct a series of tasks in the modeled environment. After completing the tasks, each participant filled out a questionnaire to obtain the results. The results showed clear benefits from the virtual model from the majority of test participants.

Eriksson et al. (2018), provides a framework for setting requirements on virtual factory layouts derived from 3D laser scanning data. They propose a purpose-oriented framework consisting of three classification areas, level of development, level of accuracy, and level of recognizability. From the authors' research approach, the purposes of having a virtual factory layout were found to be layout management and simulation. The two were then reviewed in each of the three classification areas, which led to the minimum development of design required for a virtual factory layout to fulfill both layout management and simulation purposes.

Li et al. (2018) evaluate the feasibility and performance of photogrammetry for generating point clouds in industrial manufacturing environments. The evaluation was done by comparing the photogrammetric point cloud to an accurate and reliable laser-scanned point cloud of the same industrial robot cell. A drone was used to capture the photogrammetric images, whereas a terrestrial laser scanner was used for laser scanning. The evaluation results found the performance of photogrammetry to be similar to that of laser scanning, with deviation mainly below 10 mm. The most promising feature of photogrammetry was found to be its reduction of time required on-site. The authors summarize that the applicability of photogrammetry as well suited for layout planning scenarios and can be seen as a cost-efficient alternative to terrestrial laser scanning.

Mårdberg et al. (2018) introduce a digital factory layout tool to optimize the layout of machines and the ergonomic logistics considering space constraints. A 3D point cloud of the facility and CAD files of the machines were used to create the 3D model. The model activities and their mutual relations are first ranked and then used to compute an optimized layout that considers both relations and space. The layout was further optimized with respect to logistic walking routes that are created when digital manikins perform their tasks using algorithms. The result was an optimized layout with improved logistics routes.

Gong et al. (2019) propose a point cloud-based virtual factory modeling approach for the virtual reality support of layout planning tasks. The approach combines 3D laser-scanned point clouds with CAD models to model the virtual environment. The authors exemplified and refined the approach through three cases. In each case, the stakeholders viewed and evaluated the layout and gave feedback regarding space and modifications. The feedback was then synchronized to modify the virtual layout and iterated until a final plan was agreed upon by all stakeholders for approval and implementation. The results show that a point cloud-based virtual factory modeling approach can create realistic virtual models for the virtual reality support of layout planning tasks.

Vahid and Wang (2019) propose a systematic workflow to generate and visualize a hybrid 3D factory layout where the point cloud model was combined with CAD objects of new manufacturing equipment on a web-based platform. The point cloud of a medium-sized manufacturing facility was generated using a 3D laser scanner. The authors state that the method and visualization could facilitate and optimize further planning of manufacturing facilities and systems.

Nåfors et al. (2020) present three cases of how a combined 3D laser scanned industrial layout and virtual reality digital twin can be used to benefit both decision-makers and other stakeholders for existing layout planning scenarios. The first study was based on where the equipment and machinery could be placed to minimize investment cost and maximize the utilization of the existing facility. The second study shared the planned future state with the project team, shop floor operators, and stakeholders to acquire more feedback before the start of installation. The last study was evaluating the planned future state with stakeholders to evaluate the feasibility and fit of solutions while trying to identify improvement areas before the installation. According to the authors, the three studies all showed how a hybrid digital twin could be valuable to the industry. Benefits include environmental, economic, and social sustainability.

Table 4. Analysis of 3D scanning use during facility layout design according to the articles.

Article	Scanning Type	General Overall Layout	Detailed Layout
Lindskog et al. (2013)	Laser		X
Lindskog et al. (2014)	Laser		X
Lindskog et al. (2016a)	Laser		X
Lindskog et al. (2016b)	Laser		X
Nåfors et al. (2017)	Laser		X
Berglund et al. (2017)	Laser		X
Biesinger et al. (2018)	Laser		X
Eriksson et al. (2018)	Laser		X
Mårdberg et al. (2018)	Not Mentioned		X
Li et al. (2018)	Photogrammetry		X
Gong et al. (2019)	Laser		X
Vahid and Wang (2019)	Laser		X
Nåfors et al. (2020)	Laser		X

By reviewing the limited list of research articles, it is apparent that the use of 3D scanning for manufacturing facility layout design is a relatively new area of research.

The research results suggest that 3D scanning is a valuable tool. The use of a 3D scanned model for facility layout design makes for a powerful visualization tool that increases verification and reduces risks and time.

One significant gap in the research identified in all the articles was that the design of the facility layout was focused on the detailed layout, as shown in table 4. They analyzed a production system or work cell and not the general overall layout of the facility.

Another noticeable gap that was recognized was that laser scanning is the dominant 3D scanning type used in the previous research, see table 4. The research and results by Li et al. (2018), using photogrammetry, provide opportunities to explore the use of other scanning types for manufacturing facility layout design.

From the gaps in the research identified above, the scope of this thesis was formed, which is the use of photogrammetry and structured light 3D scanning in an existing manufacturing facility to create visual layout tools to be used for the redesign of the general overall layout using SLP.

Chapter 5
Case Study Setup

5.1 Case Company

Conductive Containers Inc. is a small packaging company based out of New Hope, Minnesota. It has around 50 employees. The company specializes in the niche anti-static and conductive packaging market. They design and manufacture from their two facilities located next to each other. One facility is for plastic packaging production, while the other focuses on corrugated packaging production. The corrugated manufacturing facility is larger and connected to the main offices, tool shop, and incoming and outgoing shipping.

The focus of this case will be only on the corrugated manufacturing and assembly area, as requested by the case company. The objective of the facility layout is to optimize flow and space utilization.

5.2 Experiment Setup

The experiment uses both structured light and photogrammetry 3D scanning types to create 3D visuals of the case company's current manufacturing facility layout. Specific steps must be taken to create the visual tools for each scanning type. First, the facility is scanned, then the data is processed, after that, the visuals are downloaded, and finally, the visuals are viewed and analyzed. The respective 3D visuals are compared using specific performance metrics. The more effective solution is then used in the observations portion of the case study.

5.2.1 Structured Light Equipment, Software, and Procedure

Equipment

Camera

The Matterport Pro 2 camera was chosen because of its lower cost compared to other structured light cameras. The camera uses infrared structured light to project a pattern of infrared light onto the scene while its infrared sensors capture and calculate the 3D depth data. In addition to the depth data, a 4000-pixel camera captures visual data. The camera rotates around a tripod to get a 360-degree (left-right) x 300-degree (vertical) field of view. 3D depth-sensing has a maximum range of 4.5 m. Thus, the camera must be manually moved around to capture an entire room.

Figure 7. Matterport Pro 2 camera.

Tripod

The Manfrotto MT290XTA3US Xtra Aluminum Tripod was chosen based on the recommendation on the Matterport website. The tripod is used to keep the 3.4 kg Matterport Pro 2 stable.

Smartphone

The smartphone is needed to access the Matterport Capture app. The author’s iPhone 10 is used in this thesis.

Computer

A computer is needed to access and run the structured light software. One with a good graphics card is recommended. The authors Lenovo ThinkPad P51 Mobile Workstation was used. The mobile workstation includes a NVIDIA Quadro M1200 4 GB graphics card and Intel Core i7-6820HQ processor for strong performance.

Software

Matterport

Matterport has its proprietary cloud-based software. The software does all the processing for the user. Also, it includes an app, Matterport Capture, that connects to the Matterport Pro 2 camera during a scan to show what exactly has been scanned.

Autodesk Recap

Autodesk Recap allows point cloud files to be viewed and filtered, editing the data that is not needed. Recap is used for the point cloud file.

Autodesk 3DS Max

Autodesk 3DS Max is a 3D modeling, animation, rendering, and visualization software used to create game environments, design visualizations, and virtual reality (Autodesk, 2020a). 3DS Max is used for the meshed surface file.

Procedure

Scan

The camera is moved around the facility with about 2 m of spacing in-between scans to stay within the 4.5 m depth-sensing limit of the infrared structured light sensors.

Process

Once the scanning is complete, the data is uploaded from the Matterport Capture app to the Matterport cloud to process. The processing is done automatically in the cloud.

Download

When the processing is complete, the output 3D visuals are in the form of a point cloud, meshed surface, and digital twin. These can be accessed from the Matterport website. To download the point cloud and mesh files, they need to be bought.

View

The downloaded point cloud is viewed with the Autodesk Recap, and the meshed surface is viewed with Autodesk 3DS MAX.

5.2.2 Photogrammetry Equipment, Software, and Procedure

Equipment

Camera

The GoPro Hero 7 Silver was chosen because it was recommended for indoor 3D mapping. The camera captures a 4000-pixel video at 30 FPS. It also includes a fisheye lens, which allows for a greater field of view.

Extension Pole

An extension pole is needed to get an aerial view of the manufacturing facility. The Wooster 8 ft to 16 ft Sherlock extension pole is used.

Camera Mount

A camera mount is needed to mount the camera to the extension pole. The camera mount used consists of a GoPro shorty mini extension pole, GoPro mounting frame, and Wooster lockjaw tool holder.

Figure 8. Camera and camera mount.

Trolley

A trolley is used to capture smooth and consistent video with little camera movement. The trolley was found in the case company's manufacturing facility. The complete scanning apparatus with all the equipment is shown in appendix B.

Computer

A computer with a good graphics card is recommended to run the photogrammetry software. The authors Lenovo Thinkpad P51 Mobile Workstation was used. The mobile workstation includes a NVIDIA Quadro M1200 4 GB graphics card and Intel Core i7-6820HQ processor for strong performance.

Software

RealityCapture

RealityCapture is a photogrammetry software that helps create 3D digital models from photographs. RealityCapture is used to convert the video to a point cloud and meshed surface.

Autodesk Recap

Autodesk Recap allows point cloud files to be viewed and filtered, editing the data that is not needed. Recap is used for the point cloud file.

Autodesk 3DS Max

Autodesk 3DS Max is a 3D modeling, animation, rendering, and visualization software used to create game environments, design visualizations, and virtual reality (Autodesk, 2020a). 3DS Max is used for the meshed surface file.

Procedure

Scan

Before scanning the manufacturing facility, the route of the scan is planned to try and capture every visual feature of the facility as possible. The scanning apparatus is then slowly moved around on the planned route while the GoPro captures continuous video.

Process

The video file is uploaded to a computer where it is then imported in RealityCapture. The software then exports a sequence of frames as PNG files to a folder. The author goes through each image and removes all blurry images. The folder of PNG files is then uploaded to RealityCapture, where the software aligns the images to create the 3D visuals in the form of a point cloud and meshed surface.

Download

The RealityCapture license used for this thesis is pay per pixel, which means it is free to download the software and process input data, but once satisfied with the result, it charges per megapixel per output.

View

The downloaded point cloud is viewed with Recap, and the meshed surface is viewed in 3DS MAX.

5.2.3 Comparison

This thesis is focused on the use of 3D scanning for operations management and not the technology itself. Therefore, the comparison of the 3D scanning types and their respective 3D visuals are based on performance metrics assumed to be critical to an operations manager using the technology. According to Stevenson (2012), an operations manager's daily concern includes cost, quality, and time. Thus, the performance metrics chosen include cost, scan time, processing time, quality, and user experience.

Performance Metrics

Cost

The cost includes the costs of all equipment and software needed to produce a 3D visual. Cost is a quantitative value measured in United States dollars.

Scan Time

Scan time is the time it takes to scan the manufacturing facility. Scan time is a quantitative value measured in hours and minutes.

Processing Time

Processing time is the time spent to process the visual data to a 3D visual. Processing time is a quantitative value measured in hours and minutes.

Quality

Quality is measured by how complete and detailed the 3D visuals are. The quality of the 3D visuals will be rated on a 5-point rating scale from poor to excellent. The scaled ratings in their respective order are poor, fair, good, very good, excellent.

User Experience

User experience represents the overall experience of using the 3D scanning types and creating the 3D visuals. Therefore, the scanning experience and processing experience of each scan type are rated on a 5-point rating scale from poor to excellent.

5.3 Observation Setup

The more effective 3D visual discovered from the experiment is used in a simplified version of the SLP pattern of procedures that are assumed to need visual support. During this process, the author creates a new general overall layout of the manufacturing facility using the 3D visualization tools and observes the value-adding capabilities and support of the visual tools for layout planning and design. The capabilities and support are then presented in the discussion in chapter 7.

5.3.1 Observation Equipment, Software, and Procedure

Equipment

Wyze V2 Cameras

The Wyze V2 camera is a small indoor wi-fi smart home camera. It includes a 110-degree wide-angle lens and can take a 1080-pixel video. The camera can store continuous video data onto a MicroSD card, which is used to record flow data of the manufacturing facility.

Computer

A computer with a good graphics card is recommended to run the software needed during the observations. The authors Lenovo Thinkpad P51 mobile workstation was used. The mobile workstation includes a NVIDIA Quadro M1200 4 GB graphics card and Intel Core i7-6820HQ processor for strong performance

Software

Autodesk Recap

Autodesk Recap allows point cloud files to be viewed and filtered, editing the data that is not needed. Recap is used in this part of the case study to edit the point cloud file before uploading it to Autodesk Inventor.

Autodesk Inventor

Autodesk Inventor is a CAD software used for professional-grade 3D mechanical design documentation and product simulation tools (Autodesk, 2020b). Inventor is used to upload the point cloud and create the new general overall manufacturing layout.

VLC Media Player

VLC is an open-source multimedia player that plays most multimedia files. VLC is used to view the recorded video data and analyze the flow of materials.

Procedure

Since the focus of the thesis is on how 3D scanned visual tools help with designing and creating a new layout, a simplified version of the SLP pattern of procedures is used based on the documents that are assumed to be exploited by a visual tool. The simplified SLP pattern of procedures and its respective documents are listed in table 5.

Table 5. Simplified SLP pattern of procedures and the documents used.

Pattern of Procedures	**Documents**
1. Activities	N/A
2. Relationships	Present Flow Diagram From-To-Chart Flow Analysis and Diagram
3. Space	Activity Areas and Features Sheet Space Relationship Diagram
4. Adjustment	Layout Drawing Models and Renderings
5. Evaluation	N/A

Chapter 6
Results

6.1 Experiment Results

6.1.1 Structured Light Results

Scanning

In total, 155 scans make up the structured light model. The total scan time took 2 hours and 54 minutes.

The overall experience of scanning was very good. The setup of the equipment and software was quick and efficient. Scanning was straightforward, simply pressing the scan button on the Matterport Capture app started the scan, and then the results of the scan would show instantly on the phone to see what has been scanned. That helped knowing where to scan next and made the process of scanning very user friendly.

Processing

To process the scanned data, the only thing that was needed to do was click the upload button on the Matterport Capture app. The data was then processed in the cloud. An email was sent when the process was complete and ready to view. The total processing time to complete the model was 5 hours and 16 minutes. Due to the hands-off processing, the overall user experience of the processing was excellent.

3D Visuals

The 3D visuals were successfully created without fault. This was expected as the manufacturing environment did not contain problem features such as sunlight and high reflectivity that are known issues with structured light scanning. The 3D visuals produced from the scan include a point cloud, a meshed surface, and a digital twin. The digital twin is a colored meshed surface file that is easy to navigate. When somewhere in the digital twin is clicked, the file navigates to the closest scanning location near the click and displays a 360-degree HD image view. The meshed surface depth data is hidden behind, which is what allows 3D measurements to be taken from the 360-degree HD image view. There are many other features included that are useful in the digital twin model, such as viewing the space in virtual reality. To learn more, visit the Matterport website. The digital twin can only be accessed on the Matterport website or app. In contrast, the point cloud and meshed surface file can be downloaded and edited in other software programs such as Autodesk. The overall quality of the visuals was rated as very good. The visuals are shown below.

Point Cloud

Figure 9. Structured light point cloud aerial view.

Figure 10. Structured light point cloud zoomed-in view.

Meshed Surface

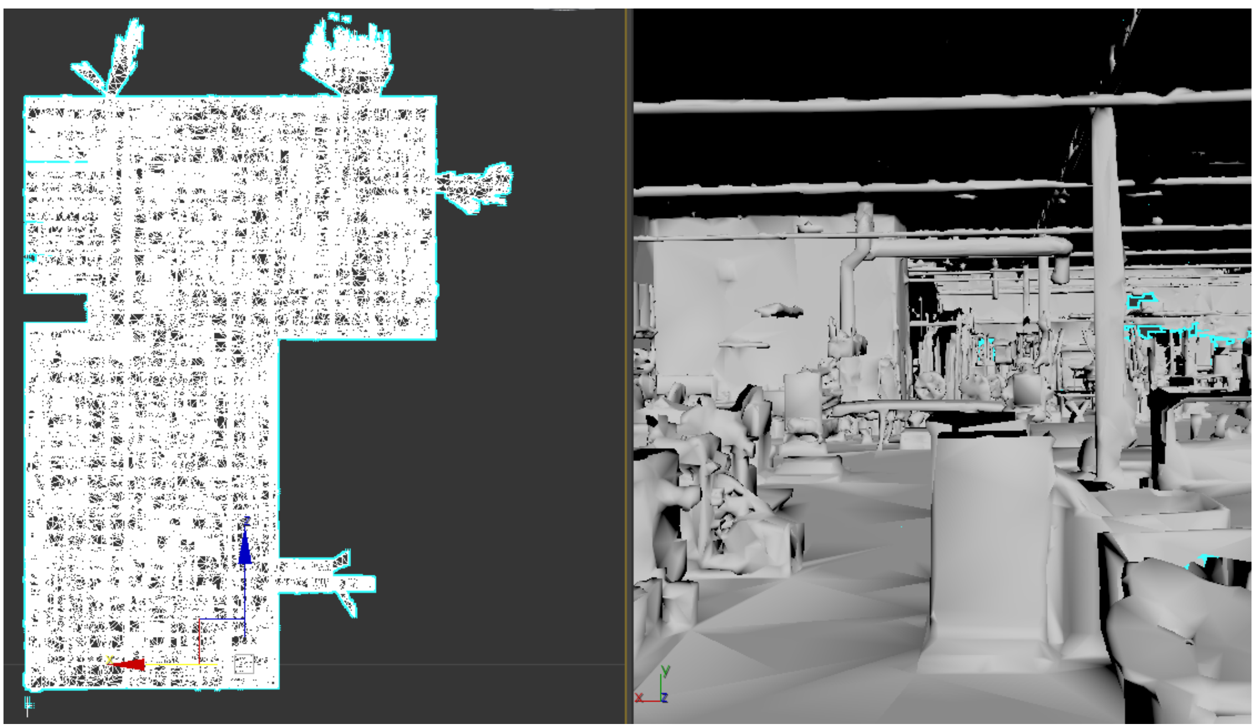

Figure 11. Structured light meshed surface model.

3D Digital Twin

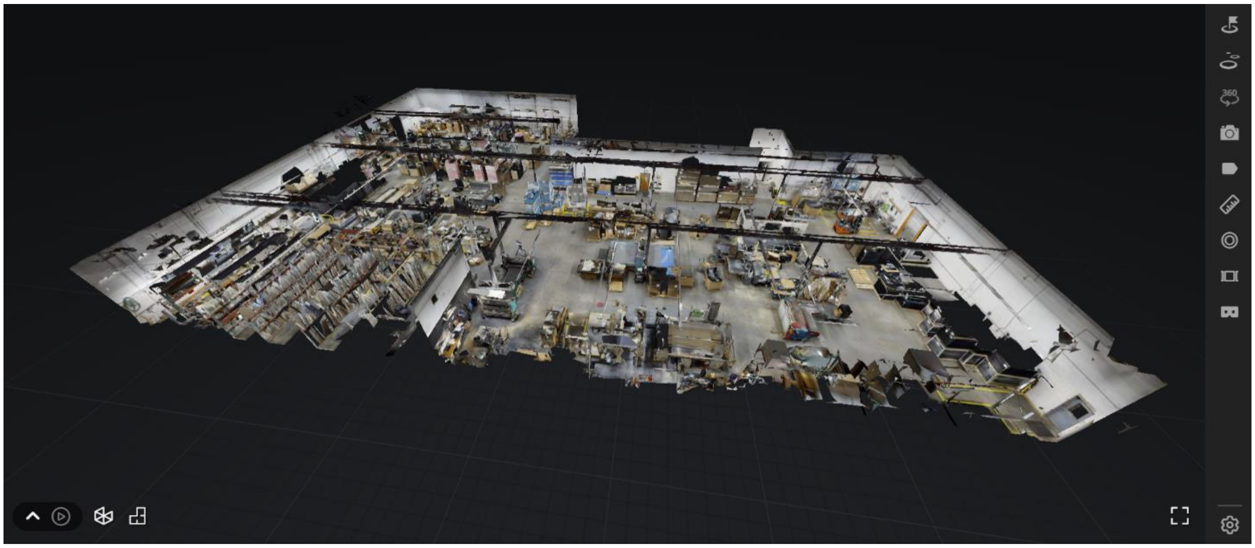

Figure 12. 3D digital twin aerial view.

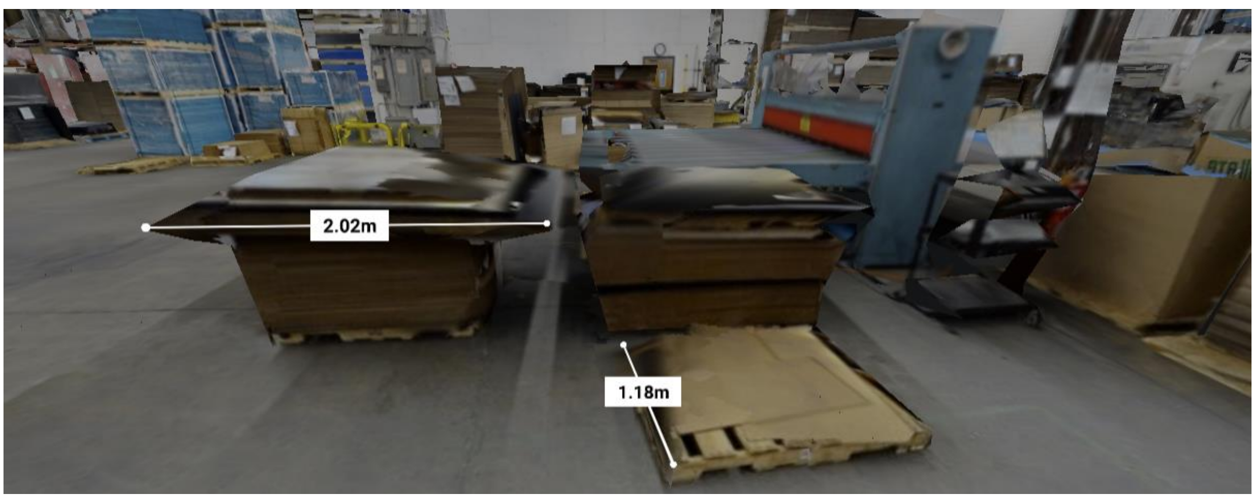

Figure 13. 3D digital twin meshed surface view.

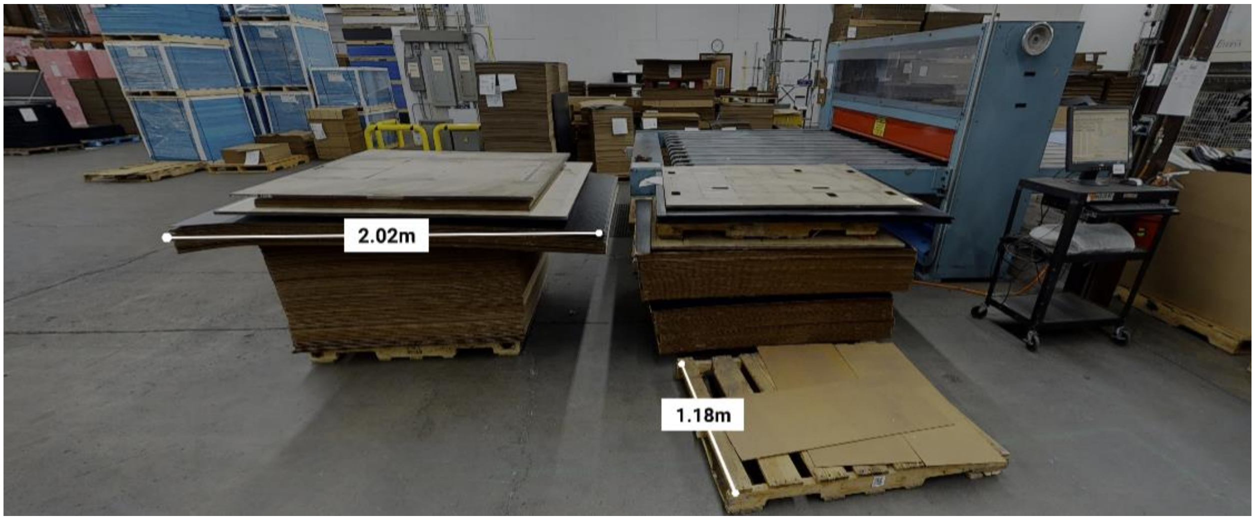

Figure 14. 3D digital twin 360-degree HD image view.

6.1.2 Photogrammetry Results

Scanning

Scanning required two attempts. The first attempt took 24 minutes to scan the facility. In this attempt, the extension pole was held by hand. This was difficult because the goal is to keep the camera as stable as possible and holding the extension pole for that long wear on the muscles. Other than that, the first attempt at scanning was efficient.

In the second attempt, the extension pole was fixed to the trolley. This allowed the camera to keep stable. The scanning of the facility took 22 minutes, and the overall experience was very good.

Processing

Many days were spent just figuring out the correct settings to get the data to process a complete point cloud file. As mentioned in section 5.2.2, the video file needed to be split into framed images. This required choosing a jump length, which equates to frames saved per second. For example, a jump length of .5 would equate to two frames extracted for every second of video. The smaller the jump length, the more frames there would be, and the longer it would take the software to process the data. However, to extract all the frames from the video takes around 3 hours on average. Much time was spent testing out different jump lengths. After multiple attempts, a jump length of .8 was chosen. The next challenge was choosing the correct image alignment settings. Finding the correct settings was done with some online research and trial and error. However, each time the images were aligned, it would take around 4 hours on average to create a point cloud. The last task was to convert the point cloud to a meshed surface, in which the level of detail of the surface model needed to be chosen. The level of detail options included preview or low detail, normal detail, and high detail. High detail was chosen first. After processing for 33 hours, an error box popped up, saying there was not enough video memory to create a surface file of the entire facility. Then, normal detail was chosen, and the same error box popped up after 12 hours of processing. Lastly, preview detail was chosen, and the result can be seen in the 3D visuals section below. The overall experience of processing the photogrammetry data was rated as fair.

3D Visuals

The 3D visuals were successfully created; however, there are some faults. The 3D visuals include a point cloud and a meshed surface. The faults with the point cloud include many missing points, and some points and sections of the cloud are not aligned correctly. The fault of the meshed surface is its limited low quality, which allows little to no visual identification. The overall quality of the visuals was rated as fair.

Point Cloud

Figure 15. Photogrammetry point cloud aerial view.

Figure 16. Photogrammetry point cloud zoomed view.

Meshed Surface

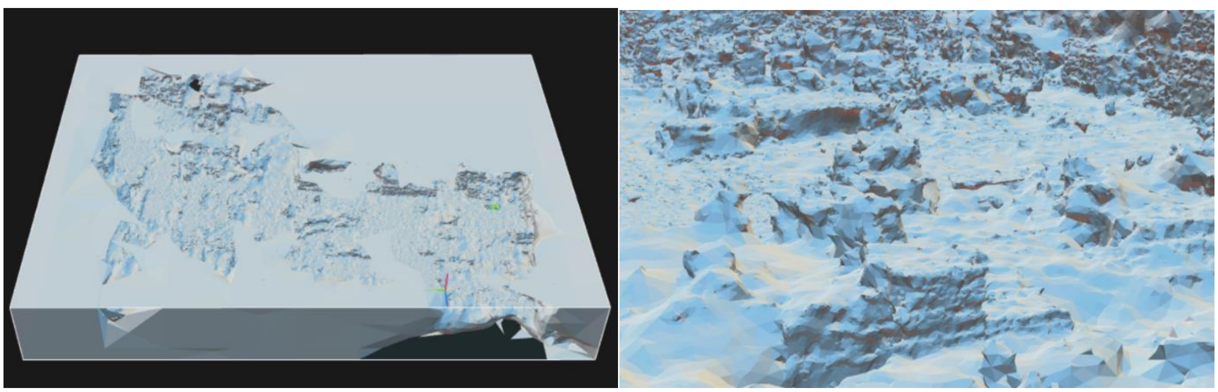

Figure 17. Photogrammetry meshed surface model.

6.1.3 Performance Metric Comparison

Each scanning type had its advantages and disadvantages in the performance metric comparison. However, structured light edged out photogrammetry for the better overall solution due to its faster processing time, 3D visual quality, and user experience throughout the structured light scanning and processing. The results of the comparison are shown in table 6.

Table 6. Structured light and photogrammetry performance metric comparison.

	Structured Light	Photogrammetry
Cost	Camera = $3645.39 Tripod = $189.89 Matterport Subscription = $74.09 Matterport Download = $52.61 Total = $3961.98	Camera = $320.99 Extension Pole = $39.70 Camera Mount = $43.56 RealityCapture Download = $59.38 Total = $463.36
Scan Time	2 hr 54 min	22 min
Processing Time	5 hr 16 min	About 120 hours
Quality	Very Good	Fair
User Experience	Scanning = Very Good Processing = Excellent	Scanning = Very Good Processing = Fair

6.2 Observation Results

6.2.1 Simplified SLP Results

Activities

It is assumed that the documents cannot be exploited by a 3D visualization tool. Only the already known activity areas are presented.

Activity Areas

The activity areas include die storage, assembly, printer, coater, WIP 1, Haire, Brausse, Splitter, Eterna, Slitter, and WIP 2. Their relative location of the activity areas in the facility can be seen in figure 18.

Figure 18. Facility layout activity areas.

Relationships

Present Flow Diagram

Usually, a company has no operations list, process sheet, or written down routing to work from (Muther and Hales, 2015). That is the case in this thesis. To better visualize the problem, the author created a present flow diagram by tracing the flow of materials on the existing floor plan. The present flow diagram was used to understand the actual movement of materials better and help identify redundancies in the flow. Usually, the layout planner must get on the shop floor to trace the material movements. However, due to the 2020 pandemic, the author was not capable of collecting this data in person. Instead, four Wyze cameras were setup up around the facility to gather five days of visual flow data. The setup of the cameras relative to the facility layout is shown in figure 19. The perspective of each camera in figure 19 can be seen in appendix C. The video data was saved on a MicroSD card in each camera and then uploaded onto a computer. Once uploaded, the data was viewed using VLC media player and traced onto a printed copy of the facility layout. The layout was created using the floor plan view of the 3D digital twin visual tool. The present flow diagram is shown in figure 20.

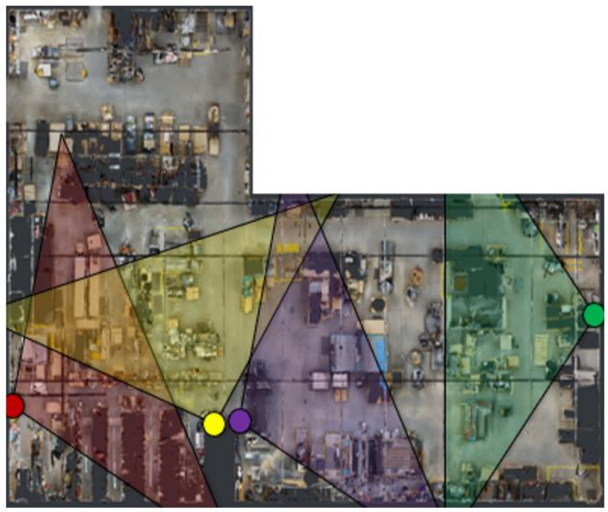

Figure 19. Wyze camera positioning in the facility.

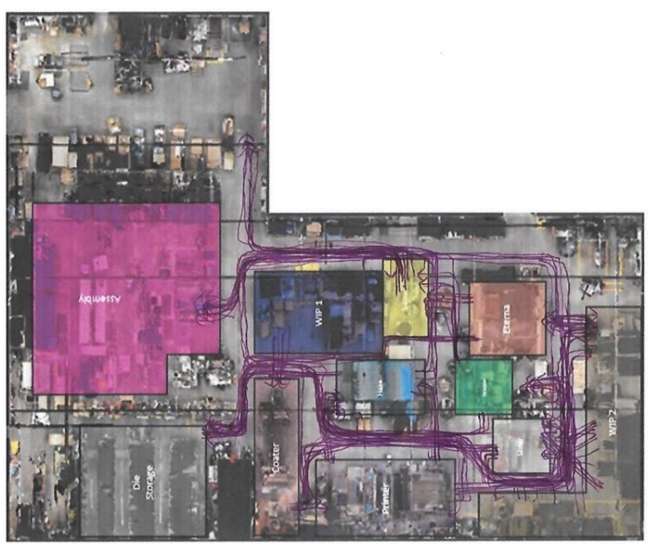

Figure 20. Present flow diagram drawn.

From-To-Chart

The from-to-chart is an analysis tool to record the number of flows and or distances between activity areas. The tool helps the planner see which activities should be located next to one another to minimize the flow and distance between each to optimize the layout. For more information on the from-to-chart, refer to page 4-20 of Muther and Hales (2015).

Video data from the Wyze cameras were used to calculate the number of flows between each activity in the from-to-chart. The measurement capability of the 3D digital twin visual tool was used to calculate the distance between the flows of the activity areas in the flow analysis. The completed from-to-chart can be seen in table 7. The consequent flow analysis is shown in table 8.

Table 7. From-to-chart.

		To										
		Die Storage	Assembly	Coater	WIP 1	Printer	Haire	Splitter	Slitter	Brausse	Eterna	WIP 2
From	Die Storage						1		6			
	Assembly											
	Coater					6			1	2		3
	WIP 1			10				1	3			
	Printer						11			2	2	7
	Haire	13	12			8						
	Splitter		12									
	Slitter	4	1	1	3		11			17		22
	Brausse	12	2					17				
	Eterna	14						9		3		
	WIP 2						3		64	1	22	

Table 8. Flow analysis.

Activity Pair		2-Way Flow	Vowel	Value	Present Distance *(m.)*
Slitter	WIP 2	86	A	4	6.6
Eterna	WIP 2	22	A	4	5.0
Printer	Haire	19	E	3	9.6
Splitter	Brausse	17	E	3	9.3
Slitter	Brausse	17	E	3	21.6
Die Storage	Haire	14	E	3	21.4
Die Storge	Eterna	14	E	3	37.2
Splitter	Eterna	13	I	2	5.5
Die Storage	Brausse	12	I	2	39.8
Assembly	Haire	12	I	2	34.1
Assembly	Splitter	12	I	2	29.2
Haire	Slitter	11	I	2	26.0
Die Storage	Slitter	10	I	2	54.9
Coater	WIP 1	10	I	2	5.1
Printer	WIP 2	7	O	1	22.3
Coater	Printer	6	O	1	6.01
WIP 1	Slitter	6	O	1	25.1
Coater	Slitter	4	O	1	17.5
Coater	WIP 2	3	O	1	40.8
Haire	WIP 2	3	O	1	24.1
Brausse	Eterna	3	O	1	6.1
Assembly	Brausse	2	O	1	35.0
Coater	Brausse	2	O	1	40.5
Printer	Brausse	2	O	1	22.1
Printer	Eterna	2	O	1	22.4
Assembly	Slitter	1	O	1	32.5
Coater	Splitter	1	O	1	27.4
WIP 1	Splitter	1	O	1	37.2
Brausse	WIP 2	1	O	1	8.6

Flow Diagram

This diagram shows the sequence of activities and the relative importance of the closeness of each activity to each other activity. It is based on flow intensity and is transferred and translated into a geographic arrangement (Muther and Hales, 2015). It is recommended that the diagram be made independent of an existing building or existing site plan to develop no preconceived ideas (Muther and Hales, 2015). However, in some cases it is known that an existing building structure or floor space of a specific building must be used with no possibility of changing building features, it may be practical to diagram directly on the floor plan of the existing site or building (Muther and Hales, 2015). See page 6-1 of Muther and Hales (2015) to understand more on the flow diagram.

Since this is a redesign of an existing manufacturing facility, it was appropriate to use the floor plan view of the 3D digital twin visual tool as a guide to create the diagram. The current layout flow diagram is shown in figure 21. The new proposed flow diagram can be seen in figure 22.

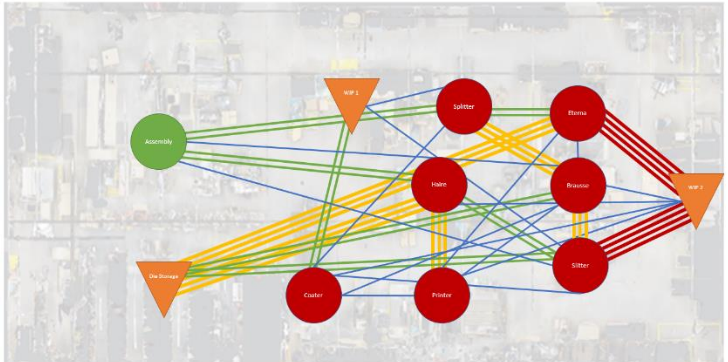

Figure 21. Current flow diagram.

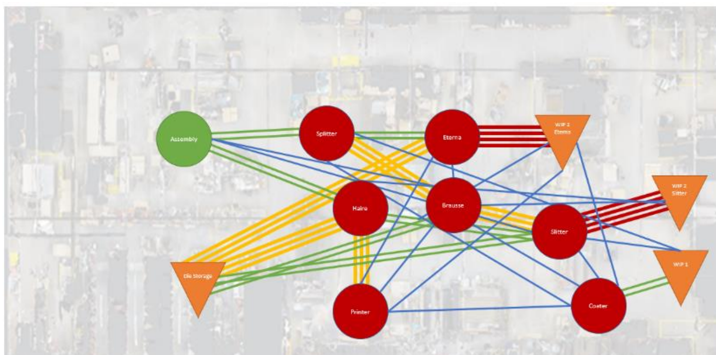

Figure 22. Proposed flow diagram.

Space

Activities Area and Features Sheet

The activities area and features sheet allows the planner to summarize the space amounts for each activity, all the appropriate features and shapes required. See page 7-16 in Muther and Hales (2015) to learn more about the activities area and features sheet.

The 3D digital twin visual tool was used to make the required measurements and identify the physical features. The completed activities area and features sheet is shown in table 9.

Table 9. Activities area and features sheet.

Activities Area and Features Sheet			Physical Features				
			Water & Drains	Compressed Air	Fire Hazard	Ventilation	Special Electric
Activity			Relative Importance of Features A = Absolutely Necessary E = Especially Important I = Important O = Ordinary Importance - = Not Required				
Name	Area *(sq. m.)*	Overhead Clearance *(m.)*					
Die Storage	(8.5 x 12.0) **102**	4.5	-	-	-	-	-
Assembly	(16.5 x 19.5) **322**	4.5	-	A	I	-	I
Coater	(4.0 x 13.5) **52**	4.5	A	-	-	A	I
WIP 1	(6.0 x 12.0) **72**	4.5	-	-	-	-	-
Printer	(6.5 x 14.5) **95**	4.5	-	E	-	-	A
Haire	(4.0 x 10.5) **42**	4.5	-	E	-	-	I
Slitter	(5.5 x 7.5) **42**	4.5	-	-	-	-	I
Splitter	(5.0 x 8.0) **40**	4.5	-	-	-	-	-
Brausse	(3.5 x 10.5) **37**	4.5	-	-	-	-	I
Eterna	(6.5 x 10.5) **69**	4.5	-	A	-	-	I
WIP 2	(5.0 x 15.0)+(3.0 x 10.0) **105**	4.5	-	-	-	-	-

Space Relationship Diagram

The space relationship diagram is essentially a replica of the flow diagram. The only difference is that the space relationship diagram includes the space of the actual area required for each activity area. Refer to page 8-1 in Muther and Hales (2015) to learn more about the space relationship diagram.

The 3D point cloud visual tool was edited in Recap to remove all the activity areas while keeping critical physical features such as walls, pillars, and ceiling lights. The point cloud was then opened in Inventor, and the required space of the activity areas was positioned in the facility relative to the flow diagram, avoiding interference with the physical features. A screenshot of the Inventor space layout was then used to add the flow relationship lines. The completed space relationship diagram is shown in figure 23.

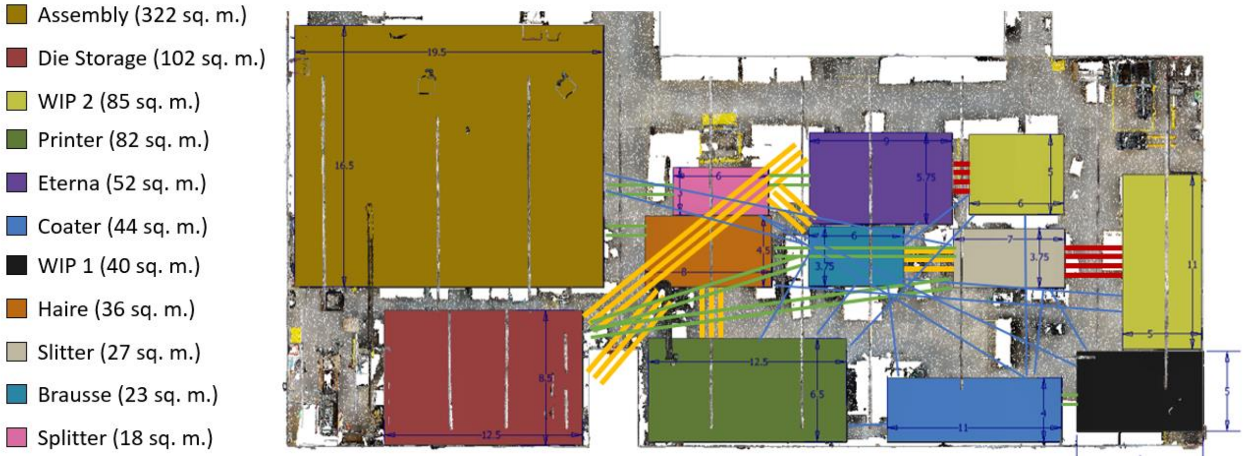

Figure 23. Space relationship diagram.

Adjustment

Layout Drawing

While creating layout drawing, the planner considers modifications and practical limitations to make adjustments. These considerations result in logical compromises for the arrangement of the layout (Muther and Hales, 2015).

Considerations were examined using the 3D digital twin, which included ceiling height, space availability, aisle location, width and congestion, safety, material handling, and available power. The Inventor file from the space relationship diagram was used, and the spaces of the activity areas were modified to create the new facility layout. The layout is shown in figure 24.

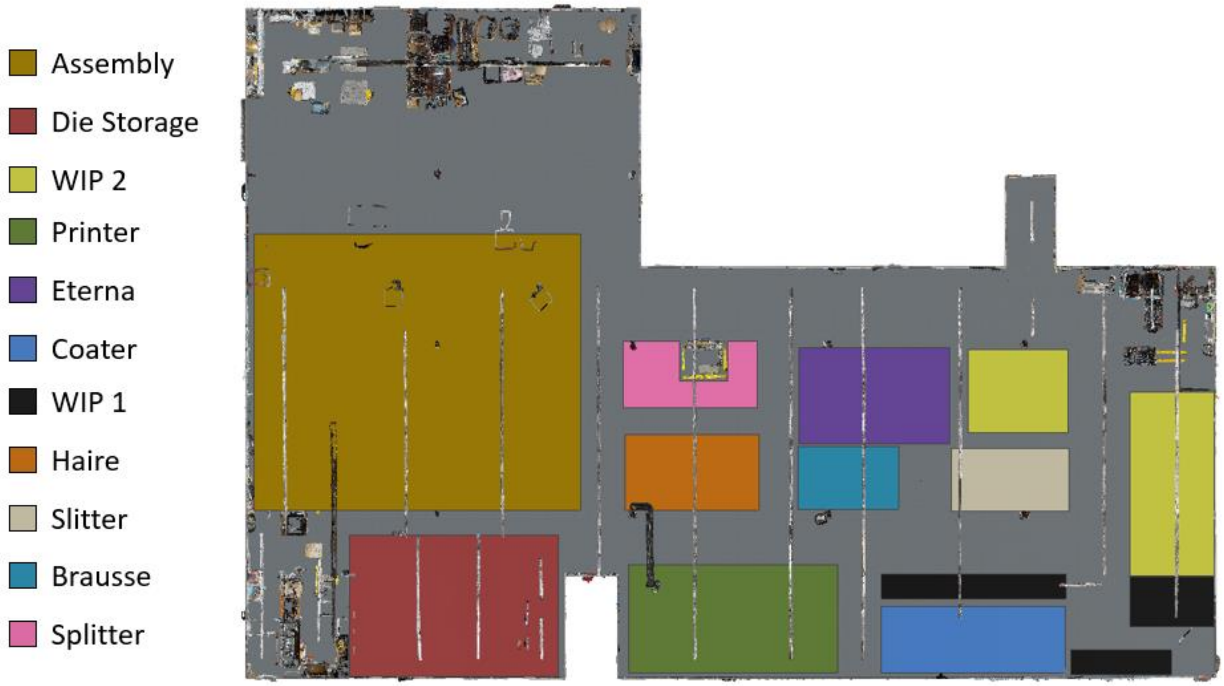

Figure 24. General overall facility layout.

Models and Renderings

Models and renderings are often used as enhanced visualization tools for improved understanding of the given layout design. Their use is dependent on the nature of the layout and the equipment being planned, the budget, tools, time and skills available, and the desire to involve operators and supervisors to review the layout plans (Muther and Hales, 2015).

In this step, the measurement tool of the digital twin was used to measure the maximum height of the activity areas. The Inventor file from the layout was altered by extruding each activity area to the maximum height measured in the digital twin. The model of the general overall layout is shown in figure 25.

To create a more detailed version of the general overall layout model, Recap was used to filter the point cloud data to only the points within each activity area. This was done for each activity area. An example of a filtered activity area is shown in figure 26. The filtered activity areas files were then imported and positioned into the general overall layout file while the colored blocks were removed. Different views of the detailed general overall layout can be seen in figures 27, 28, and 29.

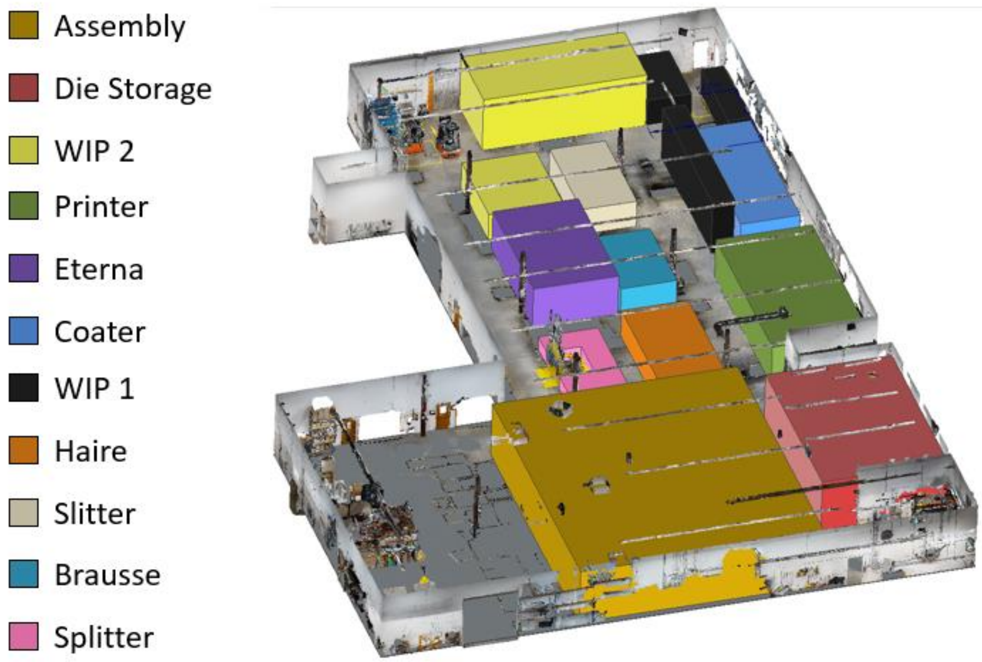

Figure 25. 3D block layout model of the general overall facility layout.

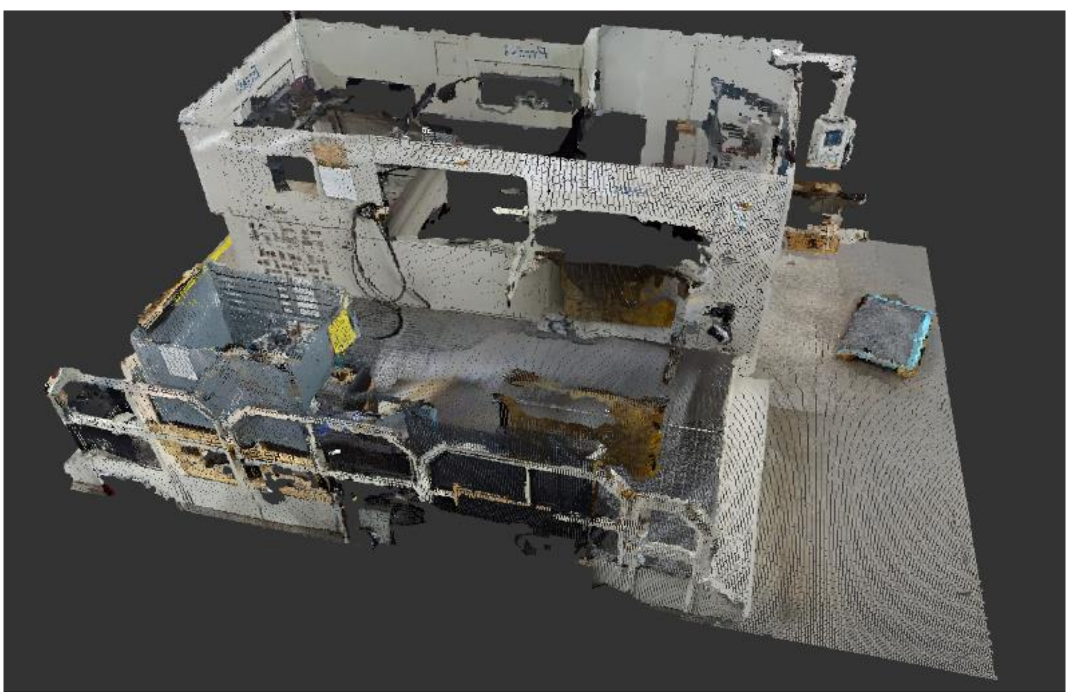

Figure 26. Filtered point cloud of an activity area.

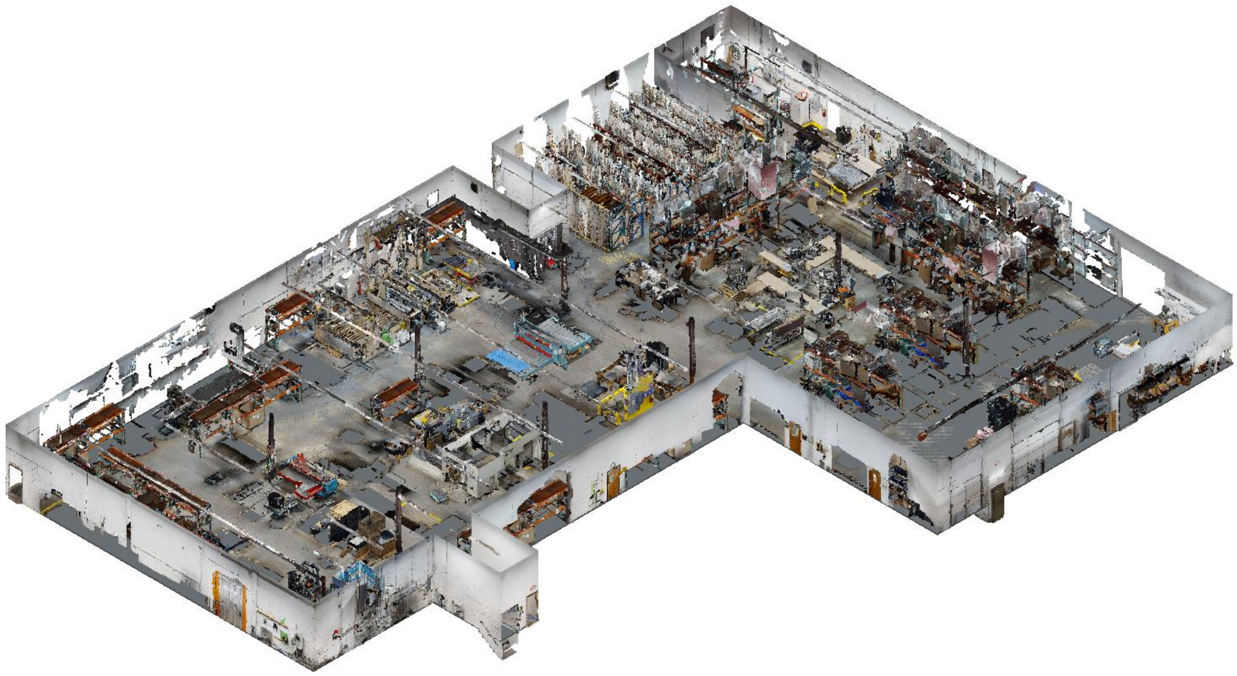

Figure 27. Detailed 3D model of general overall facility layout isometric view.

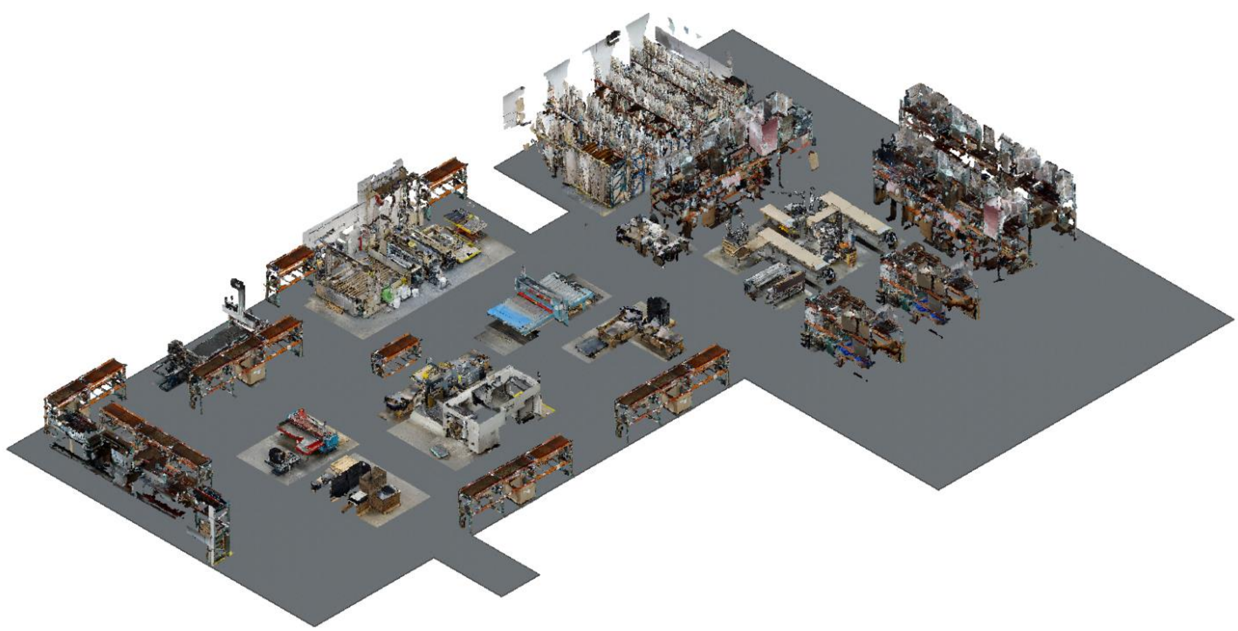

Figure 28. Detailed 3D model of the general overall layout with filtered and suppressed point cloud data.

Figure 29. Detailed 3D model of the general overall layout zoomed-in view.

Evaluation

In this simplified version of SLP, only one layout and respective model were created for the redesign of the facility layout. Therefore there was no evaluation of the layouts.

Chapter 7
Discussion

7.1 Research Question 1

What is the state-of-the-art for the use of 3D scanning for manufacturing facility layouts?

This question was designed to investigate and understand the latest research on the scoped down topic. The problem was addressed using a literature review, and a recap of the findings are listed below.

The use of 3D scanning for manufacturing facility layout design is a relatively new area of research. Consequently, almost all the research articles come from a group of researchers at Chalmers University.

The research results suggest that 3D scanning is a valuable tool for facility layout design. It makes for a powerful visualization tool that increases verification and reduces risks and time.

One significant gap identified in all the research articles was that the design of the facility layout was focused on the detailed layout. The articles focused on a production system or work cell and not the general overall layout of the facility.

Another obvious gap recognized in the articles was that laser scanning is the dominant 3D scanning type used for facility layout design.

To get a full understanding of the state-of-art for the use of 3D scanning for manufacturing facility layouts, see chapter 4.

7.2 Research Question 2

How do 3D scanning types, photogrammetry and structured light compare when used for manufacturing facility layouts?

Research question 2 was aimed at highlighting the pros and cons of each scanning type and the respective 3D visuals produced based on certain performance metrics. The objective of this question was to understand which scanning type is better suited for creating a 3D visual tool of a manufacturing facility layout. This question was addressed in the experiment, where both scan types were used to create a 3D visualization tool of the manufacturing facility. Since this thesis comes from an operations management perspective, the comparison of the 3D scanning types and their respective 3D visuals are based on performance metrics assumed to be critical to an operations manager using the technology. According to Stevenson (2012), the operations manager's daily concern include cost, quality, and time. Thus, the performance metrics chosen included cost, scan time, processing time, quality, and user experience.

In terms of costs to create a visual tool, structured light was more costly compared to photogrammetry. The overall cost of structured light was $3961.98, while photogrammetry was $463.36. The major difference was the price of the structured light camera, which cost $3645.39.

The amount of time needed to scan the facility was faster using photogrammetry. Photogrammetry took 22 minutes, while structured light took 2 hours and 54 minutes. The main reason why photogrammetry was faster is because the facility was captured on-the-go using continuous video. Had stationary photos been taken for photogrammetry, the time would have been much longer. Alternatively, structured light was scanned from 155 different stationary scanning locations.

The time it took to process the scanned data, structured light was faster than photogrammetry. Structured light took 5 hours and 16 minutes to create a model. The structured light processing was completely hands-off. The scanned data was sent to the cloud through the phone app to process, and when complete, an email notification was received. On the other hand, photogrammetry took days, around 120 hours, to figure out the software settings and process the scanned data.

Regarding the visual quality of the visual tools produced, structured light was better. The visual tool output of structured light scanning included a point cloud, meshed surface, and digital twin. The structured light visual tools were made without fault and were very detailed. The overall quality of the structured light visual tools was rated as very good. The visual tool output of photogrammetry included point cloud and meshed surface. These models had faults, including missing points and alignment problems in the point cloud and low-quality meshing in the meshed surface. The overall quality of the photogrammetry visual tools was rated as fair.

The user experience rated the overall experience of scanning and processing each 3D scanning type. The better user experience went to structured light. For structured light, the scanning experience was rated very good. Scanning with structured light was straightforward. All that was needed to be done was press the scan button on the phone app to start the scan, and when the scan was complete, the visible results of the scan would show up instantly on the phone app. This allowed the scanner to see what had been scanned. That helped knowing if any visual data was missed and identified possible locations for the next scan, which made the process of scanning very user friendly. The user experience of processing the structured light data was rated excellent. That was because the process was completely hands-off. The scanned data was sent to the cloud through the phone app to process, and when complete, an email notification was received. For photogrammetry, the scanning user experience was rated very good. Although two separate scanning attempts were needed to get a quality model, the process of scanning was efficient. The only downside was that there was no ability to see what has been scanned until the data was processed. Photogrammetry processing was rated as fair. This was because days were spent trying to figure out the correct settings to produce a quality point cloud file and meshed surface. Each time the settings were changed, the software would need to reprocess the data, which took around four hours on average. It was a lot of trial and error.

Overall, structured light was the better solution for the use of 3D scanning for manufacturing facility layouts. It was more user-friendly, faster to process, and output more 3D visual tools with better overall visual quality.

7.3 Research Question 3

How does a 3D scanned visual tool support the process of the SLP pattern of procedures?

This question is intended to uncover the effectiveness of using 3D scanned visual tools in a simplified version SLP pattern of procedures. The SLP pattern of procedures used was based on documents that were assumed to be exploited by a visual tool. The simplified version of the SLP pattern of procedures can be seen in table 5 in section 5.3.1. The objective was to highlight the value-adding capabilities and support of the visual tools.

A 3D visual tool was not used in the activities step because it was assumed that the documents in that step could not be exploited by a visual tool. However, a floor plan view of the digital twin visual tool was used as a detailed floor plan to identify the locations of the already known activity areas. The point cloud could have also been used here, and it would have been just as detailed.

In the relationships step, the digital twin visual tool was used for the present flow diagram, from-to-chart, and flow diagram.

In the present flow diagram, the same floor plan view was used to draw the current flow of materials based on recorded video data. The present flow diagram can be seen in figure 20 in section 6.2.1. The highly detailed digital twin floor plan view made it easy to identify all the features from the recorded video and allowed for accurate material paths.

For the from-to-chart, the digital twin was used in the flow analysis to measure the distance between the activity areas. The measurement tool in the digital twin made for accurate and quick measurements. Had the measurements been made manually, it can be assumed it would have taken longer, and the accuracy of the measurements would come into question. Measurements could have also been made using the point cloud; the author arbitrarily chose the digital twin.

The flow diagram was created using the digital twin floor plan view as a guide to create the diagram. In this case, an existing facility was used, and according to Muther and Hales (2015), it is practical to diagram directly on the floor plan of and existing building when there is no possibility of changing the building features. Having the floor plan view of the digital twin helped identify and consider building features such as pillars, doors, and walls when creating the flow diagram.

In the space step, the digital twin visual tool was used for the activities area and features sheet, and the point cloud was used for the space relationship diagram.

For the activities area and features sheet, the digital twin measurement tool was used to measure the area and height of each activity area, and the 360-degree HD images were used to identify physical features in each activity area. Measuring each area was quick, easy, and accurate. No time was spent at the facility getting manual measurements. This was especially beneficial for height measurements, which would have needed a ladder. The 360-degree HD images allowed for quick navigation through the facility to identify features. Had this been a larger warehouse or factory, a lot of time would have been saved. Moreover, the images were incredibly sharp, detailed, and capable of zooming in to see fine details, which made it feel natural. Had the point cloud been used instead, the level of detail would have significantly diminished the more it zoomed in.

For the space relationships diagram, the point cloud was edited and used as a guide to create the diagram. The points from the current activity areas were filtered out, leaving just the building structure points. The filtered point cloud was then edited to include the new locations and required areas of the activity areas in 2D form. The flow lines were included after. The ability to modify and edit the point cloud was valuable to productivity and reduction of future problems. In terms of productivity, the visual tool files could be saved and easily edited to be used for other SLP steps, such as the layout. Regarding the reduction of future problems, the filtered and edited point cloud was used to recognize interferences and find out if the areas of the newly located activity areas would fit.

In the adjustments step, the digital twin was used to consider modifications and practical limitations to make adjustments, and the point cloud was used to adjust and create the layout and model.

Considerations were examined using the digital twin, and this required no time spent at the facility. In addition, the 360-degree HD images of the digital twin made for sound judgment during the consideration process.

Based on the considerations, the filtered and edited point cloud from the space relationship diagram file was adjusted to create the layout. The major adjustment shown in the layout was creating the aisles and determining their widths. When the layout was complete, a 3D model was made by extruding the areas of the activities to their required height. Lastly, a more detailed model was created by combining filtered point clouds of each activity area into their respective layout locations. The ability to filter and edit the point cloud expedites the layout design process. The layouts and models created also provided exceptional visual understanding.

In general, 3D scanned visual tools can be used as support to the documents used throughout the SLP pattern of procedures. The visual tools improve productivity by expediting the layout planning and design time, increase visual understanding and judgment through realistic data, and reduce future problems through accurate data.

7.4 Research Validity

This thesis was based on both qualitative and quantitative research methods. When dealing with qualitative research, it needs to be credible, dependable, confirmable, and transferable (Lincoln and Guba, 2004). The credibility of this research, which considers that the results are true, credible, and believable, can be considered average. The research was done using sound research methods; however, it was done by one researcher so there could be some potential bias. The dependability, which ensures the findings are repeatable within the same context, can be assumed to be low. This research is impossible to replicate identically, plus the users of the technology and software have different backgrounds and experiences. The confirmability, which considers the confidence that the results would be confirmed or supported by other researchers, can be considered average. This could possibly be assessed by looking at the documentation and the results to see if the data correlates using sensible reasoning. The transferability, which considers the degree to which the results can be transferred to other contexts or settings can be considered high. Findings from the literature review have shown that results can be transferable, so this should be appropriate for this research.

7.5 Limitations

The author who scanned and processed the 3D data was new to both photogrammetry and structured light scanning and had no prior experience using the technologies. As a result, there was a learning curve with the scanning setup and software used. If an expert or someone with previous experience were to have scanned and processed the data, the results might have been much different.

The qualitative results and ratings were based on the author’s beginner experience. Had an expert opinion been used, the qualitative results and rating would have been more verified.

The thesis was self-funded, so there were limitations on the 3D scanning technology used based on costs. Had there been no budget set by the author, different scanning cameras and equipment may have been used, providing better results.

Based on the search categories provided for the literature review, almost all the research articles came from a group of researchers at Chalmers University. Gathering information from this one source could potentially provide information bias.

Chapter 8
Conclusion

8.1 Conclusion

A literature review assessed previous research on the use of 3D scanning for manufacturing facility layout designs. The results discovered laser scanning as the most used type of 3D scanning, and when used for facility layouts, the research was more focused on the detailed layout and not the general overall layout.

The thesis then compared structured light and photogrammetry scanning processes and visual tools based on performance metrics assumed to be useful to an operations manager using the technology for manufacturing layouts. The results suggest both types can create comprehensive visual tools however structured light was deemed the better overall solution because it is more user-friendly, faster to process, and outputs more 3D visual tools with better overall visual quality

The structured light visual tools were used in a simplified version of the SLP pattern of procedures to create a new general overall layout. The results indicate that the visual tools support the SLP pattern of procedures and improve productivity by expediting the layout planning and design time, increase visual understanding and judgment through realistic data, and reduce future problems through accurate data

The objective of this thesis was to understand the capabilities of 3D scanning and how the respective visual tools could be used to support manufacturing layout redesigns using the SLP pattern of procedures. The goal was to improve the layout design process for an operations manager by reducing the overall time and increasing visual understanding and quality of the layout design and analyses. Based on the thesis findings, it is apparent that both the objective and goal of this thesis were attained.

8.2 Further Research

The case study of this thesis was based on a small manufacturing company. Further cases would provide a more extensive data set to verify the use of 3D scanning for the support of manufacturing facility layout using the SLP pattern of procedures.

Another aspect that can be looked at further is researching when it is best to implement 3D scanning for manufacturing facility layouts using the SLP pattern of procedures. There are many different phases and steps in SLP, and understanding when it is best to implement 3D scanning could potentially save time and costs.

Testing the applicability of 3D scanned data with other digital technologies to improve layout design such as simulation, indoor positioning systems, augmented reality, and virtual reality is a broad area of research that should be looked at as well.

Lastly, from a technology perspective, the use of digital 3D technology and software is growing. Continuous research on the new 3D scanning technologies and software is needed to understand their capabilities and applicability for manufacturing facility layouts.

Appendix A

A.1 General Overall Layout Documents

Table 10. Documents used in the general overall layout (Muther and Hales, 2015).

Pattern of Procedures	Key Document(s); Must do	Other Potentially Useful Documents; Do if helpful	Form of Output
1. Activities	P-Q Analysis	P-Q Data Sheet Checklist of splitting or combining factors	List of Activity Areas
2. Relationships	Relationship Chart	Operation Process Chart Multi-product Process Chart From-To Chart Relationship Survey	Activity Relationship or Flow Diagram
3. Space	Activity Areas and Features Sheet	Survey of current space assigned Machinery & Equipment Area & Features Sheet Office Layout Requirements Data Space Requirements Converting form	Space Relationship Diagram
4. Adjustment	Block Layout Drawings	Scaled and grid-lined templates of activity areas	Alternative Layouts
5. Evaluation	Evaluation of Alternatives	Cost estimates and comparisons	Selected Overall Layout

A.2 Detailed Layout Documents

Table 11. Documents used in the detailed layout procedures (Muther and Hales, 2015).

Pattern of Procedures	Key Document(s); Must do	Other Potentially Useful Documents; Do if helpful	Form of Output
1. Activities	P-Q Analysis	Operation process chart Flow process chart Line balance Multi-product process chart	List of Activity Areas
2. Relationships	Relationship Chart	Line-feeding flow chart	Activity Relationship or Flow Diagram
3. Space	Activity Areas and Features Sheet	Machinery & Equipment Area & Features Sheet Office Layout Requirements Data	Space Relationship Diagram
4. Adjustment	Detailed Layout Drawings	Scaled equipment templates Models and renderings Elevation drawings	Alternative Layouts
5. Evaluation	Evaluation of Alternatives	Cost estimates and comparisons	Selected Overall Layout

Appendix B

B.1 Photogrammetry Scanning Apparatus

Figure 30. Photogrammetry scanning apparatus.

Appendix C

C.1 Wyze Camera Perspectives

Figure 31. Wyze cam perspectives.

Bibliography

AUTODESK. 2020a. *3DS Max* [Online]. Available: https://www.autodesk.com/products/3ds-max/overview?support=ADVANCED&plc=3DSMAX&term=1-YEAR&quantity=1 [Accessed].

AUTODESK. 2020b. *Inventor* [Online]. Available: https://www.autodesk.com/products/inventor/overview?plc=INVPROSA&term=1-YEAR&support=ADVANCED&quantity=1 [Accessed].

BERGLUND, J., GONG, L., SUNDSTRÖM, H. & JOHANSSON, B. 2017. Adaptation of High-Variant Automotive Production System Using a Collaborative Approach. *In:* GRÖSSER, S. N., REYES-LECUONA, A. & GRANHOLM, G. (eds.) *Dynamics of Long-Life Assets: From Technology Adaptation to Upgrading the Business Model.* Cham: Springer International Publishing.

BERGLUND, J., LINDSKOG, E., JOHANSSON, B. & VALLHAGEN, J. Using 3D laser scanning to support discrete event simulation of production systems: lessons learned. Proceedings of the Winter Simulation Conference 2014, 7-10 Dec. 2014 2014. 2990-2999.

BIESINGER, F., MEIKE, D., KRAS, B. & WEYRICH, M. 2018. *A Case Study for a Digital Twin of Body-in-White Production Systems General Concept for Automated Updating of Planning Projects in the Digital Factory*.

COFFTA, M. 2015. *Literature Review* [Online]. Scribbr. Available: https://guides.library.bloomu.edu/litreview [Accessed].

EBRAHIM, M. 2014. 3D LASER SCANNERS: HISTORY, APPLICATIONS, AND FUTURE.

ERIKSSON, A., SEDELIUS, E., BERGLUND, J. & JOHANSSON, B. 2018. Virtual factory layouts from 3D laser scanning – A novel framework to define solid model requirements. *Procedia CIRP,* 76**,** 36-41.

GONG, L., BERGLUND, J., FAST-BERGLUND, Å., JOHANSSON, B., WANG, Z. & BÖRJESSON, T. 2019. Development of virtual reality support to factory layout planning. *International Journal on Interactive Design and Manufacturing (IJIDeM),* 13**,** 935-945.

HERAGU, S. S. 2008. *Facilities Design,* Boca Raton, Fla, CRC Press.

KÄHKÖNEN, A.-K. 2011. Conducting a Case Study in Supply Management. *Operations and Supply Chain Management: An International Journal,* 4**,** 31-41.

LI, J., BERGLUND, J., AURIS, F., HANNA, A., VALLHAGEN, J. & ÅKESSON, K. 2018. *Evaluation of Photogrammetry for Use in Industrial Production Systems*.

LIBERATI, A., ALTMAN, D. G., TETZLAFF, J., MULROW, C., GØTZSCHE, P. C., IOANNIDIS, J. P. A., CLARKE, M., DEVEREAUX, P. J., KLEIJNEN, J. & MOHER, D. 2009. The PRISMA Statement for Reporting Systematic Reviews and Meta-Analyses of Studies That Evaluate Health Care Interventions: Explanation and Elaboration. *PLOS Medicine,* 6**,** e1000100.

LINCOLN, Y. & GUBA, E. 2004. But Is It Rigorous? Trustworthiness and Authenticity in Naturalistic Evaluation. *New Directions for Program Evaluation,* 1986**,** 73-84.

LINDSKOG, E., BERGLUND, J., VALLHAGEN, J. & JOHANSSON, B. 2013. Visualization Support for Virtual Redesign of Manufacturing Systems. *Procedia CIRP,* 7**,** 419-424.

LINDSKOG, E., BERGLUND, J., VALLHAGEN, J. & JOHANSSON, B. 2014. Lean Based Problem Solving Using 3D Laser Scanned Visualizations of Production Systems. *International Journal of Engineering Science and Innovative Technology (IJESIT),* 3**,** 556-565.

LINDSKOG, E., BERGLUND, J., VALLHAGEN, J. & JOHANSSON, B. 2016a. Layout planning and geometry analysis using 3D laser scanning in production system redesign. *6th Cirp Conference on Assembly Technologies and Systems (Cats),* 44**,** 126-131.

LINDSKOG, E., VALLHAGEN, J., BERGLUND, J. & JOHANSSON, B. 2016b. Improving lean design of production systems by visualization support. *Research and Innovation in Manufacturing: Key Enabling Technologies for the Factories of the Future - Proceedings of the 48th Cirp Conference on Manufacturing Systems,* 41**,** 602-607.

MARCOUX, N., RIOPEL, D. & LANGEVIN, A. 2005. Models and Methods for Facilities Layout Design from an Applicability to Real-World Perspective. *Logistics Systems: Design and Optimization.*

MÅRDBERG, P., FREDBY, J., ENGSTRÖM, K., LI, Y., BERGLUND, J., CARLSON, J. & VALLHAGEN, J. 2018. A novel tool for optimization and verification of layout and human logistics in digital factories. *Procedia CIRP,* 72**,** 545-550.

MUTHER, R. & HALES, L. 2015. *Systematic Layout Planning,* Marietta, GA, Management & Industrial Research Publications.

NÅFORS, D., BERGLUND, J., GONG, L., JOHANSSON, B., SANDBERG, T. & BIRBERG, J. 2020. Application of a Hybrid Digital Twin Concept for Factory Layout Planning. *Smart and Sustainable Manufacturing Systems,* 4**,** 20190033.

NÅFORS, D., LINDSKOG, E., BERGLUND, J., GONG, L., JOHANSSON, B. & VALLHAGEN, J. 2017. *Realistic virtual models for factory layout planning*.

NARAYAN, K. L., RAO, K. M. & SARCAR, M. M. M. 2008. *Computer Aided Design and Manufacturing,* New Delhi, PHI Learning.

PÉREZ, L., RODRÍGUEZ, Í., RODRÍGUEZ, N., USAMENTIAGA, R. & GARCÍA, D. 2016. Robot Guidance Using Machine Vision Techniques in Industrial Environments: A Comparative Review. *Sensors,* 16**,** 335.

STEPHENS, M. P. & PROJECT, M. 2019. *Manufacturing Facilities Design & Material Handling : Sixth Edition,* West Lafayette, Indiana, Purdue University Press.

STEVENSON, W. J. 2012. *Operations Management,* New York, McGraw-Hill/Irwin.

TAK, C. 2012. Improvement in Layout Design using SLP of a small size manufacturing unit: A case study. *IOSR Journal of Engineering,* 02**,** 01-07.

TAYLOR, D. 2020. *The Literature Review: A Few Tips On Conducting It* [Online]. Available: http://advice.writing.utoronto.ca/types-of-writing/literature-review/ [Accessed 7/20 2020].

TOMPKINS, J. A. 2010. *Facilities Planning,* Hoboken, N.J, J. Wiley.

VAHID, S. & WANG, S. 2019. Web-Based Visualization of 3D Factory Layout from Hybrid Modeling of CAD and Point Cloud on Virtual Globe DTX Solution. *Computer-Aided Design and Applications,* 16**,** 243-255.

VINZ, S. 2015. *Developing your theoretical framework* [Online]. Available: https://www.scribbr.com/dissertation/theoretical-framework/ [Accessed 7/20 2020].

YIN, R. K. 2003. *Applications of Case Study Research*, Sage Publications.

YOON, S.-H. 2006. *A Surface Displaced from a Manifold*.