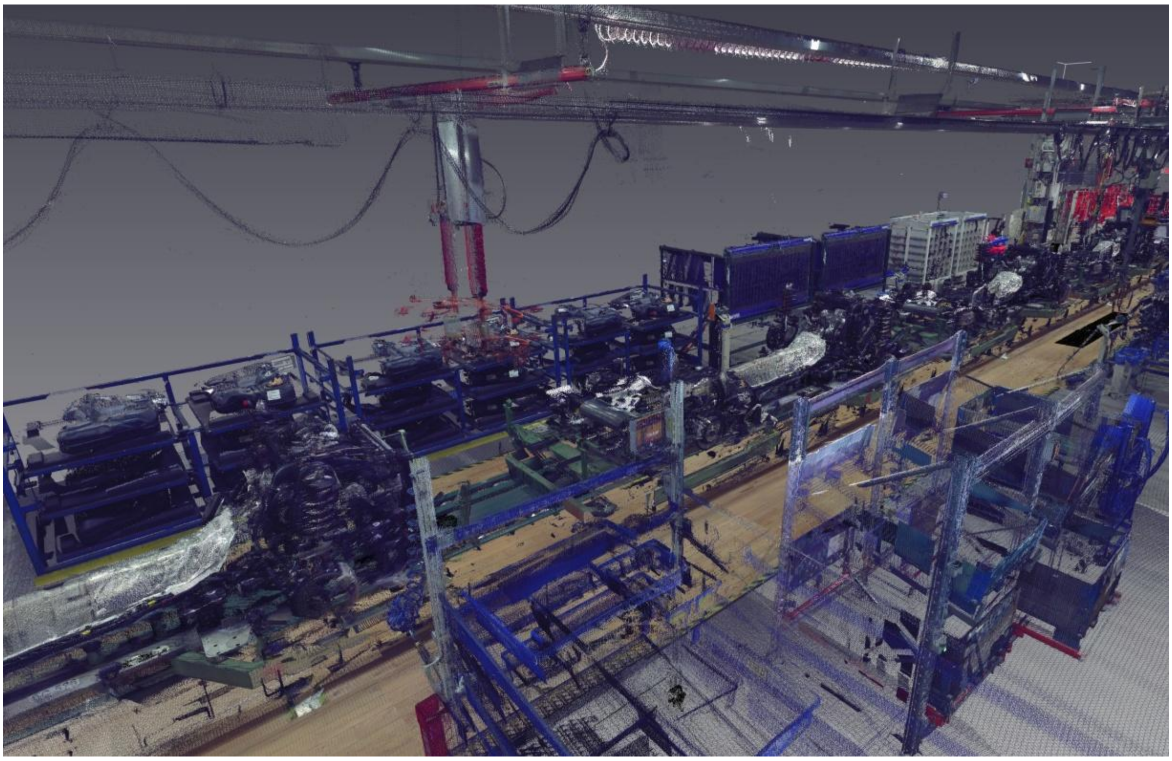

MP&L and layout design in Volvo Cars assembly shop supported by 3D laser scanning technology

Master of Science Thesis in the Master Degree Program, Production engineering

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MASTER'S THESIS 2011

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Davide Gorrasi, Milano, June 2011 Xiayang Diao, Göteborg, June 2011

Abstract

Faced with increasing global competition, almost all automobile manufacturers are struggling to improve their efficiency and enhance competitiveness.

The two major tasks of an automobile manufacturer are product development and corresponding manufacturing development, through which cars and processes are designed. After implementing the results of the design in plant, the finished cars can be delivered to the customers.

The changing market demands exert tremendous pressure on the companies. In order to meet market needs and maintain competitiveness, companies are obliged to increase product types so that they can fit more segments of customers' requirements. Accordingly, the production volume is changing over time, both in total volume and in volume of specific product type. In light of product and production development, it is very challenging for every car manufacturer to react rapidly to the market change and at the same time keep costs low.

Material Planning and Logistics (MP&L) together with layout development play critical roles in the definition of the manufacturing system. They go hand in hand with process development, industrial implementation and production planning. To avoid becoming a bottleneck in the production development system, there is a pressing need to improve MP&L and layout development.

The purpose of this thesis work is to study 3D laser scanning technology and to look into Volvo's current MP&L and layout development process, in order to figure out how this technology can effectively support the MP&L and layout design process. 3D laser scanning is a relatively new technology with numerous advantages, allowing for various valuable applications in industry. Exploiting this technology in MP&L process and layout design could yield great advantages.

The study starts with the mapping of Volvo's current working procedure, formulating problems that might be improved by 3D scanning, and then through several practical cases the functions this tool could have in MP&L and layout development will be demonstrated and discussed. These cases include building a virtual work station for the future, analyzing the capacity of engine/gearbox temporary storage area and demonstrating the possibilities of using 3D scanning data to find solutions to MP&L and layout problems, which could additionally provide suggestions for the product/process development in early project stages.

Keywords: MP&L and layout design, 3D laser scanning, Pointools, Concurrent Engineering, GPDS, sequencing, VBE, work station.

Abbreviations

MP&L	Material planning and Logistics
VCT	Volvo Car Torslanda
GPDS	Global product development system
CAD	Computer aided design
TSA	Temporary storage area
SA	Sequencing area
GB	Gearbox
ER	Engine rack
GBR	Gearbox rack
FSE	Full sequencing of engines
FSGB	Full sequencing of gearboxes
SSE	Shared sequencing of engines
SSGB	Shared sequencing of gearboxes

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1. Introduction

Due to the falling of trade barrier and the decline of transaction costs, the global competition in automobile industry continuously increases [1]. Same as all automobile manufacturers, Volvo Cars Corporation is struggling to enhance its performance in product development and manufacturing by innovating and adopting improvements and new technologies. Among these there is 3D laser scanning technology, which can be implemented for the purpose of Material Planning and Logistics (MP&L) and layout design.

1.1. Project Background

Volvo Cars Corporation is a Swedish automobile manufacturer founded in 1927, in Gothenburg, Sweden and has its products sold in over one hundred countries. Volvo produces a wide range of automobiles from sedans, wagons, coupes to crossovers.

In year 2010 the number of cars produced by Volvo amounted to 387,802 units in total. Compared with the production volume of 311,413 units in year 2009 there was a tremendous increase, as it is shown in figure 1.1. And this trend will keep going in the next years.

Car production by model and plant 2010, no. of cars

	Gothenburg	Uddevalla	Ghent	Chongqing	Thailand	Malaysia	**Total**
S40	—	—	22,779	5,509	—	378	28,666
S60	—	—	27,579	—	—	—	27,579
S80	16,803	—	—	—	531	120	17,454
S80L	—	—	—	11,495	—	—	11,495
V50	—	—	53,982	—	—	320	54,302
V60	13,404	—	—	—	—	—	13,404
V70	48,585	—	—	—	—	—	48,585
XC60	—	—	83,529	—	—	141	83,670
XC70	21,156	—	—	—	—	—	21,156
XC90	36,375	—	—	—	240	96	36,711
C30	—	—	35,248	—	—	—	35,248
C70	—	9,532	—	—	—	—	9,532
Total	**136,323**	**9,532**	**223,117**	**17,004**	**771**	**1,055**	**387,802**

(Production 2009: 311,413 cars)

Figure 1.1 Production volumes in year 2010 [2]

This project is carried out in one of the main Volvo plants, i.e. Torslanda plant, in Gothenburg. The plant will face a big challenge due to the future increase in the production volume (figure 1.2). Focal area of this project is the assembly shop. Different from some other automobile manufacturing companies, Volvo assemblies various models of car within the same plant using the same assembly line. For each car model there is even a series of variants to meet different market needs. Thus a single plant has to handle different car models satisfying the target production volume.

Moreover, there are frequent needs to modify the assembly line in small scale to adapt partial product changes, such as introducing new components and winding down old variants. These modifications may include rearrange work stations, adding new work stations, adjusting material façade, or modifying material handling methods, and they are all performed on a running production system. Every time a modification occurs, it has to be very well planned in order to avoid disruptions in the production flow. From this point of view how to manipulate these modifications in very limited space with lowest cost and highest efficiency is a critical problem.

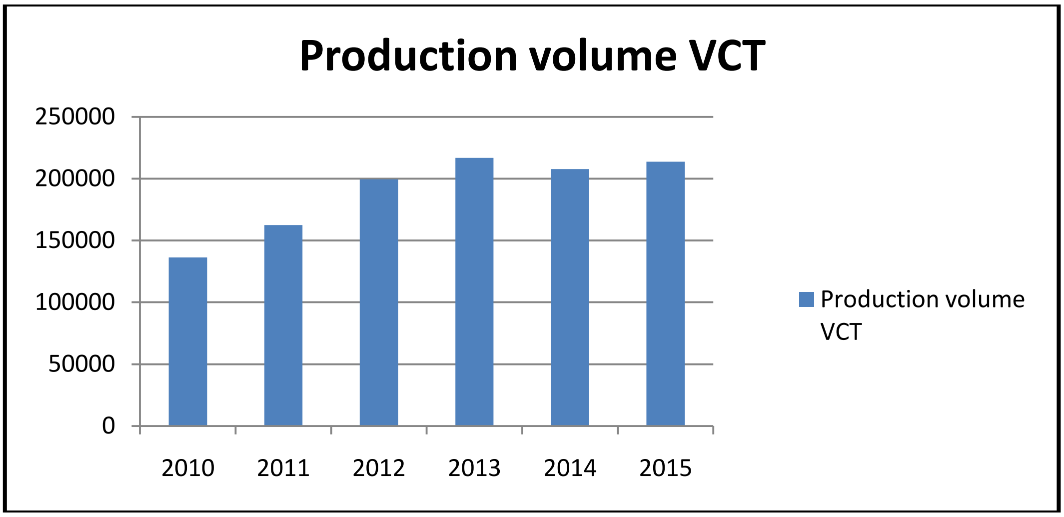

Figure 1.2 Production volume forecasting

Modeling assembly shop could bring about major contribution in enhancing the planning activity, but conventional CAD software requires a very heavy workload. The company sees the constraint on its current MP&L and layout development process and deems 3D laser scanning technology as an opportunity to break down this obstacle.

The engine/gearbox storage area aside the beginning of PP line 1 (Figure 1.3) is a critical region that faces tremendous difficulties meeting future production requirements. Utilizing 3D laser scanning to investigate upon this area is the starting point to understand how it can be exploited for further applications in the field of MP&L and layout design.

1.2. Aim and objectives

The purpose of the thesis is to examine the potential of 3D laser scanning as a tool to support MP&L and layout development. The question which is going to be answered is whether it is possible to provide MP&L and layout development with more concrete design activities. The benefits and methods of applying this technology will also be evaluated. To achieve these goals the following objectives are set:

- Map Volvo's current MP&L and layout development procedure.
- Study and master 3D laser scanning technology, which includes scanning operations and data processing.
- Find weaknesses in MP&L and layout development in Volvo and define focal points of improvement that can be supported by 3D laser scanning.

- Implement 3D scanning in case study of engine/gearbox temporary storage area proposed by the company.
- Find applications to model future working activities and methods based on 3D scanning technology in MP&L and layout development.

1.3. Delimitations

- The whole assembly line in Volvo Torslanda can be divided into three areas as Pre-trim, Trim and Final according to process characteristics. To narrow the scope, the area of investigation is defined as a part of the Pre-trim process area, which starts from the engine/gearbox buffer aside the PP line1 (Figure 1.3) to the station where finished underbodies are ready for marriage with the upperbodies.
- In the study of engine/gearbox temporary storage area, data of future scenarios is developed based on data of present production and forecasting through an algorithm, which may result in deviation to real situation.
- The focus of case study in Pallet line is on the MP&L design activity. The study is used as an example to demonstrate the possible future MP&L design work supported by 3D scanning. Assembly operations and product specifications are not considered in details.

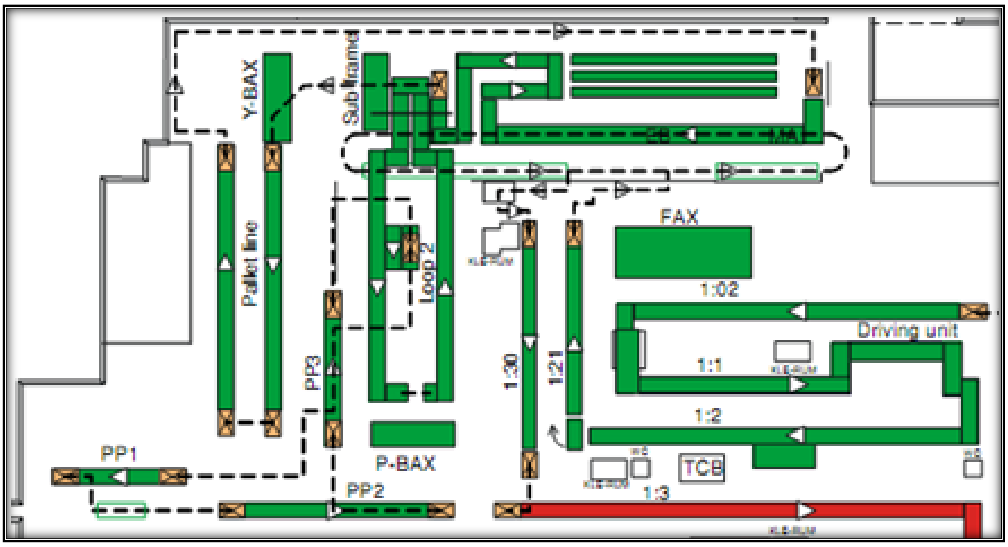

Figure 1.3 Layout of pre-trim line in assembly shop

2. Theory

2.1. Concurrent engineering

The Concurrent Engineering method is a project management system, which is now applied by more and more companies to achieve efficient development procedure. This methodology aims at making as many design and development processes as possible work parallel. And those design and development processes could mainly be divided into two categories, as product development and manufacturing process development [3].

Product development is to create product design with new or different characteristics offering new or additional benefits to the customer. It may involve modification of an existing product, or formulation of an entirely new product. Main tasks within this scope could be material selection, engineering design and verification, cost evaluation. On the other hand, production development involves all the activities from design, planning and verification works to physical industrialization down in the plant. The design and planning works will give out complete and applicable instructions to every piece of real production to be implemented.

Each of product development and manufacturing development may contain numbers of sub processes of development. For example, for a complex product each functional subsystem, such as power system and cooling system, can be developed parallel, and development of manufacturing related technologies, logistics, material dispatching, plant design can be implement as concurrent approaches as well. According to the traditional sequential project development way, the manufacturing related developments can start only when the product development is almost completed and the specifications of the product are clearly defined, which implies the need of a quite long development cycle. Chances are product engineers lack thorough understanding of manufacturing technology, equipment and facilities, so that in product development the underlying limitations from manufacturing side are not well considered. When production engineers start to work on process design, machine selection, and facility arrangement and so on, problems emerge. Often happens that the available machine, facilities and technologies are not suitable for manufacturing new designed components. The companies have to either invest in new process technologies and equipment to adapt to the design, or ask product engineers to redesign the product. Either way will require an increase of developing time and expenses. Furthermore, it increases the difficulty of project controlling of companies, since when defining budget and time schedule they face too many uncertainties.

While in parallel development mode, along with the progress of product development, and with continuously deepening understanding of product, the design of the product details becomes finer and finer; accordingly, production related design also becomes more and more specific and concrete. Large amount of information flows among parallel development processes, and by cross-functional collaborating problems can be discovered and solved earlier. The cross-functional team [2] formed by personnel from various departments owns comprehensive knowledge over the entire project, which is critical to ensure a thorough understanding of a problem and an optimum solution taking into account all factors. On one hand, finding and solving problems in early stage greatly shorten the development time and reduce effort of rework. On the other hand, it can cut back cost substantially. The cost of design work without physical building in the plant can be considered as 'soft cost', which mainly composed by salaries paid for employees' physical and mental work. In contrast, the 'hard cost', which is the expenses of equipment, facilities, plant, material and the fee of their installation and handling, is much more expensive. Changes of these 'hardware' always cost a great amount of money and any changes resulted from a poor design work is a waste. By implementing concurrent design approach problems finding and solving are shifted to early stage to make an optimum design, and the problems and changes in physical industrialization phase are able to be confined to a very limited range, which are easy to control and solve with least effort and cost.

Apart from a well defined organization structure and highly efficient cross-functional teams, tools to enable efficient flow and sharing of information, and to aid fast and accurate product/production development are critical. The burgeoning computer science, software engineering and information technology offer many tools and solutions that can satisfy these purposes. Various databases create the base for rapid information saving, organization, managing and sharing. While virtual simulation provides many tools to achieve effective and efficient product/production design and verification.

In product design, individual parts can be designed by CAD tools in both 2D and 3D models, and all related information can be included in the virtual environment in which to set up product model, such as geometrical shape, form and position tolerances, machining precision, and materials [3]. Individual components can be further assembled in the virtual environment, forming the complete product models, in order to evaluate the final result. And for production development, the application of virtual simulation can be even more multifarious. Such as in process simulation, parametric design of most manufacturing technologies can be carried out in the virtual environment, and the processing results could be validated. Typical examples include casting, metal cutting, sheet metal forming, and assembly and so on [4]. And for a manufacturing environment where a great many activities take place as function of time, discrete event simulation could easily find the bottleneck of one production system, for instance the buffers where material easily accumulated, inefficient workstations, and material transportation consuming too much time. The design and simulation can be also implemented for robots and ergonomic matters. These virtual simulation methods cover almost all aspects of product design and production, with a lot of advantages as intuitive, easy to visualize and understand, accurate, and efficient, and these technologies are relatively mature.

The goal of virtual simulation is to closely simulate the real production as much as possible. The combination of computers, software applications and databases allows an extensive collaboration among different departments in a company, as well as sharing and processing information. The more comprehensive the design and verification in virtual environment, the fewer problems will occur in physical implementation, and accordingly the less time and costs needed for the development period of a product in its lifecycle.

Though there are so many advantages of virtual simulation, it is not applied in every piece of work. This may because of the constraints when it comes to specific tasks. For MP&L and layout planning and design, there are too many elements involved in the MP&L and layout systems. Usually there are enormous number of facilities and equipments, and the locations of them are discrete and complex. Thus to build up a comprehensive and accurate virtual model of MP&L and layout system with conventional CAD tools is very time consuming and costly. Moreover, MP&L changes frequently. It is difficult to keep the virtual model up-to-date.

So in today's manufacturing industry, there is still upgoing interest in developing new virtual simulation methods and effective data sharing methods, which can not only provide better solutions for specific problems but also can strongly support the Concurrent Engineering working logic. In the area of MP&L and layout development there is a demand of tools that can build up virtual models rapidly and can easily update the models according to changes in real environment.

2.2. Layout

Every time that a new car model is put into production or a modification to an existing model occurs, inevitably the manufacturing engineer has to deal with changes in the layout of the production facilities.

Layout is referred to the physical location of production resources, including facilities, machines, equipment and staff in the production operations. Any layout is built on the basis of an integration of process design, physical layout, inventory control, material handling, scheduling, routing, and dispatching [5]. All of these elements must be carefully integrated to reach the production objective as well as to support company strategies.

Production volumes and production mix are major parameters affecting the layout of a production plant. It is possible to identify four different kind of layout: fixed position layout, functional layout, cell layout and product layout [6]. In order to well understand the aim of this thesis it is worthy to better describe product layout.

When the volume is very high and the variety is low, product flow becomes an issue and a product layout is likely to be appropriate. Product layout is locating the transforming resources entirely for the convenience of the transformed resources. Each product follows a prearranged route in which the sequence of activities that are required matches the sequence in which the processes have been located. The transformed resources 'flow' along a 'line' of processes. The flow of products or information in product layout is clear, predictable and therefore relatively easy to control.

Automobile assembly is a typical example of product layout – almost all variants of the same model require the same sequence of processes. Even between different models a lot of assembly operations are possible to be shared. Every car-body moves on the same conveyor and operators assemble different items according to features selected by the final customer, who nowadays has the opportunity to “design” his own car choosing among an overwhelming number of variants.

This suggests that storage areas and material façade are a critical factor, in that to accommodate a large amount of materials requires a wise utilization of spaces. Thus besides the design of “hardware” equipment, such as conveyors, lifters and robotic assembly cells, a major issue is represented by the arrangement of “software” equipment, such as material façade, buffers, storage area and material handling equipment.

As the computer terminology suggests, “hardware” equipments are those which after being installed can’t be modified or replaced easily. This is because generally these equipments are expensive and call for the highest utilization possible. This kind of equipment can be used for several years for the production of different car models. “Software” equipments refer to those equipments which can be easily modified. Usually when a new car model has to be manufactured or a new item is introduced, the arrangement of this equipment is always revised and developed according to the new needs and to the physical constraints of the plant.

2.3. MP&L

An important role in supporting a productive system is played by logistic. Logistic deals with material, information and money flows [7]. The thesis deals with in-plant logistic and a major issue is represented by material flow.

Internal material supply denotes the set of activities taking place inside an assembly plant [8]. It is aimed at delivering components at every assembly station by planning and controlling the deliveries, taking decisions on material handling and packaging issues, defining the transportation system and arranging the storage areas. To better understand the relying rationale of this system it is worthy to discuss upon the following issues:
-Material feeding principles;
-Materials handling equipment;
-Storage areas and inventory;
-Packaging and unit load.

Material feeding deals with the way in which parts and components are presented to lines. It is possible to identify three different feeding strategies, namely continuous supply, batch supply and sequenced deliveries [8].

With continuous supply different parts of each part number are stored in racks, which are refilled by forklift, usually in large quantities. Such a methodology call for little effort in material handling operations, but on the other hand requires large amount of space for the storage of materials.

The need for a better utilization of spaces led to batch supply, according to which assembly stations are fed through lots of homogeneous components. Every time a shift to another product occurs, old components are removed in order to be replaced by the new ones. This approach implies an increase in material handling activities.

Situations characterized by a high number of variants can be addressed through sequenced deliveries, where parts and components are delivered according to the order they are to be assembled. This solution ensures low space consumption, but it is rather costly due to the extra handling operations required. This solution best fits those environments in which production speed is a critical issue. In this way operators do not waste time in sorting and picking operations and can focus on value added activities. This approach typically applies to automotive industry, where such parameters as takt time are of paramount importance.

Materials handling equipment includes the set of tools and facilities whose aim is supporting the handling activities. Two groups of material handling equipment can be identified: transportation equipment and loading and unloading equipment. The first group includes such equipment as forklifts, push carts, conveyors, pallet jacks, AGVs and all the equipment used to carry materials, while the second one includes cranes, lifts and hoists.

The transportation equipment can be classified according to three main criteria [9]. The first one is the movement system, i.e. the way in which moves are linked. It can be direct or indirect. In a direct system different materials move directly and separately from the origin to their destination. In an indirect system different materials share the same transport unit and move together to and from different areas. A further distinction can be made according to the distance and complexity of the material flow. Another important aspect of the material handling system is the transport unit, i.e. the form of material transported, which can be in bulk, in individual pieces or in containers. In this analysis the transport unit of greater interest is represented by containers.

Feeding lines with the right components is of paramount importance in order to avoid costly stoppages. Storage and inventory play a key role, in that they make manufacturing systems robust. By functioning as decoupling points, all the processes are made independent, so that a disruption in one of them doesn't result in an immediate stoppage of the whole manufacturing process. Main issues in defining storage areas are the definition of the storage equipment, which has to be compatible with the handling equipment, and the location of storage areas. Storage equipment can be classified as simple and static, such as simple racks, or complex and dynamic, such as automated storage and retrieval system [9]. Important drives in designing the storage system are costs. On one side material storage determines handling costs linked to the operations required every time that a material is stored or is removed. On the other hand the quantity of material held, the duration of the hold and carrying the inventory determine the holding cost. This cost is an estimated value which typically reflects the interest on money invested on the material stored and on the storage equipment, taxes, occupancy cost of storage facilities and obsolescence cost. Regarding the location of storage areas it is possible to identify three main categories [9]:
- Central storage or supermarkets, where materials are stored in one or few large areas. It allows a high level of inventory control, but, on the other hand, is characterized by a slow response time;

- In-line storage, it is decentralized since materials are stored between processing operations. It is widely used in assembly line and cellular manufacturing
- Continuous flow without storage represents the ideal solution, where material flows without being held. In practice a certain level of inventory is always requested.

Packaging and unit loads give an important contribution in making the supply system more efficient and reliable. Here packaging refers to the physical structure used to carry materials and it can include equipment such as containers, pallets or racks. Unit loads refer to the transport unit, i.e. the form of material transported, which can be in bulk, in individual pieces or in containers [9]. The packaging should be selected carefully in that it affects many areas, ranging from product protection to handling and storage efficiency, including also safety and ergonomic issues. As in many other areas, tradeoffs are to be taken into account in order to come up with the optimal solution. Important drives in the selection of the right packaging system are standardization, ability in ensuring a low number of handling activities, low space consumption, low work-in-process, and low number of travel required.

2.4. 3D laser scanning technology

Fundamental tool in this thesis is the 3D scanner. To better understand this technology and the process through which scans of real facilities are carried out a description of 3D scanning is presented.

2.4.1. Fundamental theory

The laser scanning technology is based on the use of laser-based ranging instrument that can measure distance to a high degree of accuracy. This measurement of distance is always based on the precise measurement of time, and can be carried out by using two main methods [10].

For the first method, the laser scanner sends out very short but intense pulses of laser radiation which travel from the scanner to the object being measured, and after being reflected the laser pulses return back to the instrument. The time of flight of the laser pulses are measured very accurately.

In the other method, the scanner sends a continuous laser beam instead of pulses. The emitted laser beam has a sinusoidal wave pattern. Therefore, by comparing the transmitted and received versions of the wave pattern of the beam and measuring the phase difference the range between scanner and object can be calculated.

2.4.2. Scanning instrument used in this project

In this project work the laser scanner (FARO Laser scanner) works based on the second principle. The technologies featured in this instrument make it a powerful tool in industrial applications.

Figure 2.1 FARO Laser scanner Focus^{3D}

In order to scan the entire surrounding space, the laser scanner features a mirror in the middle to deflect the laser beam in a vertical plane onto the same object and the scanner itself can revolve 360 degrees horizontally. Both the vertical angle and the horizontal angle are encoded simultaneously with the distance measurement. The distance, vertical angle and horizontal angle can make up a polar coordinate, which is then transformed to a Cartesian coordinate (x, y, z). The scanner also integrates a color camera featuring an automatic 30 megapixels parallax-free color overlay. The data collected is a "point cloud" which represents the surface of a scanned project or space. More specifications are shown in appendix A.

Based on these outstanding capabilities and performances there are generally three categories of application can be realized by this kind of laser scanner, namely documentation of indoor environments, documentation of outdoor environments and product and component documentation, which means it can quickly produce 3D models of buildings, building sites, roads as well as interiors and technical installations of the buildings such as building services, conveyors systems or process installations. For inspection of machine components, in product design, it measures products and components of every possible shape and size and produces precise data and 3D surface models from them.

2.4.3. Operation flow

1. Installing Coordinate system

Before starting to scan and collect data, the Scan Reference System used for coordinate setting should be installed in the focal areas in advance. This is because when scanning operations are distributed in a broad area, and even in one single area numbers of scans are carried out, to merge data of each scan position together a coordinate system which can be referred to is required.

2. Scanning

Firstly, according to the job requirements the scanning locations and the amount of scanning in the target area should be planned. The 3D laser scanning instrument utilized in this project needs about five minutes to finish one scan. Setting too many or too few scanning points without considering job requirements is inappropriate from both the economy and efficiency perspectives. In a certain area, the more scans taken in different positions, the more surfaces of objects will be covered by laser beam, that is, the more details of data can be acquired. Thus, the number of scans needed is based on the level of details of objects for specific application purpose.

After completion of the scanning position planning the scanning operations can be carried out in turn within each target region. Data is acquired and stored automatically in a memory card by the instrument. There are two types of data. One is high resolution photographs. At each scanning position the equipment will take hundreds of pictures within 360 degree. And the second data format is called point clouds which are clusters of point in 3D space that interpret the surfaces of objects. They can be imported into applications for further analysis and editing. The amount and density of scans mainly influence the level of details and point richness of point clouds.

3. Data processing

The operation of data can be different according to those two types of data. Point clouds data acquired at all scan positions is combined together as well to demonstrate the 3D structure of certain areas. The software used to handle this kind of data is called Pointools. This specific data format use '.pod' as postfix. After starting the software and importing Pod file it is possible to work on the point clouds data. As previously mentioned, data operations generally can be divided into three classes: observation, editing and analysis. In Pointools' virtual 3D environment, by moving around in different positions and changing perspectives, it is easy to observe the position, structure and relationship of objects within that space. Furthermore, the point clouds data can be edited, which is very similar to the use of CAD models. The main edit methods include selecting, copying, moving and rotating. Through flexible using of these methods new models can be created from existing elements. The operations could be simply copy point clouds of specific objects and put them in a separated layer. Then export them as Pod file to form an individual model. When all elements are ready, they can be imported as single Pod files in the same working environment in order to develop a new model.

Besides, software has several simple but handy tools to aid analysis work such as measurement tools, which can measure distance between two space points. The precision relies on factors such as object material and distance, and is usually in millimeter range. It can almost satisfy all sorts of work requirements.

The software supports various file formats. Most 2D CAD drawings and 3D CAD models of different format can be imported into the software. It makes the software more versatile to satisfy different job purposes by combining point clouds with these data formats.

Figure 2.2 Comparison between images of the same area in Webshare and Pointools

In addition, the software's build-in ‘snap shot’ function and animation function allow several ways to present data and analysis results intuitionally and conveniently.

Photographical data can be edited and stored in Faro Webshare, which is an internet-based database that collects pictures taken by the built-in camera of the instrument during scanning and organize those photos for easy browsing (Figure 2.2).

This function makes it very convenient to have a view of certain places by simply clicking on different positions showed in the webshare. Since all the photos taken at one spot have been merged together as a whole, at each view point the viewer could look around between 360 degrees just like standing in the real world.

2.4.4. 3D Laser scanning in Volvo today

3D scanning technology has been investigated at Volvo Cars Corporation since 1999. So far it was applied in the body shop as a supporting tool in the definition of the layout of robot cells.

In such an environment narrow geometrical tolerances call for high quality ensured solutions. A capable process able to satisfy these requirements relies on one side on an accurate design and on the other hand on the ability of the installation team in installing the robots according to the specification issued by the designer. Before the description of the benefits brought by the introduction of 3D scanning technology, it is worthy to point out the main criticism in defining the features of a new robot cells or in modifying an existing one.

The main concern for the designers was the deviation between nominal model and real installation. Even if accurate and powerful, the 3-dimensional computer models adopted were not enough to ensure a right at the first time solution. These tools allow the designer to simulate the real process by providing an accurate geometry and kinematics and a faithful representation of the interaction between car and robot [11], but on the other hand they are still not able to assess the impact of the virtual models on the real environment. Often facilities like wiring, ventilation, pipes and other secondary equipment are overlooked, leading to wrong models that need modifications in order to fit the reality. In addition to this it is worth to take into account the deviation introduced during the installation: sometimes installers misunderstand 2D layouts causing further deviation between real installation and nominal models. It is worthy to note that the most of the time these deviations are matter of inches, but the accuracy required by robots to work well is within fractions of millimeters. As a consequence after the installation further verifications were needed. A large amount of time was devoted to robot programming, causing too long production shift.

With 3D scanning data it has been possible to deal with the most of these problems. Nowadays this technology is used mostly for three purposes.

Firstly it is used for measurements. Thanks to the capability of the scanner it is possible to know the distance between all the facilities, even the ones that usually are overlooked, making the process shorter. In this way it is possible both to overcome the constraints related to lack of information, typical of measurements on the site, and to reduce the number of travels to plants. This is a further benefit for an international company like Volvo Cars Corporation which owns facility in Sweden, Belgium and China and carries out engineering work mostly in Sweden.

Secondly, point clouds generated by the software allow the user to select from the scanning data existing facilities in order to rearrange them to easily visualize how the future layout will look like. It is an easy way to carry out preliminary investigation in order to define the optimal layout solution without devoting too much time in developing 3D models: selecting point clouds and moving them is rather easy.

Last but not least is the possibility to assess the suitability of the virtual 3D models developed in the detailed design stage. This tool has definitely improved the process under this point of view. Now it is possible to verify that the virtual 3D model actually fit in the reality avoiding collisions with existing facilities.

Moreover it is worthy to consider the high potential of this technology as a communication tool: providing the installation team with a documentation including pictures of the virtual model integrated in the scanned images gives a clear picture on how the work has to be carried out and it is easier to avoid mistakes.

The implementation of this technology has made a decisive contribution in reducing the overall time needed to carry out such a project. Since now it is possible to create such accurate models, it is possible to carry out most of the programming offline before the installation, making the shift of production shorter and shorter.

2.5. The Volvo way

2.5.1. VCM 15 principles

"VCMS, Volvo Cars Manufacturing System, has a target to improve QCDISME performance to Best in Class (BiC), through a lean behavior culture and with a flexible volume/product process this by working in a standardized way, based upon the VCM 15 principles. The standardized way of working is built up by 9 development areas." [12]

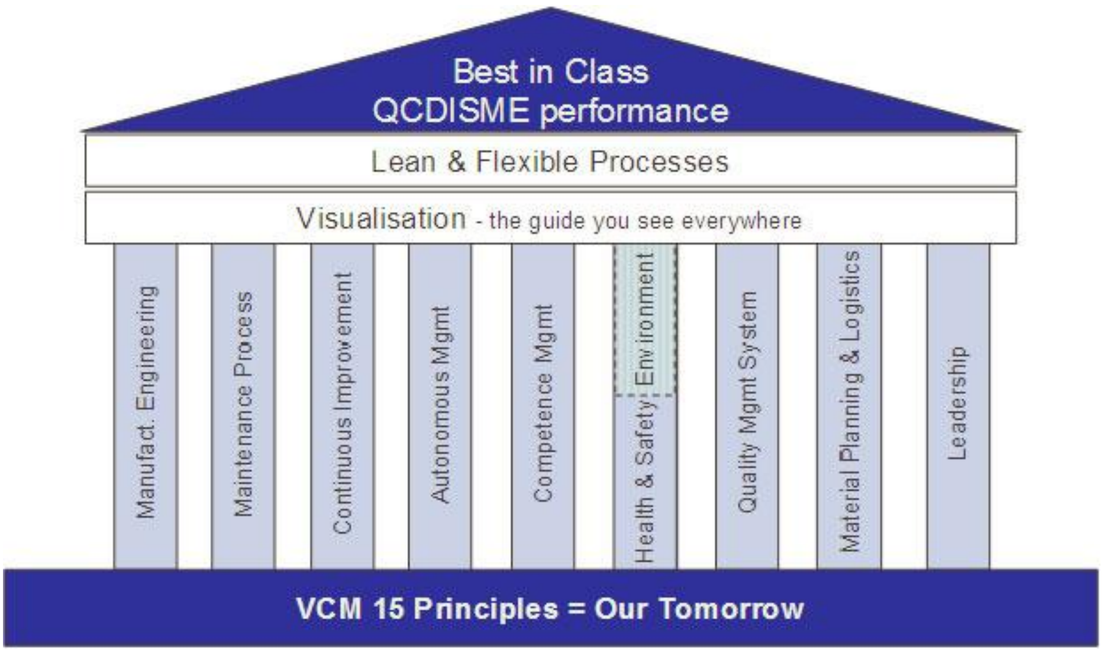

Figure 2.3 Volvo Cars Manufacturing System lean temple

This is the Volvo Cars Manufacturing System lean temple, showing the company interpretation of lean thinking applied to the manufacturing system development. The aim is to provide the organization with a well defined structure made up of nine development areas, able to apply lean values and principles to reach the ambitious goal of being Best in Class. As figure 2.3 shows MP&L is one of the nine pillars of the VCMS lean temple. The basis of the temple is made up of fifteen principles [13], which, for the aim of this thesis, are used to carry out a systematic analysis and to asses in a structured way the current MP&L activity. It is worthy to quote the fifteen VCMS principles:

1. Right from me forward – don't pass on problems
2. Planned Continuous Improvements
3. Deliver with precision according to plan
4. Support and challenge our suppliers to improve the supply chain performance
5. Visualize problems and losses - remove waste in our processes
6. Learn from others and each other
7. Business decisions are made considering total cost
8. Standardize work methods to reduce variability
9. Only implement reliable and thoroughly tested products, processes, systems and routines
10. From emergency actions to planned and preventive work in all our processes
11. Balance workload by prioritization, planning and work distribution
12. Go and see yourself to understand the process, to be able to coach and control
13. Recruit and develop leaders that live according to Volvo Cars Company Philosophy and the VCM Principles
14. Teamwork and 'medarbetarskap' is our heritage and gives us an advantage over our competitors
15. Our decision process is clear and fact based followed by rapid implementation

2.5.2. Practical issues of MP&L

In order to develop a solution fitting well the existing environment, considering best practices and rule of thumb implemented by MP&L in defining material façades is needed.

The main challenges MP&L has to cope with are lack of space aside the line and the reduction of non added value work. Finding solutions to cope with lack of space requires the implementation of techniques able to reduce space consumption and inventory level aside the line. The ability in reducing wastes like walking distances and handling activities through the improvement of part presentation ensures highest productivity, safety and ergonomic requirements fulfillment, and quality improvement due to picking faults reduction.

According to the continuous improvement philosophy Volvo Cars Corporation adopts a set of rules and principles, implemented in order to fulfill these requirements and to achieve a material façade layout able to support work station efficiency. Below a description of these principles is presented [14].

2.5.2.1. Deeper racks

Having deeper racks seems to be in contrast with low inventory level principles, in that bigger racks could mean more material stored. Volvo Car Corporation decided to shift from standard 1,2 meters deep racks to 2,5 meters deep, though. Actually these racks are used to store a higher number of boxes, but the overall quantity of components stored is the same. This device allows to feed lines with a higher variety of products without increasing the overall quantity of materials aside the line. This method proved to be effective to make production system more flexible in that it is possible to support the assembly of a higher mix of products.

2.5.2.2. 80 % principle

In accordance with 80 % principle the filling degree of a line should be less than or equal to this value (figure 2.4). This is a total goal for the overall production system, though the filling degree of a single workstation can range between 0 and 100 % according to production and cost efficiency needs. Restricting the maximum usable amount of space, results in a series of advantages. Firstly the supply system is more flexible, allowing faster integration of new product in the production flow. Thanks to space available it is possible to feed lines with racks of new materials while the old scheduled production is still running without causing any disruption in the flow. In this way the 80% limit is temporary exceeded, but it is gradually restored through a continuous improvement work.

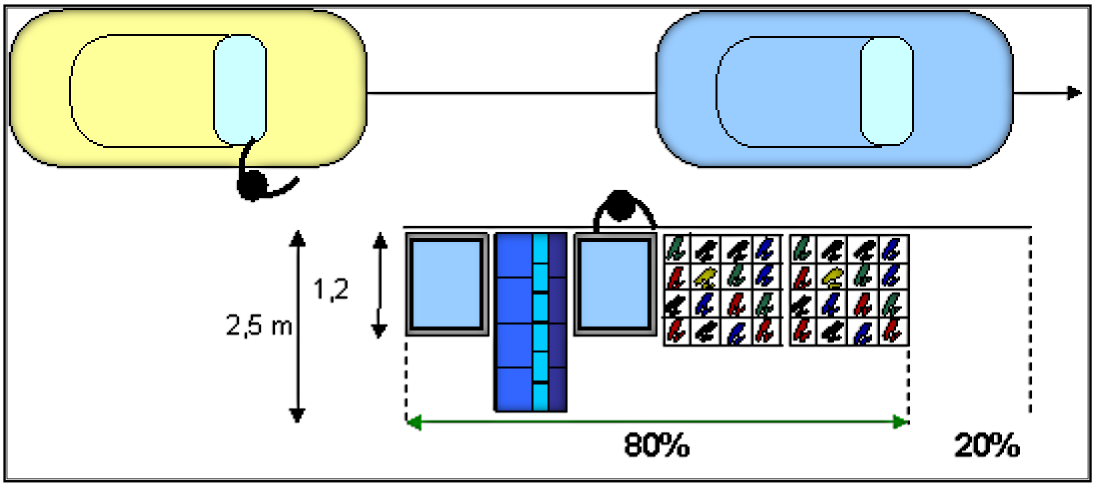

Figure 2.4 Demonstration of 80% principle applied in an assembly line

In addition to this, boundaries of each work station are better defined and operators do not disturb each other, improving working conditions. This in turn has positive effects on reduction of assembly times and on the improvement of quality, since the worker can find easily what he needs without interfering with his colleagues.

In the pictures below (figure 2.5) a comparison between three different filling degrees is presented. In the first one a 100% filling degree situation is shown: the material façade completely occupies the space aside the line. In the second picture a better organization of the material façade allow to carry out the production with a lower number of operators. In the last picture the target 80% filling degree shows how through an optimal organization of the material façade it is possible to create an ideal work environment, where the number of operator needed is lower and the interference between operators is completely avoided.

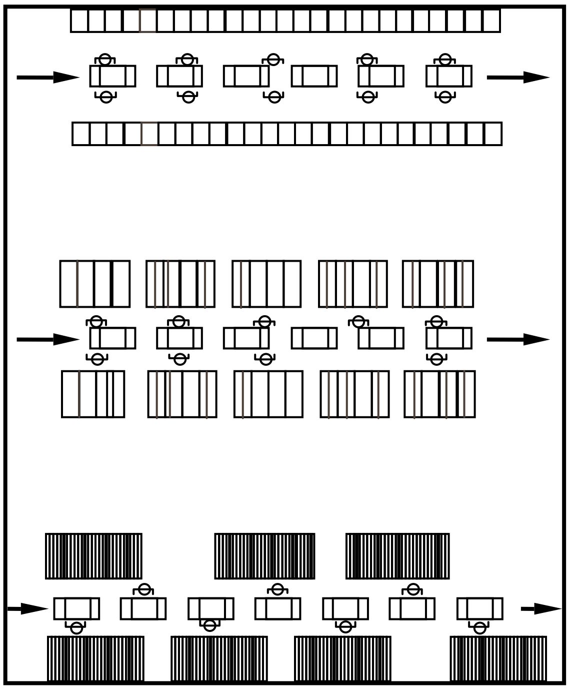

Figure 2.5 Demonstration of advantages deriving from the application of 80% principle

2.5.2.3. One pick place and line back principle

One pick place principle states that parts are to be grouped in the material façade in order to reduce the walking distance and picking time. The focus is on the reduction of wastes in order to maximize the productivity.

A work station fulfilling these requirements can be achieved through the line back principle, which states that the design work should start from the point of use and go backwards the chain to the supplier. In this way the focus shifts on the operator and on the efficiency of the assembly station work design in place of the pursuit for the transport efficiency. In the past a major effort was devoted in ensuring a cost efficient transportation system, which basically relied on a lower number of deliveries of biggest lots. The increasing products variants and the need for a higher productivity have determined the shift of focus on the layout efficiency. In this way it was possible both to overcome constraint due to lack of space and improve productivity thanks to elimination of wastes.

2.5.2.4. Two hours autonomy

According to this rule material façades should accommodate materials for two hour's production in order to avoid production disruptions. In this way it is possible to protect the production flow against possible delays in the delivery system and to ensure a continuous production in case of long cycle time for empty pallets replacement. Since often pallets can ensure only one hour production, two of them are needed to put in place this system. This is why this rule is also called 'double bin rule'

3. Method

Since this project is focusing on how to embed 3D laser scanning in MP&L development and analyze the potentiality of this technology, the whole working flow should give a comprehensive knowledge of Volvo's current MP&L development, a thorough test and understanding of the 3D laser scanning and verified problem definitions and the corresponding solutions. The following flow chart presents how this project is carried out in several major steps and the results are verified and validated.

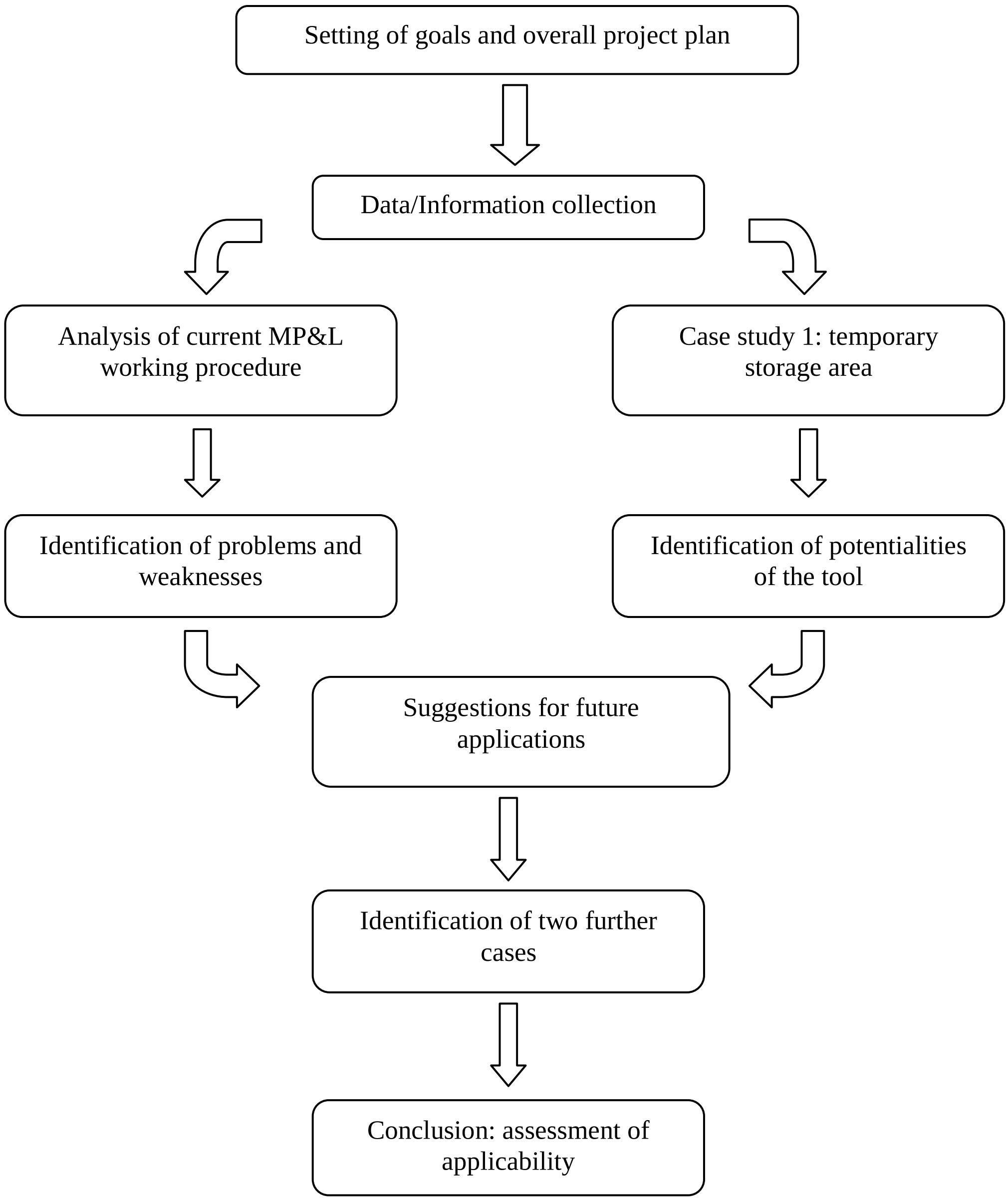

Figure 3.1 Flow chart of this thesis work

3.1. Data/Information collection

The data and information needed for analysis of Volvo's current MP&L working procedure and for case studies can be categorized into three groups according to the level of difficulty of data/information obtaining, which is shown in table 3.1 [15].

Category A	Available
Category B	Not available but collectable
Category C	Not available and not collectable

Table 3.1 Data/Information categorization

Category A comprises of all kinds of data and information that already are available in the company, for instance 2D layout of the plant, documentation, and spread sheets of production data. To collect these types of data two major approaches are adopted: searching and sorting materials from Volvo's internal website and database, and asking employees for specific data. Category B contains those that are not available but can be collected. This category includes scanned data of the assembly shop, which is collected after the goals of this project have been set (work method refers to chapter 2.4.3), and information acquired through visits to the plant and interviews with engineers. The third category of data is neither available nor collectable. Data of this class has to be estimated. For this purpose a specific algorithm has been developed to generate data needed for the analysis of case study 1.

3.2. Analytical procedure and problem mining

The analytical procedure provides the basis for the analysis of current MP&L working procedure. It can be classified as three approaches:

1. Lengthways process analysis

The process of Volvo's car project is divided into three stages. The early phase of its process is to set up the goals and foundation of the project. Thus we look at it first to understand the difficulties a project may face. Then, attention has been paid to the last phase which is the physical industrialization stage in order to find out the practical problems when realizing all the previous design work. The idea is that all the problems occur in the last should be consequences of early design ineffectiveness. After that we go back to the middle stage of the project process where major design work and verifications have been carried out to anchor the critical issues.

2. Crosswise comparing analysis

3D laser scanning has already been used for several kinds of industrial applications. Especially in Volvo body shop and paint shop it has been adopted to assist robot cell design. By comparing requirements of robot cell and assembly shop, the underlying difference between applications is defined to set the guideline for applying 3D scanning in the field of MP&L.

3. Principle-based analysis

Company's work principle reflects the most critical points that lead the company to success. The third level of analysis is based on Volvo's 15 manufacturing principles and it gives an even clearer perspective of problems and weaknesses in their current MP&L development.

3.3. Case study

Case study is a tool to practically provide solutions to the company's requirements and to build up analytical basis for the applicability of 3D scanning. The cases are designed integrating various elements:

- Meet company's requirements
- Solve the problems that has been discovered through analysis
- Take full advantage of the strength of 3D laser scanning technology
- Base analyses on data/factors that are both validated and estimated
- Evaluate outputs by numbers and feedback from specialists.

3.4. Interview and observation

In this project the most challenging thing is how to understand the complex car project development process in Volvo and find out the primary problems in a limited time. As input the obtainable resources have two types. One can be called explicit resources that are able to be acquired directly by ourselves. Another one is intelligence resources which are owned by employees in Volvo. The only way to achieve these resources is interviewing people.

Thanks to the mature concurrent engineering working manner in Volvo it is quite convenient to arrange meetings and to interview people. By meeting with people and having discussions, besides acquiring data and information needed, it is also possible to catch personal ideas as well as experience to a certain problem.

Interviews are set for two major purposes: first is to collect information and data and secondly is to verify ideas and solutions through discussions.
An interview is usually set and carried out by following steps:

1. Find the name of the person who has the knowledge of interests and find his/her e-mail address through company's internal outlook system.
2. Explain the purpose of the interview and make appointment through e-mail.
3. Prepare question list for the meeting.
4. Take part in the meeting.
5. Summarize the outcome of the meeting and draw new ideas and conclusions.

Most of the time meetings are held in individual meeting rooms which can be booked in advance. These meetings are usually based on PowerPoint and printed materials. But sometimes meetings are also held in the plant and, by observing the real production process and environment more technical questions can be initiated and the discussion can be more in depth and closer to production practice.

4. Analysis

Understanding the current working procedure allows to identify areas of improvement which can be supported by 3D scanning technology. First step is the description of the main stages through which car projects are undertaken in Volvo. Then the focus shifts on MP&L, the department which directly will implement this technology, through the description and the analysis of the current state.

4.1. Working logic - GPDS

Global Product Development System (GPDS) is the standard program for the development of a car model implemented at Volvo Car Corporation [16]. It is made up of milestones, gateways and processes. The relying philosophy is that the decision taken at each milestone cannot be changed: once the budget is fixed for a certain program, the decisions taken in the upstream processes cannot be modified. Then the final solution is defined through a continuous refining, which requires a lot of loops and adjustments. The whole process flow can be divided into four main phases, namely annual work, concept factory, industrialization factory and maintenance factory [17]. In the following discussion only the first three items will be discussed upon. From an organizational point of view it is worth noting that not all the hierarchical levels are involved in all the milestones: different steps in the process require different levels of responsibility. The matrix in figure 4.1 shows five different levels of responsibility involved.

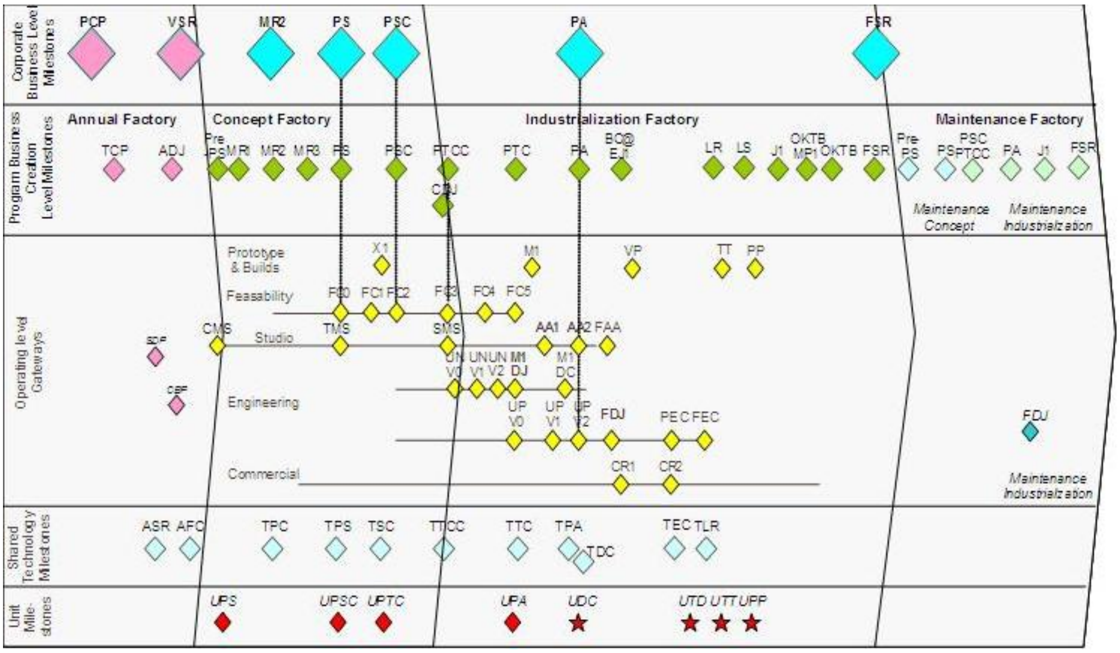

Figure 4.1 Overview of GPDS

The first stage in the GPDS is represented by the *annual work*. This task is carried out systematically during the whole year in order to assess the plan for each product coming up in the following years. It is a multi-program activity characterized by a holistic view.

It deals with strategies and plans regarding platforms, systems, vehicles and commodity business. After this activity three books are delivered:
- Red binder, in which technology and means are described. Here are assessed both available and needed means.
- Blue binder, where the market is described through the definition of target customer, pricing guidelines, needs and volumes.
- Green binder, in which business and profitability analysis are presented.

Then every single project is analyzed more deeply in the *concept factory*. The focus shifts onto a single program. It is not capable of dealing with strategic issues. Small core teams are responsible for the initial investigation, during which different solutions are taken into account. Cross functional teams with a consumer, commercial, technical and manufacturing perspective are in charge of refining the project goals. The feasibility of the program is reviewed through an iterative control system, in which different product and different manufacturing scenarios are taken into account. Each of the alternatives identified is assessed and the solution that best fulfills the program targets is chosen. Furthermore volumes, factory and industrial structure are fixed. Gradually the project takes shape so that all the issues can be addressed. The resources needed are identified, project costs are established, timing is defined, deadlines are set and the plans for the suppliers are prepared. All these ingredients together allow an overall confirmation of the project.

With the verification of the compatibility between all the subsystems of the new car model the *industrialization factory* can get started. Now the program is defined in every detail and receives its final approval. Issues like pricing finalization, remaining program financing, commercial launch plan and mass production plan are addressed. Tools and equipment are installed and tested in order to verify that the factory is ready to deliver the final product fulfilling target requirements like quality, time and costs: all the system must prove to be able to support the production. After all the verifications the mass production can start and the final product can be shipped to the external customer.

Before focusing on MP&L, it is worthy to describe other two important areas involved in a car project: product development and manufacturing process development.

4.1.1. Product development

It is about defining all the features of a car. The underlying approach is opposite to the traditional way of undertaking such a project. Companies used to start from the design of the single components with a high level of detail and consolidated them in the final product. Such an approach generates a lot of conflicts between different parts causing a lot of reworks to make the different components fit each other. Nowadays the process starts from a general overview and gradually steps into the details [16]. Major issue is the interface between different subsystems. It is of paramount importance to verify that all of them fit each other since the early stage in order to avoid costly corrective actions in late stages.

For the convenience of carrying out car development from general view to specific, it is necessary to divide a thousand-of-component composed car into several categories according to their characteristics. All car components are grouped into about forty subsystems considering their functions. Then these subsystems are assigned to three major categories, i.e. Powertrain, Underbody and Upperbody [18]. There are several benefits of this kind of classification. The development of these three categories can be relatively independent, so that they could be carried out concurrently with only little interference in the later integration stage. The relying rationale is to develop the Upperbody in the last phase, in order to ensure to the final customer the freshest design possible.
The activities carried out in order to define the subsystems' characteristics flow according to a common pattern which basically relies on a three stage alternative selection process. As a first step, alternative solutions are investigated and for each one of them new, modified and carry over parts are identified in order to understand what the company already owns and what it needs to develop and to set the budget for the renovation. Then the optimal solution is selected, even though it is still a provisional selection on a complete vehicle level. If improvement can be made there is always room to make some modifications. Eventually the system alternative is selected through a confirmation and a final selection.

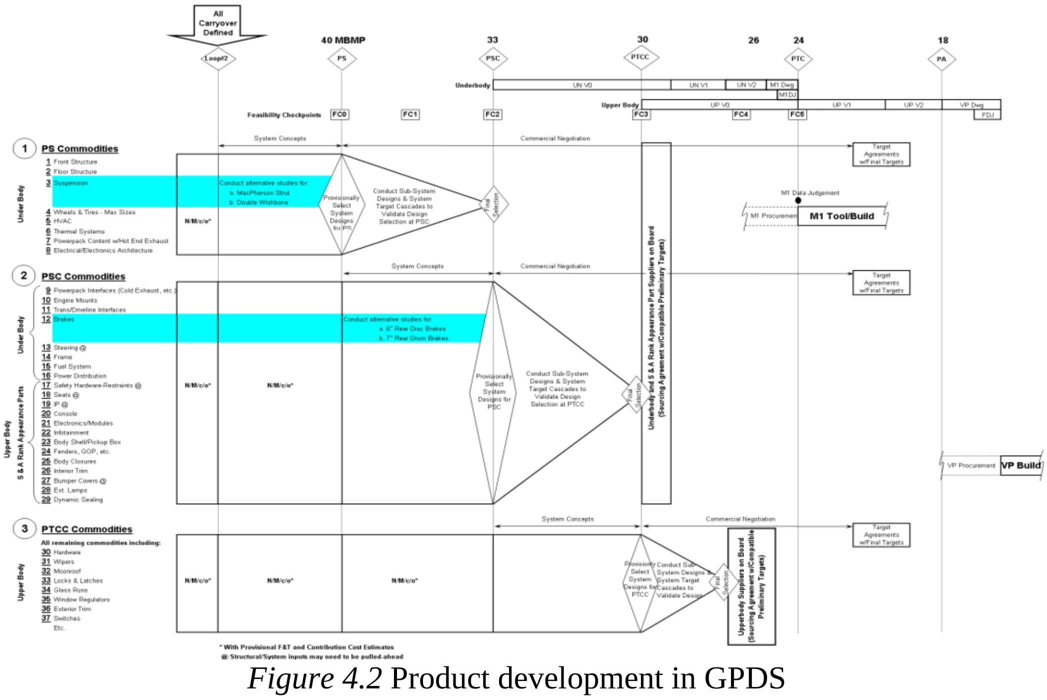

Figure 4.2 Product development in GPDS

The first subsystems addressed are those belonging to Underbody and Powertrain, while strictly design related subsystems belonging to the Upperbody are decided upon in the very end of this process. By the *program target compatibility (PTC)* milestone all the subsystem are defined.

After the definition of the subsystems the detailed design in virtual environment of all the components can get started. Figure 4.2 shows that there are two virtual design processes running in parallel: the first one is dedicated to Underbody components and the second one is dedicated to Upperbody subsystems. This activity is carried out through three steps, namely *virtual design series – phase 0 (V0), virtual design series – phase 1 (V1)* and *virtual design series – phase 2 (V2)*. In V0 mechanical packages and engineering data are developed according to program requirements and vehicle targets. In V1 systems, component and mechanical packages are further developed in a more detailed way. In V2 all the components are refined and confirmed to achieve all the vehicle engineering requirements.

When the documentation is ready the prototype is produced and tests are carried out. Firstly, during the *M-1* phase the underbody is tested using a mule upper body. Then verifications are carried out on the entire prototype during the *verification prototype (VP).*

Finally the car design which has passed all verifications is ready to be manufactured and the mass production can get started.

4.1.2. Manufacturing process development

The second important activity is the manufacturing engineering, whose working process is organized under GPDS as well. It roughly follows the same path as the product development process. The concept phase is the starting point, then the solution identified is developed and verified, and in the end there is the physical realization and testing [19].

The starting point is the *bill of process (BOP)*. Information regarding manufacturing process requirements and the plant restrictions are collected. The BOP provides a list of all the equipment available to carry out a certain activity.

The BOP has to be ready by the *PS*, so that the alternative identified can be further analyzed. The selection of the optimal process solution is performed through the *system decision alternatives-manufacturing (SDA-M)*: all the alternatives identified in the BOP are reviewed and the system solution that better fulfill the requirements is selected. This process needs to be ready by *PTCC* milestone. Once the system solution has been identified it is possible to start with the virtual simulation of the manufacturing process.

In the next stage virtual verifications are carried out. During *digital pre assembly 5-manufacuring verifications (DPA5)* the product is assessed under a manufacturing point of view, i.e. is verified whether it is possible to produce the intended product at the desired quality level, within the allocated costs and at the required line speed. Geometrical analyses are carried out to verify the compatibility between product requirements and equipment features. A 3D virtual built event (VBE) is carried out in order to simulate the construction of the car.

The physical realization starts with the *tooling trial (TT)* phase, where the first pre-production is built in the plant. In this stage all equipments, tools and facilities are modified according to the new requirements and the process capability is verified. The test is carried out with the actual production of a small number of cars. The whole TT usually takes 6 weeks.

Six more weeks are dedicated to the *pilot production (PP)* to assess the capability of new equipment to support the mass production. During this period an higher number of car is produced in order to verify 2 the ability of the manufacturing system to meet all the target requirements at the quoted production rate.

The final launch is carried out during *mass production 1 (MP1)* and *mass production 2 (MP2)*. During MP1 a low volume production is undertaken in order to get final confirmation of the vehicle quality. For new models this phase lasts two weeks and four hundred cars are produced. In case of model year MP1 lasts only two weeks and a maximum of fifty vehicles is produced. For a new model program MP2 is the ramp up through full volume production, while for a model year MP1 is directly followed by a direct switch to full production.

4.2. GPDS according to MP&L

As described in the previous section, GPDS is the framework according to which Volvo Cars Corporation carries out projects. Likewise MP&L is supposed to deliver results according to this path (Figure 4.3). This department is responsible for material and information flow from the supplier to the point of utilization implementing lean manufacturing principles and techniques. Under a practical point of view MP&L has to cope with cost efficient material façade arrangement, selection of repacking methods, implementation of the most efficient replenishment supply methods, and definition of the most cost efficient ordering method. Yet, MP&L in the past has mostly been concerned about the operational level, and little effort was put in planning. The need for an increasingly efficient layout called for a more structured approach able to involve MP&L also in the early phase [20]. It is worthy to describe the model according to which MP&L should undertake projects, in order to create a basis to analyze the process and to figure out how to support and improve it through 3D scanning technology.

Program management, packaging engineering, material handling engineering, inbound logistics and outbound logistics are involved in the whole process with responsibilities in different areas.

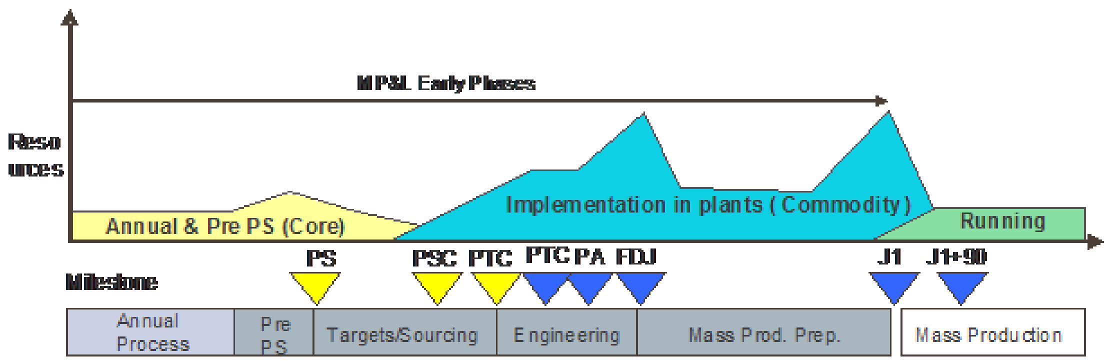

Figure 4.3 MP&L in GPDS

During the annual work program managers collect information in the annual meeting about incoming projects and initiate high level logistic studies to identify areas that will be affected by changes. Results will be presented to packaging engineers, material handling engineers, inbound logistics and outbound logistics so that they can make deeper investigations and cost estimations. At this level they have to define how the incoming projects will affect the material feeding system.

Packaging engineers have to define existing MP&L equipment, suggest modifications to adapt existing equipment to new needs, and require new equipment needed. According to the new needs they have to roughly estimate investment and running costs. Likewise material handling engineers have to define existing, carry over, and completely new in plant equipment, trying to figure out how existing layout and man hour utilization will be affected.

The investigation carried out in the early phase are further refined during the implementation in plant. As time goes by it is possible to make more accurate estimation about the equipment needed to support the assembly process. This is due to the dynamic nature of assembly lines. Continuous introduction of new variants, updated models, and new equipment cause continuous changes in addition to major modifications related to new car projects.

As a result, estimations obtained in the early phase are merely indicative, and are simply used as guidelines to set budgets. This is mainly related to the lack of designing tools able to support decisional processes. Indeed the ever changing features of assembly lines require an overwhelming amount of work to update accurate 3D virtual models. Over time this leads to a procedure which basically relies on the expertise of people working in this area, which are very skilled in defining the optimal solution according to lean production principles, company's best practices and well established rules of thumb, but still are weak in the planning activity. This results in an inefficient process, which requires a lot of loops and adjustments to deliver the final solution. In the following section these issues will be deeply discussed to understand the targets of the company and till what extent the present process is able to fulfill them. Then through the analysis of the critical aspects it will be possible to understand how the 3D scanning technology can be deployed.

4.3. Analysis of present process and identification of areas of improvement

Analyzing the current MP&L working procedure according to the 15 VCMS principles [13], it is possible to identify the following issues:

1. The lack of designing activity prevents material planners from clearly understanding how the physical disposition of material façades will evolve over time. Engineers can only have an idea about the current situation in the plant. But actually a lot of changes occur in the shop floor from the early stage to the actual installation of the material handling equipment. When a project is started the solution is developed according to how the shop floor looks like in that moment. But the closer to mass production the project is, the more the material feeding system differs from the beginning of the project. Requirements and physical constraints become clearer and solution is continuously refined. This results in a lot of reworks and adjustments which makes the material planners activity highly inefficient and resource-consuming.

2. Unlike product development and manufacturing process development, in MP&L there is no a standardized procedure. People involved do not have to follow a precise sequence of activities, and it is difficult to define clearly the steps through which MP&L come up with the final solution. The lack of standardization prevents from keeping under control a process which very likely hides a lot of inefficiency and makes difficult to carry out a systematized continuous improvement activity.

3. Since no models for a complete layout including both facilities and material façade are issued, it is not possible to develop product and assembly processes able to take into account in an effective way also material handling and logistics needs. Material façade and layout is actually decided upon only once that product and assembly sequence have been defined. While product and process are developed and actually assessed through powerful virtual simulation tools since the early stage of a project, in most cases MP&L carries out solely cost estimations and budget allocation. The impossibility to assess the interaction of the assembly process with the real environment, often results in ill-balanced assembly lines. Problems arise only after the actual installation of material handling equipment, requiring a big effort in improving performances through continuous improvement work.

4.4. 3D laser scanning in MP&L development

Outcomes from the previous analysis indicate the lack of design activities for the assembly shop as the main cause of problems of the current MP&L working procedure. On the other hand the dynamic nature of the assembly shop has prevented material planners from developing accurate models with traditional CAD software due to the high amount of work required to keep up-to-date models.

3D scanning technology implemented in the robotic cells design, actually proved to be capable of supporting a design activity. This technology can be exploited to allow material planners to develop three-dimensional models of the assembly shop. Also in the assembly stations design 3D scanning technology can be implemented for measurement, to develop models of the new layout rearranging point clouds taken by scanned data, and to verify whether 3D models of new "hardware" facilities such as conveyors actually fit in the real environment.

However, unlike the robot cells design the major advantage will not derive from the possibility of verifying 3D CAD models in scanned data of the real environment. Indeed, since the major issue is related to the rearrangement of the material façades rather than to the introduction of new "hardware" facilities, the major advantage will come from the possibility of developing models of new assembly stations. Such models can be developed by simply selecting and saving point clouds of scanned facilities as single 'pod' files, and then by importing these 'pod' files to organize a new model. This feature overcomes the traditional constraint related to the CAD software requiring a higher amount of work to model facilities and equipment. This satisfies the need of a tool able to support a fast and easy design activity.

5. Case study

In this chapter outcomes from the practical application of the 3D scanning technology are shown. Here three case studies are designed on different purposes. The first one is initiated from the demand of the company. This case study is focused on the temporary engines/gearboxes temporary storage area, attempting to find a solution to handle the future increase in the number of variants both of engines and gearboxes. Through this practice potentialities of 3D scanning for further applications are identified, leading to other two case studies. In all of the three practical applications attention is focused on how material planner's work can be improved by more concrete design activities.

5.1. Case study 1 – Engine/gearbox Temporary storage area

Main issue in the temporary storage area is represented by the future increase in the number of variants of engines and gearboxes. After the description of the current material feeding logic, the problem is addressed by developing four different material feeding logics and by analyzing all of them through the support of models developed in Pointools software.

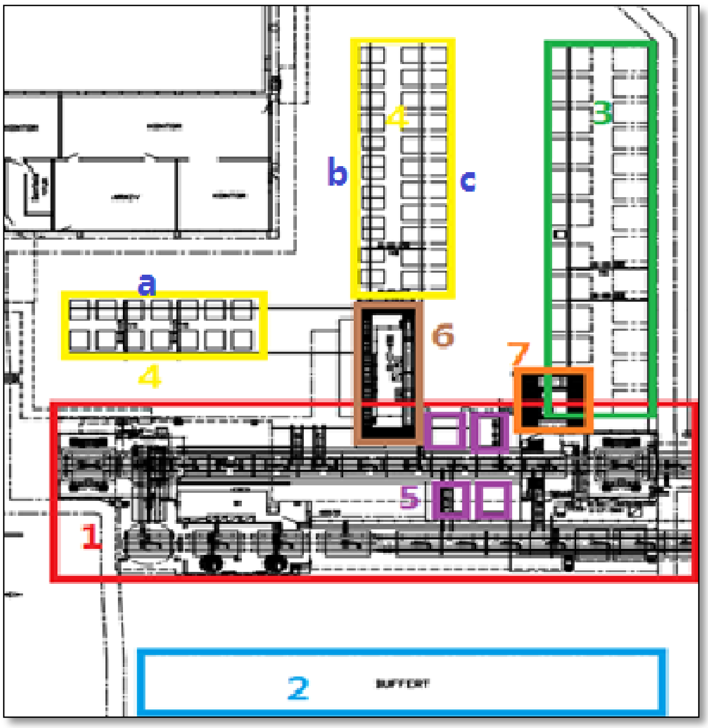

Figure 5.1 Layout of the temporary storage area

5.1.1. Description of engine/gearbox temporary storage area

In the temporary storage area engines and gearboxes are temporarily stored waiting to be loaded on PP-line 1 (area 1 in figure 5.1) where the power-pack is assembled and it can be classified as an in-line storage area [9].

Engines and gearboxes coming from suppliers are stored in the outside tent shown in figure 5.2. From here both engines and gearboxes are transported by a big forklift according to a direct movement system [9] to the buffer (figure 5.1 area 2) aside PP-line 1, waiting to replace empty racks in the temporary storage area.

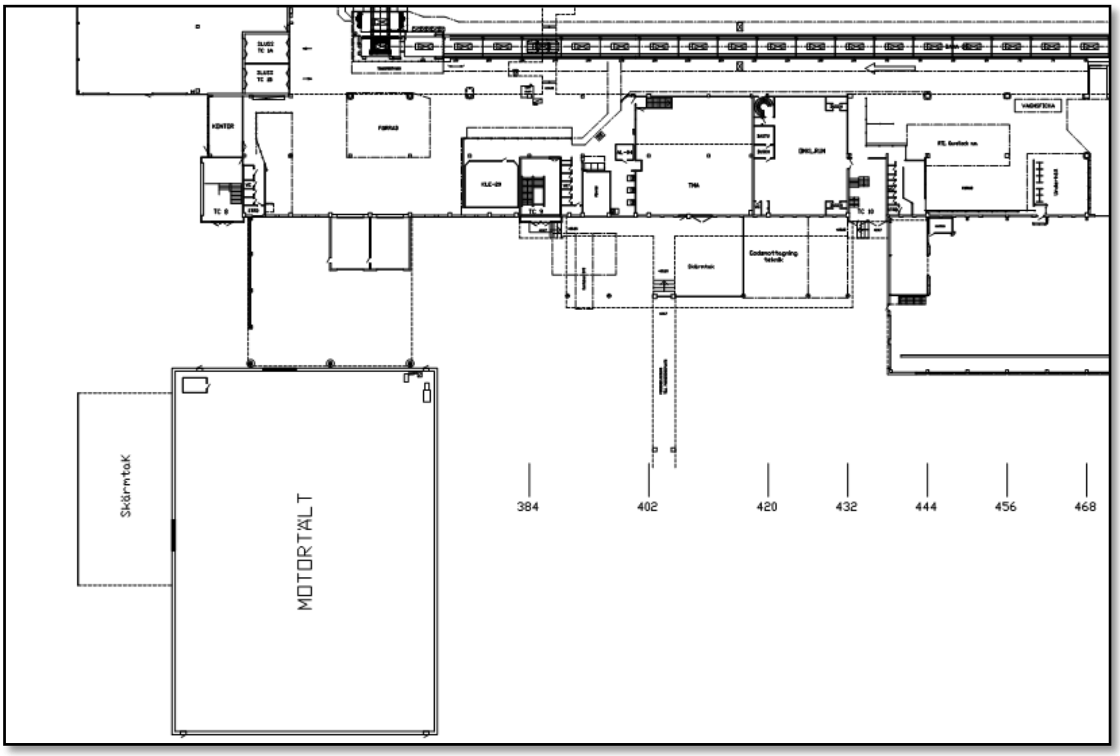

Figure 5.2 Layout of the tent outside the assembly shop

Engines of the same type are all delivered in groups of six on pallet R00, according to a batch supply system [8]. Gearboxes, on the contrary, have different pallets depending on their dimensions and on the supplier. Table 5.1 shows all the different type of pallet used, which can be grouped in two different categories: big and small pallets.

Every time that a rack in the temporary storage area is empty, it is replaced by a new one containing the same type of item waiting in the buffer.

Small gearbox pallets are stored in area 4a and 4b, while big ones are stored in area 4c. From here one operator sort them according to the production plan and load them on the pre assembly line (figure 5.1 area 6), where devices against oil leakage are assembled. Another operator is in charge of picking engines stored in area 3 and to load them in sequence on PP-line 1 (figure 5.1 area 7). In this way the line is fed according to a sequenced deliveries system [8].

pallet type	gearbox type	items/pallet	N° of variants	Classification
R40	automatic	5	18	Small
L04	manual	6	5	Small
D01	automatic	12	1	Big
R07	manual	10	1	Big
R42	manual	10	1	Big
R00	manual MMT6	20	1	Big
R41	manual MMT6	20	1	Big
R64	manual MMT6	20	2	Big

Table 5.1 List of gearbox pallets

Racks are arranged into the temporary storage area according to their consumption rate: the higher the consumption rate of a certain variant of engine or gearbox, the closer to the line it is placed. In this way it is possible to keep low the average cycle time for loading operations, which today is about 1 minute for both engines and gearboxes. Engines and gearboxes are both grouped in three classes, namely class A, class B, and class C. In class A are those items whose racks have less than two hours autonomy, in class B are those with less than two days autonomy, remaining are grouped in class C. Data is shown in appendix B.

In the current state there are twenty-five variants of engines and thirty variants of gearboxes. Top two consumption level engines are directly loaded through a small forklift on the two double bins represented in figure 5.1 as area 5. The third Class A engine is delivered according to the double bin system [14] as well, but it is stored in area 3. For each of the remaining engines of class A and class B only one spot is allocated, while for all the engines belonging to class C only two spots are allocated due to their extremely low consumption level. In this configuration twenty-seven racks are needed, meaning that all the spots available are occupied. A further increase in the number of variants cannot be handled in this area implementing the same delivery logic.

Gearboxes are handled in the same way, but in this case the storage area is less crowded and allows a higher degree of freedom. Indeed in areas 4a and 4b there is a total of twenty-five spots available and in area 4c there are eleven spots. Currently there are only twenty small racks and seven big racks.

Regarding the future evolution there is on one side an increase in the number of variants of engines and gearboxes, and on the other hand a slight reduction in the hourly production from 50 to 46,6 vehicle/h starting from 2012. Indeed even if the overall production will still increase, the introduction of the third production shift will reduce the hourly production volume.

Because of this it has been necessary to verify the solutions developed at the end of 2011, characterized by the highest number of variants at the highest production speed, and at the end of 2014, characterized by the highest number of variants at the lowest production speed. Figures below show the increase of variants of engines and gearboxes. Series A represents the number of variants that will be surely produced, while series B includes also those variants which are still in under investigation. As a result four scenarios will be analyzed, namely 1147A, 1147B, 1420 A and 1420B.

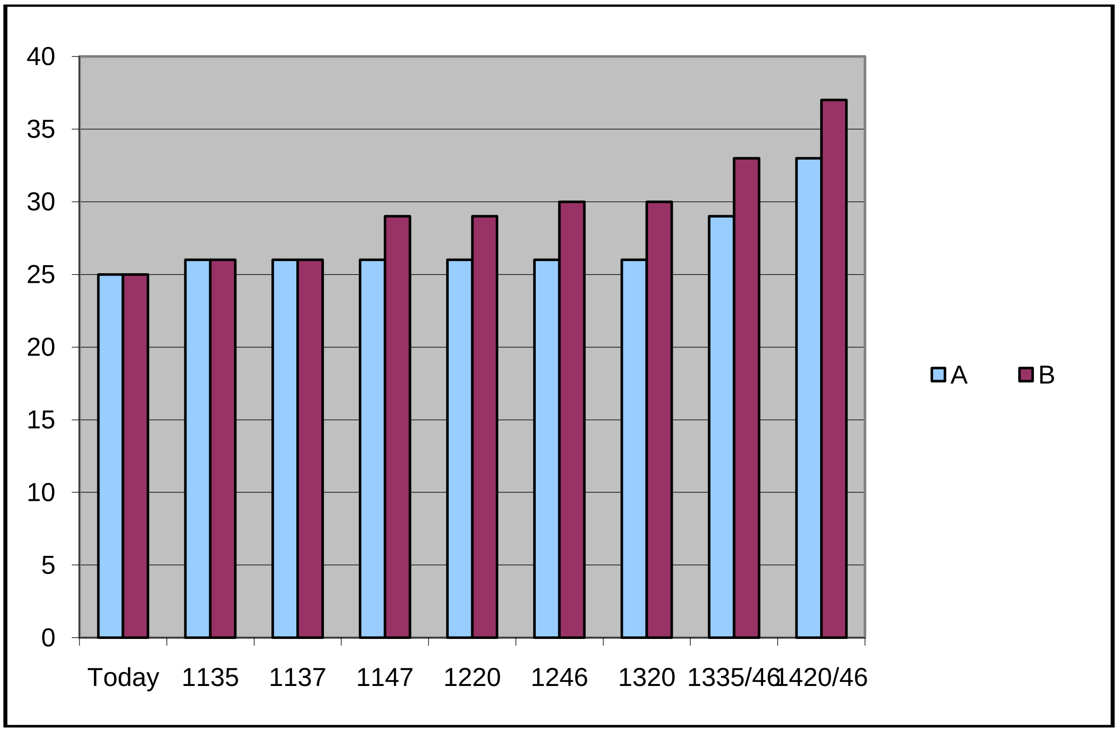

Figure 5.3 Forecasting of engine variants increase

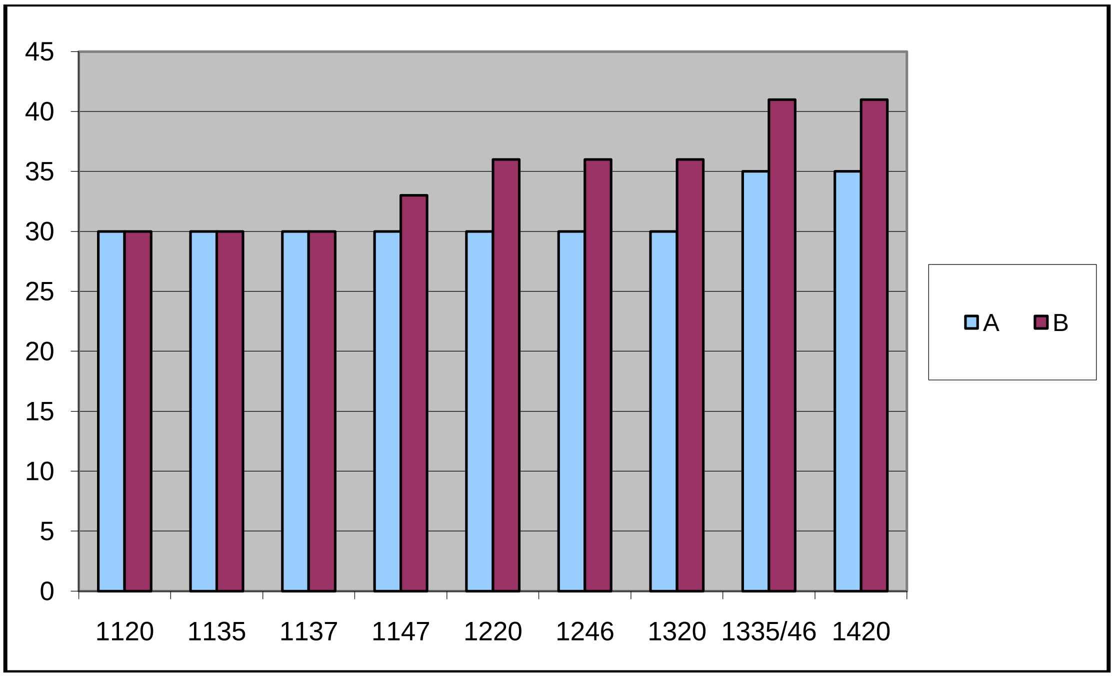

Figure 5.4 Forecasting of gearbox variants increase

Main goal of the analysis carried out is the definition of the space requirements to handle the increase of the number of variants. In order to do this the number of racks needed in every scenario has been calculated. Calculations are shown in appendix B. Then the scenarios developed have been analyzed according to four different material feeding logics, which are presented in the following section. An important part of the analysis includes the definition of space requirements for each of the material feeding logic, investigated through the use of 3D scanned data on Pointools software. Examples of models developed are shown in appendix D.

5.1.2. Analysis and results

The current sequencing area will not be able to support the future increase of engines and gearboxes variants. Safety rules, physical constraints, and fulfillment of accessibility criteria for forklifts and operators prevent from increasing the size of the storage area. As a result the only opportunities are represented by a better utilization of spaces dedicated to gearboxes and by the location of the sequencing activity in another area of the plant, which very likely will be placed in the engine tent. This facility will be soon expanded, and looks like the best solution for the creation of a new sequencing area. Aim of this analysis is to consider four different material feeding logics and to evaluate the space required to implement them through Pointools software and whether it will be possible to satisfy the increasing production requirements.
Below the alternatives identified are listed:
- Full sequencing of engines;
- Full sequencing of gearboxes;
- Shared sequencing of engines;
- Shared sequencing of gearboxes.

All the solutions identified will introduce a further handling operation in that engines or gearboxes will be sequenced before to be delivered to the temporary storage area, where there will be no a reduction in the workforce employed. Along with space consumption, this is an important factor in the choice of the material feeding logic.

5.1.2.1. Full sequencing of engines

According to this first solution all the engines will be sequenced in the sequencing area, a big central storage area [9]. All the racks will be stored in this area and engines will be sequenced in an empty R00 rack according to the production plan. Then sequenced racks will be delivered to the line according to a sequenced deliveries system [8]. Table 5.2 shows results of the investigation for all the four scenarios.

Most important results are about number of engines to be sequenced every hour and about the amount of space required. Table shows that in scenarios 1147 A and B the operator has to sequence 50 engines/h, while in scenarios 1420 A and B he has to sequence 47 engines every hour due to the slight reduction in the hourly production rate. The sequencing cycle time in the temporary storage area is 1 min and it is possible to assume that the performance will be the same even by sequencing engines in the tent. This means that the operator has to sequence engines for 50 min/h in scenario 1120 A and B and 47 engines/h in scenario 1240 A and B. Considering 85 % efficiency due to allowances the operator can sequence 51 engines/h, which is barely enough to satisfy the requirements. Moreover this solution needs another operator in order to pick batches from the racks and to drive them to the sequencing area every time that a batch is over. The space consumption in the temporary storage area will decrease. Today all the spots in this area are occupied while through the sequencing in the engine's tent and through deliveries made on an hourly basis there will be the need to store maximum nine batches in scenarios 1120 A and B. Among these, four will be loaded directly on the line on the double bin racks, causing a consumption of only five spots in the temporary storage area, which as a result will be almost empty.

FULL SEQUENCING OF ENGINES	1147A	1147B	1420A	1420B
N° of ER in SA	28	30	34	37
N° of ER in TSA	9	9	8	8
N° of small GBR in SA	0	0	0	0
N° of big GBR in SA	0	0	0	0
N° of small GBR in TSA	23	26	27	29
N° of big GBR in TSA	7	7	8	9
Engines to be sequenced [engines/h]	50	50	46,6	46,6
Gb to be sequenced [gb/h]	0	0	0	0
Sequencing time [min/h]	50	50	46,6	46,6
Additional operator	2	2	2	2
Space freed in TSA [m^2]	147	147	164,5	164,5
Space needed in SA [m^2]	855	893	978,5	1083

Table 5.2 Full sequencing of engines – analysis results

The space for the sequencing area in the tent depends on the number of variants that are to be sequenced. Table 5.2 shows how space requirements vary according to the number of racks that need to be stored.

5.1.2.2. Full sequencing of gearboxes

FULL SEQUENCING OF GEARBOXES	1147A	1147B	1420A	1420B
N° of ER in SA	0	0	0	0
N° of ER in TSA	28	30	34	36
N° of small GBR in SA	23	26	27	29
N° of big GBR in SA	7	7	8	9
N° of small GBR in SA	10	10	10	10
N° of big GBR in TSA	0	0	0	0
Engines to be sequenced [engines/h]	0	0	0	0
Gb to be sequenced [gb/h]	50	50	46,6	46,6
Sequencing time [min/h]	50	50	46,6	46,6
Additional operator	2	2	2	2
Space freed in TSA [m^2]	87,5	86,25	46	21
Space needed in SA [m^2]	658	723,8	752	789,6

Table 5.3 Full sequencing of gearboxes – analysis results

In this case all the gearboxes will be sequenced in the sequencing area. Here all the variants will be stored in their corresponding pallets and will be sequenced in pallet R40. It is one of the small pallets, can accommodate five gearboxes and is the only one which fits well all the kind of gearboxes. Even in this case items will be delivered according to a sequenced deliveries system [8] from big central storage area [9]. Table below shows the result for this material feeding logic.

5.1.2.3. Shared sequencing of engines

The relying rationale of this solution is on one side to reduce the workload for the operator in the sequencing area and on the other hand to fully exploit the capacity of the temporary storage area in order to reduce the space requirement in the tent, whose main aim is to store engines and gearboxes coming from suppliers.

According to this logic class A engines will be delivered directly on the temporary storage in batches [8]. Then all the gearboxes will be delivered directly to the temporary storage area according to the current material feeding logic. If any room left in area 3 and area 4c, it has to be fully occupied by other engines racks, while exceeding engine racks are to be stored in the sequencing area. The delivery logic integrate batch supply with a sequenced deliveries system [8] relying both on central and in-line storage areas [9]. Table 5.4 shows the results related to this logic.

SHARED SEQUENCING OF ENGINES	1147A	1147B	1420A	1420B
N° of ER in SA	0	0	6	11
N° of ER in TSA	28	30	28	27
N° of small GBR in SA	0	0	0	0
N° of big GBR in SA	0	0	0	0
N° of small GBR in TSA	23	26	27	29
N° of big GBR in TSA	7	7	8	9
Engines to be sequenced [engines/h]	0	0	0,93	1,77
Gb to be sequenced [gb/h]	0	0	0	0
Sequencing time [min/h]	0	0	0,93	1,77
Additional operator	0	0	0	0
Space freed in TSA [m^2]	0	0	0	0
Space needed in SA [m^2]	0	0	397,5	494

Table 5.4 Shared sequencing of engines – analysis results

In this way, compared to the full sequencing of engine logic, the number of racks to be stored in the sequencing area and, in turn, the number of engines to be sequenced every hour will dramatically reduce. Since engines to be stored in this area are those with the lowest consumption rate, the sequencing time will be lower than 2 min/h in the worst case. In this case the sequencing is not a critical activity and it does not need a dedicated operator.

Models developed on Pointools showed that for 2011 the sequencing area is not needed: using the space available in the area dedicated to gearboxes it will be possible to handle the increase of variants. Regarding 2014 data shows that in the worst scenario, i.e. 1420 B, the space needed in the tent will be the way lower than the space needed by both full sequencing of engines and gearboxes.

5.1.2.4. *Shared sequencing of gearboxes*

In this case gearboxes with the lowest consumption rate are delivered to the temporary storage area after being sequenced in the sequencing area. The aim of this feeding system is to reduce the number of gearboxes' pallet in the temporary storage area in order to gain an adequate amount of space able to accommodate a higher number of engine racks. However, in this case there is a physical limitation: engine racks can be stored only in areas 3 and 4c, in that the forklift used to carry them needs a 6,5 m wide aisle. As figure 5.1 shows area 4a and area 4b cannot be used for this aim, since surrounding aisles are too small.

That said, it is possible to address the feeding logic. Firstly all the spots in area 3 are occupied by engine racks, while those in area 4a and area 4b are occupied by small gearbox pallets. Then big racks for gearboxes belonging to class A are placed in area 4c. If there is any room left, it can be dedicated to exceeding engines racks. Regarding exceeding gearbox pallets, they can be stored in area 4c if there is still any space available, otherwise it is necessary to store them in the sequencing area.

The table below shows the result related to the application of the shared gearboxes sequencing logic.

SHARED SEQUENCING OF GEARBOXES	1147A	1147B	1420A	1420B
N° of ER in SA	0	0	0	4
N° of ER in TSA	28	30	34	34
N° of small GBR in SA	0	0	3	5
N° of big GBR in SA	0	0	6	7
N° of small GBR in TSA	23	26	25	25
N° of big GBR in TSA	7	7	2	2
Engines to be sequenced [engines/h]	0	0	0	0,58
Gb to be sequenced [gb/h]	0	0	4,33	4,19
Sequencing time [min/h]	0	0	4,33	4,19
Additional operator	0	0	0	0
Space freed in TSA [m^2]	0	0	0	0
Space needed in SA [m^2]	0	0	323	431,3

Table 5.5 Shared sequencing of gearboxes – analysis results

This solution ensures the lowest space consumption in that for the worst scenario only 431.3 m^2 are needed, even if the advantage is small compared to shared sequencing of engines logic. On the other hand it requires a slightly higher sequencing time, due to the fact that a lot of big racks containing class B gear boxes need to be stored in this area. Moreover in the last scenario the space available in area 4c is not enough to accommodate all the engine racks, and four of them need to be placed in the sequencing area, making the sequencing more complex.

5.1.3. Solution proposed

Solutions identified ensure very different performances and show that 1420B is the most critical scenario. For this reason the choice has been made comparing results referred to this time period. Figure 5.5 and table 5.6 show quantitative data obtained.

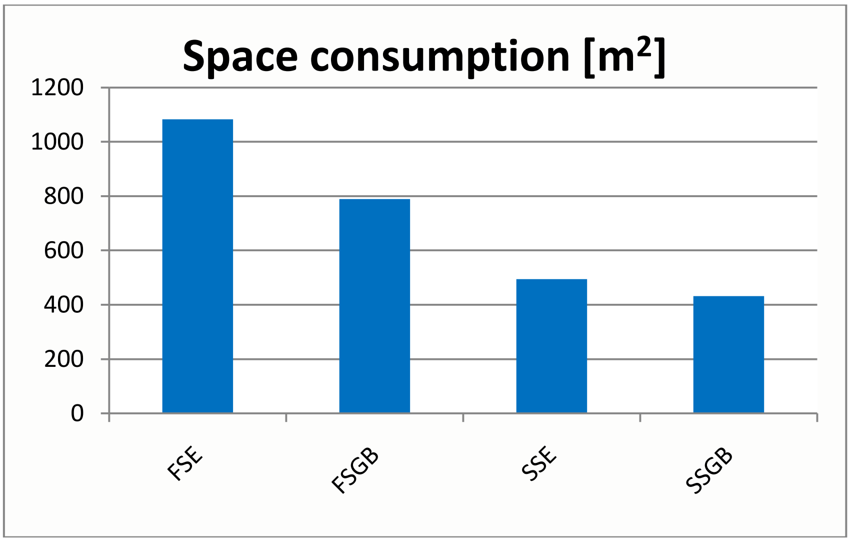

Figure 5.5 Space consumption for the four material feeding logics in SA (1420B)

	Space consumption [m^2]	Sequencing time [min/h]	Additional operators
FSE	1083	46,6	2
FSGB	789,6	46,6	2
SSE	494	1,77	0
SSGB	431,3	4,19	0

Table 5.6 Comparison between results referred to scenario 1420B

On one hand full sequencing of engines (FSE) and gearboxes (FSGB) requires a large amount of space in the sequencing area and implies the introduction of two additional operators. The space freed in the temporary storage area is of little account and it cannot be easily dedicated to other activities. The inefficient utilization of space in the temporary storage area and the increase in the workforce suggest that this is not a good solution.

On the other hand, shared sequencing of gearboxes (SSGB) and engines (SSE) offers similar performances. The space needed for both of them in the sequencing area is far lower than the space needed for the full sequencing and for both of them the number of items to be sequenced is so low which can be handled without any additional operator. Anyhow, even if under a space consumption point of view the sequencing of gearboxes ensures a slightly better performance, the higher number of items to be sequenced and the fact that not all the engine racks can be placed in the temporary storage area suggests that the shared sequencing of engines is the best solution.

5.2. Proposal for the future

The first application shows that modeling critical areas of the assembly shop provides MP&L activity with a concrete basis on which to develop more accurate analyses. This suggests that 3D scanning technology can be exploited for two purposes. On one hand to make MP&L more involved in the early stage decisional processes, and on the other hand to enable material planners to carry out analysis since the beginning of a new project upon the efficiency of the assembly process set by manufacturing engineers. The following case studies have been carried out with the aim of practically exemplifying these issues.

5.2.1. VBE

Besides the design activity, every new product requires a series of check up and assessment work. An important check point is represented by the Virtual Build Event (VBE). In this occasion new or modified components are analyzed and engineers from different departments give their suggestion on how to achieve the best design both from the product and the assembly process point of view. The discussion of each component is carried out following the order in which they are to be assembled and the basis for this discussion is provided by the 3D model developed by product designers.

Usually this procedure does not involve any model of the assembly lines resulting in a discussion which is strongly product oriented and unable to clearly specify requirements and constraints related to the working environment.

3D scanning technology has attracted the interest of many departments in the company, and for this reason has also been used experimentally to support the VBE with the model of a new assembly station. This station will be installed next to PP-line 1 to carry out extra assembly operations on a specific engine variant. This is a small area currently used for the storage of empty pallets (figure 5.6).

Figure 5.6 Image from FARO Webshare – area for the new station

2D layout in figure 5.7 is the basis on which the 3D model has been developed. Figure 5.8 shows the final result.

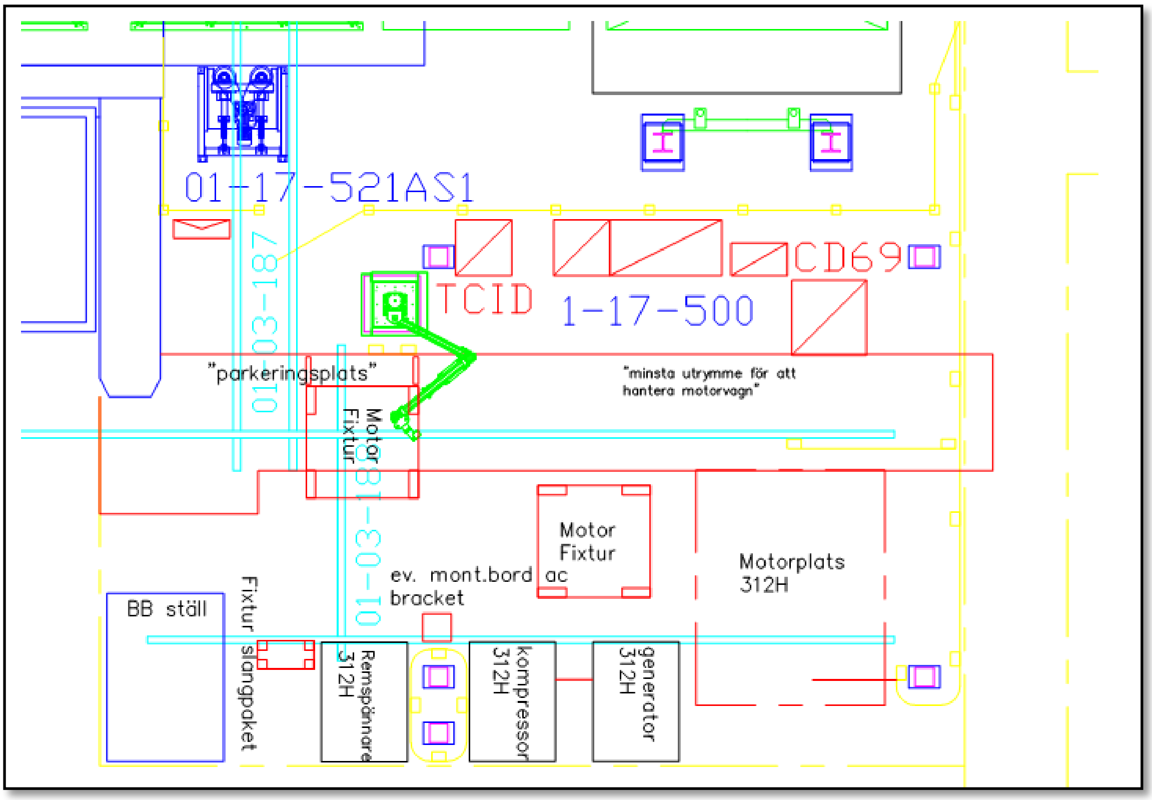

Figure 5.7 2D layout of the new station

This application shows that 3D scanning is a powerful visualization tool. The model built in such a virtual environment presents the future workstation vividly, allowing people involved in VBE to have a better understanding of the assembly process. In this way problems are clearly visible and it is easier to find solutions. By implementing this procedure regularly in future VBEs it will be possible to take into account the interaction of the assembly process with the surrounding environment. This is an opportunity to broaden the scope of current product oriented VBEs and to turn them into more comprehensive processes, where it will be possible to assess how new products will actually affect assembly plant environment and on the other hand how the environment and facilities will impose constraints on manufacturing processes. From concurrent engineering point of view, this is an opportunity to help MP&L and layout development work parallel with product and process development from early stage. Also it is a tool to support cross-functional team's decision-making [3].

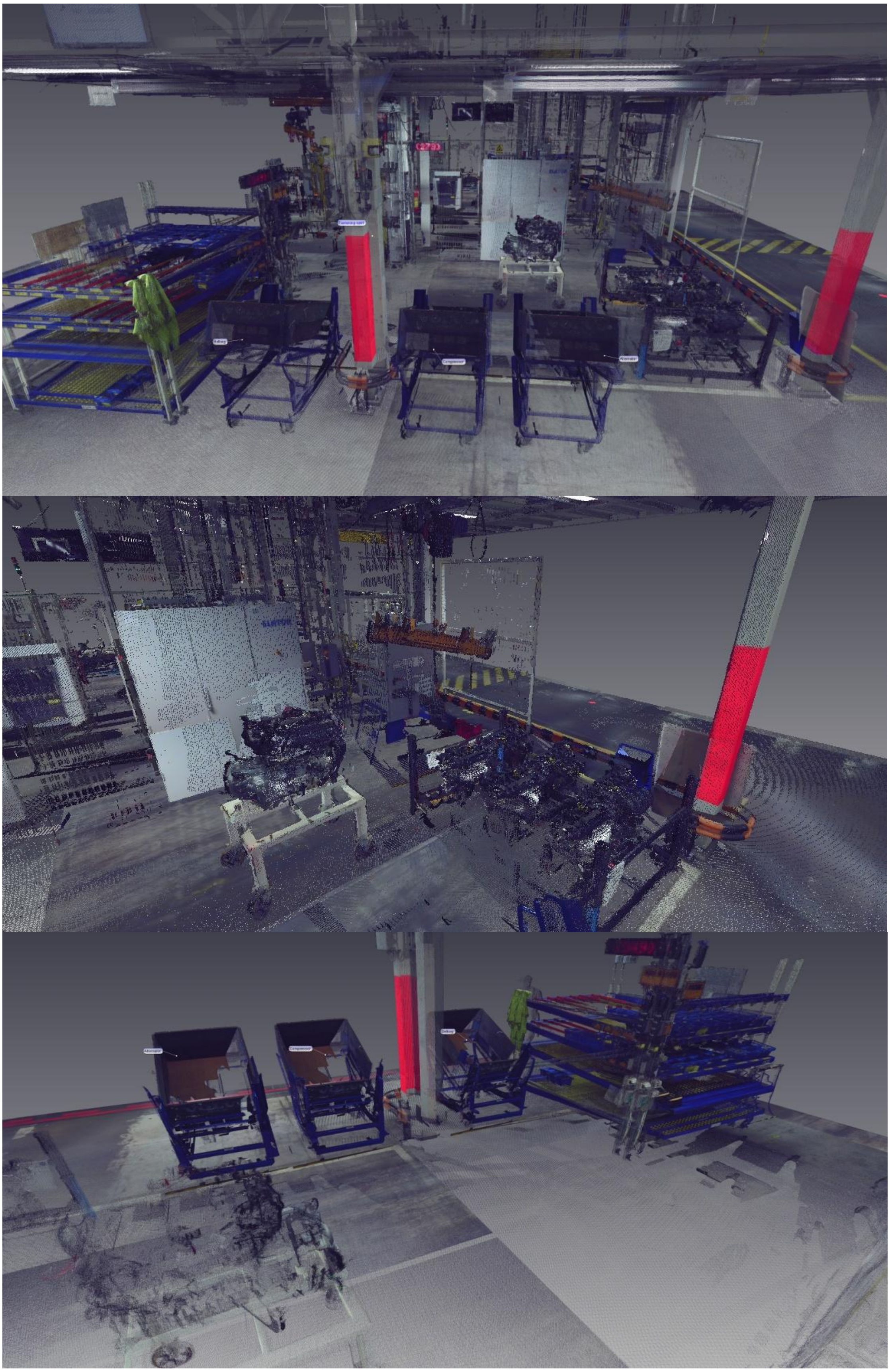

Figure 5.8 New station modeled in Pointools

5.2.2. Pallet line 1

3D scanning technology together with Pointools software provides a powerful graphical tool, which proved to be very useful in the material planning activity by making possible a more accurate space requirements analysis. The implementation of this tool can give further contribution in the improvement of assembly operations efficiency. Indeed, as stated in the analysis of the current work procedure in chapter 4, nowadays material planners' main task is to arrange the material façade according to the assembly sequence set by manufacturing engineers and are not able to give suggestions to improve it.

Often this results in ill-balanced assembly lines, where some assembly stations have very poor efficiency performances forcing the operator to work in an uncomfortable way.

In order to figure out whether this technology can give a contribution also in this sense, a brief study about the working conditions on pallet line has been carried out. TMU data (figure 5.9) shows that, even if the overall performance of the whole line is good, there are some inefficient stations due to long walking distances that operators have to cover.

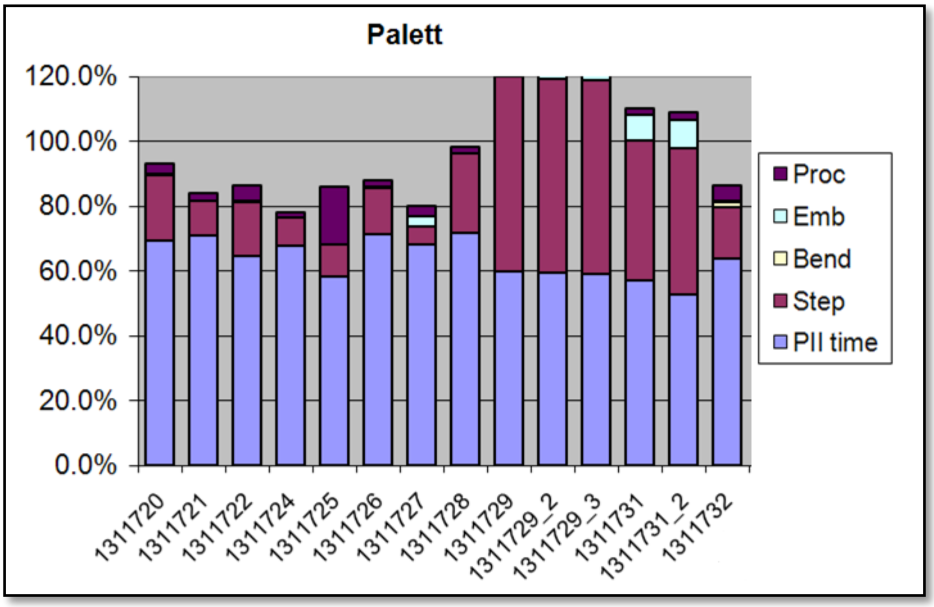

Figure 5.9 Data from TMU analysis

As shown in figure 5.9, station 1311729 has very bad step performance. This is a triple assembly station, meaning that there are three operators working together. Here operators have to tighten catalyst to the exhaust and have to assemble fuel lines, electrical wirings for the fuel pump, fuel line for the parking heater and refueling pipe to the tank. This station is about twenty meters long, and operators have to sort items from the material façade and to fix them onto the pallet. Pallets are moving along with the conveyor, thus the operators are pushed to keep pace with the moving pallets and try to finish their operations within the length of the station. Once an operation cannot be properly finished the conveyor will be stopped to fix the problem instantaneously, and this occurs hundreds times every day. Main issue is the fact that operators have to walk long distances and the station is overcrowding. Here the 80 % principle [14] is not at all fulfilled forcing operators to overlap their activities. On the left side of the conveyor there is station 1311732 which is little used. There is only one operator picking the fuel tank with a lifter from the racks and placing it on the powertrain. Tanks are stored on five big racks, but only three of them are used for the actual production. The remaining two racks are used as emergency stock in case that the tank falls from the lifter. In this case the team leader together with another operator can sort a tank from the safety racks and place it by hand on the powertrain preventing long stoppages in the flow. But this problem occurs rarely and the use of emergency racks is not necessary. As a result only half of this station is actually used.

This is a striking example of inefficient balancing in which one side of the conveyor is overcrowded while the other side is underutilized.

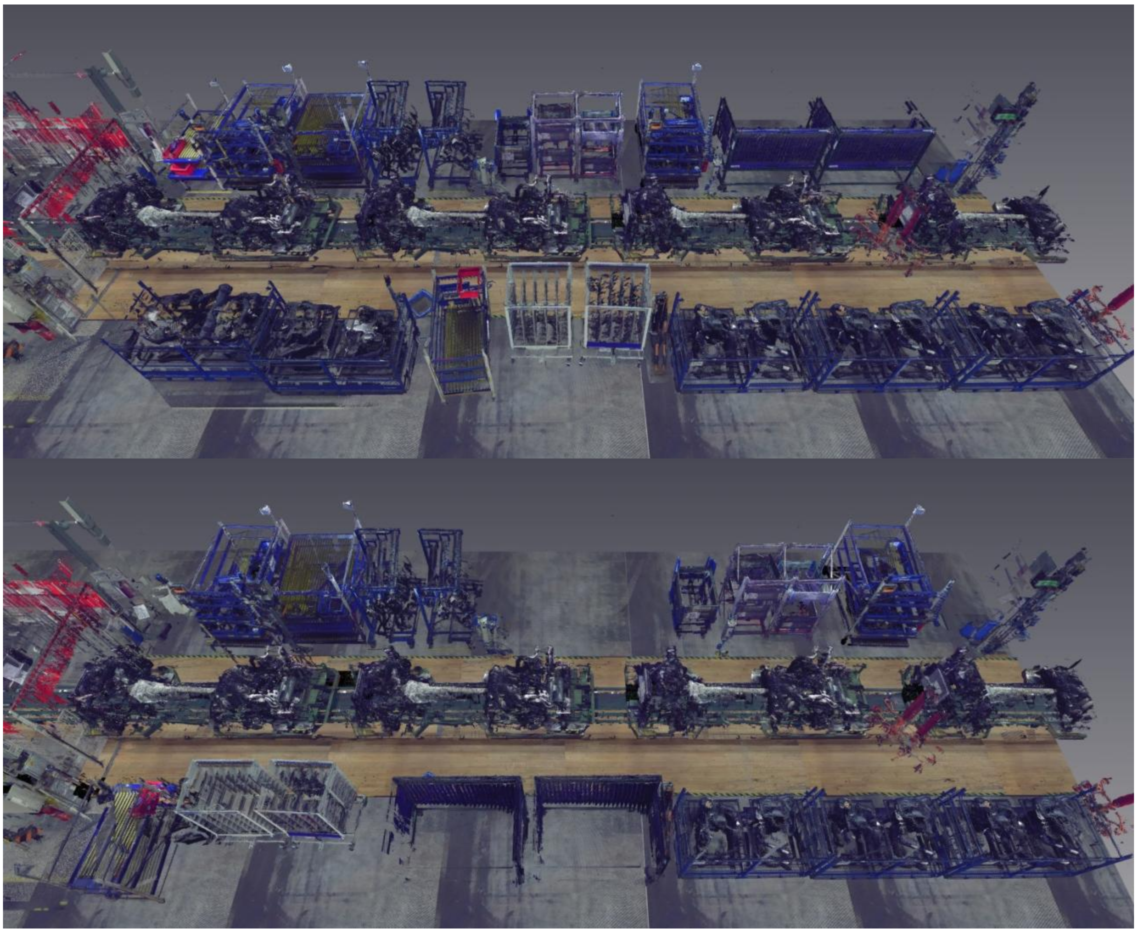

Figure 5.10 (a) Comparison between current and optimized situation - left view

Images elaborated in Pointools (figure 5.10a and 5.10b) show that by removing tank emergency racks it is possible to get some space and dedicate it to some of the assembly operations carried out on the other side of the conveyor. In this case 80 % principle [14] is fulfilled.

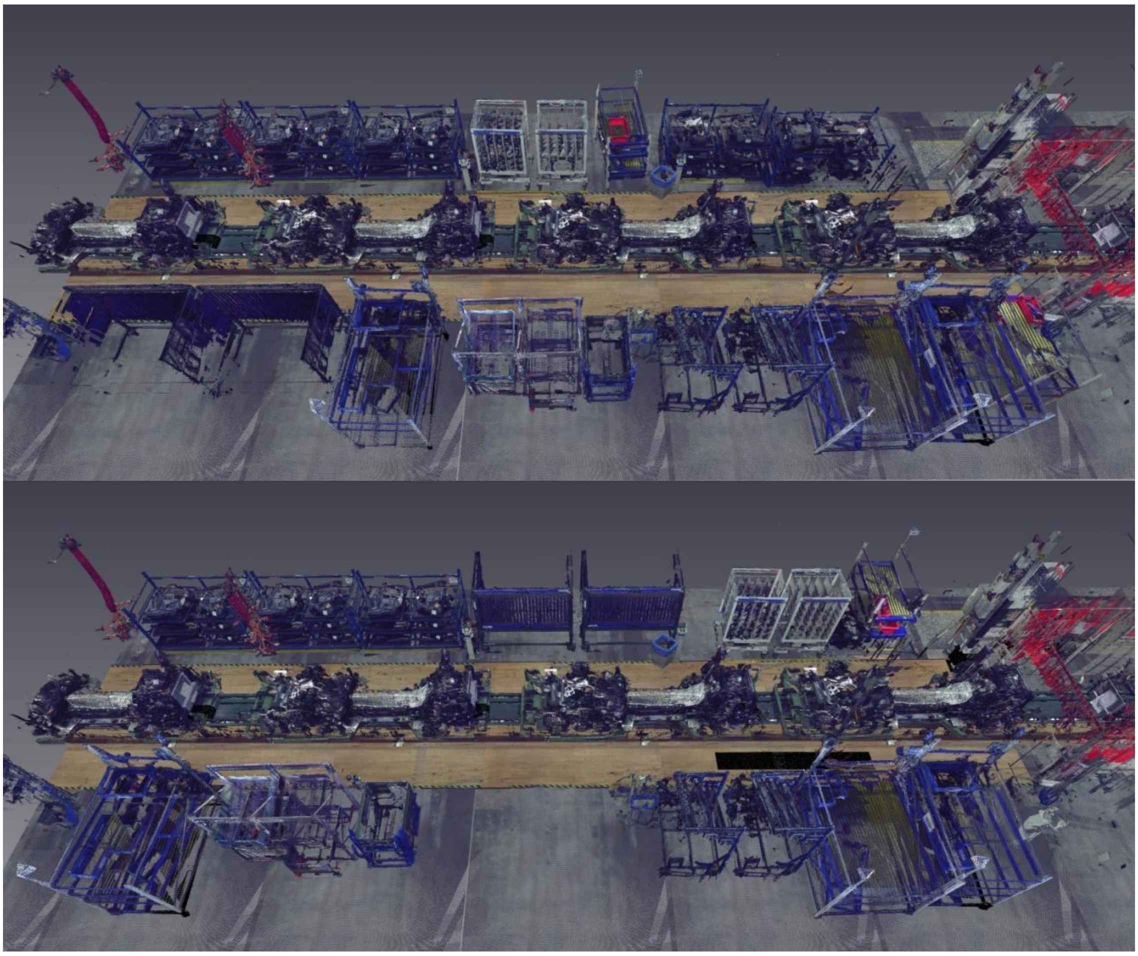

Figure 5.10 (b) Comparison between current and optimized situation - right view

Anyhow this solution cannot be implemented because all those items are placed on the right side of the car (figure 5.11). In other words now it is too late to propose such a solution. This suggests that if such investigation is carried out in the early stage of the project it is still possible to discuss with product designer and manufacturing engineers about these issues and to verify whether it is possible to place some of these items on the left side of the car.

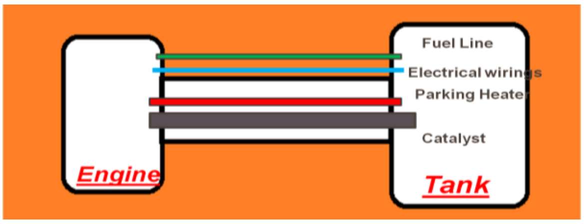

Figure 5.11 Product structure with components assembled in station 1311729

This simple example clearly shows that by supporting material planning activity with a design procedure it is easier to identify problems and to implement in a more effective way the line back principle [14]. With such a tool, material planners can give a higher contribution in the development of more efficient assembly processes. And in return it is also valuable for the company to reach more effective concurrent engineering working procedure [3].

6. Conclusions

Volvo's car projects are controlled by GPDS working logic, which is based on the idea of Concurrent engineering (CE). This working logic ensures the final quality of the project and controls costs and time schedule effectively. However, compared with product development and manufacturing process development, MP&L and layout development is not as sophisticated. One major reason is that material planners lack powerful graphical tools to support their work with clear visualization of both the current state and future evolution of layout arrangement. A well defined model of the layout should involve multiple facilities and equipment scattered in the plant, therefore requiring considerable effort and time to build such a model by conventional CAD modeling methods. Moreover, material façade arrangement changes frequently in the plant. It is therefore impossible to keep models up-to-date by conventional CAD approaches.

In this sense, 3D laser scanning technology with its rapid data acquisition and model building abilities provides MP&L great opportunities to improve performance, as proven by case studies in the assembly shop in Torslanda. Scanning a large area of the plant takes only a short period of time and provides basis data for modeling done in Pointools software. By simply copying, importing and moving point clouds of objects, new models can be easily built. Thanks to the precision of scanned data and well defined coordinate system, defining locations for facilities is simple and accurate. The resulting benefits are prominent. Studies of engine/gearbox temporary storage area and new station building in VBE show that with these tools visualization of MP&L and layout is enhanced, the evolution of MP&L and layout can be demonstrated in the virtual environment similar to a time machine, and the development process can be based on more concrete design activities. The case study of pellet line1 proposes more potential applications in MP&L and layout. Armed with graphical design tools, material planners are capable of being more involved in product and process development. Not only they would be able to discover and solve problems in their own work, but they would also be able to offer suggestions to product and process engineers to adjust their design in early stage, curtailing any future problems caused in the early stages.

In addition, rapid and accurate models enable further standardization of current working procedure, enabling engineers to make correct decisions initially in order to reduce the amount of future changes.

References

[1] Baily MN, Farrell D, Greenberg E, Henrich J, Jinjo N, Jolles M, Remes J. *Increasing global competition and labor productivity: lessons from the US automotive industry*: Mckinsey Global Institute; 2005.

[2] Volvo Car Corporation. *Volvo Cars pocket guide 2011*. Volvo Car Corporation. 2011.

[3] Skalak SC. *Implementing concurrent engineering in small companies*. New York: Marcel Dekke, Inc.;2002.

[4] Kusiak A. *Concurrent engineering: automation, tools, and techniques*. New York: John Wiley & Sons, Inc.; 1993.

[5] Niebel B, Freivalds A. *Methods, standards, and work design*. 11th ed. London: McGraw-Hill Companies; 2003.

[6] Slack N, Chambers S, Johnston R. *Operations management*. 3rd ed. Edinburgh: Pearson education; 2001.

[7] Baudin M. *Lean logistics: the nuts and bolts of delivering materials and goods.* New York, NY: Productivity Press; 2004.

[8] Hanson R. *On the options available in the design of in-plant material supply system*. PhD thesis. Chalmers University of Technology; 2009.

[9] Hales HL, Andersen BJ. Industrial engineering support for material management. In: Zandin KB (ed.) *Maynard's industrial engineering handbook*. 5th ed. New York: McGraw-Hill; 2001. p10.3-10.30.

[10] Petrie G, Toth CK. Introduction to Laser Ranging, Profiling, and Scanning. In: Shan J, Toth CK (eds.) *Topographic laser ranging and scanning - Principles and processing*. Boca Reton, FL: CRC Press; 2008 p4-5.

[11] Jivefors M. *Geometric simulation and OLP-preparation of robots*. Volvo Car Corporation; 2010.

[12] Volvo Cars Manufacturing System. *VCMS.* http://www.manufacturing.volvocars.ford.com/vcms/ (accessed 24 February 2011).

[13] Nord C. *VCM principles*. Volvo Car Corporation; 2008.

[14] Brynzér H. *MP&L & ME vision to support production efficiency*. Volvo Car Corporation; 2010.

[15] Robinson S, Bhatia V. *Winter Simulation Conference 1995: conference proceedings, Secrets of successful simulation project*，Orlando, Florida; 1995.

[16] Andersson L, Gennert H. *GPDS puzzle.* Volvo Car Corporation; 2008.

[17] Volvo Car Corporation. *Product Creation Process.* http://dspgot04.gothenburg.vcc.ford.com (accessed 7 March 2011).

[18] Lundgren I. *GPDS logic – 3 stage System alternative selection process.* Volvo Car Corporation; 2007.

[19] Klingstam P. *Mass Production Preparation.* Volvo Cars Manufacturing Engineering; 2010.

[20] Volvo Car Corporation. *MP&L Involvement in early phase.* http://dspgot04.gothenburg.vcc.ford.com (accessed 14 March 2011).

Appendices

Appendix A - FARO Laser Scanner Focus

FARO® Laser Scanner Focus3D

Intuitive touchscreen display
Control all scanner functions with a touch interface for unparalleled ease of use and control

Stand-alone solution
Ultraportable design allows for operation without external devices

Small and compact
With a size of only 24 x 20 x 10cm and a weight of just 5.0kg, the Focus3D is the smallest 3D scanner ever built

Integrated colour camera
Photorealistic 3D colour scans due to an integrated colour camera featuring an automatic 70 megapixels parallax-free colour overlay

High-performance battery
Integrated lithium-ion battery provides up to five hours of battery life and can be charged during operation

Data management
All data is stored on a SD card enabling easy and secure transfer to a PC. Using SCENE WebShare images can be shared on the internet

FARO Focus3D: Small, light, user-friendly

The Focus3D is a high-speed 3D scanner for detailed measurement and documentation. The Focus3D uses laser technology to produce incredibly detailed three-dimensional images of complex environments and geometries in only a few minutes. The Focus3D has a touch operated screen to control scanning functions and parameters. The resulting image is an assembly of millions of 3D measurement points in colour which provides an exact digital reproduction of existing conditions.

A leap in innovation and efficiency to lower your costs

The Focus3D offers the most efficient method for three-dimensional documentation of building construction, excavation volumes, façade and structural deformations, crime scenes, accident details, product geometry, factories, process plants and more. Given its minimal size and weight as well as touch interface, the Focus3D is easy to work with and saves up to 50% of scan time compared to conventional scanners.

Benefits

- **Complete 3D documentation:** Suitable for documentation of large spaces, quality control of components and reverse engineering
- **Precise & fast:** Its millimetre-accuracy and its 976,000 measurement points/sec mean precise and efficient measurement
- **Economical:** Unsurpassed cost-value proposition make every scanning project economical
- **Easy:** Compact design and touch interface

FARO® Laser Scanner Focus^{3D}




Specifications

Ranging unit

Unambiguity interval: 153.49m (503.58ft)

Range Focus^{3D} 120[1]: 0.6m - 120m indoor or outdoor with low ambient light and normal incidence to a 90% reflective surface

Range Focus^{3D} 20: 0.6m - 20m at normal incidence on >10% matte reflective surface

Measurement speed: 122,000 / 244,000 / 488,000 / 976,000 points/sec

Ranging error[2]: ±2mm at 10m and 25m, each at 90% and 10% reflectivity

Ranging noise[3]:

@10m - raw data: 0.6mm @ 90% refl. | 1.2mm @ 10% refl.

@10m - noise compressed[4]: 0.3mm @ 90% refl. | 0.6mm @ 10% refl.

@25m - raw data: 0.95mm @ 90% refl. | 2.2mm @ 10% refl.

@25m - noise compressed[4]: 0.5mm @ 90% refl. | 1.1mm @ 10% refl.

Colour unit

Resolution: Up to 70 megapixel colour

Dynamic colour feature: Automatic adaption of brightness

Deflection unit

Vertical field of view: 305°

Horizontal field of view: 360°

Vertical step size: 0.009° (40,960 3D pixels on 360°)

Horizontal step size: 0.009° (40,960 3D pixels on 360°)

Max. vertical scan speed: 5,820rpm or 97Hz

Laser (Optical transmitter)

Laser power (cw Ø): 20mW (Laser class 3R)

Wavelength: 905nm

Beam divergence: Typical 0.16mrad (0.009°)

Beam diameter at exit: 3.8mm, circular

Data handling and control

Data storage: SD, SDHC™, SDXC™; 32GB card included

Scanner control: Via touchscreen display

1) Depends on ambient light, which can act as a source of noise. Bright ambient light (e.g. sunshine) may shorten the actual range of the scanner to lesser distances. In low ambient light, the range can be more than 120m for normal incidence on high-reflective surfaces.
2) Ranging error is defined as the maximum error in the distance measured by the scanner from its origin point to a point on a planar target.
3) Ranging noise is defined as a standard deviation of values about the best-fit plane.
4) A noise-compression algorithm may be activated to average points in sets of 4 or 16, thereby compressing raw data noise by a factor of 2 or 4.
Subject to change without prior notice.

General

Power supply voltage: 19V (external supply), 14.4V (internal battery)

Power consumption: 40W and 80W respectively (while battery charges)

Battery life: Up to 5 hours

Ambient temperature: 5° - 40°C

Humidity: Non-condensing

Cable connector: Located in scanner mount

Weight: 5.0kg

Size: 240x200x100mm³

Maintenance calibration: Annual

Parallax-free: Yes

Dual-axes inclination sensor: Accuracy 0.015°; Range ±5°

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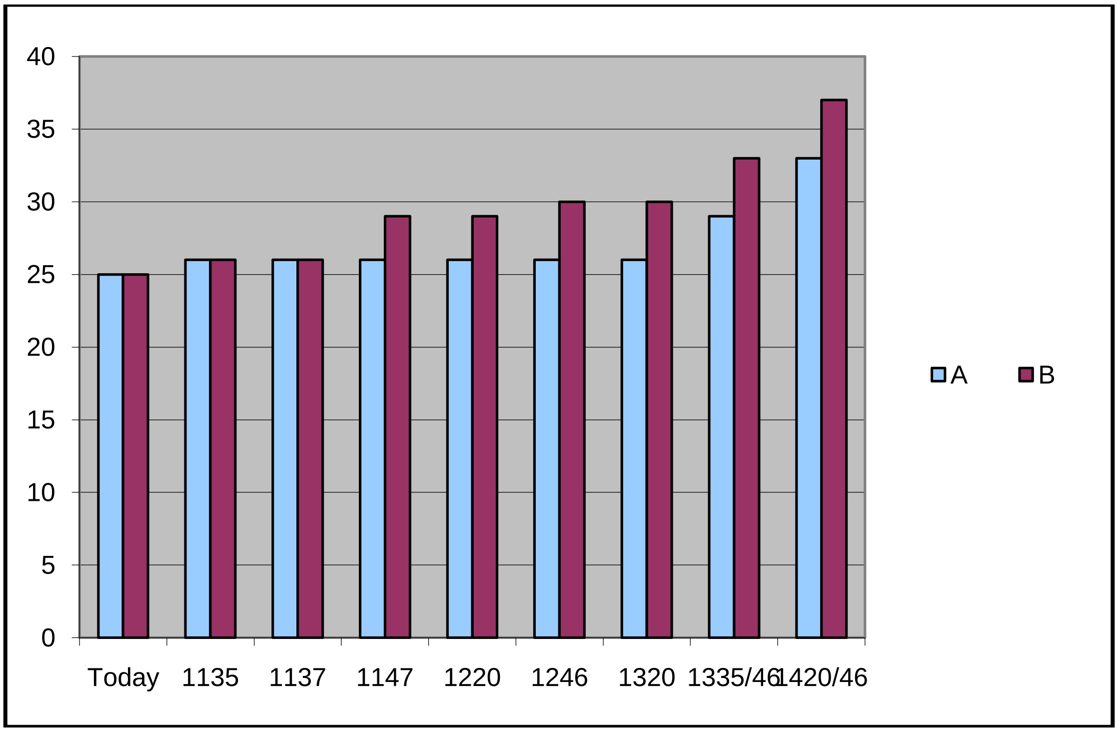
Appendix B – Data processing algorithm

The data received from Volvo for this practice is:
1. Nominal daily production rate:
   - 800 cars/day by 2 shifts till the end of year 2011
   - 1118 cars/day by 3 shifts from year 2012
2. Change in variants number

Engines



Vecka	A	B
Today	25	25
1135	26	26
1137	26	26
1147	26	29
1220	26	29
1246	26	30
1320	26	30
1335/46	29	33
1420/46	33	37

3. Current consumption data (the data in the following table is extracted from the original file)

Engine code	Engines/ day	Engine s/h	Production volume percentage (%)	Batch permanence time (h)	Classification
6906266	1.34	0.08	0.17	71.83	**Class C**
6906109	1.64	0.10	0.21	58.50	
6907037	1.74	0.11	0.22	55.09	
6906046	3.45	0.22	0.43	27.82	**Class B**
6908018	3.86	0.24	0.48	24.89	
6906243	4.06	0.25	0.51	23.64	
6906272	4.16	0.26	0.52	23.07	
6907049	4.47	0.28	0.56	21.49	
6907043	4.77	0.30	0.60	20.12	
6906261	4.87	0.30	0.61	19.70	
6908023	6.95	0.43	0.87	13.81	
6908007	8.02	0.50	1.00	11.97	
6906189	9.03	0.56	1.13	10.63	
6906276	10.15	0.63	1.27	9.46	
6907047	15.84	0.99	1.98	6.06	
6906253	24.57	1.54	3.07	3.91	
6906262	32.99	2.06	4.13	2.91	
6907041	33.09	2.07	4.14	2.90	
6906101	56.03	3.50	7.01	1.71	**Class A**
6906191	67.30	4.21	8.42	1.43	
6906263	88.52	5.53	11.08	1.08	
6906273	90.45	5.65	11.32	1.06	
6906274	95.22	5.95	11.92	1.01	
6906269	97.96	6.12	12.26	0.98	
6906214	128.61	8.04	16.10	0.75	

The distribution of variants in classes and the consumption rate of each variant in future scenarios are deduced from this data through the following algorithm. And the calculations of engines in week 1147 B are taken as an example.

1. Start with data of current state and calculate the percentage of variants in each class. Compare the number of variants in each class with the total number of variant to calculate the percentage of each class. Denote the percentages for Class A, B and C as a, b and c respectively.

	Engine	Gearbox
Class A	0.28	0.23
Class B	0.6	0.6
Class C	0.12	0.17

An assumption is made as the basis for further data processing: the percentage of each class remains the same at every scenario

2. Calculate the number of variant in each class for every scenario. Assume for a specific scenario the total number of variants is N. Thus the number of variants in class A, B and C are $a \cdot N$, $b \cdot N$ and $c \cdot N$.
   Usually the results are not integers. Then round up/down the results and keep the summation of them equals N.

Engine	Week 1147		Week 1420	
	A	B	A	B
Class A	7	8	9	10
Class B	16	17	20	22
Class C	3	4	4	5
N	26	29	33	37

3. Spread the production volume percentage over all the items obtained in the new list through the following steps:

3a) Calculate the number of additional variants in each class; N_1 represents the number of additional variants in Class A, while N_2 in Class B and N_3 in Class C.
In the case of week 1147 B one new variant is added to Class A and C, and two new variants are added to Class B, that is, N_2 equals 2 while N_1 and N_3 equal 1.
3b) Divide Class A into N_1 intervals, Class B into N_2 intervals and Class C into N_3 intervals.
3c) For each interval defined calculate the average production volume percentage n%.
3d) Assign each of the n% value obtained to the additional variants.
3e) Sum up n% values obtained in step d) and the result is denoted as K%

	New	% assigned
Class A	1	11.16
Class B	1	2.20
	1	0.53
Class C	1	0.20
Sum	4	14.08

3f) Calculate the production volume percentage of each old variant from the state of today as $p \cdot (1-K)\%$. Here the alphabet p stands for the production volume percentage of an old variant today.
3g) Insert the n% of additional variants in the new list obtained in the previous step and sort them in ascending order.

% list of today	New % list of week 1147 (B)	New % list of week 1147 (B) in ascending order
0.17	0.14	0.14
0.21	0.18	0.18
0.22	0.19	0.19
0.43	0.37	0.20
0.48	0.41	0.37
0.51	0.44	0.41
0.52	0.45	0.44
0.56	0.48	0.45
0.60	0.51	0.48
0.61	0.52	0.51
0.87	0.75	0.52
1.00	0.86	0.53
1.13	0.97	0.75
1.27	1.09	0.86
1.98	1.70	0.97
3.07	2.64	1.09
4.13	3.55	1.70
4.14	3.56	2.20
7.01	6.02	2.64
8.42	7.24	3.55
11.08	9.52	3.56
11.32	9.72	6.02
11.92	10.24	7.24
12.26	10.53	9.52
16.10	13.83	9.72
	11.16	10.24
	2.20	10.53
	0.53	11.16
	0.20	13.83

4. Calculate three critical values for production rate.

If the average production rate is V cars/day and for a certain variant its production volume percentage is p, then the consumption rate of engine can be calculated.

4a) Daily consumption rate: $V \cdot p$ per day
4b) Hourly consumption rate: $V \cdot p$ divided by working hours
4c) Batch permanence time: Batch capacity divided by hourly consumption rate

In the case of week 1147 B, V equals 800; working hours is 16, and batch capacity is 6. The result of calculation is listed in the following table.

Engines/day	Engines/h	Production volume percentage (%)	Batch permanence time (h)	Classification
1.15	0.07	0.14	83.60	Class C29
1.41	0.09	0.18	68.08	
1.50	0.09	0.19	64.12	
1.57	0.10	0.20	61.01	
2.97	0.19	0.37	32.37	Class B29
3.31	0.21	0.41	28.97	
3.49	0.22	0.44	27.52	
3.58	0.22	0.45	26.85	
3.84	0.24	0.48	25.02	
4.10	0.26	0.51	23.42	
4.19	0.26	0.52	22.93	
4.23	0.26	0.53	22.67	
5.97	0.37	0.75	16.07	
6.89	0.43	0.86	13.93	
7.76	0.49	0.97	12.37	
8.72	0.55	1.09	11.01	
13.61	0.85	1.70	7.06	
17.58	1.10	2.20	5.46	
21.11	1.32	2.64	4.55	
28.35	1.77	3.55	3.39	
28.43	1.78	3.56	3.38	
48.14	3.01	6.02	1.99	Class A29
57.83	3.61	7.24	1.66	
76.05	4.75	9.52	1.26	
77.71	4.86	9.72	1.24	
81.81	5.11	10.24	1.17	
84.16	5.26	10.53	1.14	
89.15	5.57	11.16	1.08	
110.50	6.91	13.83	0.87	

Data of other scenarios are calculated using the same algorithm and the results are listed below.

Week 1147 A

Engines/day	Engines/h	Production volume percentage (%)	Batch permanence time (h)	Classification
1.32	0.08	0.16	72.86	**Class C26**
1.62	0.10	0.20	59.34	
1.72	0.11	0.21	55.88	
3.40	0.21	0.43	28.22	**Class B26**
3.80	0.24	0.48	25.25	
4.00	0.25	0.50	23.98	
4.10	0.26	0.51	23.40	
4.40	0.28	0.55	21.80	
4.70	0.29	0.59	20.41	
4.80	0.30	0.60	19.99	
6.85	0.43	0.86	14.01	
7.91	0.49	0.99	12.14	
8.91	0.56	1.11	10.78	
10.01	0.63	1.25	9.59	
11.35	0.71	1.42	8.46	
15.61	0.98	1.95	6.15	
24.22	1.51	3.03	3.96	
32.52	2.03	4.07	2.95	
32.62	2.04	4.08	2.94	
55.24	3.45	6.91	1.74	**Class A26**
66.35	4.15	8.30	1.45	
87.26	5.45	10.92	1.10	
89.16	5.57	11.16	1.08	
93.86	5.87	11.75	1.02	
96.57	6.04	12.08	0.99	
126.79	7.92	15.87	0.76	

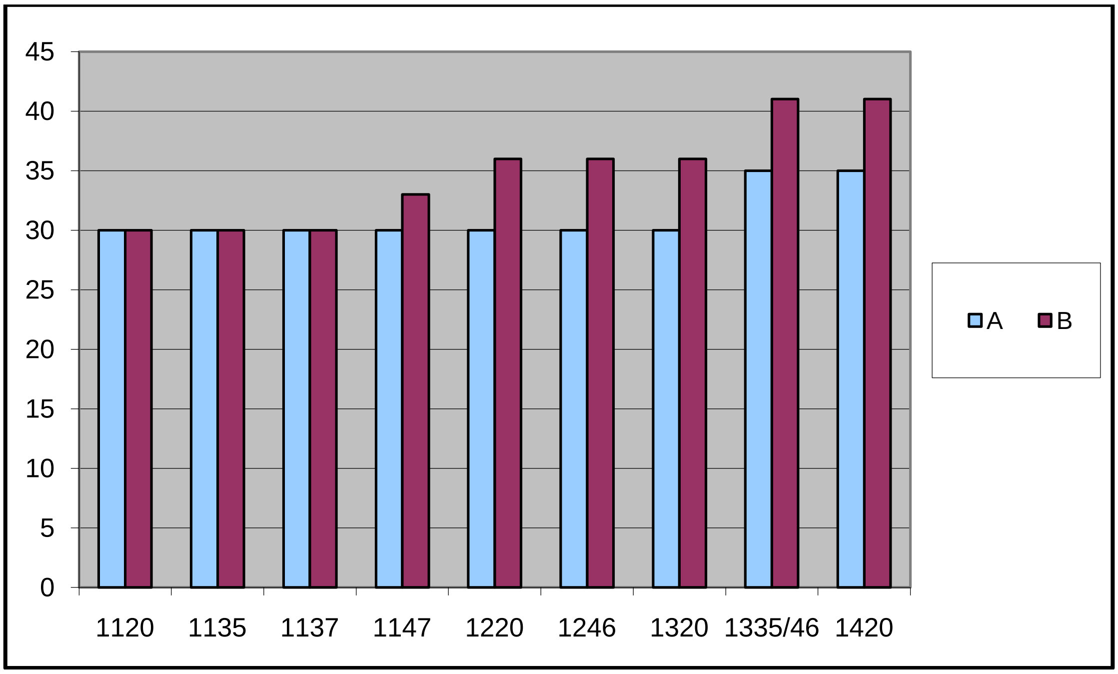
Week 1420 A

Engines/day	Engines/h	Production volume percentage (%)	Batch permanence time (h)	Classification
1.32	0.06	0.12	108.92	Class C33
1.62	0.07	0.15	88.70	
1.72	0.07	0.15	83.54	
2.20	0.09	0.20	65.41	
3.41	0.14	0.31	42.18	Class B33
3.82	0.16	0.34	37.74	
4.02	0.17	0.36	35.85	
4.12	0.17	0.37	34.98	
4.42	0.18	0.40	32.59	
4.72	0.20	0.42	30.51	
4.82	0.20	0.43	29.88	
5.30	0.22	0.47	27.16	
6.25	0.26	0.56	23.04	
6.88	0.29	0.62	20.94	
7.93	0.33	0.71	18.15	
8.94	0.37	0.80	16.11	
9.26	0.39	0.83	15.56	
10.04	0.42	0.90	14.34	
15.66	0.65	1.40	9.19	
16.33	0.68	1.46	8.82	
24.30	1.01	2.17	5.93	
32.63	1.36	2.92	4.41	
32.74	1.36	2.93	4.40	
42.28	1.76	3.78	3.41	
55.43	2.31	4.96	2.60	Class A33
66.57	2.77	5.95	2.16	
87.56	3.65	7.83	1.64	
89.47	3.73	8.00	1.61	
94.19	3.92	8.42	1.53	
96.90	4.04	8.67	1.49	
98.81	4.12	8.84	1.46	
127.23	5.30	11.38	1.13	
144.20	6.01	12.90	1.00	

Week 1420 B

Engines/day	Engines/h	Production volume percentage (%)	Batch permanence time (h)	Classification
1.06	0.04	0.10	135.40	Class C37
1.31	0.05	0.12	110.28	
1.39	0.06	0.12	103.85	
2.08	0.09	0.19	69.13	
2.37	0.10	0.21	60.83	
2.75	0.11	0.25	52.44	Class B37
3.07	0.13	0.27	46.92	
3.23	0.13	0.29	44.57	
3.31	0.14	0.30	43.48	
3.55	0.15	0.32	40.52	
3.80	0.16	0.34	37.93	
3.88	0.16	0.35	37.14	
5.11	0.21	0.46	28.16	
5.53	0.23	0.49	26.03	
5.92	0.25	0.53	24.33	
6.38	0.27	0.57	22.57	
6.75	0.28	0.60	21.34	
7.19	0.30	0.64	20.03	
8.08	0.34	0.72	17.83	
10.47	0.44	0.94	13.75	
12.60	0.53	1.13	11.43	
13.42	0.56	1.20	10.73	
19.55	0.81	1.75	7.37	
26.25	1.09	2.35	5.49	
26.33	1.10	2.36	5.47	
28.26	1.18	2.53	5.09	
44.59	1.86	3.99	3.23	
46.23	1.93	4.13	3.11	Class A37
53.55	2.23	4.79	2.69	
70.43	2.93	6.30	2.04	
71.97	3.00	6.44	2.00	
75.76	3.16	6.78	1.90	
77.95	3.25	6.97	1.85	
86.28	3.60	7.72	1.67	
102.34	4.26	9.15	1.41	
125.20	5.22	11.20	1.15	
150.08	6.25	13.42	0.96	

Gearboxes



Vecka	A	B
1120	30	30
1135	30	30
1137	30	30
1147	30	33
1220	30	36
1246	30	36
1320	30	36
1335/46	35	41
1420	35	41

Data about gearboxes are generated following the same procedure as engines until step 4b)
Here is needed a procedure to define also the type of pallet in which additional gearbox variants will be stored.

5. Evaluate the proportion of each type of pallet in every class of gearboxes. Assume that this proportion will remain the same also in the future scenarios.

Today	**R40**	**L04**	**R07/R42**	**D01**	**R00/R41/R64**
n of pallets	18	5	2	1	4
%	0.60	0.17	0.07	0.03	0.13

6. For each scenario calculate the new number of each pallet type for every class of gearboxes rounding up/down results obtained.

1147 B	R40	L04	R07/R42	D01	R00/R41/R64
Current %	0.60	0.17	0.07	0.03	0.13
	19.8	5.5	2.2	1.1	4.4
Future n of pallets	20	6	2	1	4

7. Assign to each of the additional variants a new pallet type.

8. Evaluate batch permanence time: Batch capacity divided by hourly consumption rate

Week 1120 & 1147 A

GB code	GB/day	GB/h	%	Pallet capacity	Batch permanence time (h)	Class
31272381	0.20	0.01	0.03	5	394.05	**Class C**
1283169	0.71	0.04	0.09	5	112.59	
31259314	1.02	0.06	0.13	5	78.81	
1283161	1.22	0.08	0.15	5	65.68	
1285018	2.54	0.16	0.32	6	37.83	
31259509	3.86	0.24	0.48	6	24.89	**Class B**
31272291	4.06	0.25	0.51	20	78.81	
31259572	4.16	0.26	0.52	6	23.07	
1283137	4.87	0.30	0.61	5	16.42	
1283163	6.90	0.43	0.86	5	11.59	
1283145	7.82	0.49	0.98	5	10.24	
1283182	9.03	0.56	1.13	10	17.71	
30783235	10.15	0.63	1.27	6	9.46	
1283190	10.56	0.66	1.32	20	30.31	
1283160	11.57	0.72	1.45	5	6.91	
1283158	12.59	0.79	1.58	5	6.36	
31256204	13.09	0.82	1.64	5	6.11	
1283191	14.21	0.89	1.78	20	22.52	
1283144	16.75	1.05	2.10	5	4.78	
31259859	23.35	1.46	2.92	5	3.43	
31259758	24.67	1.54	3.09	10	6.49	
1283143	24.67	1.54	3.09	5	3.24	
1283168	25.17	1.57	3.15	5	3.18	
1283162	50.25	3.14	6.29	5	1.59	**Class A**
31259858	52.99	3.31	6.63	5	1.51	
31259278	56.03	3.50	7.01	12	3.43	
31259317	84.05	5.25	10.52	5	0.95	
1283142	100.62	6.29	12.59	5	0.80	
1285017	102.68	6.42	12.85	6	0.93	
1285030	119.30	7.46	14.93	20	2.68	

Week 1147 B

GB/day	GB/h	%	Pallet capacity	Batch permanence time (h)	Class
0.18	0.01	0.02	5	454.40	Class C
0.62	0.04	0.08	5	129.83	
0.88	0.06	0.11	5	90.88	
1.06	0.07	0.13	5	75.73	
2.20	0.14	0.28	6	43.62	
3.35	0.21	0.42	6	28.70	Class B
3.52	0.22	0.44	20	90.88	
3.61	0.23	0.45	6	26.60	
4.23	0.26	0.53	5	18.93	
5.99	0.37	0.75	5	13.36	
6.78	0.42	0.85	5	11.80	
6.82	0.43	0.85	5	11.72	
7.83	0.49	0.98	10	20.42	
8.80	0.55	1.10	6	10.91	
9.16	0.57	1.15	20	34.95	
10.04	0.63	1.26	5	7.97	
10.92	0.68	1.37	5	7.33	
11.36	0.71	1.42	5	7.04	
12.32	0.77	1.54	20	25.97	
14.52	0.91	1.82	5	5.51	
18.45	1.15	2.31	6	5.20	
20.25	1.27	2.53	5	3.95	
21.39	1.34	2.68	10	7.48	
21.39	1.34	2.68	5	3.74	
21.83	1.36	2.73	5	3.66	
43.57	2.72	5.45	5	1.84	Class A
45.95	2.87	5.75	5	1.74	
48.59	3.04	6.08	12	3.95	
72.89	4.56	9.12	5	1.10	
80.85	5.05	10.12	5	0.99	
87.26	5.45	10.92	5	0.92	
89.04	5.57	11.14	6	1.08	
103.45	6.47	12.95	20	3.09	

Week 1420 A

GB/day	GB/h	%	Pallet capacity	Batch permanence time (h)	Class
0.24	0.01	0.02	5	494.64	Class C
0.85	0.04	0.08	5	141.33	
1.21	0.05	0.11	5	98.93	
1.38	0.06	0.12	5	86.99	
1.46	0.06	0.13	5	82.44	
3.03	0.13	0.27	6	47.49	
4.61	0.19	0.41	6	31.24	Class B
4.85	0.20	0.43	20	98.93	
4.97	0.21	0.44	6	28.95	
5.82	0.24	0.52	5	20.61	
8.25	0.34	0.74	5	14.55	
9.34	0.39	0.84	5	12.85	
9.40	0.39	0.84	5	12.76	
10.80	0.45	0.97	10	22.23	
12.13	0.51	1.08	6	11.87	
12.62	0.53	1.13	20	38.05	
13.83	0.58	1.24	5	8.68	
15.04	0.63	1.35	5	7.98	
15.57	0.65	1.39	20	30.83	
15.65	0.65	1.40	5	7.67	
16.98	0.71	1.52	20	28.27	
20.01	0.83	1.79	5	6.00	
25.43	1.06	2.27	6	5.66	
27.90	1.16	2.50	5	4.30	
29.48	1.23	2.64	10	8.14	
29.48	1.23	2.64	5	4.07	
30.08	1.25	2.69	5	3.99	
60.04	2.50	5.37	5	2.00	Class A
63.32	2.64	5.66	5	1.90	
66.96	2.79	5.99	12	4.30	
100.44	4.18	8.98	5	1.19	
111.40	4.64	9.96	5	1.08	
120.24	5.01	10.75	5	1.00	
122.70	5.11	10.97	6	1.17	
142.55	5.94	12.75	20	3.37	

Week 1420 B

GB/day	GB/h	%	Pallet capacity	Batch permanence time (h)	Class
0.19	0.01	0.02	5	632.95	**Class C**
0.66	0.03	0.06	5	180.84	
0.95	0.04	0.08	5	126.59	
1.08	0.04	0.10	5	111.31	
1.14	0.05	0.10	5	105.49	
1.36	0.06	0.12	5	88.10	
2.37	0.10	0.21	6	60.76	
3.60	0.15	0.32	6	39.98	**Class B**
3.79	0.16	0.34	20	126.59	
3.89	0.16	0.35	6	37.05	
4.55	0.19	0.41	5	26.37	
6.45	0.27	0.58	5	18.62	
6.75	0.28	0.60	10	35.56	
7.30	0.30	0.65	5	16.44	
7.35	0.31	0.66	5	16.33	
8.44	0.35	0.75	10	28.45	
9.48	0.39	0.85	6	15.19	
9.86	0.41	0.88	20	48.69	
10.81	0.45	0.97	5	11.10	
11.75	0.49	1.05	5	10.21	
12.17	0.51	1.09	20	39.45	
12.23	0.51	1.09	5	9.81	
13.27	0.55	1.19	20	36.17	
13.66	0.57	1.22	5	8.78	
15.64	0.65	1.40	5	7.67	
19.87	0.83	1.78	6	7.25	
21.80	0.91	1.95	5	5.50	
23.04	0.96	2.06	10	10.42	
23.04	0.96	2.06	5	5.21	
23.51	0.98	2.10	5	5.10	
25.62	1.07	2.29	6	5.62	
46.92	1.96	4.20	5	2.56	**Class A**
49.48	2.06	4.43	5	2.43	
52.33	2.18	4.68	12	5.50	
72.69	3.03	6.50	5	1.65	
78.49	3.27	7.02	5	1.53	
87.06	3.63	7.79	5	1.38	
93.97	3.92	8.40	5	1.28	
95.89	4.00	8.58	6	1.50	
111.40	4.64	9.96	20	4.31	
124.22	5.18	11.11	5	0.97	

Appendix C – Number of racks for each scenario

Engines

1120

	n of variants	n of racks
Class A	7	10
Class B	15	15
Class C	3	2

1147 A

	n of variants	n of racks
Class A	7	10
Class B	16	16
Class C	3	2

1147 B

	n of variants	n of racks
Class A	8	11
Class B	17	17
Class C	4	2

1420 A

	n of variants	n of racks
Class A	9	12
Class B	20	20
Class C	4	2

1420 B

	n of variants	n of racks
Class A	10	13
Class B	22	22
Class C	5	2

Gearboxes

1120

	n of variants	n of small racks	n of big racks
Class A	7	8	2
Class B	18	13	5
Class C	5	2	0

1147 A

	n of variants	n of small racks	n of big racks
Class A	7	8	2
Class B	18	13	5
Class C	5	2	0

1147 B

	n of variants	n of small racks	n of big racks
Class A	8	10	2
Class B	20	15	5
Class C	5	2	0

1420 A

	n of variants	n of small racks	n of big racks
Class A	8	10	2
Class B	21	15	6
Class C	6	2	0

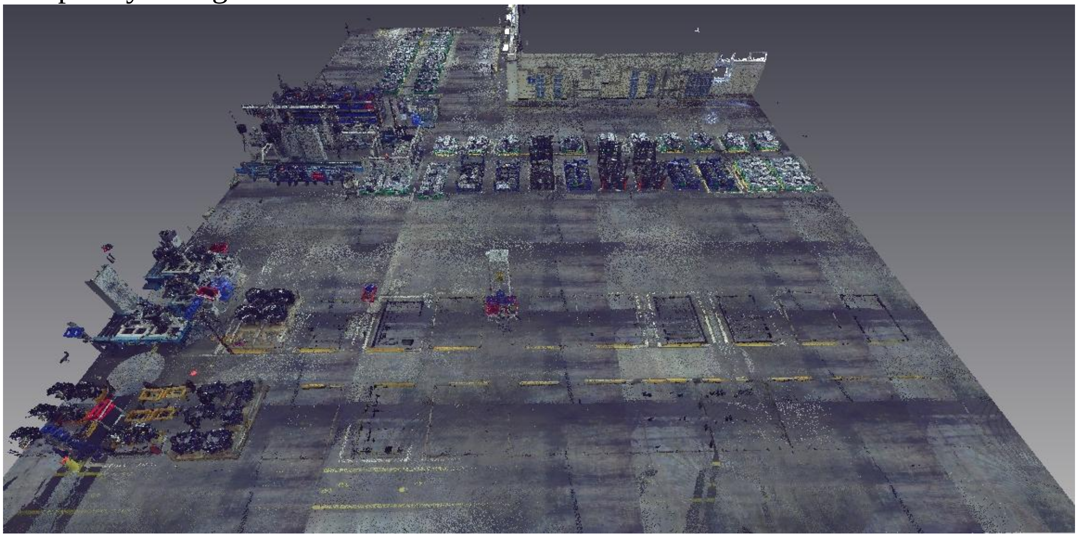
1420 B

	n of variants	n of small racks	n of big racks
Class A	10	11	2
Class B	24	17	7
Class C	7	2	0

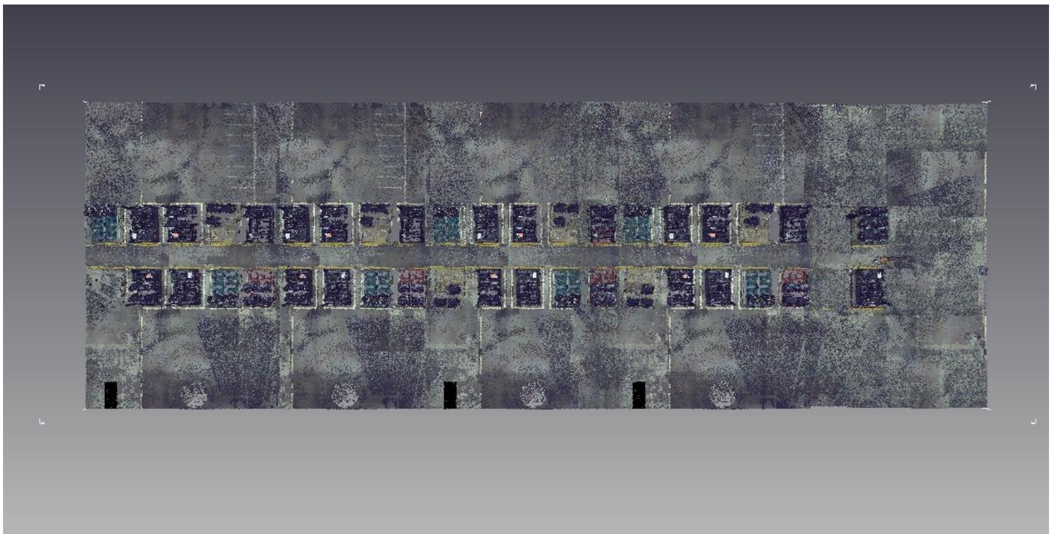
Appendix D – Pointools models for TSA and SA

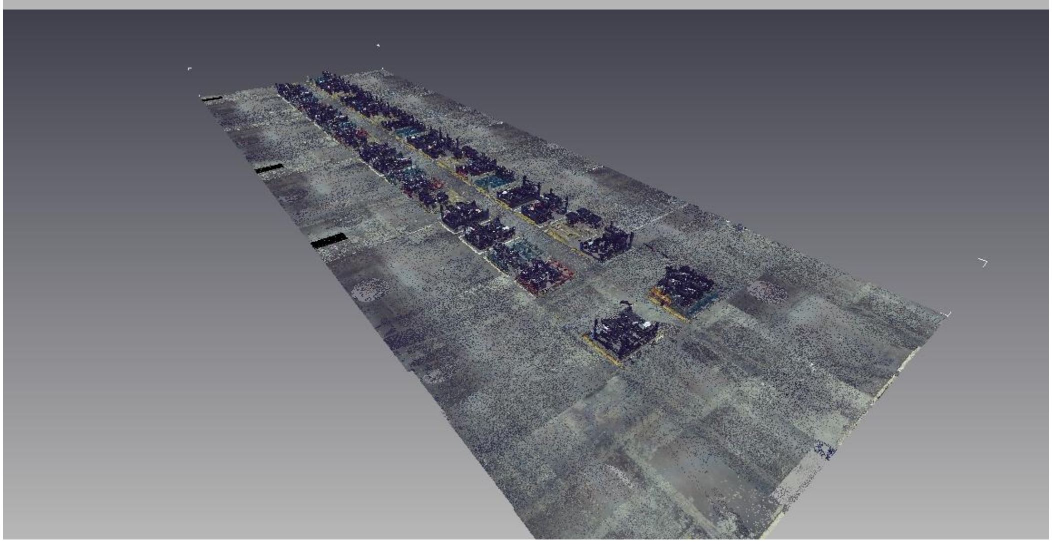
I. Full sequencing of engine (1420 B)

Temporary storage area



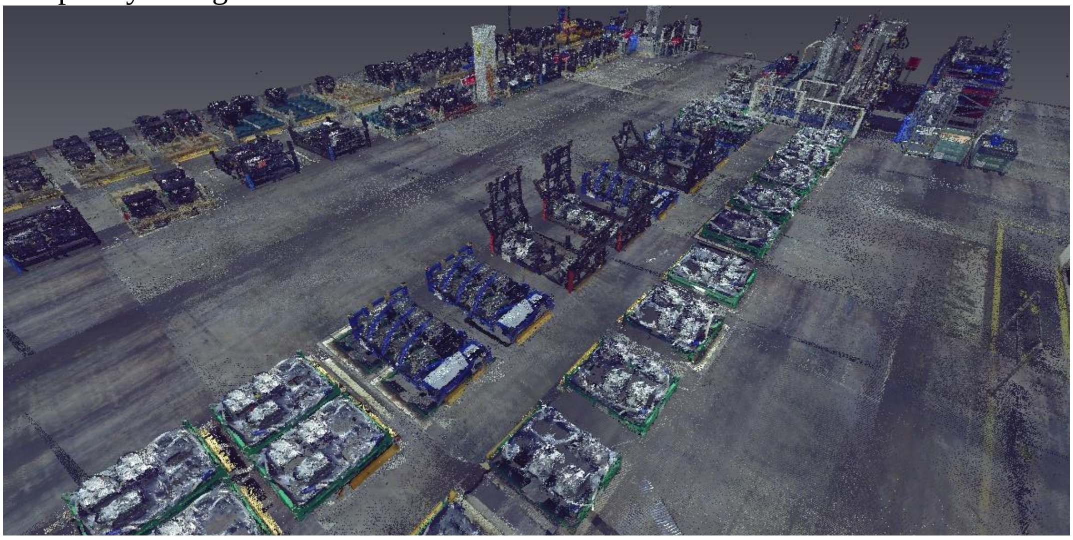
Tent





II. Shared sequencing of engines (1420 B)

Temporary storage area



Tent