An Applied Manufacturing System for
Highly-Complex Assembly Factory

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Abstract
This thesis focuses on a manufacturing system at a semiconductor equipment manufacturing company (SEMC). The company faces highly variable demand for its products that require highly-complex assembly within the factory. When the demand is low, the manufacturing factory must adjust the production performance, and implement various cost reductions in order to maintain profit. Hence, the major motivation of this thesis is to explore how a manufacturing factory that assembles highly-complex products can increase the degree of production volume flexibility.

The current situation of the factory is analyzed, using a three dimensional model of the current layout, based on the manual measurements on the floor. The key metrics to describe the concrete problems are defined, and the possible solutions for each problem are generated. Proposed layouts are designed to embody these solutions. The feedback on the proposals is collected from the different levels of managers, line leaders, and operators at the job floor. Based on the feedback, various analyses are performed to prove the practicality and effectiveness of proposed improvements, and the pilot proposal that focuses on one floor are made.

Potential solutions include sharing test equipment with several working spaces, aligning the product lines parallel to the overhead cranes, and consolidating inventory area. The results of simulations and experiments show clearly the reduced costs, improved safety and operations, efficient use of space and improved inventory management. Finally, the scaled-down pilot proposal, which focuses on the consolidated inventory and generic workbenches, was implemented.

Thesis Supervisor: Duane S. Boning
Title: Professor of Electrical Engineering and Computer Science
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5 Current Operations ............................................................................................................. 36
  5.1 Products ......................................................................................................................... 36
  5.2 Manufacturing ................................................................................................................. 36
    5.2.1 Machines and Modules .......................................................................................... 37
    5.2.2 Lines ......................................................................................................................... 37
  5.3 Subassembly Build .......................................................................................................... 37
    5.3.3 Cells ......................................................................................................................... 37
    5.3.4 Inventory ............................................................................................................... 38
    5.3.5 Tools and Fixtures ................................................................................................. 39
    5.3.6 Procedures ............................................................................................................. 39
    5.3.7 Testing .................................................................................................................... 39
    5.3.8 Delivery of Subassemblies ..................................................................................... 39
  5.4 Build and Test of Modules .............................................................................................. 40
    5.4.1 Build Bays ............................................................................................................... 40
    5.4.2 Inventory ............................................................................................................... 41
    5.4.3 Tools and Fixtures ................................................................................................. 41
    5.4.4 Procedures ............................................................................................................. 41
    5.4.5 Testing .................................................................................................................... 41
  5.5 Material Flow ................................................................................................................ 42
  6 Current Floor Layout ...................................................................................................... 46
  6.1 The Building .................................................................................................................. 46
    6.1.1 Material Flow in the Layout .................................................................................. 48
    6.1.2 Factory Assembly Lines in General ..................................................................... 48
  6.2 North Floor ...................................................................................................................... 48
    6.2.1 SE3 Line ............................................................................................................... 49
    6.2.2 SE2 Line ............................................................................................................... 50
    6.2.3 SE1 Line ............................................................................................................... 52
    6.2.4 Cells of the North Floor ..................................................................................... 52
  6.3 Mid Floor and the South Floor ....................................................................................... 53
    6.3.1 SE4 Line ............................................................................................................... 54
    6.3.2 SEMOD1 Line .................................................................................................... 55
6.3.3 SE5 Line.......................................................................................... 56
6.3.4 Lowermost Line................................................................................ 58
6.4 Summary and Conclusion of the Current Layout................................... 60

7 Driving Principles for New Floor Layouts.................................................... 61
7.1 Subassembly Build .............................................................................. 61
  7.1.1 Cells ................................................................................................ 62
  7.1.2 Centralized Inventory ........................................................................ 62
  7.1.3 Comparison ...................................................................................... 62
7.2 Module Build.......................................................................................... 63
  7.2.1 Line Inventory and Product Specific Build Areas.............................. 63
  7.2.2 Product Specific Centralized Inventory and Build Areas.................. 63
  7.2.3 Kitted Inventory and Flexible Areas................................................... 64
  7.2.4 Comparison ...................................................................................... 64
7.3 Module Test ........................................................................................... 65
  7.3.1 Product Specific Areas for Testing ..................................................... 65
  7.3.2 Centrally Located Test Equipment ..................................................... 65
  7.3.3 Movable Test Equipment .................................................................. 66
  7.3.4 Comparison ...................................................................................... 66
7.4 Summary ................................................................................................ 67

8 Three Layout Proposals ............................................................................. 69
8.1 Proposal A ............................................................................................ 70
8.2 Proposal B ............................................................................................ 72
8.3 Proposal C ............................................................................................ 73

9 Proposal B in Detail .................................................................................. 77
  9.1 Layout of Build Areas of Subassemblies .............................................. 77
  9.2 Layout of Build Area of Modules .......................................................... 78
  9.3 Potential Benefits ................................................................................ 79
  9.4 Utilization Analysis of SE1 Work Spaces.............................................. 81
    9.4.5 Results of Utilization Analysis ......................................................... 81
    9.4.6 Results of Analysis and Proposed Layout ....................................... 82
  9.5 Possible Cost Reduction ....................................................................... 84
List of Figures

Figure 3-1: Logic Steps of Methodology ............................................................. 24
Figure 3-2: Chronologic Steps of Methodology .................................................... 25
Figure 5-1: Material supply at SEMC ................................................................ 43
Figure 6-1: Current Layout of the whole factory at SEMC .................................... 47
Figure 6-2: Current Layout of the North Floor ....................................................... 49
Figure 6-3: Current Layout of the SE3 Line .......................................................... 50
Figure 6-4: Current Layout of the SE2 Line .......................................................... 51
Figure 6-5: Current Layout of the SE1 line ........................................................... 52
Figure 6-6: Current Layout of the Cells of the North Floor .................................... 53
Figure 6-7: Current Layout of the Mid Floor and the South Floor ......................... 54
Figure 6-8: Current Layout of the SE4 Line ......................................................... 55
Figure 6-9: Current Layout of the SEMOD1 Line ................................................ 56
Figure 6-10: Current Layout of the SE5 Line ....................................................... 57
Figure 6-11: Current Layout of the Lowermost Line ........................................... 59
Figure 7-1: Necessary Movement of Modules ....................................................... 65
Figure 7-2: Centrally Located Test Equipment ..................................................... 66
Figure 8-1: Floor Layout Proposal A [8] ............................................................... 70
Figure 8-2: Layout Proposal A for the SE4 Line [8] ............................................. 71
Figure 8-3: Floor Layout Proposal B ................................................................. 73
Figure 8-4: Proposal C Floor Layout [9] ................................................................. 75
Figure 9-1: Build Area of the SEMOD1 Subassemblies ........................................... 78
Figure 9-2: Build Area of the SE2 Modules .............................................................. 79
Figure 9-3: Utilization Analysis of the SE1 Cells and Bays ........................................ 81
Figure 9-4: The Proposed Layout of the SE1 Line .................................................. 83
Figure 10-1: Pilot Layout (North Floor) ...................................................................... 87
Figure 10-2: Proposed Design of Generic Workbench ............................................... 93
Figure 10-3: Layout of the Bins for the Subassembly E11358690 ............................ 101
Figure 10-4: Layout of the Bins for the Complex Subassembly ............................... 102
Figure 10-5: Supermarket Simulation ...................................................................... 104
Figure 10-6: Cycle Time Distribution Function for Material Handlers .................... 105
Figure 10-7: Cycle Time Distribution Function for Assemblers ............................... 105
List of Tables

Table 2-1: Key metrics in ranked order ........................................................................ 20
Table 6-1: Sizes of Floor Areas .................................................................................. 47
Table 8-1: Combinations of principles for the different floor layout proposals ......... 69
Table 10-1: Combinations of Principles for the Different Proposals ......................... 85
Table 10-2: List of regular tools stored at the generic workbenches ......................... 92
Table 10-3: Estimation of costs to purchase tools ...................................................... 94
Table 10-4: Example to illustrate worst cast scenario of needed tray space ............. 98
Table 10-5: A good solution for cavity sizes ............................................................ 99
Table 10-6: Four standard sizes of bins ..................................................................... 100
Table 10-7: Inner size and foot prints of the bins ...................................................... 100
Table 10-8: Cost analysis of required bins for the entire system .............................. 102
Table 10-9: Average utilization of during 1000 hour simulation period ................... 106
Table 10-10: Units done within 1000 hours simulation period .................................. 106
Table 10-11: Time study results: Time to gather 81 parts in “supermarket” ............ 108
Table 10-12: Build time comparison for subassembly build .................................. 109
Table A-1: Groups of necessary special tools (part 1) ............................................. 117
Table A-2: Groups of necessary special tools (part 2) ............................................. 117
Table A-3: Groups and part numbers of subassemblies .......................................... 117
Chapter 1

Introduction

Semiconductor Equipment are machines required for one of approximately 40 different types of process steps in semiconductor manufacturing. The machines are highly complex tools, since they consist of several thousand parts and subassemblies. They are also of large size and weight, on the order of 30 ft and 20 tons.

The equipment is part of every semiconductor fabrication facility and their market is characterized by high differentiation among competitors. That is, equipment built by different companies is of very different quality from the customers’ perspective. The customers’ willingness to pay strongly correlates with the equipment’s performance and productivity, mainly evolving from the company’s expertise and patents in equipment R&D. This is the core competency of the Semiconductor Equipment Manufacturing Company (SEMC).

However, manufacturing operations have a high impact on the company’s performance, since they are a big cost driver. Customers, who typically have a high buying power, expect on-time delivery and high quality. These are as well attributes affected by manufacturing operations. The company’s main focus within this domain is accordingly to reduce costs while meeting the customers’ expectations in terms of quality and timeliness. SEMC manufacturing operations consist of assembly, testing,

\[\text{\footnotesize\textsuperscript{1}}\text{ Company and product names are disguised for confidentiality reasons} \]

16
and shipping as well as the setup of new equipment at the customer’s site. Also, SEMC offers customer service around the globe for repair and maintenance.

Due to the equipment’s high part count and the high amount of parts that differ upon customer request, a key challenge in SEMC’s manufacturing operations is management of complexity.

1.1 The MIT-SEMC Project

Part of the Master of Engineering in Manufacturing program in the Department of Mechanical Engineering at MIT, is a company based project. Students work in teams of three on a project that currently concerns the host company. This includes on-site visits to the company once a week during the spring term, which is the second term of the 12 months long program, and full time work at the company during the adjacent summer term.

As SEMC is currently facing a period of low demand, the assembly plant is running under low workload. This setting is robust towards changes in operations and floor layout; that is, the risk of falling behind the production schedule due to such changes is lower. Therefore, our team was given the task to develop proposals for a new floor layout of the main assembly area that is tailored to SEMC’s operational characteristics and future strategic directions.

1.2 Overview

Chapter 2 defines the scope and the goals and therefore serves as a basis for the entire project. Chapter 3 introduces the reader to the approaches used throughout the project at a high level. Chapter 4 provides background information from the literature, and explains the links between the project and the literature used. Chapter 5 and Chapter 6 present the results of the first activities at SEMC; documenting the current state of the floor layout and associated operations. Prior to generating actual floor layout proposals, operational driving principles are identified (Chapter 7) that would
guide the subsequently generated layout proposals (Chapter 8), which are presented to SEMC managers. After the decision is made by SEMC management that a changeover would not be taken in a single step, our team develops a pilot proposal (Chapter 10) in an iterative process based on feedback from SEMC employees. The pilot proposal idea is to prove the concepts that were used in our initial proposals on a smaller scale, prior to large scale implementation, in order to reduce the risks associated with factory floor layout changes.
Chapter 2

Problem Statement

This section describes what the issues within the manufacturing operations are and what should be improved in the future. The team tackles these issues during the project by proposing new floor layouts and operational solutions.

Operational improvement can be achieved by a change of the floor plan at SEMC. This may also lead to or enable changes in operational processes. Improvement is measured by several key metrics that were developed in discussions with the SEMC manufacturing management team. The key metrics describe areas within SEMC’s manufacturing activities that are perceived as not optimal and that need improvements. The key metrics have not been measured in the past and are therefore used as qualitative guidelines and not as quantitative hard numbers. Lead time reduction and improvement of inventory management share the most important rank, as shown in Table 2-1. Metrics that deserve the same importance also receive the same ranks.

The project team was asked to propose new floor layouts and operations that improve the key metrics.

Table 2-1: Key metrics in ranked order

<table>
<thead>
<tr>
<th>Rank</th>
<th>Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Lead Time Reduction</td>
</tr>
<tr>
<td>1.</td>
<td>Inventory Management</td>
</tr>
<tr>
<td>3.</td>
<td>Floor Space</td>
</tr>
<tr>
<td>4.</td>
<td>Testing</td>
</tr>
<tr>
<td>4.</td>
<td>Cross-Training</td>
</tr>
<tr>
<td>4.</td>
<td>Volume Flexibility</td>
</tr>
</tbody>
</table>
2.1 Lead Time Reduction

The unpredictable demand for semiconductors is one of the main reasons for the cyclical fluctuating demand of SEMC’s customers. For the benefit of these customers, it is important to enable swift delivery of machines so the customers can react to demand changes. On the manufacturing side of SEMC, the high capital cost of unfinished machines make a short lead time desirable. Therefore, operational changes that reduce the lead time are crucial to increase customer satisfaction and reduce manufacturing costs.

2.2 Inventory

Inventory on the job floor creates capital costs and takes up floor space. Too much inventory increases search and pick times and inventory management costs. Missing inventory, on the other hand, interrupts the assembly process and creates additional cost due to idle time. Therefore, inventory reduction on the job floor is important, but must not lead to decreased availability of inventory and reduced assembly performance. Higher availability of inventory than in the current system is sought-after.

An inventory system within the facility that allows easy relocation of some portion of the inventory to a different building is desirable because of the increased volume in the future, since floor space in the assembly area is more expensive than in a warehouse.

2.3 Floor Space

Floor space is critical for manufacturing at SEMC. SEMC is planning to increase revenue by 100% through increased volume within the same facility. New products and increasing demand have taken up floor space and sacrificed space that was used
for new product introductions (NPI). To be able to add more new products and to improve the NPI process, free floor space is necessary and valuable for SEMC. Floor space should therefore be used as efficiently as possible.

### 2.4 Testing

Testing is often a bottleneck in the assembly process. A module that does not pass the testing process and requires rework might block the test equipment and hinder subsequent machines from being tested. This can lead to a stop in the build line until the machine in the test bay has passed the test process. Moving machines from assembly bays to test bays is associated with high costs and safety concerns for the employees. Therefore, an assembly system that increases testing flexibility and reduces the movement of modules is desirable.

### 2.5 Cross-Training

Changing demand and changing workforce and new machines are typical for SEMC. A transparent and standardized assembly system that facilitates cross-training is important. Cross-training is most active when demand is rising and new employees are added to the assembly facility.

### 2.6 Volume Flexibility

Demand for machines changes quickly. Demand can increase and decrease within a product line, but also shift from one product line to a different one with short notice. An assembly system that allows SEMC to change the distribution of assembly resources or to increase or decrease these rapidly as demand changes is critical.
Chapter 3

Methodology

This section describes the methodology that the team applies to understand the system, create proposals and improve proposals as well.

The goal of the project is to improve manufacturing. The upper level of the methodology of the improvement process can be described as five steps. These are defining goals, capturing current state, creating proposals, challenging proposals, and improving proposals. The last two steps are repeated in an iterative process. If improving proposals fails, going back to the step creating proposals is required.

Figure 3-1: Logic Steps of Methodology
In the chronologic view the steps translate into the process, shown in Figure 3-2; several tasks happen parallel and iterations occur when layout proposals are created and the pilot floor plan is created and analyzed.

Figure 3-2: Chronologic Steps of Methodology

3.1 Defining Goals

The goals are defined in the initial meeting with the mid-level manufacturing managers. Key metrics (Chapter 2) are defined and used to explain the goals. A review of the goals is conducted in different discussions with manufacturing managers from all levels throughout the project. This is necessary to better understand the underlying situation that the key metrics represent.

3.2 Capturing the Current State

To understand the company and to create a baseline for potential improvement, the current state is recorded. This includes assessment of both the physical environment and the operational systems used in the SEMC factory.
To capture the physical environment, the manufacturing facility is measured with common tools such as measuring tapes. The facility is modeled with the CAD program Solidworks ©. In the next step, the project team members each assign to an individual part of the facility, and all furniture and work in process is measured and added to the CAD model.

During the CAD modeling process, the team members interview operators on the job floor and identify the assembly steps and constraints of the manufacturing operations. The interviews also reveal different symptoms that are discussed as key metrics for improvement in Chapter 2. Notes are taken during the interviews and the topics are discussed within the team. In addition, a web based knowledge database supports the team in the process of collecting information.

3.3 Creating Proposals

The process in which new factory layout proposals are developed is described thoroughly in Chapter 7 and Chapter 8. In the first step, driving principles of manufacturing operations are found through discussions within the team. The principles strongly affect the key metrics from Chapter 2. In the second step, an idea generation methodology called the *Morphologic Approach* is applied to derive new concepts for floor layouts by combining driving principles [1]. Three concepts that appear most interesting to the team are identified. In the final step, each team member creates one floor layout proposal using Solidworks and the three dimensional models of the facility, the furniture, the work in process and the equipment that were created in the previous step.

In addition, proposals for operational solutions and detailed practical aspects are also created. These range from work flow diagrams that are created with tools like Microsoft Visio, to the identification of possible suppliers that can produce foam cut-outs for a parts picking process.
3.4 Challenging Proposals

Proposals are challenged in different ways. Proposals are first discussed with operators who are affected by the proposal. If the proposal appears to be feasible to the operators, it is presented in a meeting to the managers of manufacturing. Questions during the meetings or follow up discussions reveal problems within the proposal and add suggestions that can improve the proposal. In addition, some proposals are challenged by calculations and simulations. E.g. floor space savings are measured in the CAD program; required inventory storage space is determined from a sample on the job floor and scaled up. Possible savings are calculated through a comparison of the current state and the proposed state. New operations are tested as an experiment in a mock up scenario and measurement are taken. Physical solutions are prototyped and examined. Operational alternatives are simulated with the Excel plug-ins. Chapter 10 explains the detailed analyses that are conducted.

3.5 Improving Proposals

Problems that are found during the challenge of the proposal are now solved. It is a creative process. In the case of floor layout proposals, the furniture is rearranged keeping the constraints of the operations in mind. If the problem cannot be solved and the proposal proves to be infeasible, the proposal is discarded. A new proposal is created according to process discussed in section 3.3.
Chapter 4

Literature Review

This project draws upon relevant literature and previous work in the fields of Lean manufacturing and idea generation. This chapter summarizes key literature in each of these areas.

4.1 Manufacturing Theory

Since the project was performed in the assembly facility of SEMC, manufacturing theory proves to be helpful. In particular, queuing theory and supply chain management concepts help guide the design of alternative factory floor layouts and systems.

4.1.1 Queuing

The MIT course *Introduction to Manufacturing Systems* provides an overview of different queuing systems [2]. The chain of assembly related tasks in the subassembly area of SEMC is analyzed with queuing theory to be able to find the best mode of operations. While this is a vast area of research, analyses based on a few key ideas and scenarios provide the basic insight needed to guide the factory floor design.

In many cases the assembly line is set up such that one station or cell services parts or tasks. An M/M/1 queue means that the interarrival time is Markovian distrib-
uted (first M), the service time is also Markovian distributed (second M), and only one server is available (1). The arrival rate is described as $\lambda$, which means that the arrival time is $1/\lambda$. The service rate is described as $\mu$, which means that the service time is $1/\mu$.

In many other cases, the assembly floor can be arranged so that multiple stations or cells are capable of servicing parts or tasks. The M/M/k queue is similar to the M/M/1 queue. The only difference is that not one but k servers are available. The M/M/k queue has only one queue, and the items choose the available server when they arrive at the end of the queue. This is a common practice in airports, where passengers wait in one queue before they check in and choose the counter when it's their turn.

In the scenario at SEMC, different orders wait to be assembled. In the M/M/k queue, they wait for one out of several operators to be assembled. In the M/M/1 queue, each operator has a couple of waiting orders that are dedicated to him.

### 4.1.2 Supply Chain Management

At SEMC, Supply Chain Management theory helps to understand the system of bringing parts to or storing parts at the assembly location where they are needed. The MIT courses *Supply Chain Planning* and *Manufacturing Systems and Supply Chain Design* offer an introduction to the current concepts of supply chain management [3], [4]. The courses use the book *Designing and managing the supply chain: concepts, strategies, and case studies* which provides a solid basis to understand how supply chains work, including key ideas in inventory management [5].

The ability to have necessary inventory on hand when it is needed in the assembly process is crucial for SEMC. The large number of parts, the high level of customization and the fluctuation and poorly predictable demand justify the need to explore inventory management alternatives in detail. Four basic concepts of inventory management have been introduced in the course: Economic Order Quantity (EOQ) Model is simple model to optimize the quantity of order under consistent demand. News vendor model also optimizes the order quantity but the demand is uncertain. Continuous
review policy sets the reorder point of inventory, and periodic review policy sets the base stock level. These theories are used to assess the inventory level of the manufacturing floor.

The objective of the EOQ model is to minimize an average cost per unit of time over an infinite planning time without shortage of inventory. The model simplifies a real inventory system, and it assumes the constant demand per unit of time, a fixed order cost, and an inventory holding cost. In the EOQ model, the lead time, the time between an order and its receipt, is neglected. Using these three parameters, which are an order cost, holding cost and demand, the order quantity is optimized [4].

The objective of the news vendor model is to find the order quantity that maximizes the expected profit under the condition of a random demand. The news vendor model is effective for a single transaction, and considers unit selling price, unit order cost, and unit salvage value, which is the value when the news vendor sells the unsold newspapers back to the wholesaler. Considering these parameters and the distribution function of the random demand, the optimized order quantity is decided [4].

The objective of the continuous review policy is to set the reorder point with the desired service level, which indicates the probability that no stock-out occurs during the lead time. In this model, demand per unit of time is assumed to follow the normal distribution. The reorder point of inventory consists of two components, the safety stock and safety factor. The safety stock equals the cumulated demand during lead time. The safety factor considers the service level, standard deviation of demand, and lead time. Compared to the periodic review model, usually the continuous review policy keeps the inventory level low [5].

Finally, in this periodic review policy, the inventory level is reviewed at regular intervals, which is closer to the realistic approach typically used. The model optimizes the base stock level, considering parameters: the review interval and lead time. When the inventory level is reviewed, the order that raises the inventory level to the base-stock level is placed. The base-stock level consists of two components: cumulated demand during the sum of the review period and lead time, and safety factor, which
depends on the several parameters; service level, standard deviation of demand, and the sum of review period and lead time [5].

In addition to decisions and policies about the inventory levels, another question considered in supply chain management is the location of inventory. From the perspective of upper levels of supply chain management, such as logistic systems and locations of production and warehousing facilities, the concepts of decentralized and centralized inventory are discussed. The advantage of decentralized inventory is to decrease the lead time to market if the facilities are close enough to the market, which also may result in higher service level and customer satisfaction. On the other hand, centralized inventory system has advantages based on the fact that it can reduce the safety stock, overhead cost, and transportation cost. The sizes of these benefits depend on the economies of scale; in general, in the larger economy, the benefits from consolidating inventory become larger although the necessary operation and cost for centralizing inventory also increase [3].

SEMC has decentralized the inventory within the assembly area to be able to provide inventory close to the place where it is used. However, the complexity of the current system is creating problems and an analysis of a possible centralization of inventories is therefore a core topic within this project.

4.2 Lean Manufacturing

The term Lean Manufacturing refers to a set of principles and practices in production management. These techniques were developed and first applied at Toyota, Japan. For that reason, the acronym TPS (Toyota Production System) is often used as a synonym for Lean Manufacturing. Within our work at SEMC, we use the definition and description given in the book *The Machine that Changed the World* [6]. During the past 20 years, Lean Manufacturing became popular and implementation of Lean Manufacturing principles and practices is often a major goal in manufacturing companies. The general idea of Lean Manufacturing is to reduce "waste" in production.
Typically, seven kinds of waste are distinguished; defects, overproduction, conveyance, waiting, inventory, motion, and overprocessing.

SEMC's production is characterized by high mix and low volume. That is, semiconductor equipment has a number of customer specific parts and the number of equipment SEMC manufactures per year is small compared to other industries such as the automotive industry for instance. However, many "standard" Lean Manufacturing practices described in the literature, such as "Kanban" de-couplers, are tailored for low mix and high volume manufacturers. Applying these practices at SEMC might lead to inefficiencies. Upon adapting Lean Manufacturing practices at SEMC, it is important to challenge their suitability.

### 4.3 Idea Generation

Concepts of idea generation are often taught in business and product development lectures. Methodology is important when new ideas need to be generated without missing important aspects or other possibilities. Two approaches in particular are used in this project: brainstorming and a morphologic approach. The concepts are especially useful in the first weeks of the SEMC project when no solutions have yet been found.

Alex F. Osborn published his book *Applied imagination; principles and procedures of creative thinking* in 1957. Known to everyone as brainstorming, this work has become the basis of many creative solution finding and idea generation processes. The team uses this method to find the driving principles of floor layouts in Chapter 7.

The Swiss physicist Fritz Zwicky published the book *Discovery, invention, research through the morphological approach*, which offers a powerful tool to generate solutions based on different nondependent concepts [1]. Possible solutions for different functional areas are collected in the first step. In the second step, one solution of each functional area is picked. The method allows one to split a bigger problem into smaller problems and to connect solutions afterwards that together provide a solution.
for the whole problem. A morphologic approach is used to derive the floor layout proposal in Chapter 8 using the driving principle of Chapter 7.

4.4 Summary

Available literature for manufacturing focuses mostly on high volume production and low mix. However, in the situation of SEMC, low volume is combined with high mixture. This requires flexibility from the system because the assembly process does not allow standardization to a high level, since the common denominator of assemblies is quite big. In addition, the fluctuating demand makes forecasts difficult. The models that can be created with manufacturing math cannot comprise special factors of SEMC's operations and deliver therefore only rough estimates. Manufacturing systems that are used in other companies are often not feasible for SEMC because they translate into too high costs due to the big variety of products. These high costs cannot be justified at low volume.

Literature was used as far as it makes sense and new creative solutions were found to tackle the problem of low volume high mixture operations.
Chapter 5

Current Operations

The section of current operations describes how SEMC is dividing machines into different modules and subassemblies and how the manufacturing operations for each of these components function. The chapter also explains how SEMC defines words such as “procedures”, “build bay”, and so on.

5.1 Products

SEMC offers a variety of products that are related to semiconductor manufacturing. The products differ in process and performance. The machines have a high degree of customization for different regions of the world and for specific customers.

5.2 Manufacturing

Manufacturing operations at SEMC involve assembling products and testing modules and machines. All parts and many subassemblies are bought from suppliers and are delivered to the warehouse or directly to the factory. Outsourced SEMC-specific subassemblies are called high level assemblies (HLA). SEMC outsources subassemblies that do not include critical core technology and cannot be assembled at a lower cost at SEMC than at a supplier.
5.2.1 Machines and Modules

A machine that is sold to a customer consists of several modules. Due to the size of a machine, the modules have to be shipped to the customer fabrication facility separately. If the machine is tested before it is shipped to the customer, the modules are connected to each other in the clean room and tested. The test process resembles the operation that the machine will be doing at the customer site. Often, the modules are shipped directly to the customer without undergoing a test as a whole machine. In this case, the modules are tested separately only. Shipping modules without testing them in the integrated machine configuration is called "smart shipping."

Modules are built from subassemblies and parts. Most modules are product specific.

5.2.2 Lines

The factory is divided into different areas. Assembly areas within the factory are called lines and are dedicated to specific products or modules. Only two modules are not product specific and are therefore used in different products. The lines include space to build modules, cells to build subassemblies, storage area to store inventory, and space to test modules and for test equipment. All lines are covered by one or more overhead cranes.

5.3 Subassembly Build

Subassemblies are used in modules or are sold to customers as spare parts. Subassemblies use between two and 190 different parts and their size ranges from a few pounds to hundreds of pounds. Building subassemblies is an important and big part of SEMC's assembly operations.

This section explains how SEMC builds subassemblies. This includes the organization of cells, inventory, and tools that are used for the subassembly activity.

5.3.3 Cells

Cells are areas that include at least one workbench and the necessary inventory and tools to build a group of subassemblies. At SEMC, subassemblies that are not bought from suppliers are
built in cells. Subassemblies are built from parts and smaller subassemblies, such as screws or electronic subassembly components. One cell is able to build between one and approximately ten different subassemblies. The cells are dedicated to specific products. Inventory within the cell is mostly handled manually, but some of the subassemblies are heavy and require a crane. Therefore, cells must be covered by overhead cranes and cannot be located in areas of the factory that are not accessible by cranes. Some of the large subassemblies also require movable fixtures. This means that the cell needs additional floor space.

In terms of the North Floor, there are eight physical cells for three product lines: the SE1, SE2 and SE3. The maximum number of subassemblies built in a cell is nine, while the minimum number is three. The sizes of subassemblies, in terms of the number of different parts, are different from two to 168 parts. The biggest subassembly takes forty hours for assembly, while the smallest subassembly takes 15 minutes. Thus, the subassemblies built at one floor have the great variety.

SEMC is increasing the outsourcing of subassemblies especially in high production volume products such as SE2. On the other hand, most subassemblies of low production volume or new products such as SE1 or SE3 are built in the SEMC factory.

Because SEMC needs to offer customer service for previous products, some old versions of subassemblies are still built in the factory.

5.3.4 Inventory

Parts and subassemblies that are needed within one cell are stored in shelves within the cell. Some of the hardware is stored in the workbench. Inventory is either organized in build sequence of the subassemblies that are built, or by part number. Cells that build different subassemblies and thus have different build sequences cannot store the inventory perfectly in build sequence. Some cells, which neither are sorted by build sequence nor by part number have therefore evolved, and lead to a difficult parts picking process for operators unfamiliar with the cell. If a subassembly uses a bigger part or subassembly, this part or subassembly is mounted onto a movable fixture that is rolled into the cell.
5.3.5 Tools and Fixtures

All tools and fixtures that are needed within one cell are also available in the cell. Tools are mainly stored in drawers of workbenches, and some large tools such as soldering guns or arbor presses are installed on the workbenches. Also, there are blue toolboxes that store general tools for replenishment of tools in cells, and tools in red toolboxes that are used in the lines. Assemblers may pick up tools from the blue boxes when they find missing tools in their tool boxes.

5.3.6 Procedures

There is a database containing procedures that describe assembly processes, deployed through the Lotus Notes system at SEMC. The procedures can be accessed through PCs installed at the workbench. Assemblers have to check each assembly process by the procedures. The procedures are usually in Adobe PDF format, and are maintained by the technical documentation group, while BOMs or other databases are managed by the engineering change order (ECO) department. Some similar subassemblies share the same procedure, but each subassembly has one specific document. Procedures provide detailed information including tools, part numbers of necessary parts, pictures, and notes warning about potential danger.

5.3.7 Testing

Most subassemblies are tested before they are used in a module or sold as spare parts. The test equipment is either available in the same cell or a centralized test equipment is used for different subassemblies of different cells. The most common test is a leaking test of subassemblies, which is performed by vacuum test equipment. Some subassemblies need specific fixtures for the leaking test, but usually vacuum test equipment is designed generically for several subassemblies.

5.3.8 Delivery of Subassemblies

When the subassembly is finished, it is either put into a storage location that is used as a buffer or it is brought directly to the area where the subassembly is used. Customers can order
specific subassemblies in the purpose of maintenance of their semiconductor equipment. These subassemblies are directly sent to the customers after the testing and package process.

5.4 Build and Test of Modules

SEMC’s semiconductor equipment consists of three to six modules. Each module typically fulfills a certain set of functions. Every module consists of a frame structure and a set of parts and subassemblies, which are either outsourced or assembled in house. Parts that feed into the module assembly vary in weight and size and some parts need the overhead crane for handling.

This section describes in five passages how modules are built in the SEMC manufacturing area. The first passage explains the bay were the module is built, the second passage shows the organization of inventory that is used to build a module, the third paragraph gives details about the handling of tools and fixtures that are needed. The fourth passage describes procedure documents that explain the assembly steps of the module build, and finally the fifth passage explains the module test that is performed before the module is shipped to the customer site or brought into the clean room for an integrated machine test.

5.4.1 Build Bays

Modules are built in marked areas that provide enough space for the module itself and the assemblers. SEMC calls these areas “bays.” SEMC builds all modules in the “garage build” mode. Previously, modules were built using a “real” flow line concept. That is, modules were moved from one assembly station to the next along the flow line and each station was doing the same assembly steps over and over. Approximately two years ago, SEMC switched to the garage build assembly mode, where all assembly steps are performed at the same bay without moving the module. Due to less time in transition, lead time and labor were reduced significantly. To be able to build several modules at a time, the lines can have several bays for the same sort of module.
5.4.2 Inventory

The inventory that is used to build a module is either stored on shelves that are close to the build bay or brought to the bay on movable wire racks. If larger parts or bigger subassemblies are needed, these are stored on pallets or movable fixtures in a bulk storage area within the same line before they are brought to the bay. The bulk storage area is located at one of the ends of the line. Parts and subassemblies are either carried by the operator or moved with a movable rack, a cart, a movable fixture, a pallet jack, a crane, or a pallet truck depending on the size and shape of the part or subassembly.

5.4.3 Tools and Fixtures

Tools are stored in movable tool boxes that both include generic and line specific tools. The drawers for generic tools use foam cutouts to signal where tools belong and what tools are missing. If a tool breaks or is lost, new tools can be picked at central tool box replenishment boxes. Fixtures are stored in closets or cages within the line.

5.4.4 Procedures

Usually up to two operators work on one module at the time. Similar to the subassembly build, there are also procedures for the assembly steps at the build bays. There are several separate procedure files, typically one for each significant and independent assembly operation (i.e. installation of cryo pumps). The procedures are also embedded into the Lotus Notes system, allowing time and status monitoring. That is, Lotus Notes automatically keeps track of which procedures are being performed at the moment, which procedures are already done and which procedures are still due. This tool is used by the line leads to check if modules are finished according to the build schedule.

5.4.5 Testing

When the assembly process of a module is finished, the module is moved into a test bay within the same line. The equipment that is used to move the module depends on the weight and shape of the module. Pallet jacks, forklifts, air pads or wheels that are mounted to the
module are used to move modules at SEMC, depending on the module's weight and the way the module needs to travel. Moving a module requires between two and five operators. The test bays are big enough for one module each and include the test equipment that is necessary to test the module. If the modules are "smart shipped" (not tested as a whole machine before shipping), the test process of the modules is more thorough and therefore also requires a longer testing time. Testing of modules is done by specialized test technicians that often work in different test bays at the same time. This is feasible because testing steps usually run autonomously for a while until the test technician needs to prepare the next test.

5.5 Material Flow

There are several different ways of inventory replenishment in use at SEMC. Figure 5-1 shows the supply side of material flow. Typically, parts are stored not only on the shelves in the Main Building, i.e. within the cells and the lines, but also at the SEMC warehouse. When the bin on the shop floor needs to be replenished, the cell operator or bay technician wands the part using a UPC-scanner. The information is electronically delivered to the SEMC warehouse, which will send out the required parts by a SEMC truck commuting between the Warehouse and the Main Building approximately every two hours. However, the actual turnaround time of the SEMC warehouse is usually on the order of 12-24 hours.

Not all parts are double-stored at the SEMC warehouse. So called "point-of-use" parts are only stored on the shop floor. These are usually parts that are product specific and therefore they are only stored at one shelf location on the assembly floor. These parts get delivered to the SEMC warehouse by external suppliers and are then directly brought over to their stocking location in the Main Building.
External suppliers deliver smaller parts, such as hardware, to the shop floor. That is, the suppliers actually place the parts into the appropriate bins and shelves in the cells and lines. These parts are ordered using the same wanding system that is used for SEMC warehouse orders.

Parts that are used less frequently are usually either ordered by SAP release based on the SAP inventory level or by the Purchasing Department, based on the forecast or production schedule.
The reason for double storing parts at the SEMC warehouse is to save production floor space and to have smaller bin sizes on the production floor.

Upon start of assembly of a machine, the "big parts", i.e. frames, etc., are delivered to a staging area close to the assembly bay. At the same time, shop orders for subassembly builds are sent out to the associated cells. Parts that feed into these subassemblies are stored within the cells, so that the cell operators do not need to leave their cell in order to obtain parts. The part bins in the cells are either replenished by material handlers or by external contractors, depending on the kind of part. As soon as subassemblies are finished, they are stored in a buffer area that is typically close to or within the cell, until material handlers bring them to the module assembly bay.

The smaller parts for the module assembly within the bays are stored in shelves along the build lines. Technicians take parts from these shelves as they are assembling the module, requiring them to sometimes walk significant distances (on the order of 60 ft) to pick their parts. These line inventory shelves are replenished by material handlers. However, there are some parts that feed into each machine that are customer specific due to special customer requests or configurations. These parts are delivered to the assembly bays on a module-specific wire rack which is kitted in the SEMC warehouse. For shipping between SEMC warehouse and Main Building, these kits are stored in plastic boxes. Material handlers in the Main Building unpack these plastic boxes and place the parts on wire racks.

As soon as assembly of modules is done, the modules are moved to the test bay and eventually into the clean room at the SEMC factory, where integration testing is performed.
Chapter 6

Current Floor Layout

This section describes how the floor space of the factory is used in the current state. This serves as a base line for comparison of new layout proposals. The capturing process of the current state also helped the team to understand the details of current operations and to get familiar with common practice and available furniture within SEMC.

6.1 The Building

SEMC’s campus includes many buildings. Manufacturing is located in the main building. The manufacturing area is divided into two big areas; the assembly area and the clean room. The clean room is located next to the assembly area according to Figure 6-1. The assembly area is used to build and test subassemblies and modules, while the clean room is used for testing of integrated machines and associated rework. The clean room resembles the environment that is typical for a customer wafer fabrication facility. The clean room has not been considered in this project.

The main aisles in the assembly area split the factory into three main floors. To facilitate the description of floor plans, we call the upper floor that is almost quadratic in Figure 6-1 the “North Floor,” the floor in the central region the “Mid Floor,” and the floor that is on the lower right side the “South Floor.” The small floor on the upper right side is called the “Northeast Floor,” but this floor is not considered in the project. All assembly area floors, except the Northeast Floor, are covered by five ton or ten ton overhead cranes that are parallel to each
other. The bridges can move in the left - right direction. The two cranes that cover the Mid Floor run across the aisle in the middle and therefore also cover the upper half of the South Floor. These two cranes have one five ton and one ten ton bridge each. The North Floor is covered by three ten ton bridges, and the lower half of the South Floor is covered by two five ton cranes.

![Diagram of factory layout](image)

Figure 6-1: Current Layout of the whole factory at SEMC.

<table>
<thead>
<tr>
<th>Floor</th>
<th>Length (ft)</th>
<th>Width (ft)</th>
<th>Area (sqft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>North Floor</td>
<td>108</td>
<td>105</td>
<td>11304</td>
</tr>
<tr>
<td>Mid Floor</td>
<td>105</td>
<td>65</td>
<td>6802</td>
</tr>
<tr>
<td>South Floor</td>
<td>124</td>
<td>89</td>
<td>11067</td>
</tr>
<tr>
<td>Northeast Floor</td>
<td>59</td>
<td>25</td>
<td>1490</td>
</tr>
</tbody>
</table>

Table 6-1: Sizes of Floor Areas

Total (sqft) 30663
Total (m²) 2849
6.1.1 Material Flow in the Layout

Material is received in the area above the North Floor. Finished modules are brought to the clean room which is on the right side of the South Floor. The aisles between the different floors are used to transport parts and assemblies that are related to different products. These aisles are wide and kept free from inventory because movement of fork trucks must not be interrupted. The lines also have aisles for material transport, but these are only used for transport of parts and assemblies that are related to the same line. Since these aisles are only used for the immediate activities within the same line, they are sometimes blocked by inventory.

6.1.2 Factory Assembly Lines in General

The lines in the current layout are product specific. The lines include the cells, the storage area, the build bays and the test bays that are necessary to build the modules of the line. This means that the operations of the lines are independent of each other. The manufacturing activities are also organized into lines. Managers of lines are called line leads and the operators working in a line are also specialized on the subassemblies and modules of the same line.

6.2 North Floor

The North Floor is dedicated to three different products and has therefore three assembly lines, as pictured in Figure 6-2. The products are SE1, SE2, and SE3. Aftermarket assembly and test of assemblies for an older product called SEO is also being done on the North Floor. While the SE1 is close to the end of the product life cycle and is built in a small number (one or two per month), the SE3 is at the very beginning of the product life cycle and SEMC anticipates a rising demand within the next one or two years. The SE2 is in the middle of its life cycle. In average one SE2 machine has been shipped every week during the last year. A decrease of the SE2 volume is likely soon.

The assembly lines of the three products are perpendicular to the direction of the cranes. The SE3 line is on the left side, the SE2 is in the middle and the SE1 is on the very right side of
the North Floor. Free space is available between the SE2 and the SE1 line, since the SE0 ma-
chine was assembled here in the past.

The cells that are used to build subassemblies are set up along the upper wall of the North
Floor. Three cells are dedicated to the SE2 line. A new cell will create subassemblies for the
SE3 line. Four cells are dedicated to the SE1 line.

![Figure 6-2: Current Layout of the North Floor](image)

6.2.1 SE3 Line

The SE3 is a completely new line that has not yet built any machine in its current layout.
However, the SE3 line has already taken a certain space next to the SE2 line as Figure 6-2
shows. Due to the early phase of the new line, the line has not been completely set up yet and
some electrical connections are still missing. The current layout expects that the incoming ma-
terial from the receiving area uses the left sided gate, and these parts enter the SE3 line through
a gate between the backside of one cell and a shelf on the HE line from the aisle. The end of
the HE line is connected to the aisle that separates the North and Mid Floor.
The test equipment of the HE line includes a concept for test equipment that is new within the SEMC factory. Arms that are approximately 12 ft long are mounted in the middle of the line under the beams of the cranes. Hoses and cables run from the test equipment to the pivot of an arm, along the arm, and down to the machine at the end of the arm. Since the arm can be turned, the test equipment connectors can reach to different bays. This allows connecting modules in two different bays without moving them to a special test bay close to the test equipment. When testing of one module on one side of the line is finished, the arm can swing over to the other side of the line and the test equipment can test the next module. This means that the same bay is used to build and to test a module.

The inventory within the HE line is stored in shelves on both sides of the line. Since the SE3 is an all new product, the variety of inventory is relatively small because no additional versions have yet been added that would bring new types of parts and subassemblies.

6.2.2 SE2 Line

The SE2 modules are relatively large-sized and have the highest production volume among the modules built on the north floor. The SE2 modules, the beam line and the terminal, are built in build bays and are thereafter moved into the test bays. There are two build bays and one test
bay for the beam line module, and one build bay and one test bay for the terminal module. Because the demand for SE2 is not big enough to use two build bays, only one bay for each module is currently used, and the other empty bays are used for the bulk storage area temporarily. Wheels are mounted to the modules to prevent the modules from tipping during the moving process. A modified pallet jack with long forks is used for the movement of the modules between the build bays and the test bays. Due to the massiveness and high production volume, the SE2 line is located nearby the gate that leads to the receiving area, and the build line lies on a straight line from the gate. The test bays of both terminal and beam line modules, which are located in the end of line, face to the aisle that leads to the clean room. The inventory for the modules is stored in shelves on both sides of the line. Bulk inventory is delivered on pallets and is stored at the beginning of the line.

Smart shipping often applies to the SE2 modules. The modules that are subject to smart shipping need additional test time. After testing, the modules are moved to an open space next to the assembly line, instead of the clean room, and they are packed for direct shipping to the customers.

Figure 6-4: Current Layout of the SE2 Line
6.2.3 SE1 Line

The SE1 line is not organized as a linear assembly line; rather, the assembly system is structured as multiple build bays. There are six modules for one SE1 machine. Each module of the SE1 is built in a dedicated bay that is surrounded by inventory shelves. There is no movement of modules between assembly bays. Since the SE1 line is currently only producing a small number of machines per year, no dedicated test bays are available. Final assembly and testing processes of the SE1 are done in the clean room. Since every module is necessary for testing the machine and there is no buffer space for the SE1 in the clean room, each module that finishes assembly has to wait for the completion of the assembly of other modules; and then all finished modules are moved to the clean room at the same time. Due to the weight, some of the modules require air pads for the moving process.

![Top View with Labels]

Figure 6-5: Current Layout of the SE1 line

6.2.4 Cells of the North Floor

Physically, there are eight different cells on the North Floor. Six cells of the North Floor are located on the upper-end wall of the North Floor, and the remaining two cells lie between those six cells and the SE3 line. All eight cells are allocated along the beams of one crane. All cells
can access the same aisle, and material handlers come from the left sided gate in order to re-
plenish stock inside the cells. Cell 307, which is a subassembly of the SE1 and some other older types of machines such as the SE00 and the SE000, uses a large space on the right upper corner of the North Floor because of the large-sized subassemblies and large test equipment.

![Top View](image)

**Top View**

![Top View With Labels](image)

**Top View With Labels**

Figure 6-6: Current Layout of the Cells of the North Floor

6.3 Mid Floor and the South Floor

The Mid Floor and the South Floor are dedicated to two products and two modules that are used in different products, as shown in Figure 6-7. In addition, one area is reserved for new product introduction (NPI). New products are built in this area before they are built in an assembly line, to ensure their manufacturability within the factory. The products SE4 and SE5, and the module SEMOD1 each have their own line. Since the SE4 product and the SEMOD1 module are assembled in high volume (approximately three every week), their lines are long and reach from the left end of the Mid Floor to the right end of the South Floor. The size allows accommodating more work in process (WIP).
All lines are set up between the beams of the cranes and every line has its own crane. This means that the lines are not perpendicular to the cranes and the cranes can therefore be used to transport material in the line. The upper line belongs to the SE4 product; the neighboring line underneath belongs to the SEMOD1 module. The next line, which is shorter and only uses the width of the South Floor is the SE5 line. The bottom-most line is shared by the Buffer module, the NPI area, the SES1 cell that is building subassemblies for the SEMOD1 module, and two offices.

![Floor Plan](image)

Figure 6-7: Current Layout of the Mid Floor and the South Floor

### 6.3.1 SE4 Line

The SE4 line is depicted in Figure 6-8. On the very left side of the line, facility modules for power supply and remote rack modules are assembled and tested. Two of each module can be built at the same time. Inventory on pallets that is used for these assemblies is also delivered to this area and stored as bulk storage on the factory floor. On the right side of this area, bays, storage area, and cells that are related to the 70’s and 90’s module assemblies are located. Two different modules are used for one machine. Since the first has a 90 degree architecture, and the second module has a 70 degree architecture, we call the modules 70’s and 90’s. Five pairs of
bays are available to build the modules. Each bay has space for one movable wire rack of inventory; inventory is also stored in shelves along the line. All bays are on one side of the line, and the other side is used for cells, offices and storage space. Two test bays at the right end of the line are available for module test. The modules can only be moved with air pads and this process requires approximately five people.

![Top View](image)

**Figure 6-8: Current Layout of the SE4 Line**

### 6.3.2 SEMOD1 Line

The SEMOD1 Line is located between the SE4 Line and the SE5 line and is shown in Figure 6-9. It is segmented into three areas.

The first area, located at the end of the SEMOD1 line lying away from the clean room, consists of five cells for subassembly build. These cells only build subassemblies that feed into the SEMOD1 module. The major part of these subassemblies is assembled into a module within the SEMOD1 line and some are built for sales orders, i.e., subassemblies directly ordered by customers for repair or maintenance purposes.

The second area is located adjacent to the cell area, but still on the left of the aisle that splits the SEMOD1 line. Three bigger subassemblies that are mounted on fixtures during assembly are assembled in this area. There are two fixtures for each of these subassemblies, enabling SEMC to build two of the same subassembly at a time. Also, these three subassemblies (Wafer Handler, Top Head, Process Chamber) as well as the facilities rack are installed on a
SEMOD1 base frame in this area. In the next step, the base frame, with these subassemblies installed, is moved to an empty build bay using a pallet jack.

In the current layout, a maximum of five modules can be assembled in build bays at the same time. Once the frame is in the build bay, mostly small parts that can be handled without equipment are installed in the module. These small parts are both parts from line inventory as well as subassemblies from the SEMOD1 cells.

When the assembly process is complete, the SEMOD1 module is moved to a test bay in the third area, which is the test area on the right side of the line. Again, a pallet jack is used. Currently, there are four test stations, each located at one test bay. Thus, four modules can be tested at a time. After test is complete, the modules are advanced to the clean room.

6.3.3 SE5 Line

SE5 is using a semiconductor manufacturing process that SEMC recently decided to offer to its customers. Other companies have been active in this area for a longer time. To offer more advantages to customers, SEMC’s second generation of a SE5 machine will be shipped in approximately six months. The new generation is called SE6 and will offer more performance at a smaller footprint and comes as a more modular machine.

So far, the assembly line is able to assemble the modules of one machine and test the modules of a second machine at the same time. The line is shown in Figure 6-10. The assembly and
test bays are at the right end of the line. Cells are on the upper side of the line, and bulk inventory is stored in shelves and on the floor on the lower side of the line. The SE5 machine module can be moved with two pallet jacks; the remote rack module needs a fork truck to be moved. Since the first generation can be considered as a new machine as well, the assembly operations have not reached a mature status yet. This means that rework is common and assembly processes are not yet fully defined and standardized.

Top View

![Top View](image)

Top View With Labels

![Top View With Labels](image)

Figure 6-10: Current Layout of the SE5 Line
6.3.4 Lowermost Line

The lowermost line can be divided into four different areas as shown in Figure 6-11. These are wafer buffer assembly, new product introduction (NPI), SES1 assembly and testing, and offices. In distinction from the other lines that are dedicated to one product or one module, the areas within this line belong to different resorts. The areas have been placed in the lowermost line because the product and module specific lines that the areas are associated with do not have enough space.

The wafer buffer modules are assembled at the right end of the lowermost line of the South Floor. Two build bays are available and the inventory is stored in shelves. Special testing equipment is not necessary.

Next to the buffer assembly area is the new product introduction (NPI) area that offers generic space to build new products. In the past, the NPI occupied the whole area of the line. Space has been taken away from the NPI because the activities of other products did not fit into their assigned areas.

The middle part of the line is occupied by the SES1 cell which builds and tests one of the subassemblies that are used in the SEMOD1. In the past, SEMC's customers have experienced problems with the SES1 subassemblies. To increase quality, SEMC has enabled better identification of failures in SES1 subassemblies. A more thorough testing process requires a plenitude of test equipment.

Two offices are located next to the SES1 cell. Employees affiliated with the SEMOD1 line use both offices. A location closer to the SEMOD1 line is desirable.
Figure 6-11: Current Layout of the Lowermost Line.
6.4 Summary and Conclusion of the Current Layout

The floor space is strictly separated into lines that either belong to specific products or specific modules. The lines include almost all activities that are associated with the modules that are built there.

The strong dedication of lines to products or modules allows creating a feeling of ownership for the operators that work within one line. The reason is that the material flow is isolated within one line. This also means that operational problems in one line do not automatically propagate to other lines.

However, strongly dedicated lines tend to isolate knowledge as well. Solutions are not shared within the factory and the same problems are only solved in some lines. Operational improvements in one line are not communicated through the factory and remain unique. Dedicated lines have a fixed floor space. This means that a line with rising demand experiences a floor space shortage while a line with dropping demand enjoys excess floor space within the same building at the same time. In contrast, concepts that use the same real estate for different products experience no shortage or excess while the average demand is unchanged.
Chapter 7

Driving Principles for New Floor Layouts

To find new floor layouts, different important domains of assembly operations are identified. These are building and testing of subassemblies, building of modules, and the testing of modules. Different operational alternatives for each of these domains are found through a brainstorming session [7]. Connecting the alternatives of each domain with each other according to the morphological approach yields a plenitude of possible theoretical factory operations [1]. A discussion of the feasibility of each of these theoretical factory operations allows picking the three best scenarios and generating floor layout proposals accordingly.

In this chapter, the different driving principles for the domains subassembly build, module build, and module test are presented. Alternative principles for each domain are compared and advantages and disadvantages are explained.

7.1 Subassembly Build

Building subassemblies is an important part of the manufacturing operations at SEMC. For example the SE1 line and the SE2 line alone account for eight subassembly cells and 58 different subassemblies with over 1500 storage locations.
7.1.1 Cells

The concept of cells is applied in the current operations. Inventory is stored in the cells according to the subassemblies that each cell is dedicated to. Parts are picked by the operator while he or she is building the subassembly. The workbenches within the cell include only the tools and fixtures that are needed for the subassemblies that are built in that cell.

7.1.2 Centralized Inventory

Inventory of several cells are consolidated and stored in a centralized area. Parts are picked according to the bill of material (BOM) of the subassembly that the operator will build. Generic workbenches offer space to build any kind of subassembly.

7.1.3 Comparison

A decentralized system requires more safety stock than a centralized system [5]. The reason is that centralizing means risk pooling, and this reduces the ratio of standard deviation of demand and average demand [5]. Generic workbenches in a centralized system also lead to a better utilization of workbenches. This can be explained with simple queuing theory. In a dedicated system (as in the case of cells), every cell has a separate queue of job orders. In queuing theory this is an M/M/1 queuing system, meaning that only one operator (one cell) is available for each queue. In a centralized system, every workbench can process any subassembly [2]. This means that all job orders can wait in the same queue that is served by k similar workbenches, resulting in an M/M/k queue. It is obvious that the cell system (M/M/1) can have queues in some of the cells, while other cells are idle. This is not possible in the system of generic workbenches (M/M/k), as waiting can only occur when all workbenches are busy.

It is easier to manage centralized inventory, and the material picking process does not interrupt the assembly process when all parts are picked before the assembly process starts. Pulling parts during the assembly process is more time consuming than
pulling all parts at the same time in a centralized concept. The cell concept allows for
greater optimization since one work area can be specialized for certain subassemblies.
But this sacrifices flexibility, since only specialized cells can build certain subassemblies and not any workbench can be used.

The centralized system uses a standardized environment for all subassemblies that
are built. This means that cross-training is more efficient, since more steps in an assembly are the same. The picking process is the same for every subassembly and all workbenches are similar and include the same tools. The cell system, on the other hand, requires operators to get familiar with the storage locations within the cells and the workbench.

7.2 Module Build

Building modules accounts for a large number of man-hours within the factory.
Due to the size of modules, the WIP is limited since floor space is not unlimited.
Throughput and efficiency are therefore important metrics for SEMC. Two aspects of building modules are discussed here. The first one describes the way the inventory is presented to the operator. The second one specifies the location that is used to build the module.

7.2.1 Line Inventory and Product Specific Build Areas

In the current operations, inventory is stored in the line and the modules are built in build bays. The inventory is stored as close as possible to the modules. The operators pick the parts from the shelves when they need them.

7.2.2 Product Specific Centralized Inventory and Build Areas

Inventory for one line is stored in one central area within the line. The needed inventory is pulled with carts and brought to a specific build area within the line where
the module is built. This means that several parts are picked at the same time and are brought to the module.

7.2.3 Kitted Inventory and Flexible Areas

Inventory is not stored in a product specific location; rather, all the inventory of all modules is stored in one area. Parts are pulled in kits and brought to a generic area where any module can be built.

7.2.4 Comparison

Centralized inventory is easy to manage. However, delivery of inventory needs more coordination effort. The reason is that the time frame of the delivery to the site where the module is built is smaller. Storage space close to the module is limited so delivered material should arrive when it is needed. If material is delivered, it is closer to the module and a more efficient assembly process is likely, since the kit only includes parts that are needed for the module assembly. Missing parts in the kit lead to more effort when the build area does not include any of its own storage. If parts are left over in the kit when the assembly is finished, this indicates that the operator has made a mistake during the assembly or the BOM is not correct and needs to be verified. Both cases lead to quality improvement if the problem is solved. The area where the module is built has more space, since no storage shelves are used within the lines.

Generic build space for modules gives greater flexibility but reduces the degree of possible customization of the build area to the process, since the same area needs to stay capable to build any other module and may not have product or module specific features. Therefore, product specific build areas are likely to allow a more efficient build process, while sacrificing product and volume flexibility. The flexible system is capable of redistributing the floor space resources to different products on a day to day basis without changing the floor layout.
7.3 Module Test

Almost every module undergoes a test process. Testing capacities are limited and interruption within the test process can lead to a bottleneck that makes subsequent finished modules wait for available test resources while using floor space and thereby preventing new modules from being built. Therefore, module testing is another important domain that needs to be analyzed. We first summarize the current approach using product-specific testing areas. We then present an alternative layout taking advantage of centrally located test equipment. A third different approach is following before we compare the three approaches.

7.3.1 Product Specific Areas for Testing

In the current operation, lines have specific areas for module testing that are called test bays. When modules are built, they are moved into the test bay and tested with the test equipment that is set up next to the test bay.

![Figure 7-1: Necessary Movement of Modules](image)

7.3.2 Centrally Located Test Equipment

In the alternative proposed approach, test equipment is located between build bays where modules are built, as shown in Figure 7-2. When a module is finished, it stays in its build bay for testing. Neither the test equipment nor the module needs to be moved, as the shared test equipment can be directed to one of the adjacent modules. The module is moved away when both building and testing is finished. The same bay is used for both building and testing of the module.
7.3.3 Movable Test Equipment

In another proposed layout, the module stays in the same spot where it has been built, and the test equipment is moved to the module and the module is tested. The module is moved away when both building and testing is finished.

7.3.4 Comparison

Specific areas for testing require one additional movement of the module than either the centralized or moveable test equipment approach. Moving modules leads to non value adding costs and safety hazards. Back injuries are a potential problem that the operators at SEMC need to avoid. A module that is in the test bay and requires more rework will need to be moved to free up the test equipment for a waiting module or will block the test equipment until the rework is finished and the test process can continue.

Centrally located test equipment minimizes the number of module movements but might also result in less space for the assembly process, since the build area is neighboring to test equipment and an active test technician. Flexibility to test differ-
ent modules that surround the test equipment is high; however, no more than approximately four modules can surround one single test equipment. This means that more test equipment is needed if a bigger WIP is desired and moving test equipment or moving WIP is not possible between the assembly process and the test process.

Movable test equipment offers the greatest flexibility. However, the movement of test equipment requires additional effort. Depending on how efficient moving test equipment can be, this can be either more or less effort than moving modules. Making the test equipment movable implies up-front investments both for the test equipment itself and for the facility side that requires more dropouts.

7.4 Summary

Driving principles for the domains of subassembly build, module build and module test were examined. Each principle within the domains brings disadvantages and advantages.

The next challenge is to find good combinations of principles from each domain that describe the future operations. Based on the chosen combinations of principles, new floor layouts are developed in the next chapter.
Chapter 8

Three Layout Proposals

Using the underlying driving principles of each domain discussed in Chapter 7, three different layout proposals are presented here. Each layout proposal focuses on a combination of principles. The three layout proposals are summarized in Table 8-1, highlighting how subassembly build, module build, and test are accomplished. As a reference, the principles that are applied to the current layout are introduced on the table.

Table 8-1: Combinations of principles for the different floor layout proposals

<table>
<thead>
<tr>
<th>Layout</th>
<th>Subassembly Build</th>
<th>Module Build</th>
<th>Test Equipment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current</td>
<td>cells</td>
<td>bays</td>
<td>test bays</td>
</tr>
<tr>
<td>A</td>
<td>cells</td>
<td>bays</td>
<td>central, max. 4 modules</td>
</tr>
<tr>
<td>B</td>
<td>centralized product</td>
<td>bays</td>
<td>central, max. 2 modules</td>
</tr>
<tr>
<td>C</td>
<td>centralized all</td>
<td>generic space</td>
<td>movable</td>
</tr>
</tbody>
</table>

This chapter will explain each of the proposals. The details of proposal A were developed by Simon Treis. The details of proposal B were developed by the author, and Richard Schwenke prepared the details of proposal C.
8.1 Proposal A

Proposal A is the "conservative" floor layout, considering the various levels of constraints. In this proposal, the numbers of shelves, workbenches and other kinds of facilities at the floor are not changed. The changes made by proposal A are related to test equipment, and the alignments of product lines. Figure 8-1 gives the overview of proposal A, indicating the location of the product lines.

Figure 8-1: Floor Layout Proposal A [8]
Figure 8-2: Layout Proposal A for the SE4 Line [8]

Figure 8-2 shows the detailed layout of the SE4 line. As the figure shows, proposal A keeps the cells for dedicated subassemblies, and bays for dedicated modules. Thus, two of the principles about subassembly and module build in Table 8-1 are as same as the current layout.

One principle that differentiates proposal A from the current layout is to share the test equipment with up to four build bays. In proposed layout, build bays are allocated around the test equipment. The test equipment is not shared between the different product lines. Therefore, the test equipment does not need to update its software, nor change anything of the hardware. For instance, the long arms for distant build bays, which are installed with the test equipment of the SE3 line, are not necessary in the proposed layout. As Figure 8-1 shows, the test equipment is located under the beam of the overhead cranes. Sharing the test equipment for the several build bays removes
the movement of modules from the build bays to the test bays, and increase the safety of operators.

Besides the principles introduced in Table 8-1, the change proposed in proposal A is to rotate the product line in the North Floor, so that the product lines are in parallel to the overhead cranes. In the current layout, the SE2 and SE3 lines are perpendicular with the overhead cranes. The current layout requires both the pallets jacks that transport heavy materials from the bulk storage areas to the build bays, and the overhead cranes that are used to lift the heavy materials at the build bays. An advantage of aligning the product lines parallel to the cranes is to reduce the lead time of building modules by removing the operation of pallet jacks from the product lines.

The layouts proposed in proposal A also give a solution for the build of the new version of the SE5 machine. In the current layout, it has not yet been defined where the second generation of the SE5 tool will be built. Because building both the older and the newer generation at the same time is required in the future, the proposed layout provides larger area for the SE5 line.

The details about proposal A are discussed at the thesis by S. Treis [8].

8.2 Proposal B

Proposal B is the “intermediate” floor layout, because the amount of change necessitated by this proposal, in terms of manufacturing system and physical design of layout, is larger than in proposal A and smaller than in proposal C. As pictured in Figure 8-3, proposal B centralizes inventory of subassembly for each product into one area, and provides generic workbenches for fabrication of subassemblies, instead of the current cells. These changes of layout require assemblers to compose a kit of necessary parts for the assembly before they start to assemble, as Section 7.1.2 discusses. In terms of work space for modules, inventory area is consolidated and provides flexible work space within each assembly line. In this layout, the North Floor and left half of the Mid Floor are allocated for building subassemblies, and the right half of
the Mid Floor and the whole South Floor are used for building modules. Although this layout rearranges the location of every work area and consolidates the inventory storages, proposal B keeps a dedicated area for each product. Details layouts and benefits of proposal B is discussed at Chapter 9.

Figure 8-3: Floor Layout Proposal B

8.3 Proposal C

Proposal C is the “revolutionary” floor layout because proposal C considers the only top level of constraints, which requires significant investment, and this proposal changes the biggest portions of operations and physical layout among the three proposals. Figure 8-4 gives an overview of proposal C. The two things that identify proposal C are the supermarket for subassembly build area and the blocks, which are the
standardized work spaces, for module build area. The North Floor is designed for the supermarket for subassembly and the consolidated inventory area for all kinds of modules. The supermarket area includes the consolidated inventory area for all subassemblies, generic workbenches, test area, and storage area for finished subassemblies. In the Mid Floor and South Floor, the rectangle blocks are prepared. Facilities necessary for building modules, such as tool boxes, wire racks, and test equipment are brought to the blocks from the consolidated inventory area. Because there is no dedicated area for the product lines, proposal C encourages that the assemblers receive the cross-training and become capable of building the modules of the different product lines.

At the supermarket, the assemblers pick up the necessary parts with the foam cutouts and carts. The operations at the supermarket are similar to the subassembly build area that is introduced at proposal B, but the size of the consolidated inventory area at the supermarket is bigger, due to the fact that the supermarket covers all subassemblies. Although foam cutouts are shared among the very similar subassemblies, basically foam cutout is prepared for each subassembly. The foam cutouts have the cavities in the shape of the outlines of parts, and the parts in the foam cutouts are sorted by assembly sequence. Using the foam cutouts, the assemblers can check the missing parts before they start building subassemblies. Another advantage of the foam cutout is that assemblers can pick up the parts without seeking the parts of every assembly step. Also, the picking list of each subassembly that is used in the process of picking up parts at the supermarket is designed as the assembler walks through the supermarket only once.

The block system defines the number of WIPs per the block for each product. Once the assembly of the modules is completed, the facilities used for building the modules are removed from the block; after that, the block becomes empty and is ready to build other modules. These advantages of the block system enable to increase the utilizations of work spaces and the degree of flexibility of production volume.

The details of operations about proposal C are discussed at the thesis by R. Schwenke [9].
Inventory for module build

Work area for subassembly build including "supermarket"

Figure 8-4: Proposal C Floor Layout [9]
Chapter 9

Proposal B in Detail

In this chapter, the detailed layout of proposal B is introduced. The proposed layouts of subassembly areas and modules are explained with the drawings and descriptions of operations.

9.1 Layout of Build Areas of Subassemblies

The build area for SEMOD1 subassemblies is introduced as an example of the layout for subassembly area. The consolidated inventory area dedicated for all SEMOD1 subassemblies is located beside the work spaces. The parts for subassemblies are picked up at the consolidated inventory area. There are two kinds of work spaces; standard ones and work spaces that have fixtures. The assembler chooses the appropriate work space, depending on whether the subassembly needs a specific fixture or not. There are four test stations beside work spaces, and three or four work spaces share one test station. After the assembler finishes the assembly and test process, he or she transfers the finished assembly to the storage area. The finished assemblies are moved to the module build area or the shipping area if the subassembly is ordered directly from a customer.

Although the other subassembly build areas have different layouts, in terms of operations, other build areas of subassemblies have basically the same features.
9.2 Layout of Build Area of Modules

The build area of SE2 modules is introduced to explain the layouts of module building area. Similar to the subassembly building area, the build areas of modules have the consolidated inventory area at the end of the lines. There, assemblers make kits at the consolidated inventory area and put them on the wire rack that is used for transportation of parts to the build bay. Because the shelves are consolidated into one area, there are no shelves around the build bay. Instead of the shelves, the build bay is surrounded by the wire racks filled with necessary parts. Test bays are integrated to the build areas, and the test equipment is shared with up to two build bays. The details about the shared test equipment are mentioned at the section of proposal A. Since the build area is integrated with the test bays, module movement from the build area to test area is not necessary. When the module assembly is finished, the test technician can start the test at the same build bay. After the test process, the modules are sent to the clean room or shipped directly to the customer site.
The layouts for the build areas of other modules are based on the same principles. The numbers of shelves and build bays are different for each product. However, the numbers are unchanged from the current layout except for test bays.

Top View

Top View with Labels

Figure 9-2: Build Area of the SE2 Modules

9.3 Potential Benefits

Potential benefits of proposal B are described in this section. Some problems that are discussed in Chapter 2 are solved by these benefits. Proposal B focuses on the improvements of the following aspects: production flexibility, utilizations of work spaces, lead time, and inventory control.

Increased Flexibility and Balanced Utilizations

The major purpose of proposal B is to increase flexibility and balance utilizations of work spaces by providing generic work space instead of dedicated cells. The observation of the existing subassembly area reveals a difference of utilization between cells due to the different demands for every subassembly. While one cell is always busy for building subassemblies, other cells are seldom utilized. In the worst case, somebody uses a cell to build a subassembly that is supposed to be built in another
cell, because the original cell has too much demand and is too busy. In proposal B, in contrast, consolidated inventory area and generic workbenches make it possible to build any kind of subassembly within the subassembly line, corresponding to the changing demands. Moreover, proposal B enables efficient use of floor space.

**Reducing Time of Moving Modules**

The proposal allocates subassembly areas to the left side of the factory, which has a longer distance from the cleaning room, and module assembly areas to the right side that is closer to the clean room. This is because moving a subassembly is easier than moving a finished module. The advantage of this layout is to reduce the time to move finished modules; on the other hand, the disadvantage is the increased time necessary to transport finished subassemblies from workbenches to the module assembly areas. Although a time study is necessary to show how much time could be saved, proposal B could reduce the lead time of modules.

**Easy Replenishment of Stock**

A side effect of consolidating the inventory area is to simplify inventory replenishment. In the current layout, shelves are set up along the assembly line, and they are not organized to facilitate the replenishment process. The current layout requires material handlers to walk around the assembly area to replenish parts. Proposal B has one inventory area for each product, which improves the performance of material handling process. Material handlers perceive this as a system that allows easier replenishment, and results in less dislocation of stock.

**Better Management of Tools**

Generic workbenches are provided in the subassembly areas. Since generic workbenches do not allow operators to own their spaces, operators are expected to use different workbenches according to the order. It is critical that the dedicated locations of tools are respected, so that the systems of consolidated inventory areas and generic workbenches work fine. Therefore, generic workbenches result in solving the problem that operators take extra time to seek the necessary tools. Details of generic workbenches are mentioned in Section 10.3.2.
Easy Partial Implementation of Concept

Additional benefit of this proposal comes from keeping a dedicated assembly area for every product. Since each assembly area is independent from other assembly areas in this proposal, it does not require changing the structure of management. In addition, from the perspective of manufacturing systems, it is possible to implement the concept of consolidated inventory and generic workbenches only for a subset of the products if the locations of production lines do not change.

9.4 Utilization Analysis of SE1 Work Spaces

Detailed observations of the SE1 work spaces are performed in order to assess the potential benefits referred in Section 9.3. The SE1 has currently a low and stable demand, of one machine per month. As a result, the utilizations of both cells and bays of the SE1 line are lower than at other products. Thus, the SE1 brings many benefits when consolidated inventory and generic work space ideas are applied.

9.4.5 Results of Utilization Analysis

<table>
<thead>
<tr>
<th>Current Design</th>
<th>Proposed Design</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Week</strong></td>
<td><strong>Cells</strong></td>
</tr>
<tr>
<td></td>
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</tr>
<tr>
<td><strong>Cells</strong></td>
<td></td>
</tr>
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<td>301 302</td>
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<tr>
<td>303</td>
<td></td>
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<td>305 306</td>
<td></td>
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<tr>
<td>307</td>
<td></td>
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<tr>
<td><strong>Bays</strong></td>
<td></td>
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<tr>
<td>311 312</td>
<td></td>
</tr>
<tr>
<td>313</td>
<td></td>
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<td>314</td>
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<td>317</td>
<td></td>
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<tr>
<td>318</td>
<td></td>
</tr>
</tbody>
</table>

Figure 9-3: Utilization Analysis of the SE1 Cells and Bays

(Left: current design; Right: proposed design.)
Figure 9-3 shows the working schedule of cells and bays of the SE1 within one month, which equals to one building period of one machine. Due to the low demand of the SE1, the number of workers is not large enough to utilize all cells and bays simultaneously. Thus, there is long idle time in both cells and bays. The utilizations of cells are 25 or 50 percent, and the utilizations of bays are 25 or 75 percent, for the current design. In proposal B, it is recommended to consolidate cell 301 through 304 into one cell, and cell 305 through 307 into another cell, respectively. Also, the recommendation for bays is to make three incorporated bays, grouping bay 311 through 313, bay 317 and 314, and bay 318 and 315 together.

Integrating work spaces is effective for the production lines that have a long run time and do not have high demand. This is because the potential maximum capacity to produce the products decreases by integrating work spaces in general; in other words, the lines lose the flexibilities in terms of production capacities. Hence, if the demands of products are likely to increase again, the idea of integrating work spaces should not be applied that a product line. In terms of demand, the SE1 line is appropriate for the idea of consolidating work spaces, because the SE1 line has already been operated for several years and the demand is stable and lower than it used to be.

9.4.6 Results of Analysis and Proposed Layout

From the analysis of utilization of cells and bays, it is possible to keep the same production capacity and reduce the number of work spaces. The number of work areas for subassemblies is reduced from five to two. However, this does not mean the area of total work spaces of cells will be reduced to two fifths, because only some parts are redundant over these cells. Detailed analysis of redundant inventory of consolidated inventory area is performed in Chapter 10.1. Comparison of drawings between the current layout and proposal B shows that the work space of the SE1 is 2,512 square feet in the current layout, and 2,227 square feet in proposal B. The proposed layout of the SE1 line is shown in Figure 9-4.

Compared to the current layout, the number of part supply racks for hardware is reduced from 21 to 7, while the number of shelves is unchanged. This is because the
removed is that some shelves are available for hardware. There are 38 shelves in the SE1 area, and the utilization of the shelves in the current layout is approximately 80 percent; hence, we can omit shelves if the inventory is rearranged properly at the consolidated inventory area. Each shelf is capable to store twice as many standard bins as a part supply rack does. Therefore, the proposed layout has enough space to store all necessary parts.

Top View

![Top View with Labels](image)

Figure 9-4: The Proposed Layout of the SE1 Line

As Figure 9-4 shows, the old test equipment is placed next to storage area. The old test equipment is only used for the accelerator columns of the previous products, and the frequency of use of the old test equipment is two or three times annually. Thus, the old test equipment is located out of the work areas, but it would not affect the operation.

9.5 Possible Cost Reduction

Cost reduction of this proposal mainly comes from the additional free space. The measurements of drawings indicate that the proposed layout has 3,343 square feet of free space, including 1,820 square feet created by removing SE0 cells. Because one square foot has a value of US$25 a year, the proposal can save US$83,000 a year. Ad-
ditional free spaces are generated by the rearrangement of work spaces, rather than removing extra shelves or workbenches. Except for the SE1 assembly area, the numbers of shelves and workbenches are not changed; consolidating inventory area and work spaces makes it possible to organize shelves and workbenches more efficiently.
Chapter 10

Pilot Layout Proposal

After presentation of three different layouts described in Chapter 8, the company decided to pilot some of the new principles. In a series of interviews with the different stakeholders, the group determined which principles are most popular and have the greatest potential for pilot evaluation.

In a meeting with the managers, the constraints of the pilot layout were defined. The pilot considers only the North Floor and involves the SE1, SE2, and SE3 products. This translates to ten subassembly cells of which two have been merged in the past. This means that the pilot involves eight physical cells and three product lines.

The driving principles are centralized subassembly inventory and centralized test equipment. The line inventory that is used for the modules is stored close to the bays similar to the current operations. The testing operations and subassembly operations change based on centrally located test equipment and centrally stored subassembly inventory.

Table 10-1: Combinations of Principles for the Different Proposals

<table>
<thead>
<tr>
<th>Proposal</th>
<th>Subassembly Build</th>
<th>Module Build</th>
<th>Test Equipment</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>cells</td>
<td>bays</td>
<td>central, max. 4 modules</td>
</tr>
<tr>
<td>B</td>
<td>centralized product</td>
<td>bays</td>
<td>central, max. 2 modules</td>
</tr>
<tr>
<td>C</td>
<td>centralized all</td>
<td>generic space</td>
<td>movable</td>
</tr>
<tr>
<td>Pilot</td>
<td>centralized all of pilot</td>
<td>bays</td>
<td>central</td>
</tr>
</tbody>
</table>
The pilot is therefore a hybrid version of the proposals A and C, as summarized in Table 10-1. The concept of centrally located test equipment from proposal A is adopted; the subassembly inventory is centralized for all products that are involved in the pilot according to the method of proposal C.

The pilot layout proposal not only includes a new layout; data driven analyses are also performed in order to estimate the benefit to the company and to facilitate decision making when different solutions within one principle are possible.

10.1 The Physical Pilot Layout

The pilot layout was developed through an iterative process. Proposals were discussed with different stakeholders and problems could be identified and solved. The presented layout in Figure 10-1 depicts the final state of the pilot layout.

The subassembly inventory is stored centrally, and we call this storage area supermarket. The supermarket is located at the upper end of the North Floor. The workbenches are on the right side of the supermarket. This allows a short walking distance when parts are picked for subassembly. Test equipment for subassembly test is located on the right side of the workbench area. An office area is located next to the supermarket.

The SE1 line is not changed from the current state. The cell 307 that builds and tests subassemblies for SE1 and older products remains as well. The SE0 test equipment will be needed on the North Floor for less than a year. Until it is completely removed, it is located in the lower left corner of the North Floor. The SE3 line and the SE2 line are turned 90 degrees and are now parallel to the crane beam. Inventory and test equipment is located under the beams.
10.2 Analysis of Inventory

An analysis is performed to quantify the effects from an inventory point of view, resulting from the two different operational scenarios, cells and centralized inventory for subassemblies. Changing the operations from cells to consolidated subassembly inventory on the North Floor raises important questions: How much inventory is stored in each case? What is the value of the stored inventory stored? How big is the synergy effect when inventory is consolidated? We first summarize the analysis methodology, and then present answers to these questions.
10.2.1 Methodology

This section explains how we analyze the difference of storing inventory in the current system and in the new centralized system. First, the minimum number of storage locations in the current cell system is calculated. Thereafter, storage redundancies that occur when different cells have to store the same parts are identified. The third part of this section explains the difficulties of analyzing the value of the inventory.

Storage Location Count

The analysis is based on the bills of material (BOM) of the subassemblies that are built in the cells. Parts that are used in different subassemblies within the same cell are only counted once; if the same part is used in different cells, it is counted several times. Since every part in a cell has a storage location, this analysis delivers an accurate estimate of the number of storage locations that are needed within one cell. The method cannot analyze parts in obsolete bins that are not related to any subassembly that is built in the cell. Such parts can exist if a subassembly is not produced in the cell any more but the bins that were used for this subassembly were not removed.

In the case of consolidated inventory, all parts are only counted once, and the total number of minimum storage locations is determined.

Estimation of Redundancy

If parts have more than one storage location, they are stored redundantly. If a part has one storage location it has zero redundancies, if it has two storage locations it has one redundancy, if it has three storage locations it has two redundancies and so on.

Dividing the redundancy by the minimum number of storage locations yields the percentage of redundancy. If the redundant parts are not stored more than two times, this number is telling us what percentage of the parts is redundant.

Estimation of Stored Value

The IT based inventory management system (SAP) used by SEMC only counts parts that cost more than US$25.00 each accurately. Since many parts that are used for subassemblies cost less, it is difficult to estimate the stored value, and a manual inventory count would be necessary to accurately estimate the value. Therefore only a report of the stored value of parts that cost more than US$25.00 is possible. However,
the IT system includes cost information for each part and this allows reporting the range of cost per part.

10.2.2 Results of the Analysis

This section presents the results of the inventory analysis. The current situation is described in the first paragraph. The second paragraph shows the difference of the current situation and the pilot.

Cell Operations - The Current Situations

In the current operations on the North Floor, the affected eight cells need to have 1548 storage locations to store the parts that are listed in the BOMs in the different cells. According to SAP, the cells store inventory at a total value of US$533,738.54. As stated earlier, this number is not accurate and must be higher because inventory that costs less than US$25.00 is not tracked accurately. The inventory ranges to a cost of US$7,774.50 per unit. The lower boundary is below US$0.01, considering that parts like small washers are stored in the cells.

Comparison with Consolidated Subassembly Inventory

The analysis determined that 172 redundancies are needed among the 1548 storage locations when cells are used to store the inventory. These redundancies can be eliminated when the inventory is stored in a central area. The redundancy percentage is 11%, which means that approximately every tenth part is stored twice. Redundant parts cost as much as US$234.98 per unit. According to the approximate data from SAP and the current inventory levels, eliminating the redundant bins would reduce the total inventory by approximately US$9,000.00. Considering that the safety stock levels of the remaining bins would need to be higher if more subassemblies use parts from the same bin, eliminating of bins alone is not sufficient. Safety stock levels need to be adjusted as well. Since the value of redundant inventory is smaller than 3% of the total value of inventory, reducing this inventory only yields a minimal financial benefit. However, the changed operations that come with consolidated inventory might bring bigger savings through more efficient inventory management, parts picking, and assembly processes.
10.3 Analysis of Needed Subassembly Tools

In the current layout, most tools for assembly are stored in the cells because each cell is dedicated for specific subassemblies. However, in the pilot layout, it is not feasible that generic workbenches store all necessary tools for all possible subassemblies. The reason is that generic workbenches should have multiple functions for every subassembly built on the North Floor, and it would need even more additional storage capacity and lead to higher costs if generic workbenches stored all tools. Therefore, a tool analysis is performed with the aim of optimizing which tools should be stored at generic workbenches.

10.3.1 Methodology

A matrix that states the required tools for subassemblies built at the North Floor is made, based on the procedures and interviews with assemblers. Also, the space to store each tool is estimated while building the matrix. All tools found in the matrix are sorted into two categories: regular tools that are stored at workbenches and special tools that are stored in the consolidated inventory area. The appropriate category of each tool is determined by the frequency of use of the tool, and constraints such as storage capacities of a workbench and inventory area.

In the actual analysis, the tools are sorted by the number of cells that use the tools. Initially, the tools used at only one cell in the current operation are counted as special tools; while any tools that are used at more than two cells are counted as regular tools. Then, if the number of regular tools is larger than the storage capacity of the workbenches, the next iteration would categorize tools that are used at one or two cells as a special tool. However, if the initial condition shows a feasible result, then the second iteration is not performed.

10.3.2 Results of Tool Analysis

This section represents the results of the tool analysis. Special tools are discussed at first, followed by regular tools. An appropriate workbench design is proposed, this
workbench stores the regular tools, while special tools are stored at the consolidated inventory area. Cost estimation is given in the third part of this section, followed by an outlook that describes necessary further analysis.

**Special Tools**

The detailed results of special tools are considered here. In the pilot case, all special tools are small enough to be transported with the inventory cart, and can therefore be picked up in the consolidated inventory area and be brought to the workbench. The biggest special tool is the 1\(\frac{1}{4}\) inch combo wrench that belongs to the source chamber built at the cell 130. The size of the wrench is 30 x 4.5 x 1 inch, which fits in the cart.

In terms of volume and number of special tools for one subassembly, the necessary tool set for the source chamber is the largest, including a file, torque wrench, lifting accessories, 1\(\frac{1}{4}\) inch combo wrench and fixtures for magnets. The set of special tools for the source chamber requires an extra area for 1\(\frac{1}{4}\) inch combo wrench and one large standard plastic bin, which is 16 x 14 x 4 inch, for other tools mentioned above. Therefore, it is concluded that there is no risk that the operations at the consolidated inventory area and workbenches are negatively affected by treating these special tools as inventory.

The seven groups of special tools are organized according to the cell where subassemblies are built currently. The cell for the SE3 line is not included here because the cell is still in the developing phase and the specific tools for the cell are not ready. The subassemblies built at the cell 301/302 belong to the group A. Other group numbers and part numbers of subassemblies are referred in Appendix A. The groups F and G need large sized standard plastic bins for the sets of special tools. The size of large bin is 16 x 14 x 4 inch. Except for the groups F and G, the set of special tools fit in the middle sized standard plastic bin, which is 8 x 14 x 4 inch. Therefore, five middle bins and two large bins are necessary to store these special tools.
Regular Tools

The regular tools that are stored at the generic workbenches are discussed next. From the analysis of tools, the tools identified in Table 10-2 are characterized as regular tools that should be stored at the generic workbenches.

Table 10-2: List of regular tools stored at the generic workbenches

<table>
<thead>
<tr>
<th>Gloves, hair covers</th>
<th>Vac Goop</th>
<th>Screw drivers</th>
<th>Wire cutting pliers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Goggles</td>
<td>PST</td>
<td>Xcelite</td>
<td>Retaining ring pliers</td>
</tr>
<tr>
<td>Torque wrenches</td>
<td>Ratchet wrenches 3/8 (1/4-13/16)</td>
<td>Chapman set</td>
<td>Scissors</td>
</tr>
<tr>
<td>Multimeter</td>
<td>Ratchet wrenches 3/4 (3/8-1(\frac{1}{4}))</td>
<td>Tape measure</td>
<td>Craft knife</td>
</tr>
<tr>
<td>Blue loctite</td>
<td>Allen wrench (small and large)</td>
<td>Cable crimpers</td>
<td>Heat gun</td>
</tr>
<tr>
<td>Braycote 600EF</td>
<td>Hammer</td>
<td>Molydag</td>
<td>Soldering gun</td>
</tr>
<tr>
<td>Molydag</td>
<td>Combo wrenches (1/4-13/16)</td>
<td>Needle nose pliers</td>
<td>Arbor press</td>
</tr>
<tr>
<td>Green scotch-brite</td>
<td>Open end-wrenches (1-2(\frac{1}{4}))</td>
<td>Tube cutter</td>
<td>Lifting strap</td>
</tr>
</tbody>
</table>

Since, in the current layout, workbenches store different tools and often those tools are stored in a random fashion, it is difficult to compare the numbers of tools between the current workbench and the future generic workbench. However, as a conservative assumption, the regular tools suggested in Table 10-2 are expected to increase the required space. Therefore, the constraint of storage capacity needs to be considered.

In terms of the storage capacity of the current workbench, a drawer under the desk provides the storage. The drawer has four trays, and the sizes of trays are width 12 x length 24 x heights 2, 3, 3, and 9 inches, respectively. Each tray has enough space to store the set of ratchet wrenches and the sockets. Also, the workbench has a space to mount a wall shelf on the desk. In the current design, the cabinet for hardware is mounted on the desk. The consolidated inventory area should include the hardware; hence the cabinet is removed from the workbench, and the wall shelf is installed as the additional storage location on the workbench. The capacity of the wall shelf is large enough to store several sets of wrenches and pliers. The proposed storage locations of regular tools at the workbench and wall shelf are shown in the following figure.
In Figure 10-2, "lubricants" includes all kinds of lubricants or adhesive introduced in Table 10-2 as regular tools: Blue loctite, Braycote 600EF, Molydag, Green sotch-brite, Vac Goop, and PST.

**Estimation of Cost to Implement**

Cost to implement the results of the tool analysis mostly considers the cost to purchase tools. The tools that need to be purchased are heat guns, soldering guns, arbor presses, and torque wrenches. The current cells already have at least two of each tool, except for the torque wrench. Torque wrenches are completely new tools because recent new assembly procedures have indicated specific torques for some assembly steps. Although the actual cost may change depending on the suppliers that SEMC deals with, this estimation is performed according to the price found on the website of McMaster Carr. The torque wrench that has the appropriate range for the use of building subassemblies costs approximately US$400. Also, it is considered that there are
five generic workbenches that are put on the pilot layout. Including the costs of other tools, the total cost becomes US$3,000. The cost estimates are shown in Table 10-3.

Table 10-3: Estimation of costs to purchase tools

<table>
<thead>
<tr>
<th>Tools</th>
<th>Unit price</th>
<th>Necessary Number</th>
<th>Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>Torque wrench</td>
<td>$386.06</td>
<td>5</td>
<td>$1930.3</td>
</tr>
<tr>
<td>Heat gun</td>
<td>$70.82</td>
<td>3</td>
<td>$212.46</td>
</tr>
<tr>
<td>Soldering gun</td>
<td>$7.2</td>
<td>3</td>
<td>$21.6</td>
</tr>
<tr>
<td>Arbor press</td>
<td>$298.74</td>
<td>3</td>
<td>$896.22</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td>$3060.58</td>
</tr>
</tbody>
</table>

Further Analysis

Further analysis could be done by sorting the tools at the level of different wrench sizes or bits of screw drivers. Because the assembly procedures are not updated or not existing for some subassemblies, a detailed analysis is not possible at this time.

10.4 Analysis of Tray Space

Pulling the parts from centralized subassembly storage requires practical solutions to a number of needs. The operator should be able to pull all parts that are listed in the BOM at the same time. In addition, the parts should be presented in a way that supports the assembly process. It is important to assure that the parts will fit onto the cart for every BOM. Different concepts for the storage of parts on a cart have been found and are discussed next.

10.4.1 Different Ways to Store Parts on a Cart

This section introduces four different concepts to store parts on a cart: foam cutouts, printed sheets with four standard sizes of bins, printed sheets with fixed small bins and loose bigger bins, printed sheets and transparent trays with cavities. Advantages and disadvantages are discussed with the descriptions of concepts.
Foam Cutouts

The first concept to support the picking and storing of parts on a cart is to ensure that every BOM has a specific set of foam cutouts, where the foam templates are approximately as big as the cart. Cutouts have the shape of the corresponding parts, and the parts are grouped on the foam according to assembly steps. The cutouts support the assembly process and support quality since the cutout-part pairing ensures that the correct part has been picked. If a part has not been used when the operator switches to the next assembly step, this signals that the assembly step has not been fulfilled correctly. Problems with this concept are the large number of needed cutouts and the storage of these, the associated costs to implement and maintain the system, the associated lead time to produce foam templates, and the storage of small parts such as washers. Small parts need inlays in the cutouts which increase the complexity of the system.

Printed Sheets with Four Standard Sizes of Bins

In the proposed approach, every BOM has a specific set of printed sheets. The sheets are approximately the size of the cart, and tell the operator where to put the parts and group the parts according to the assembly steps. Four different sizes of bins are available. A large part that cannot fit in the largest bin is put on another shelf of the cart. For smaller sized parts, appropriate sized bins are chosen from the four standard bins, depending on the sizes of parts. For example, assembly step A could have three small sized bins and two middle size bins. Basic operation is to pick up parts from the shelves, and place these into empty bins. The bins that now contain parts are put on the marked locations on the printed sheet of the cart. The advantage of this method is reduced initial costs to implement the concept of trays because sheets can be printed with available equipment, and the same bins can be used for all of the different subassemblies. Bins are cheap and bring high flexibility in terms of design of the sheets. The storage capacity of the tray can be adjusted by changing the number and size of bins, and also the number of trays may change, depending on the subassemblies. A disadvantage of this method is the required additional time to handle bins when the assembler collects parts. One obvious problem is the number of bins: some
BOMs require more than 50 bins and this would slow down the picking process and require time to organize bins before and after the assembly.

**Printed Sheets with Fixed Small Bins and Loose Bigger Bins**

An alternative concept, similar to that above, is to surround the cart by small bins that are fixed to the cart. This reduces the effort of handling bins since approximately fifty percent of the parts require small bins. Bigger parts are placed directly on the sheet or in bigger bins, similar to the last concept.

**Printed Sheets and Transparent Trays with Cavities**

In another variant, standardized transparent trays with cavities are placed on printed sheets. The sheets include information of part locations and assembly sequence. The cavities have different discrete sizes, and all cavities of one size are in the same area within the tray. The printed sheet groups cavities of one size into the different assembly steps; e.g., assembly step C could have three cavities of size one, five cavities of size two, and two cavities of size three. The cavities of one size and one step are in one group, next to the group of cavities that belong to the next assembly step and have the same size. The advantage is that no loose bins need to be handled and the transparent trays are standardized. One problem is that this solution cannot be based on available standard bins, and requires custom made thermoforming molds that cost approximately US$8,000.00 each.

**10.4.2 Methodology of Analysis**

The goal of the analysis is to determine if every BOM would fit on the cart, how many trays are necessary, and what cavity sizes are most appropriate given a maximum number of different cavities. The method considers a rectangular footprint of the parts.

The first part of this section explains what data was used to perform the analysis. The second part describes the logical function that is used to match parts to bins. The third and the fourth parts explain how results are interpreted and used to drive an iterative process that delivers a good solution.
Data

The analysis is processed with the spreadsheet program Microsoft Excel ©. The BOMs are exported from SAP © into Excel, and columns for width, length and height are added. Four different cavity sizes and one unlimited cavity size are listed in a separate sheet and references are dynamic. The unlimited cavity size is created for parts that are too big for cavities and therefore stored as bulk parts directly on the cart. The parts in the cells are measured and the dimensions are entered into an inventory list that feeds to the BOMs.

Matching Parts to Bin Sizes

Boolean functions in the BOM’s spreadsheet determine the appropriate cavity size and the number of cavities according to this logical procedure:

1. Choose the smallest cavity size by comparing width and length of the parts with the sizes of the cavities in the central list.

2. If more than one part is needed in the BOM, the spreadsheet determines how many parts fit into the cavity. The Boolean function picks the better solution in terms of the orientation of the part (the length of the part can be either parallel or perpendicular to the length of the cavity). Thereafter, the necessary number of cavities is determined.

Note that the height of parts is not considered in this analysis, since not all parts allow piling. For small parts the spreadsheet assumes that all parts fit into one cavity, since small parts are often hardware and can be stored densely in a cavity.

To receive the necessary area on the cart, the spreadsheet counts the number of cavities of each sort in each BOM and multiplies the numbers with the footprint of the related cavities. For parts that do not fit into cavities the footprint of the parts are taken and added.

Worst Case Scenario

To obtain a conservative estimate of the needed space, we calculate the needed space for the scenario "printed sheets and transparent trays with cavities." The trays are required to have the maximum number of cavities for each cavity size out of all BOMs. To illustrate what this means, we show an example with four cavity sizes,
unlimited bulk storage and four different BOMs. The resulting scenario is summa-
ized in Figure 10-4.

Table 10-4: Example to illustrate worst cast scenario of needed tray space

<table>
<thead>
<tr>
<th>BOM</th>
<th>small cavities</th>
<th>medium cavities</th>
<th>big cavities</th>
<th>long cavities</th>
<th>unlimited size</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>15</td>
<td>20</td>
<td>5</td>
<td>2</td>
<td>100 in²</td>
</tr>
<tr>
<td>2</td>
<td>25</td>
<td>15</td>
<td>7</td>
<td>3</td>
<td>150 in²</td>
</tr>
<tr>
<td>3</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>10</td>
<td>10</td>
<td>5</td>
<td>5</td>
<td>200 in²</td>
</tr>
</tbody>
</table>

In this case, the trays need to be able to accommodate 25 small cavities, 20 me-
dium sized cavities, ten big cavities, five long cavities and 200 in² of bulk area. Addi-
tional space should be available for future subassemblies. The worst case scenario of-
fers auxiliary resources because small parts can be stored in empty big cavities as
well. If BOM #2 changes and the number of small cavities increases by five, these
parts can be stored in the medium sized cavities since five medium sized cavities are
available (15 out of 20 are used in BOM #2). The more BOMs are used to determine
necessary space for the worst case, the more unlikely it is that a new BOM does not fit into the system.

Finding the Best Solution

The spreadsheet has stored the information of the cavity sizes centrally and uses
only dynamic references. The cavity sizes can be changed and the total area for the
worst case is returned instantly. This allows one to iteratively find a good solution for
cavity sizes. At present, this iterative solution must be driven manually, as the Excel©
Solver does not work. The reason might be that the underlying Boolean functions are
too complicated and too many calculations must be performed for each optimization
step. The returned function is discontinuous.
10.4.3 Results of the Analysis

The analysis was performed for 21 BOMs in three cells. One of the cells is the cell with the largest parts on the North Floor according to the operators.

Table 10-5: A good solution for cavity sizes

<table>
<thead>
<tr>
<th></th>
<th>width</th>
<th>length</th>
<th>area [in^2]</th>
<th>worst #</th>
<th>area in cavities [in^2]</th>
<th>cavity area [in^2]</th>
</tr>
</thead>
<tbody>
<tr>
<td>small cavities</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>40</td>
<td>40</td>
<td>90</td>
</tr>
<tr>
<td>medium cavities</td>
<td>2.75</td>
<td>3</td>
<td>8.25</td>
<td>53</td>
<td>437.25</td>
<td>602.875</td>
</tr>
<tr>
<td>big cavities</td>
<td>3.9</td>
<td>4.4</td>
<td>17.16</td>
<td>14</td>
<td>240.24</td>
<td>301.84</td>
</tr>
<tr>
<td>long cavities</td>
<td>3</td>
<td>24</td>
<td>72</td>
<td>13</td>
<td>936</td>
<td>1114.75</td>
</tr>
<tr>
<td>unlimited size</td>
<td>9999</td>
<td>9999</td>
<td>9999</td>
<td>17</td>
<td>2116.1075</td>
<td>2116.1075</td>
</tr>
</tbody>
</table>

Table 10-5 shows the cavity sizes in the second and third column and the needed space on the tray in the right-most column. "area in cavities" describes the area that is available for parts within the cavities, while "cavity area" is the area that is required to store the cavities. The reason that two different numbers for the area are needed is that the thermoforming process needs a distance between the cavities, and cavities require a wall thickness. The Table 10-5 shows one solution that was returned after several iterations. Carts are approximately 24 in x 48 in, which is equal to 1152 in^2. This means that the small, medium, and large cavities will fit on one tray, the long cavities on another tray, and two bulk trays are used for bigger parts. Using four trays on one cart is feasible. Two different molds for thermoformed transparent trays are necessary if the last concept is chosen. This means that the cost of molds will be approximately US$16,000.

10.4.4 Another Analysis for the Idea Using Standard Bins

Another possible solution is generated from another analysis that uses the same method and data set as the previous section uses, but in this case the analysis is performed with the aim of estimating the number of necessary trays when the four standard bin idea applies. Cavities are simply replaced by bins. Since the method to store parts is the four standard bin idea discussed in Section 10.4.1, the goal of this analysis is to estimate the numbers of trays for every subassembly in the three cells. Different
than in the previous analysis, we do not try to find the common tray design that can be used for all subassemblies. The actual sizes of bins and results of analysis are showed in Table 10-6.

Table 10-6: Four standard sizes of bins

<table>
<thead>
<tr>
<th></th>
<th>width</th>
<th>length</th>
<th>area [in²]</th>
<th>worst #</th>
<th>area in bins [in²]</th>
<th>bin area [in²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small bins</td>
<td>2.5</td>
<td>3.5</td>
<td>8.75</td>
<td>71</td>
<td>621.25</td>
<td>853</td>
</tr>
<tr>
<td>Medium bins</td>
<td>5.5</td>
<td>7.5</td>
<td>41.3</td>
<td>27</td>
<td>1113.8</td>
<td>1296</td>
</tr>
<tr>
<td>Big bins</td>
<td>7.5</td>
<td>11.5</td>
<td>86.3</td>
<td>9</td>
<td>776.25</td>
<td>864</td>
</tr>
<tr>
<td>Extra big bins</td>
<td>11.5</td>
<td>15.5</td>
<td>178</td>
<td>6</td>
<td>1069.5</td>
<td>1162</td>
</tr>
<tr>
<td>unlimited size</td>
<td>9999</td>
<td>9999</td>
<td>N/A</td>
<td>2</td>
<td>240</td>
<td>240</td>
</tr>
</tbody>
</table>

Because the goal of this analysis is different from the last one, it is not critical to consider the number of each bin required in the worst case. However, one important difference between these two results from the analysis is that the number of parts that are categorized to the unlimited size is reduced from 17 to 2. The reduced number of unlimited sized parts means more parts become fit to the standard bins, and less bulk storage area is required. This means that the templates of the tray are better organized in terms of assembly processes.

The next step is to compare sizes of four standard bins. In order to estimate the number of trays, the relationship of foot prints between bins are important.

Table 10-7: Inner size and foot prints of the bins

<table>
<thead>
<tr>
<th></th>
<th>Inner width</th>
<th>Inner length</th>
<th>Outer width</th>
<th>Outer length</th>
<th>Foot print [in²]</th>
<th>Necessary blocks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small bins</td>
<td>2.5</td>
<td>3.5</td>
<td>3</td>
<td>4</td>
<td>12</td>
<td>1</td>
</tr>
<tr>
<td>Medium bins</td>
<td>5.5</td>
<td>7.5</td>
<td>6</td>
<td>8</td>
<td>48</td>
<td>4</td>
</tr>
<tr>
<td>Big bins</td>
<td>7.5</td>
<td>11.5</td>
<td>8</td>
<td>12</td>
<td>96</td>
<td>8</td>
</tr>
<tr>
<td>Extra big bins</td>
<td>11.5</td>
<td>15.5</td>
<td>12</td>
<td>16</td>
<td>192</td>
<td>16</td>
</tr>
<tr>
<td>unlimited size</td>
<td>9999</td>
<td>9999</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>

As Table 10-7 shows, the foot prints of the medium bins, big bins and extra big bins are respectively four, eight, and sixteen times as large as the foot print of the small bins. The size of the small bins is designed to equal 1/96 the size of the 24 inch x 48 inch tray. Then, one tray has 96 blocks (8 x 12), and the necessary numbers of blocks are allocated for all kinds of bins. Hence, the minimum number of required
trays for a subassembly is calculated by the following equation using the ROUNDUP function of Excel.

\[
X = \text{ROUNDUP}\left(\frac{A + 4 \cdot B + 8 \cdot C + 16 \cdot D}{96}\right)
\]

(10-1)

Here, X is the number of trays, A is the number of small bins, B is the number of medium bins, C is the number of big bins, and D is the number of extra big bins required.

The result is that the minimum number of trays required is one, and the maximum number is four, including the tray for the large parts categorized to the unlimited size. Figure 10-3 shows the actual layouts of the bins for a subassembly that requires only one tray. In the figure, the different colored fields named A, B, C, and D correspond to the small, medium, big, and extra big bins, respectively.

![Figure 10-3: Layout of the Bins for the Subassembly E11358690](image)

**Cost Analysis of the idea of standard sized bins**

For a conservative cost analysis, the necessary numbers of all bins are estimated based on the worst case. The required bin numbers are calculated to be five times the number of bins in the worst case shown in Table 10-8, because the number of workbenches in the pilot plan is five. This conservative estimation expects the situation that all five workbenches are busy for the subassemblies that required the largest numbers of bins.

The unit cost for each bin is quoted from the unit prices of similar sized bins found on the McMaster-Carr Website. Using these numbers, the cost of the necessary bins for the standard bin method is calculated to be approximately US$4,500. The detailed results of calculations are summarized in Table 10-8.
Table 10-8: Cost analysis of required bins for the entire system

<table>
<thead>
<tr>
<th>Inner width</th>
<th>Inner length</th>
<th>Worst number</th>
<th>Total number</th>
<th>Unit cost</th>
<th>Cost of bins</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small bins</td>
<td>2.5</td>
<td>3.5</td>
<td>71</td>
<td>355</td>
<td>$3.35</td>
</tr>
<tr>
<td>Medium bins</td>
<td>5.5</td>
<td>7.5</td>
<td>27</td>
<td>135</td>
<td>$4.47</td>
</tr>
<tr>
<td>Big bins</td>
<td>7.5</td>
<td>11.5</td>
<td>9</td>
<td>45</td>
<td>$20.07</td>
</tr>
<tr>
<td>Extra big bins</td>
<td>11.5</td>
<td>15.5</td>
<td>2</td>
<td>30</td>
<td>$59.16</td>
</tr>
<tr>
<td>Total cost</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Total $4,471</td>
</tr>
</tbody>
</table>

10.4.5 Proposed Designs of Templates

To identify the practicality of the proposed methods to make templates, a subassembly that has more than 100 kinds of parts and 39 steps for the assembly is used as a test. Not every assembly step requires parts, but the reference between the area on the template and the procedure needing parts is made clear by indicating the step number (e.g. M, DD, FF, etc) on the bin layout.

Printed Sheets with Four Standard Sizes of Bins

![Figure 10-4: Layout of the Bins for the Complex Subassembly](image)

(Left: According to assembly sequence, Right: According to bin sizes)

As the previous section describes, the bin layouts on the templates are flexible and easily modified according to the priorities of the functions of templates. Figure 10-4 shows the different layouts based on the two different giving goals. The left side of Figure 10-4 shows a bin layout for the subassembly organized according to assembly sequence. The advantage of this design is that necessary parts for each assembly step
are consolidated into one place, making it easier for an operator to assemble the parts. In this proposal, the engineering department is responsible for the layout of trays. The layout is created parallel to the BOM lists and the procedure documents. Maintenance is necessary if parts are added or procedure steps are changed. An automated solution has not been examined in this project.

The right sided design in Figure 10-4 facilitates the manual design of the tray layout of the bins. In this design, small bins are allocated to the upper half, and the lower half is used for bigger bins. Rather than maximizing space utilization of the tray, a straightforward methodology that creates a feasible solution without several layout iterations is preferred. This design is able to save time in the design of the templates, compared to the previous design. However, the disadvantage of the design on the right side is that necessary parts for an assembly process could be allocated on separate trays. For example, in the assembly process Z, the medium part is put on the first tray, but the small parts that belong to the assembly process Z are put on the second tray. This unorganized design could deteriorate the efficiency of assembly processes.

10.5 Analysis of Operations of Supermarket

The supermarket system as described in section 8.3 and leaves room for different approaches of labor organization. One way is to have assemblers walking through the supermarket kitting the foam cut-outs right before they start an assembly process. Alternatively, dedicated material handlers can kit the foam cut-outs in the supermarket and deliver the cut-outs to the assemblers' work stations.

Both solutions have their own advantages and disadvantages. The first solution vertically integrates the processes of assembly and kitting into one process. That is, there will be no queuing between kitting and assembly, which will be inevitable in the other system. This reduces lead time, defined by the time from placing a new order for a subassembly until the subassembly is finished. Also, the vertical integration lowers system complexity. Due to this fact, less supervision effort will be required; the system is self-managing to a certain extent.
On the other hand, kitting of parts by material handlers has the advantage of lower labor rates. Material handler’s imputed labor rates are US$80 per hour whereas assemblers’ rates are at US$92 per hour. These figures include a surcharge for overhead.

Also, there might be an advantage to dedicated material handlers in terms of work efficiency. Material handlers could be more efficient in kitting foam cut-outs than assemblers, because they could focus on this task. On the other hand, the effect of fatigue due to highly repetitive work might compromise this advantage.

In order to understand and analyze the system more deeply, we consider a discrete event queuing simulation of the supermarket system. This simulation focuses on the queuing effects taking place between kitting and assembly. That is, the queue consists of kitted foam cut-outs waiting to be assembled.

The simulation is performed using the discrete-event simulation software “CellSim.” CellSim is a set of macros for Microsoft Excel. Models in CellSim consist of buffers and processes and there is always a buffer at the beginning and the end as well as between every two processes. Figure 10-5 shows the CellSim model for the supermarket system. The production control buffer at the beginning provides an unlimited number of orders, so that the material handler process is never starved. Although starving of the material handlers might happen in reality due to a temporarily low order input, this is not part of this analysis. This analysis rather focuses on the system performance under full capacity.

Figure 10-5: Supermarket Simulation
Figure 10-6 exhibits the assumed cycle time distribution of the process “material handlers” as set up in CellSim. The abscissa is in units of hours. The average is at 0.67 hours and an Erlang distribution function is used. Choosing this type of distribution and setting up an appropriate standard deviation allows modeling a long tail. This is realistic because problems like part shortages lead to significant delays in a certain fraction of kitting processes. Similar reasoning was used to create the distribution function for the assembler processes. In this case however, the average cycle time is six hours, Figure 10-7. The average cycle time was derived from historical data from SEMC.

As Figure 10-5 shows, we analyzed a system with one material handler kitting foam cut-outs for five assemblers. Based on the cycle time distributions, this setup
will meet the current target capacity. The buffer between material handlers and assemblers has a maximum capacity of six. That is, material handlers will only kit new foam cut-outs as long as there are less than six foam cut-outs in the buffer.

This model was simulated over a 1000 hour period. Before the actual period began, there was a 100 hour run-in period to reach steady state. This run-in period is not included in the statistics; thus, the statistics in Table 10-9 and Table 10-10 represent steady state values.

Table 10-9: Average utilization of during 1000 hour simulation period

<table>
<thead>
<tr>
<th>Material Handler</th>
<th>0.526065</th>
</tr>
</thead>
<tbody>
<tr>
<td>Assembler</td>
<td>1</td>
</tr>
<tr>
<td>AssemblerA</td>
<td>1</td>
</tr>
<tr>
<td>AssemblerAA</td>
<td>1</td>
</tr>
<tr>
<td>AssemblerAAA</td>
<td>1</td>
</tr>
<tr>
<td>AssemblerAAAA</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 10-10: Units done within 1000 hours simulation period

<table>
<thead>
<tr>
<th>Material Handler</th>
<th>811</th>
</tr>
</thead>
<tbody>
<tr>
<td>Assembler</td>
<td>157</td>
</tr>
<tr>
<td>AssemblerA</td>
<td>173</td>
</tr>
<tr>
<td>AssemblerAA</td>
<td>169</td>
</tr>
<tr>
<td>AssemblerAAA</td>
<td>152</td>
</tr>
<tr>
<td>AssemblerAAAA</td>
<td>159</td>
</tr>
</tbody>
</table>

The average inventory in the foam cut-out buffer is 5.8. This simulation shows some of the disadvantages mentioned above. First of all, the material handler is only utilized at 52%. The random nature of this queuing system does not allow both material handler as well as assemblers to work at 100% utilization. Since starvation of assemblers is costly, there needs to be a certain overcapacity of material handling workforce. Another reason for the low utilization of material handler is the problem of
discrete numbers. In this simulation setup, the average output rate of the material handler is higher than the average output rate of these five assemblers. Thus, we would only need a fraction of a material handler. However, keeping the under-utilized material handler busy with secondary jobs would lead to worse system reactivity and starvation of assemblers, as there will be times where the material handler will not be able to observe the buffer level of filled foam cut-outs. Also, assigning secondary tasks to the material handler would require supervisory effort and would also require that there actually are appropriate tasks the material handler could be assigned to, which is most likely not always the case.

As the size of the system scales up, the effects of discrete numbers become less important in relative terms. Also, the needed overcapacity of material handlers – again in relative terms – could be smaller, due to the Central Limit Theorem. The more assemblers that are working at a time, the smaller the coefficient of variation (i.e. standard deviation divided by average production rate) of the assemblers’ production rate would be.

10.6 Time Study of Assembly

Time studies are performed in order to predict the economic viability of the supermarket subassembly system. First, we measure the time it takes to build a Flood Gun subassembly, a typical and thus representative subassembly, using our foam cut-out. Before doing the time study, the cut-out was equipped with parts.

To analyze the time difference between the current cell system and the proposed supermarket system, a baseline time study is performed. For this purpose, the time that the same operator needs to build the same subassembly in the current system, including picking parts from shelves within the cell, is measured.

However, these two times are not comparable, since the build from the foam cut-out does not include gathering parts in a supermarket and placing them on the cut-out, while the baseline build includes gathering the parts from shelves.
It is therefore necessary to estimate the time needed for filling the foam cut-out in a supermarket environment. This is done by using estimates for the time it takes to pick one part and multiplying this time with the number of parts. However, the result of this calculation might not be accurate, as the estimation of the time for picking one part in the supermarket and placing it on the cut-out is rather unreliable.

Thus, we decided to create a supermarket mock-up and to do several test runs of equipping the cut-out. To keep setup effort of our mock-up to a minimum, we used an aisle of the SEMC warehouse that contains parts of sizes that are typical for subassemblies. Also, the bins in this warehouse aisle are assorted by bin size, as it would be in a supermarket. In addition, a shelf numbering system makes it easy to localize the bins. We proceeded by creating a “shopping list” of parts from this aisle that would be similar to the parts of the Flood Gun subassembly and would thus fit into the pockets of our cut-out. The shopping list contained the shelf location, the part number, the find number and the quantity for each part. The find number is a number that helps to locate the right pocket on the foam cut-out for a certain part. The shopping list is sorted by shelf locations in a way that allows to only moving forward. After attaching the foam cut-out to a cart, we started our time study. Altogether, we picked 81 parts each run and this took between 20 and 29 minutes, as summarized in Table 10-11.

Table 10-11: Time study results: Time to gather 81 parts in “supermarket”

<table>
<thead>
<tr>
<th>Run</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simon Treis, 1st run</td>
<td>29 minutes, 15 seconds</td>
</tr>
<tr>
<td>Richard Schwenke, 1st run</td>
<td>21 minutes, 24 seconds</td>
</tr>
<tr>
<td>Koji Umeda, 1st run</td>
<td>24 minutes, 50 seconds</td>
</tr>
<tr>
<td>Simon Treis, 2nd run</td>
<td>20 minutes, 50 seconds</td>
</tr>
<tr>
<td>Richard Schwenke, 2nd run</td>
<td>20 minutes, 19 seconds</td>
</tr>
</tbody>
</table>

Accounting for learning effects as well as the fact that the shelf location system in the warehouse was not optimized for a supermarket system, the shortest time was chosen as the result of this study rather than the average time. These times are based
on gathering 81 parts; however, the actual Flood Gun subassembly has 111 parts. Therefore, we extrapolate the time to 27 minutes and 51 seconds.

Table 10-12: Build time comparison for subassembly build

<table>
<thead>
<tr>
<th>Current System (“Cell”)</th>
<th>Proposed System (“Supermarket”)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Gross Total Time</strong></td>
<td>248.64 min</td>
</tr>
<tr>
<td>- Break</td>
<td>33.63 min</td>
</tr>
<tr>
<td>- Personal</td>
<td>2.93 min</td>
</tr>
<tr>
<td>- Missing Parts</td>
<td>5.13 min</td>
</tr>
<tr>
<td>- Rework</td>
<td>9.96 min</td>
</tr>
<tr>
<td>+ Step Z skipped</td>
<td>3.16 min</td>
</tr>
<tr>
<td>+ Step JJ skipped</td>
<td>4.08 min</td>
</tr>
<tr>
<td>+ Step NN skipped</td>
<td>3.38 min</td>
</tr>
<tr>
<td>+ Packaging</td>
<td>4.81 min</td>
</tr>
<tr>
<td>+ Final clean up of workbench</td>
<td>2.70 min</td>
</tr>
<tr>
<td><strong>Total Time (adjusted)</strong></td>
<td><strong>215.12 min</strong></td>
</tr>
<tr>
<td><strong>Gross Total Time excl. delays</strong></td>
<td><strong>166.52 min</strong></td>
</tr>
<tr>
<td>+ Gathering Parts in “Supermarket”</td>
<td>27.85 min</td>
</tr>
<tr>
<td>+ Detrashing Parts</td>
<td>22.82 min</td>
</tr>
<tr>
<td>+ Moving cart between “Supermarket” and workbench</td>
<td>5 min (Estimated)</td>
</tr>
</tbody>
</table>

In order to compare the times from our time studies with each other, several adjustments to the raw data are necessary, as shown in Table 10-12. The Gross Total Time from the Current System column is the actual elapsed time between start and finish of the assembly job. Non-value added times are subtracted. Estimated times for steps that are not performed during this time study but are in the supermarket time study are added. The estimates are based on the times these steps took within the Supermarket build, plus 30 seconds per step for picking parts and 30 seconds per step for detrash, if this was necessary.

As a result of the time studies, building this subassembly in the “supermarket” environment takes 7 minutes longer than in the current “cell” system. However, assem-
bly times are subject to variation, and due to resource restrictions, we did not accomplish any replicate samples of our time study. Still, the result of this time study can be used as an indicator that the labor required for the “cell” and the supermarket system are comparable.

Not included in this time study is the learning effect. Operators are used to the cell system and know the location of parts within their cell. On the other hand, the operator from our time study is not used to build from a foam cut-out. Also, doing the time study at the SEMC warehouse, our team only accomplished two runs per person. Therefore, operators working in this environment for a longer time could potentially decrease both the time of gathering parts in the supermarket as well as the actual assembly time compared to the times that were determined in this time study.

10.7 Implementation

After the pilot proposal and detailed analyses of the supermarket system were introduced to the managers at the SEMC, the decision to implement the scaled-down pilot plan was made. The scaled-down pilot plan focuses on the supermarket system: in particular, the generic workbenches, foam cut-outs, sorting bins by the bin sizes, tags for replenishing inventory, and updating the assembly procedures. Physically, the scaled-down pilot plan consolidates Cell 131 and 303.

**Generic Workbenches**

Two generic workbenches were prepared for this pilot plan. The generic workbenches were designed to be capable building 14 different subassemblies that belong to Cell 131 and 303. The result of tool analysis was optimized to prepare the necessary tools only for those 14 subassemblies. As a result of rearrangement of tools, the drawer under the workbench was emptied out. All regular tools are stored at the wall shelf that is mounted on the workbench.

**Foam Cut-outs**

Using the engineering models, the outlines of parts are drawn as the layouts of foam cut-outs. The engineers can make the layouts of foam cut-outs quickly; however,
the challenge is that the engineering department does not have extra workforce to maintain the layouts of foam cut-outs. Also, the different types of foam cut-outs were tried.

**Sorting Bins by Bin Sizes**

The biggest change of sorting bins by the bin sizes was that each bin is identified by the storage location. The information of storage location includes the shelf number, column, and row within the shelf. The list of part numbers and storage locations is provided at the entrance of the supermarket which improves the replenishment process. Another benefit of re-sorting bins was that many unnecessary parts were removed from the floor.

**Tags for Replenishing Inventory**

Tags were prepared for every bin for the purpose of inventory control. The tag shows the part number, storage location, barcode for replenishment order, re-order point, and re-order quantity. Once the inventory reaches the re-order point, the barcode on tag is scanned. Until the replenish process is completed, the scanned tag is flipped to avoid that the tag is scanned more than twice.

**Updating the Assembly Procedures**

The assembly procedures related to the 14 subassemblies were updated or created. The revised procedures include the find numbers for all necessary parts. The find numbers indicate assembly steps, and also, are used to match the parts and cavities on the foam cutout.
Chapter 11

Conclusion

The goal of this project was to solve the problems referred to in Chapter 2. Especially, the focus was on the lead time reduction and improvement of inventory control which have a higher priority than the other problems. Through various analyses performed in this project, the following list of conclusions was made:

1. In terms of lead time reduction, the idea of centrally located test equipment in proposal A makes it possible to reduce the lead time from 0.1 hour to 0.5 hour per machine, depending on the product line. The savings from this lead time becomes approximately US$80,000 annually [8].

2. Inventory management will be improved by consolidating inventory. The analysis of redundant parts across the three cells reveals that consolidation could reduce approximately US$9,000 of redundant inventory. The cost reduction by removing redundant inventory will increase if more cells are consolidated.

3. In terms of floor space, the pilot layout saves an additional 680 feet square, compared to the current layout. Based on the annual cost for one square foot on the factory floor, which is US$25, the additional floor space saving will reduce cost by approximately US$17,000 per year.
4. The problems related to the testing process are mostly solved by the idea of central test equipment around the work spaces. The idea increases the utilization of test equipment and reduced safety concerns in the test process, without any major changes of the test equipment.

5. Cross training is achieved by providing the environment of generic work spaces that are proposed in proposal B, C and the pilot layout. The expected cost savings by cross training are not estimated in this thesis; however, the managers at the manufacturing engineering department of SEMC agree that the supermarket idea is an effective way to implement cross training.

6. The block system that is demonstrated in proposal C is the most effective to increase the degree of production volume flexibility. However, the system needs to be assessed in detail, for instance, the cost of implementation of the idea and the difference of running costs between the current manufacturing system and proposed system needs to be analyzed.

11.1 Further Analysis and Recommendation

As a further step, the scope of detailed analyses should be expanded to the entire production floor. In terms of the consolidated inventory idea, before SEMC applies the consolidated inventory area on the other production floors, detailed assessments are necessary to focus on the current utilization and the work hour and cost required for the implementation. The advantages of consolidating inventory that Section 9.3 refers to could be decreased if the product floors have higher utilizations and less redundant inventory. Therefore, the detailed assessment of each production floor is recommended.

If the company implements growing the consolidated inventory area that covers over the different product lines, which is discussed in detail and called as “supermarket” in proposal C, the scale effects of supermarket should be considered. Especially,
the generic workbench needs to store more tools, when more subassemblies are built at the generic workbench. Therefore, at a certain point, it could become impossible to store all regular tools at the generic workbench. If the required storage for regular tools reaches the storage capacity at the workbench, additional tools are categorized as special tools, and more special tools are stored at the supermarket. Then, it will increase the coordination of the special tools. In order to avoid the struggles of handling the tools, one possible solution is that all tools are handled as well as general inventory, with parts numbers controlled by SAP and find numbers controlled by the documents of assembly procedures. However, even if the problem with handling tools is solved, the workbench with too many functions, due to many subassemblies built there, might decrease the ease of use.

Also, the organizational structure may be an interesting topic. The process required to maintain the consolidated inventory system should be considered. Since the new system requires the correspondence between the BOMs in SAP, documents of assembly procedures, and engineering drawings, it increases the interdepartmental activities between SAP department, technical documentation department, and manufacturing engineering department. Ideally, it is recommended that an independent department controls any changes on these three types of departments as an upper level of management. In the current system, the ECO department manages the documents and databases. However, the ECO will not be appropriate, because the changes of the BOM, assembly procedure, and engineering drawings happen frequently, and the change orders exceed the capacity of ECO. In addition, on the job floor, the consolidated inventory system encourages the assemblers to be involved with the processes that maintain the correspondence of the documents, which could require the organizational change of the job floor. Therefore, another project focused on the organizational structure in the consolidated inventory system will be interesting.
Appendix A

Additional Tables of Tool Analysis

Table A-1: Groups of necessary special tools (part 1)

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pin pushers</td>
<td>1/2-13 die</td>
<td>Customized wrench (cut arm)</td>
<td>Dice (305_306)</td>
</tr>
<tr>
<td>Drill Tap for deburr</td>
<td>Alignment fixtures</td>
<td>Fixtures (water panel)</td>
<td>Alignment pins</td>
</tr>
<tr>
<td>Customized retaining ring pliers</td>
<td>Modified tip wrenches</td>
<td>Additional wrenches</td>
<td>Fixtures (305_306)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>5/16 retaining ring pliers</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Wrap</td>
</tr>
</tbody>
</table>

Table A-2: Groups of necessary special tools (part 2)

<table>
<thead>
<tr>
<th>E</th>
<th>F</th>
<th>G</th>
</tr>
</thead>
<tbody>
<tr>
<td>Swivel eye bolt</td>
<td>Special cock, ANT-4613, S/N TE5996</td>
<td>Fixtures (132)</td>
</tr>
<tr>
<td>Lifting strap</td>
<td>BNC Connector Removal Tool</td>
<td>Slim file</td>
</tr>
<tr>
<td>Vacuum bag</td>
<td>Dice (131)</td>
<td>Double end-scribe</td>
</tr>
<tr>
<td>Dimer magnet fixture</td>
<td>Extraction tools (3 pieces)</td>
<td>Rule</td>
</tr>
<tr>
<td>Alignment pin</td>
<td>Fixtures (two plastic, one metal)</td>
<td>Vernier Caliper</td>
</tr>
<tr>
<td>UltraSOLV scrub pad 2000 diamond</td>
<td></td>
<td>Tape Gun</td>
</tr>
<tr>
<td>Superlube</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table A-3: Groups and part numbers of subassemblies

<table>
<thead>
<tr>
<th>Group</th>
<th>Part numbers of subassemblies</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>E11293860</td>
</tr>
<tr>
<td>B</td>
<td>E11285780</td>
</tr>
<tr>
<td>C</td>
<td>E11298170</td>
</tr>
<tr>
<td>D</td>
<td>E11102070</td>
</tr>
<tr>
<td>E</td>
<td>E11135490</td>
</tr>
<tr>
<td>F</td>
<td>E11285750</td>
</tr>
<tr>
<td>G</td>
<td>E11096860</td>
</tr>
<tr>
<td></td>
<td>E11102100</td>
</tr>
</tbody>
</table>
References


