A Flexible Assembly System for Low Volume and High Diversity Production

By Richard Clemens Schwenke

Submitted to the Department of Mechanical Engineering in partial fulfillment of the requirements for the degree of Master of Engineering in Manufacturing

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Abstract

This thesis project seeks to optimize floor layouts for semiconductor equipment assembly operations. The assembly of semiconductor equipment is characterized by low volume and high product diversity and complexity. Demand for semiconductor equipment is highly periodic and often shifts rapidly from one type of semiconductor equipment to the other. Thus, the goal is to develop an assembly system that easily handles high part counts per assembly and facilitates material management, but at the same time allows reacting to changes in demand quickly and efficiently. Lead time and floor space usage are further metrics that are considered.

Capturing the current state of the floor layout in a 3D drawing software and documenting important aspects of current operations is the first step towards achieving those goals. Current assembly operations consist of the build of subassemblies in dedicated cells and the final assembly of machines in dedicated build lines. That is, each type of product is assembled in a specific area and the required inventory is stored within these areas.

In order to increase production flexibility, reduce inventory levels, and to lower floor space usage, a new assembly system is developed. This system features consolidated inventory for both the build of subassemblies and final assembly. It is proposed that technicians pull parts for subassemblies by driving with a cart and attached foam cut-outs as part trays through an inventory aisle. This aisle accommodates inventory for all subassemblies, which is currently stored within approximately 20 cells spread over the production floor. Subsequently, technicians drive these carts to generic workbenches and start assembly. Using generic, standardized workbenches rather than dedicated workbenches boosts flexibility and efficiency.

Parts for the final assembly would be kitted for each machine by material handlers on movable racks. This allows building any type of machine in any area of the production floor. A block system is proposed to decouple assembly of different machines and to enable easy management of assembly operations. A floor layout based on these ideas is developed.

Finally, a pilot proposal is developed to serve as a stepping stone towards full scale implementation and this proposal is in part physically implemented.

Thesis Supervisor: Duane S. Boning
Title: Professor of Electrical Engineering and Computer Science
I would like to thank my thesis supervisor, Prof. Duane Boning, who gave valuable and insightful advice. I am also grateful to all MIT professors involved in teaching in the Master of Engineering in Manufacturing program for presenting the class topics in a way that enabled me to apply them in practice during this project.

My thank goes to SEMC for the generous funding of the project. Special thanks to Tom, who helped us throughout the project by solving uncountable problems, and to the rest of the production engineering department for their readiness to help. I would also like to thank all the managers, engineers, and technicians we interviewed during the project for their valuable input and feedback.

This project relied on team work and I therefore thank my teammates and friends Simon Treis and Koji Umeda for the fruitful cooperation and the friendly atmosphere. Due to the fact that we worked together on this project, our theses share large parts of Chapter 1 through Chapter 7 and Chapter 9.

I thank my parents in Germany for their support and my little sister Clara for reminding me of the important things in life.
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Chapter 1

Introduction

SEMC manufactures a type of semiconductor equipment\(^1\) that is required for one of approximately 40 different types of process steps in semiconductor manufacturing. The products are highly complex tools, since they consist of several thousand parts and subassemblies. They are on the order of 30 ft and 20 tons.

While R&D is completely done in house, manufacturing operations are outsourced to a large extent. No parts manufacturing but rather only assembly and testing operations are performed at SEMC. Parts feeding into the assembly process are ordered from local as well as international suppliers.

Although a high fraction of costs of goods sold is due to parts that are bought from external suppliers, in house manufacturing operations still have a high impact on the company’s performance. On the one hand, assembly and testing are cost drivers and the efficiency of these operations has direct impact on the profit margin. On the other hand, customers, who typically have a high buying power, expect on-time delivery and high quality. The company’s main focus is accordingly to reduce costs while meeting the customers’ expectations in terms of quality and timeliness.

As of 2007, SEMC has annual revenues of over US$1 billion and holds a market share of over 60%. Its customers are international and represent the major part of the

\(^1\) Specific type of semiconductor equipment, company name and product names are disguised for confidentiality. The company is referred to as Semiconductor Equipment Manufacturing Company (SEMC) and the different products are referred to as SE1, SE2,...
global players in semiconductor manufacturing. As SEMC’s mid-term goal is to increase revenues by almost 100%, its manufacturing operations’ capacity needs to be capable of responding to this potential scenario. However, the demand for semiconductor equipment is highly cyclical, leading to periods of low as well as high activity in SEMC’s assembly plant. Accordingly, capacity flexibility is the key to not only meeting the demand during upturns, but also maintaining low manufacturing costs while facing downturns.

Due to the products’ 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 on a high level. Chapter 4 provides background information on 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 9) 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 im-
prove 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 semiconductor equipment 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.

![Diagram of Methodology](image)

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 in 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.](image)

### 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 9 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 average arrival time is $1/\lambda$. The service rate is described as $\mu$, which means that the average 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 is 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 a 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 the parameters 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, every machine has a number of customer specific parts and the number of machines SEMC manufactures per year is small compared to other industries such as automotive 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. This 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 for a certain step of semiconductor manufacturing. The products differ in attributes related to the process parameters. 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. At SEMC, 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 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 operators on the assembly floor, supervisors, and engineers, while bills of materials (BOMs) or other databases are managed by engineering change order (ECO). 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 machines. These subassemblies are directly sent to the customers after the testing and package process.

5.4 Build and Test of Modules

SEMC's products consist 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 where the module is built, the second passage shows the organization of inventory that is used to build a module, and the third passage 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 a 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 wandung 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, magnets 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 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.

Figure 6-1: Current Layout of the whole factory at SEMC.
Table 6-1: Sizes of Floor Areas.

<table>
<thead>
<tr>
<th></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>
<tr>
<td><strong>Total (sqft)</strong></td>
<td></td>
<td></td>
<td><strong>30663</strong></td>
</tr>
<tr>
<td><strong>Total (m²)</strong></td>
<td></td>
<td></td>
<td><strong>2849</strong></td>
</tr>
</tbody>
</table>

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 SE0 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 SE00 machine 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 material 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 SE3 line from the aisle. The end of the SE3 line is connected to the aisle that separates the North and Mid Floor.

The test equipment of the SE3 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 SE3 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.

Figure 6-3: Current Layout of the SE3 Line.
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 are built in build bays and are thereafter moved into the test bays. There are two build bays and one test bay for one of the types of modules, and one build bay and one test bay for the other. Because the demand for SE2 is not big enough to use two build workspaces, only one workspace for each module is currently used, and the other empty workspaces 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 between the build bays and the test bay. 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 types of 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.
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.
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 replenish stock inside the cells. Cell 307, which is the accelerator column cell 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.
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 modules SEMOD1 and SEMOD2, 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, a cell that is building subassemblies for the SEMOD1 product, and two offices.

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

6.3.1 SE4 Line

On the very left side of the SE4 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 magnet module assemblies are located. Two different magnet modules are used for one machine. Since the first magnet module diverts the ion beam 90 degrees, and the second magnet module averts the beam 70 degrees, 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 in-
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 magnet module test. The magnet modules can only be moved with air pads and this process requires approximately five people.

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. 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
SEMODI 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 SEMODI cells.

When the assembly process is complete, the SEMODI module is moved to a test bay, again by using a pallet jack. 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

Products SE5 and SE6 perform a 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 "High Performance" (HP) 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 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.

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

The lowermost line can be divided into four different areas. 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 under the southernmost crane. Space has been taken away from the NPI because the activities of other products did not fit into their assigned areas.

The left 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.
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 does also mean that operational problems in one line do not automatically propagate to other lines.

However, strongly dedicated lines tend to isolate knowledge. 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 the 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 does sacrifice flexibility, since only specialized cells can build certain subas-
semmbles 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 as-
sembly 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 opera-
tors pick the parts from the shelves when they need them.

7.2.2 Product Specific Centralized Inventory and Product
Specific Build Areas

Inventory for one line is stored in one central area within the line. The needed in-
ventory 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: Illustration of Product Specific Areas for Testing and the necessary movement of modules for testing.](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 variant, 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.

Table 8-1: Combinations of principles for the different floor layout 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>
</tbody>
</table>

The layouts 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. In addition, building both the older and the newer generation at the same time must be possible, since customer orders for the older generation of the tool cannot be rejected.

8.1 Proposal A

As proposal A implicates only small changes in manufacturing operations, it can be considered a conservative layout. Basic principles that served as a basis for this
The idea of shared test equipment is applied for all products but the SE1. In order to enable this change, modules of the same type are no longer built under the same crane but rather have the crane pillars in between. The test equipment is located between the crane pillars in the dead zones of the cranes. It therefore does not occupy any floor that could be used for production. The reason why this idea is not applied to the SE1 product is that the production of this product will be discontinued during the next months and the investment associated with a change would not be justified.

Turning the build lines by ninety degrees in the North Floor aligns them perpendicular to the cranes and facilitates the material flow. The location of each area in proposal A is exhibited in Figure 8-1.

Figure 8-1: Illustration of Floor Layout Proposal A

Benefits in proposal A compared to the current system mainly evolve from the use of centralized test equipment. First, centralized test equipment reduces movement
costs, since the modules stay in the same bay where they are assembled. Especially heavy modules take up to 30 minutes to move from assembly bay to test bay. Next, shared and centralized test equipment leads to safety improvements as moving modules constitutes a safety hazard due to their weight. In the current situation, problems during testing block the test bay and the associated test equipment so that it cannot be used for other modules until the problem is solved. Problems during testing happen frequently and often lead to unexpected delays. Centralized test equipment improves this situation as it allows the use of a certain piece of test equipment for another module while the module initially tested needs rework.

Both the reduced movement and the improvement in testing operations lead to a reduction in lead time and a reduction in labor costs [8].

8.2 Proposal B

The implementation of proposal B would lead to several changes in manufacturing operations. However, these changes were estimated to be smaller than those associated with proposal C (section 8.3). Thus, proposal B can be considered an intermediate layout.

The main features of proposal B are consolidated subassembly inventory, consolidated module build inventory, generic workbenches for subassembly build, and shared test equipment. Subassembly inventory is consolidated product wise, creating a subassembly build system similar to that described in section 8.3.1 for each product. Also, inventory required for the assembly of modules is stored in stored in inventory areas at the end of each line. Similar to proposal A (section 8.1), test bays are integrated into build bays and modules do not need to be moved from build to test bay. Also, each piece of test equipment can be used for two different bays. Figure 8-2 shows an overview of proposal B.
Proposal B seeks to improve production flexibility by using generic workbenches for the subassembly build. The increase in flexibility also leads to higher utilization of floor space, because dedicated and inflexible floor space is often idle in the current system.

Easier replenishment of inventory is related to the consolidation of subassembly as well as module build inventory. Finally, lead time will be reduced due to the higher flexibility in production and due to less movement of modules [9].
8.3 Proposal C

The idea of proposal C, which can be considered a “revolutionary” layout, is to only consider top level constraints. That is, only those constraints whose elimination would require significant investments, such as changes in the building structure, were retained. On the other hand, the feasibility of removing the constraints as needed for this layout for a reasonable investment was validated. The key principles of proposal C are a “supermarket” subassembly build system and a line build system with centralized inventory. Figure 8-3 gives an overview of proposal C.
8.3.1 Subassembly Build

The idea of the “supermarket” subassembly system is to centralize the inventory for all subassemblies that are assembled in this building in an aisle of shelves similar to a supermarket aisle. Equipped with a sorted picklist and a cart with a foam cut-out, the operators can gather the parts that they need for the next subassembly just before they start the actual assembly process. Once the operator has all of his/her parts,
he/she moves his cart to any available workbench, which could be located in an area next to the supermarket. Figure 8-4 shows the supermarket and the adjacent work area as a detail of Figure 8-3. Parts in the supermarket are ordered by size rather than by part number or assembly sequence in order to increase space efficiency. That is, space efficiency is improved by having only one bin size per shelf rather than multiple sizes and unused space between large and small bins. Workbenches in this subassembly system are not dedicated to specific subassemblies. Rather, they are generic and accordingly only include tooling and fixturing that is used for the major part of the subassemblies. Located next to this flexible work area is a testing area where subassembly tests can be performed.

Figure 8-4: Subassembly System Layout
The subassembly build system is set up such that operators can move in a circular fashion within the system. After picking up a new order, they would first attach the associated foam cut-out to their cart. Foam cut-outs could be stored within shelves at the beginning of the supermarket aisle. Subsequently, the operator moves the cart with the cut-out attached through the supermarket while filling it with parts. The order that is picked up at the beginning of the process includes a pick list which is sorted by shelf locations, enabling the operator to only move forward in the supermarket while picking the parts in order to minimize walking. After leaving the supermarket, the operator chooses any available workbench and starts the assembly process. Since the parts on the foam cut-out are sorted in assembly sequence and the assembly steps are indicated on the cut-out according to the assembly procedure, the operator has all parts right in place during assembly and does not spend significant time in searching. Most of the subassemblies require testing after or during assembly, which can be performed in a testing area. Finally, the operator places the finished subassembly on a “Kanban” shelf, where material handlers will pick it up.

In order to validate the feasibility of storing all parts of a subassembly in foam cut-outs, we prepared a prototype foam cut-out as pictured in Figure 8-5 for the Flood Gun assembly, which is built in the SEMOD1 line.
8.3.2 Benefits in Subassembly Build

The proposed subassembly build system creates benefits in terms of system transparency, flexibility, scalability, and floor space efficiency.

System transparency is increased by centralizing inventory. In the current system, subassemblies are built in cells and the inventory used to build these subassemblies is stored within those cells. However, this leads to redundantly stored parts, i.e. equivalent parts stored at different locations, when different subassemblies that are built in different cells use the same parts. Also, material replenishment and inventory level monitoring is difficult in a cell environment. Centralized inventory has no need for redundant part locations and is easier to replenish and to monitor.

The transparency of the system is increased by the implementation of well defined processes. That is, technicians are performing standardized and deterministic tasks, which are always in the same order. The order is given by the layout of the system,
i.e. the circular path the operators are following. Both supervision effort as well as inefficiencies due to technicians waiting for orders from supervisors is reduced.

Flexibility is improved in different ways. First, the proposed system is able to build several subassemblies of the same type at one time, which is currently difficult or impossible. Next, in the present system most technicians are trained to only build those subassembly types that are assembled in one specific cell and they use their experience to locate certain parts within the cell. However, this implies that new operators in a cell require time to become familiar with the way the inventory is stored and to memorize the location of parts within the cell. The proposed system uses a pick list to locate parts in the supermarket and is therefore not relying on operators memorizing part locations. New operators can find parts as quickly as experienced operators. Also, this effect enables cross training, such that operators can be trained to build several different subassemblies. In the ideal case, every operator is able to build every subassembly. This increases flexibility dramatically. Such a system is also self-balancing. That is, the workload is equally shared among operators, whereas in the current system it is common that some operators are at their capacity limit and others are waiting for orders. This leveling effect therefore removes labor inefficiencies due to unbalanced task assignment.

Scalability refers to the ability of increasing or decreasing capacity. If the capacity of the current system needs to be increased, new cells including dedicated cell operators are added for those subassemblies that are required in a higher output rate or additional workbenches are added to an existing cell. However, these measures are rather costly and inflexible. In contrast, the capacity of the proposed system can be increased by adding the required number of operators and workbenches. Since workbenches are generic, their setup can be standardized. Adding or removing workbenches accordingly needs relatively little planning effort. Also, adding operators and workbenches increases not only the capacity for a few subassembly types, as is the case in the current system. It rather extends capacity for the whole system such that the added capacity can also be used for other subassemblies if necessary.
The present system comprises cells that are only used infrequently, because the subassemblies built in these cells are only required occasionally. Thus, these cells and the floor space they use are idle for a certain fraction of time. Another effect is the already mentioned redundant storage of inventory, which also accounts for a floor space difference between the current and the proposed system.

8.3.3 Module Assembly and Test

Within the current floor layout, part inventory that is used for the module assembly is stored on shelves within the build line. These shelves are typically located along the sides of the build lines. In contrast, the idea of proposal C is to consolidate the inventory of all modules in one inventory area. In Figure 8-3, this area is located on the left side of the North Floor. Material handlers working in this area would place all parts needed for a specific module on movable wire racks. These wire racks would be moved to a build bay upon start of assembly.

After the assembly process, the modules are tested. This process requires test equipment that is currently already equipped with wheels, allowing it to be moved as long as it is not hooked up to a machine or power supply. Currently one piece of test equipment stays in a test bay while machines are moved from the build bay to the test bay for testing. In contrast, proposal C requires the test equipment to move from module to module, while the module stays in the same bay where it was built. Thus, after the assembly process is done, the empty wire racks flow back to the inventory area while test equipment is moved and hooked up to the module. Finally, after testing, the finished module advances into the clean room and the test equipment proceeds either to the next module that needs to be tested or to a test equipment parking area.

Toolboxes that are typically needed during assembly as well as testing would also be positioned close to the module upon start of assembly. A toolbox parking area can accommodate unused toolboxes similar to the test equipment.

In this process, all equipment and inventory needed for module assembly is movable. Thus, after assembly and testing is done, the floor space where the module was
built is empty. It is therefore feasible to assemble different types of modules on the same piece of floor space one after another. In other words, every module can be theoretically built everywhere on the floor. In order to capture the benefits of this opportunity, and in order to facilitate operational management, the division of the floor space into “blocks” as exhibited in Figure 8-3 is proposed. That is, a block is a rectangular piece of floor space with standardized dimensions. In this proposal, the length of a block is chosen in a way that two blocks fit side by side onto the southfloor. The width of a block allows two rows of blocks underneath each of the crane lines, still leaving an aisle in between for material movement. As a one time project, the layout of a block for each module needs to be defined and standardized. For the Universal Endstation module, for instance, three modules could be built one at a time in the footprint of a block. It needs to be determined where the modules, the wire racks, the toolboxes, and finally the test equipment are located within the block rectangle. For high volume products, like the SEMOD1 or the SE4 modules, one block contains multiple modules of the same type. However, it is also feasible to build one whole machine, comprising several different modules, at one time in the same block. In this case, one block would accommodate two modules of the SE2 product, for instance. This way of block setup could be used for low volume products like SE1, SE2, and SE3, since the situation of building several of these machines at the same time is unlikely and using blocks that accommodate multiple of the same module would lead to free space within the blocks and accordingly to inefficient floor space usage. Figure 8-3 shows an example arrangement of blocks. The actual number of blocks used depends on the floor space that is required at a given time. If required capacity and thus floor space is low, the number of blocks can be reduced, freeing up valuable floor space.

8.3.4 Benefits in Module Assembly and Test

The proposed module build system has benefits in different dimensions. The use of blocks has significant impact on floor space efficiency. Generally, during periods of low demand, less work in progress is required. This directly translates into less
floor space requirements during low demand periods, since the floor space usage is mainly driven by the number of modules being built at a time. Dedicating whole lines, as done currently, to one module type or machine type, will lead to unused space within these lines during low demand periods. However, this unused space within the lines is not valuable, since its use for other purposes such as assembly of other products would disturb the operations within the line.

The block system allows allocating only as much floor space as needed for each module or machine type. Since the blocks are independent and decoupled from its environment once the wire rack inventory is delivered, blocks can be located on the floor as desired and different machine types can be built in adjacent blocks in an arbitrary manner without negative interactions. Thus, the floor space allocated for each module type can be changed on a day to day basis, depending on the production schedule.

Some machine types are only built very infrequently, such as one machine per month. Dedicating a build line for these machine types leads to idle space during a major fraction of time. The block layout would allow to only allocating floor space if a machine of this type is actually being built. Also, the block layout is almost unrestricted in terms of product mix. In the current line based system, the number of different products that can be assembled is limited by the number of lines on the assembly floor. However, in the block based system, there can be theoretically even more product types in the production mix than the maximum number of blocks, which is 24, if some of the products are low volume and only assembled infrequently. Another floor space related advantage of the block system is the creation of coherent floor space. That is, the blocks can be arranged as densely packed as possible, freeing up coherent space on the South Floor. Coherent space is more valuable than many smaller patches of free space, since it can easily be used for other purposes, such as R&D testing.

However, the block system does not only have floor space related benefits. Delivering parts on wire racks rather than stocking them on shelves in build lines simplifies material management, because it allows the inventory to be centralized. Centralized
inventory can typically be stored more systematically, as the need for walking reduction is not the biggest concern. A flexible sorting system of inventory similar to warehouse inventory systems can be applied, which leads to more transparency. Also, centralized inventory allows easier visual monitoring of inventory levels. It therefore helps to solve the issue of part shortages, which is one of the managers' major concerns. Further down the road, this system enables one to stock all inventory and prepare the wire racks in a different building, for instance in the SEMC Warehouse, leading to economical advantages due to significant cost differences between warehouse and assembly floor space. However, this step does not tolerate kits with wrong or missing parts and requires a tight logistical link between production and the warehouse. Therefore, this step is not included in the proposal, as it requires the process of kitting wire racks to run stable and error free.

In terms of labor, the proposed system includes the kitting of wire racks by material handlers, which is not part of the current system. On the other hand, material handlers spend less time on replenishment of inventory shelves, due to the fact that centralized inventory is easier and faster to replenish. Also, assembly technicians do not have to leave their block in order to gather parts, saving time of highly skilled assembly technicians. Currently, technicians pull parts from shelves that are distributed along the build lines. This may include walking of up to 100 ft one way in order to gather a part. It is also favorable to create a standardized working environment where each part and tool is always located at the same place. Using blocks, standardizing their layout for each product, and also standardizing the way parts are located on wire racks accomplishes this goal and thereby results in further gains in labor efficiency, which balances or even overcompensates for the additional labor required for kitting the wire racks.

Assembly lead time, defined as the time that elapses between start of assembly of a new machine and advancing the machine to the clean room, is a crucial metric for the assembly area. It directly affects the customer lead time, i.e. the time between order placement and delivery of the machine to the customer. Furthermore, work in progress at SEMC is capital cost intensive and the work in progress is proportional to
lead time, as can be shown using Little's Law. Little's Law gives an equation relating the work in progress (L) with the production rate (λ) and the lead time (W) that is valid for virtually all types of factories.

\[ L = \lambda \cdot W \]  

(8-1)

Proposal C has the potential of reducing lead time by creating a more transparent system. Transparent and centralized inventory helps to reduce part shortages, currently a major reason for lead time delays. Also, building modules in autonomous and decoupled blocks that technicians do not need to leave once they start building reduces walking time and distraction and accordingly improves lead time as well.
Chapter 9

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 SE3, SE2, and SE1 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 will be 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 9-1: Combinations of principles for the different floor layout proposals and the pilot

<table>
<thead>
<tr>
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<th>Module Build</th>
<th>Test Equipment</th>
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<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 9-1. The concept of centrally located test equipment from proposal A is adopted; the subassembly inventory will be 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.

9.1 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 9-1 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 test accelerator columns 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.
9.2 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.

9.2.1 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.
9.2.2 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.
9.3 **Analysis of Needed Assembly Tools for Subassemblies**

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.

**9.3.1 Methodology**

A matrix that states the required tools for subassemblies build 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 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 regular tools were over the store capacity of 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.
9.3.2 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 brought to the workbench. The biggest special tool is the $1\frac{1}{4}$ in. combo wrench that belongs to the source chamber built at the cell 130. The size of the wrench is $30 \times 4.5 \times 1$ in., 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 largest, including a file, torque wrench, lifting accessories, $1\frac{1}{4}$ in. combo wrench and fixtures for magnets. The set of special tools for the source chamber requires an extra area for $1\frac{1}{4}$ in. combo wrench and one large standard plastic bin, which is $16 \times 14 \times 4$ in., for other tools mentioned above. Therefore, it is concluded that there is no possibility 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 $16 \times 14 \times 4$ in. Except for the groups F and G, the set of special tools fit in the middle sized standard plastic bin, which is $8 \times 14 \times 4$ in. 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 9-2 are characterized as regular tools that should be stored at the generic workbenches.

Table 9-2: 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 1/2 (3/8-1 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>Diagonal-cutting pliers</td>
<td>Soldering gun</td>
</tr>
<tr>
<td>Molydago</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 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 9-2 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 in., 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 on the following figure.
In Figure 9-2, "lubricants" includes all kinds of lubricants introduced at Table 9-2 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 at 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 9-3.

Table 9-3: 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, the detailed analysis needs updated procedures.

9.4 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.

9.4.1 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 to require 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 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.

**9.4.2 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 bin size is most appropriate given a maximum number of different bins. 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 bin sizes and one unlimited bin size are listed in a separate sheet and references are dynamic. The unlimited bin size is created for parts that are too big for bins 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 BOMs spreadsheet determine the appropriate bin size and the number of bins according to this logical procedure:

1. Choose the smallest bin size by comparing width and length of the parts with the sizes of the bins in the central list.
2. If more than one part is needed in the BOM, the spreadsheet determines how many parts fit into the bin. 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 bin). Thereafter, the necessary number of bins 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 bin, since small parts are often hardware and can be stored densely in a bin.

To receive the necessary area on the cart, the spreadsheet counts the number of bins of each sort in each BOM and multiplies the numbers with the footprint of the related bins. For parts that do not fit into bins 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 bin sizes, unlim-
ited bulk storage and four different BOMs. The resulting scenario is summarized in Figure 9-4.

Table 9-4: Example to illustrate worst cast scenario of needed tray space

<table>
<thead>
<tr>
<th>BOM</th>
<th>small bins</th>
<th>medium bins</th>
<th>big bins</th>
<th>long bins</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 bins, 20 medium sized bins, 10 big bins, 5 long bins and 200 in² of bulk area. Additional space should be available for future subassemblies. The worst case scenario offers auxiliary resources because small parts can be stored in empty big bins as well. If BOM #2 changes and the number of small bins increases by 5, these parts can be stored in the medium sized bins since 5 medium sized bins 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 bin sizes centrally and uses only dynamic references. The bin 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 bin 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.

9.4.3 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 9-5 shows the bin sizes in the second and third column and the needed space on the tray in the right-most column. "Area in bins" describes the area that is available for parts within the bins, while "bin area" is the area that is required to store the bins. The reason that two different numbers for the area are needed is that the thermoforming process needs a distance between the cavities, and bins require a wall thickness.

The Table 9-5 shows one solution that was returned after several iterations. Carts are approximately 24 in x 48 in, which is equal to 1152 in². This means that the small, medium, and large bins will fit on one tray, the long bins 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.

9.4.4 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. Since the method to store parts is the four standard bin idea discussed in Section 9.4.1, 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 9-6.
Table 9-6: 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 9-7: 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 9-7 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 in. x 48 in. shelf. 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.
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 results of calculations of the numbers of trays for all subassemblies in the three cells indicate that the minimum number of trays required is one, and the maximum number is four, including the shelf for the large parts categorized to the unlimited size. Figure 9-3 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 9-3: Layout of the Bins for the Subassembly E11358690](image)

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

For 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 9-8, 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 9-8.
Table 9-8: Cost analysis of required bins for the entire system

<table>
<thead>
<tr>
<th></th>
<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>
<td>$1,189</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>
<td>$603</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>
<td>$903</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>
<td>$1,775</td>
</tr>
<tr>
<td><strong>Total cost</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td><strong>$4,471</strong></td>
</tr>
</tbody>
</table>

### 9.4.5 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 9-4: Layout of the Bins for the Complex Subassembly](image)

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 9-4 shows the different layouts based on the two different giving goals. The left side of Figure 9-4 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 9-4 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.

9.5 Analysis of Operations of Supermarket

The supermarket system as described in section 8.3 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.

![Figure 9-5: Illustration of supermarket simulation](image)

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 9-5 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 9-6: Cycle Time Distribution Function for Material Handlers

Figure 9-6 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 9-7. The average cycle time was derived from historical data from SEMC.

Figure 9-7: Cycle Time Distribution Function for Assemblers

As Figure 9-5 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 9-9 and Table 9-10 represent steady state values.

Table 9-9: Average utilization of material handler and assemblers during 1000 hour simulation period

<table>
<thead>
<tr>
<th>Material</th>
<th>Utilization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material Handler</td>
<td>0.526065</td>
</tr>
<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 9-10: Units done within 1000 hours simulation period

<table>
<thead>
<tr>
<th>Material</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material Handler</td>
<td>811</td>
</tr>
<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.

9.6 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 does include 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 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 9-11.

Table 9-11: 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 9-12: Build time comparison for subassembly build

<table>
<thead>
<tr>
<th></th>
<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>
<td>166.52 min</td>
</tr>
<tr>
<td>- Break</td>
<td>33.63 min</td>
<td>+ Gathering Parts in “Supermarket” 27.85 min</td>
</tr>
<tr>
<td>- Personal</td>
<td>2.93 min</td>
<td>+ Detrashing Parts 22.82 min</td>
</tr>
<tr>
<td>- Missing Parts</td>
<td>5.13 min</td>
<td>+ Moving cart between “Supermarket” and workbench 5 min (Estimated)</td>
</tr>
<tr>
<td>- Rework</td>
<td>9.96 min</td>
<td></td>
</tr>
<tr>
<td>+ Step Z skipped</td>
<td>3.16 min</td>
<td></td>
</tr>
<tr>
<td>+ Step JJ skipped</td>
<td>4.08 min</td>
<td></td>
</tr>
<tr>
<td>+ Step NN skipped</td>
<td>3.38 min</td>
<td></td>
</tr>
<tr>
<td>+ Packaging</td>
<td>4.81 min</td>
<td></td>
</tr>
<tr>
<td>+ Final clean up of workbench</td>
<td>2.70 min</td>
<td></td>
</tr>
<tr>
<td><strong>Total Time (adjusted)</strong></td>
<td>215.12 min</td>
<td><strong>Total Time (adjusted)</strong> 222.19 min</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 9-12. 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.

9.7 Implementation

SEMC representatives showed interest in an implementation of the pilot proposal. However, several uncertainties, costs, and risks are associated with this change. According to supervisors, changing the layout of module build bays to enable shared test equipment can be considered a low risk change as operational implications are low. On the other hand, the supermarket system for subassembly build goes along with heavy operational changes. In spite of extensive prototyping and testing of the supermarket concept (sections 8.3.1 and 9.6), there are still important factors that have not been not examined. These include the acceptance of the new system by assemblers and material handlers and robustness of the system towards frequent engineering change orders. The supermarket system as proposed in 9.1 comprises 58 different types of subassemblies and approximately 1600 different types of parts. Accurate procedures are crucial for an implementation of the supermarket system. However, a major part of the relevant procedures is outdated and ten procedures do not exist. Writing the missing procedures and updating the existing ones is estimated to equal 280 man-hours. Another large cost during of the changeover is manufacturing of foam cut-outs. Each type of subassembly requires an individual foam cut-out. Before the actual
manufacturing of cut-outs, their layout needs to be generated. Layout is estimated to take two man-hours per cut-out and manufacturing would cost in the order of US$250 per cut-out. This adds up to 116 man-hours for layout and US$14,500 for manufacturing. Effort related to procedures and foam cut-outs is estimated to be the biggest cost regarding the changeover to the supermarket system as proposed in the pilot plan. The costs for both of them scale proportionally to the number of different types of subassemblies in the system.

Another cost is associated with the material management system. The effort of rearranging and labeling to form the supermarket is proportional to the number of different types of parts in the system.

Therefore, the number of different types of subassemblies and the number of different types of parts in the system can be considered the largest cost drivers upon changeover to the supermarket system.

In order to further reduce risks of change, the implementation of a smaller version of the supermarket system will be accomplished. This system will only comprise 15 different types of subassemblies and approximately 400 different types of parts. Thus, the costs of change for this smaller version of the supermarket system are approximately 75% percent lower than for the pilot supermarket system with 58 different types of subassemblies. These 15 subassemblies are now built in two cells, which will be transformed into the new supermarket system. The cells that will be transformed were chosen in a way that the effort of writing new procedures and updating existing ones is minimized.
Chapter 10

Conclusion

Reflecting on the results in light of the key metrics defined in Chapter 2, an underlying theme of risk versus potential benefit becomes apparent. While proposals that only implicate small operational changes can be considered low risk, their potential benefit is relatively small as well. On the other hand, implementing severe operational changes as proposed in Section 8.3 constitutes a high risk of a complete fail, causing production delays and high sunk costs related to the failed change. This uncertainty is due to the complexity of the system and due to aspects that cannot be foreseen or tested before implementation. Keeping the importance of good service to the customer as well as the extremely high delayed delivery penalties in mind, this benefit versus risk trade-off gets skewed towards small risk. Therefore, the only way of achieving the high benefits of the more revolutionary concepts without taking the associated risks, is by performing a step wise implementation. Doing so, potential operational problems will occur in a smaller scale and can be solved before the concepts are implemented in large scale. Also, the stakeholders of the system can become familiar with it, further reducing the risk of change.

The implementation can be separated into two different parts; changes in the assembly of modules and changes in the subassembly build. In terms of module assembly, the changeover to the block system as described in Section 8.3.3 is highly suggested, because it has potential to significantly reduce lead time, floor space usage and production flexibility. An implementation of this block system requires the ability
of efficiently moving pieces of test equipment from one module to the other. The first step of a stepwise implementation would therefore be to experiment with one piece of test equipment in order to find a way of quickly switching it between modules. Once this "prototype" test equipment is set up, the changes that have been made to it can be copied to all other pieces of test equipment. However, in order to keep risks and sunk costs low, this should not happen before the operations of the block system have been tried in a small scale. Therefore, the block system could be implemented for only one module as a pilot version. Similar to the pilot of the supermarket concept as described in section 9.7, this small scale version allows assessing problems and analyzing operational metrics with relatively low costs.

For subassembly build, the proposed supermarket system (Section 8.3.1) allows for higher production flexibility by enabling cross-training, reduces floor space usage, and simplifies material management. The already running implementation of a small scale version of the supermarket system is therefore expected to yield a high benefit to risk ratio.
### 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>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 E11286060 E11358690 E11358760</td>
</tr>
<tr>
<td>B</td>
<td>E11285780 E11120440 E11113580 E11113590 E11097210 E11351110 E11408390</td>
</tr>
<tr>
<td>C</td>
<td>E11298170 E11302780 E11049530 E11049531 E11049532 E11049533 E11049534 E11049535</td>
</tr>
<tr>
<td>D</td>
<td>E11102070 E11100930 E11146711 E11098200 E11325840 E11095220 E11302980 E11302981</td>
</tr>
<tr>
<td>E</td>
<td>E11135490 E11124571 E11128700 E11300220 E11135540 E11111500 E11306870 4372400</td>
</tr>
<tr>
<td>F</td>
<td>E11285750 E11095600 E11095590</td>
</tr>
<tr>
<td>G</td>
<td>E11096860 E11096900 E11364730 E11107770 E11101800 E11108770 E11101810</td>
</tr>
<tr>
<td></td>
<td>E11102100 4384300 E11141100 E11141090 E11291620 E11111280 E11100190</td>
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</table>
References


