DECISION ELEMENTS IN THE DESIGN OF A CONSUMER ELECTRONICS ASSEMBLY PLANT

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Abstract

This thesis is the result of a six-month internship at Celestica, Inc, an electronics contract manufacturer. The internship period covered the entire design and construction process for a new personal computer final assembly plant.

The main purpose of this thesis is to document the process that was followed at Celestica. Factors affecting the major decisions that were made will be discussed, as well as how they are affected by the product and the manufacturing process, and their effect on the design of the factory.

The design process at Celestica consisted of six steps: Benchmarking and research, design concept development, design guideline development, detailed design process, material and personnel requirements development, and procedure definition. This design process enabled the use of a cross-functional team to make decisions on factors which affected different functions of the plant, and provide guidance that allowed individual team members to work on design elements that would be compatible with the rest of the design. The key to this design method was the development of design guidelines, within which team members could work individually.

One of the primary decisions the team made was that the assembly process would be done in parallel. This decision was based on the variation of the process, dependencies between process steps, the length of the process, expected workforce skills and training, required assembly equipment, demand variability and individual product demand volume.

A kitting system was designed to present material to assembly. This was based on the security requirements and risk of component part obsolescence, and the reduced inventory costs, increased process control, and high degree of product flexibility that the kitting system provided.

Finally, the plant layout and personnel requirements were designed to balance the flow of material, not capacity. The assembly process was the desired system constraint. Other steps in the overall process provided capacity and inventory buffers that ensure the assembly process wouldn't be blocked or starved. The throughput of the plant is aligned as closely as possible to the theoretical capacity of the assembly bottleneck.

This design process led to a factory that is flexible enough to adapt to rapidly changing demand and product mix, while keeping costs at a minimum. Further research in the design of capacity and inventory buffers is recommended to enable future plant design efforts to more easily identify optimal design characteristics.

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As I'm sure all of those who have been exposed to it would agree, the Leaders for Manufacturing program at MIT provides an unparalleled educational experience to students interested in pursuing manufacturing as a career. The rich academic curriculum, and especially the exposure to different manufacturing leaders, plants and experiences combine to produce an intensely rewarding two years. I am grateful for the opportunity to have been a part of this program, and look forward to continued contact and growth through the network of friends and colleagues I have been able to develop at MIT, Sloan and in industry.

Mostly, I would like to thank my wonderful family for the support and love they have given me throughout our time here. My children, Nicholas and Megan, have had to endure many hours without a father during my course of study. My wonderful wife Karen has been a friend, an advisor, and a truly understanding wife and mother, making up for my unavailability with our children, and forgiving my endless disappearances into the "dungeon" to study. Her love and devotion have been truly inspirational.

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Chapter 1 *Introduction*

1.1 Thesis Objectives

This thesis is the result of a six-month internship at Celestica, Inc, an electronics contract manufacturer. The internship period covered the entire design and construction process for a new personal computer final assembly plant.

As we realized when beginning this effort, very little current literature can be found that discusses the factory design process, while myriad sources provide information on improving current facilities. This may be because most companies engage in improvement projects almost continually, while new plants are built much less frequently. Another reason may be the uniqueness of factory designs, based on industry, company, product, and the structure of the supply chain. Regardless of the cause, the lack of available resources on the factory design process led to a significant amount of effort in developing the general framework that was to be followed. This effort should be leveraged in future design efforts.

The main purpose of this thesis is to document the process that was followed at Celestica. Factors affecting the major decisions that were made will be discussed, as well as how they are affected by the product and the manufacturing process, and their effect on the design of the factory.

While designing the new facility, many decisions were made based on some combination of experience, intuition, analysis, and current industry "best practices." In many of these decisions, quantitative analyses were or could have been used to determine the effects of the alternatives considered on cost, quality, and time. This work will discuss some of the analytic techniques that were used, and attempt to develop and document methods of analysis that could have been used to predict these effects more accurately.

Finally, it is hoped that this work will provide a starting point for future factory design efforts at Celestica. While the design process was quick and effective, many hours were spent trying to discuss and understand the effects of various decisions on the products, and the effects of both controllable and uncontrollable factors on the optimal design. This thesis obviously can't answer all of the questions nor provide guidance in most of the situations that will arise in the design of a factory, but it will document those factors that were addressed in this specific project.

1.2 Organization of Thesis

Chapter 2 will provide a description of the products that were to be built at the Celestica facility, the overall final assembly process, and the steps that occurred during the design process. The design criteria will be discussed, as well as some of the guidelines that were developed to ensure the individual portions of the design effort could be integrated into an effective whole.

The following chapters will document some of the major decisions that were required in the design process, along with the factors that affected the decision and their effect on the rest of the design. Chapter 3 discusses the tradeoffs between serial and parallel assembly structures. In Chapter 4 the positioning of material within the plant will be addressed, and finally the design of capacity and the use of the Theory of Constraints will be discussed in Chapter 5. Chapter 6 will conclude the thesis.

Chapter 2 *The Celestica Factory Design Process*

2.1 Products

The design of a factory obviously depends on the product or products to be produced. It is therefore useful to discuss the characteristics of the product prior to discussing the factory intended to manufacture it.

The factory that we designed at Celestica would house the final assembly of a line of personal computers. The products were of two types, a desktop model computer and a "mini-tower" computer. Both types would contain various configurations of components; the basic chassis type could house different processors, motherboards, memory, hard drives, CD-ROM drives, floppy disk drives, and software. Units of each type could be shipped with various localization options (keyboards, software and manuals.)

Although there were many configurations, the manufacturing processes for all types and configurations of this line of computers were very similar. The final assembly process for each of these configurations was approximately as shown in Figure 1.

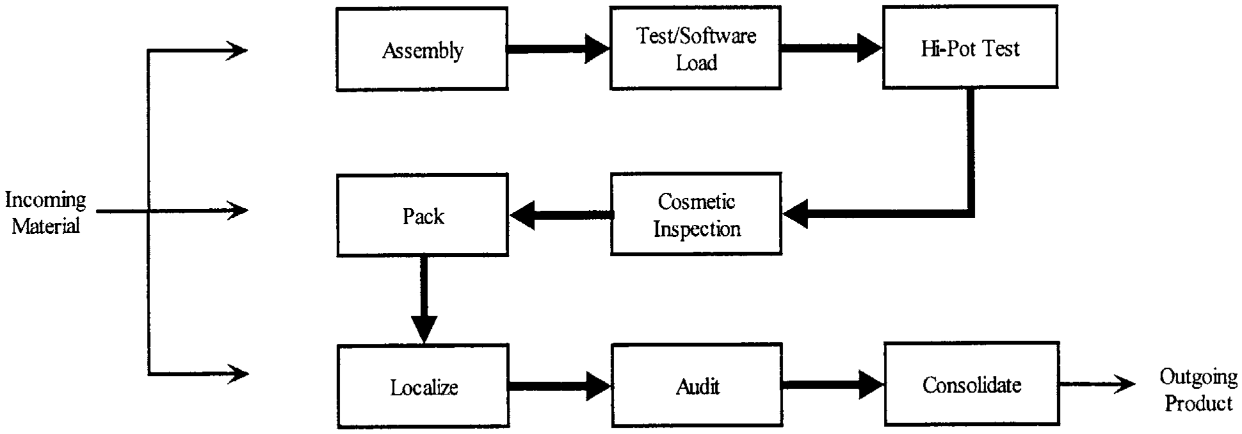


FIGURE 1: PC FINAL ASSEMBLY PROCESS

2.2 Factory Design Process

The factory design process took about six months from the discussion phase through the implementation and initial production runs. The development of the design went through six distinct phases:

- Benchmarking and research
- Design concept development
- Design guideline development
- Detailed design process
- Material and personnel requirements development
- Procedure definition

2.2.1 Benchmarking and Research

The design process at Celestica began with research and benchmarking. Current "best practices" in the personal computer industry were reviewed through literature searches and factory visits. The Celestica design team then selected the processes that best fit with our ideas of how computers could most successfully be assembled and tested, and adapted those to our needs.

2.2.2 Design Concepts

Prior to engaging in detailed design discussions, the team agreed upon some overarching principles that would guide the design process. Some of these concepts were based on constraints in time and budgeting inherent in the project, some were based on the team's knowledge and experience in electronics manufacturing, and some were based on modern Operations Management theories.

These initial design concepts covered all areas of the future operation of the factory, including manufacturing, training, metrics, and management. Since we are only concerned here with the design of the physical factory, we will limit our discussion to those which applied to the layout and design of the shop floor areas. They were:

- Focus on time: total cycle time, dwell time, touch time, exception process times, time fences, etc.
- Propinquity between key sub-processes to promote quality, time and cost objectives
- Theory of Constraints design of capacity
- Single-piece flow
- JIT-driven flows and queues
- Minimal touch time
- Simple solutions – reduced number and complexity of automated systems

2.2.3 Design Guidelines

After generating the overarching design concepts, the team then began to discuss the details of what the factory should look like, and how it should operate. The factory designs that were observed through research and benchmarking were reviewed, and parts of each of these were selected based on the design concepts. It was during this phase that the majority of the design formulation was done; once this was complete, a picture of what the factory would look like emerged, with only the details left to be added.

The main guidelines that were defined during this phase included:

- Kitted material delivered to assembly
- Parallel processes for assembly and test
- Sequential process for material positioning, kitting, hi-pot, cosmetic inspection, packing, localization, blind verification/audit, and order consolidation
- Assembly and test stations grouped together in modules

The majority of this thesis will focus on the specifics of how these guidelines were developed. These guidelines became the defining characteristics of the factory; they provide for the efficient use of resources to minimize the cost of final assembly and test, and they provide flexibility for assembling different products and maintaining differing levels of capacity.

2.2.4 Detailed Design Process

Once the above guidelines were developed, the specific factory layout was defined. Because the guidelines had been developed as a cross-functional team, the individual team members were now able to design their areas of the plant's layout, without risk of incompatibilities between functional areas.

The detailed design process consisted mainly of comparing various vendors' workstations and abilities to customize their products to the specific tasks required in this factory. Many of the ideas for workstation design came from the benchmarking process. Once the workstations and work area equipment were defined, the biggest issue became space utilization. The factory building was under lease, and therefore the total factory area became a predefined constraint. The industrial engineer was tasked with designing a factory layout that would allow for capacity expansion up to forecasted demand levels, while providing for the functionality required for all of the raw material storage, assembly, test, shipping and support functions.

2.2.5 Material and Personnel Requirements Development

Once the layout of the factory was determined, simple formulae based on the expected hands-on cycle time for the different areas of the factory were developed in order to calculate the number of personnel required for different levels of production. This also led to the forecasted material requirements for workstations, conveyors, carts, flow racks and warehousing equipment. These forecasts were based on the expected mean cycle times for the different operations: data that had been collected during the benchmarking phase. Required warehousing equipment was based on the planned inventory levels to be maintained in the factory, and the forecasted demand levels for the future.

2.2.6 Procedure Definition

The final phase of the factory design process was to install all of the equipment, verify the operation of the planned processes, and to develop procedures that would be used for training and execution. As these procedures were developed, the errors in any assumptions were analyzed, and adjustments to the layout, equipment and personnel requirements were made.

Chapter 3 *The Assembly Process*

Most of the value that is added to the product in the industry under discussion occurs in the assembly process. While the assembly process generally takes less time than loading software or testing the machine, it is arguably more valuable to the end customer. Customers can and will load software, but choose not to assemble their machines from individual components.

Since the value of the assembly process makes it essentially the *raison d'être* of the factory, one of the first decisions to be made in designing the factory layout will be the structure of the assembly process. This decision must include how the assembly process will be broken up in time and in space, and what portions of the process will be completed by what part of the workforce.

In a factory such as a computer final assembly plant, the assembly process development can be broken into two decisions. First, the team must decide whether the assembly process will be parallel or serial. Issues pertinent to this decision include the variability of the product assembly process, quality concerns, and demand volume. Once this decision has been made, the team must determine how different products or variations will be assembled. Dedicated lines or stations can be setup for each distinct product or product family, or a single line or generic station can be used at which all of the different products will be assembled.

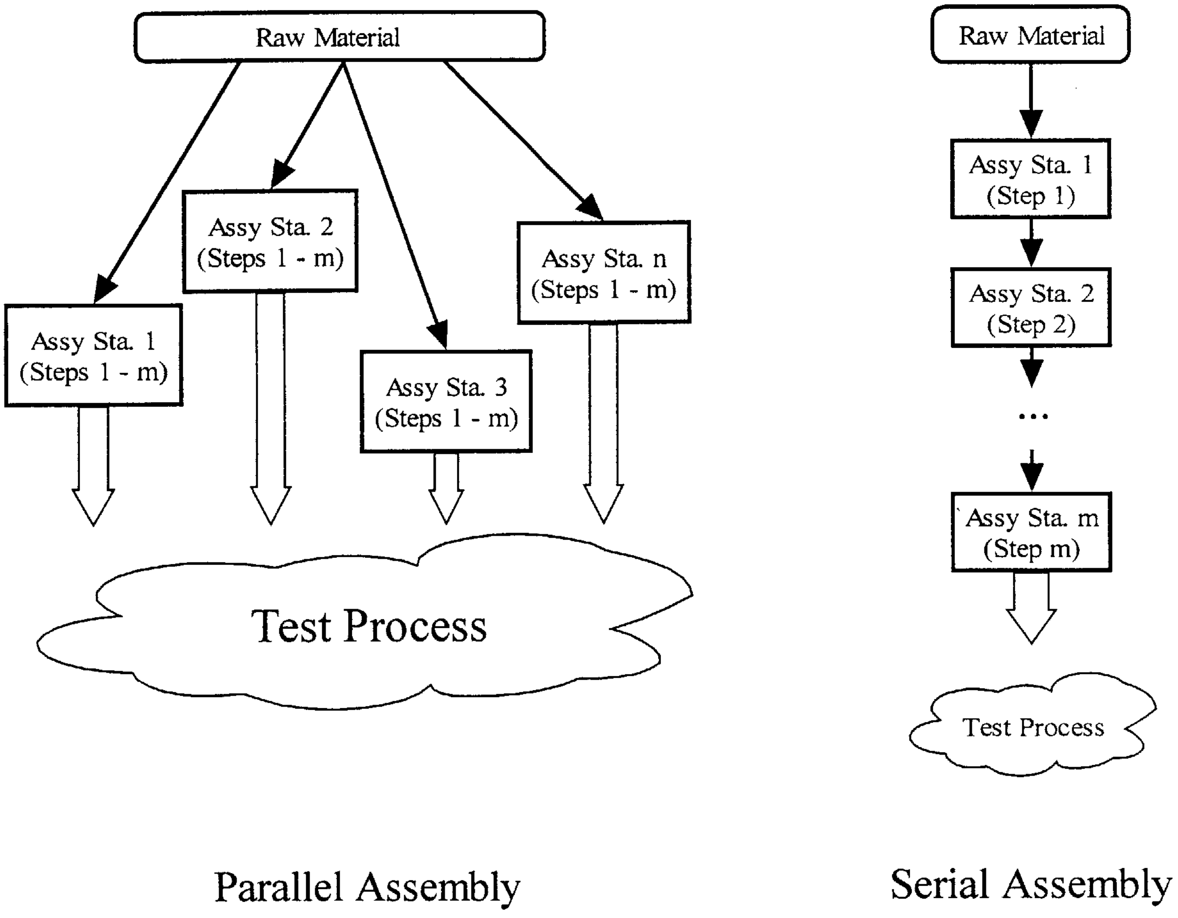
3.1 Parallel vs. Serial Assembly

3.1.1 Parallel Assembly

In a parallel assembly structure the entire assembly process is completed at a single station, with stations replicated based on cycle time in order to meet demand quantities. One or a small group of assemblers is responsible for the entire assembly process for units scheduled at their station.

3.1.2 Serial Assembly

A serial assembly process is more commonly known as an assembly line. The assembly process is broken into individual steps, and completed by different assemblers in a specific sequence. Demand quantities are met by increasing the number of steps in the process, and thereby decreasing the cycle time at each individual step. As throughput requirements are increased, the amount of work on an individual unit performed by each assembler decreases. A schematic of serial and parallel assembly is shown in Figure 2.



Parallel Assembly

Serial Assembly

FIGURE 2: PARALLEL AND SERIAL ASSEMBLY SCHEMATIC

3.1.3 Variability of Assembly Process

Variability within the assembly process may be the primary driver in selecting the assembly structure for a factory. Variations in the process can come from four major sources: individual assembler variation, variation between assemblers, sub-process variation, and product variation. There are other sources of variation that can affect the assembly process, such as variation in component quality, but most of these other sources' effects should be minimal in comparison to the above.

3.1.3.1 Individual Assembler Variation

Individual assembler variation is inherent in the fact that humans are responsible for the assembly process. Assemblers will become tired over time, or bored, or distracted. There are many obvious reasons for this variation, but it is important to keep in mind that even a well-defined process performed by a well-trained assembler will produce results that vary through time. This variation can be easily observed and measured in an existing process. In designing a new plant, however, there may be little or no data with which to determine the magnitude of this variation. The design team must therefore use the limited data and their knowledge of the product to estimate the variation that will occur in the assembly of the product. One simple approximation that can be used for examining design tradeoffs is to classify the assembly times of subsequent units of the same product for a single assembler as exponentially distributed. This approximation implies the following:

1. Individual unit assembly times are random, with a mean ($1/\mu$) and a standard deviation (σ_μ) equal to the mean ($1/\mu$).
2. Because they are exponentially distributed, the assembly step follows a *Poisson process*. The process is said to be *memoryless*, or purely random. This means that the probability that a unit completes a step in the time interval

(t, t+Δt) does not depend on *t*, where *t* represents the amount of time already spent in the assembly process.

3. The arrival stream must also be a Poisson process. The arrival stream can be the orders arriving in the system, or the output of the prior step if a portion of the entire process is being modeled.

An advantage in this assumption is that a serial process can be modeled as a network of M/M/1 queues and a parallel process as an M/M/c queue, where *c* is the number of assembly stations. A comparison of these queuing systems can help determine the effects of variation on inventory levels and lead time. A disadvantage is that it assumes that learning does not occur, which must be accounted for at some point during the analysis. Also, assuming the standard deviation of assembly times equal to the mean probably overstates the variability of the process.

A queuing analysis using Markovian processes shows a distinct advantage for parallel systems, due to the lack of inventory buildup between steps. This inventory buildup occurs due to the inherent variation in each step. The first two data columns in Table 1 show a comparison between serial and parallel systems using queuing analysis. The systems for comparison assume the same number of workstations, divided equally within the serial line (a "balanced" line with equal service rates) or in parallel. The same arrival rate into the system implies the total throughput will be the same, and the cost of capacity will be approximately the same because the same number of assemblers is required. The serial system generates much longer queues – inventory between stations – yielding a total lead time and total system inventory significantly higher than those in the parallel system. While this simple analysis assumes infinite buffer space between process steps, it is obvious that introducing finite buffers would yield a higher probability of blocking in the serial system and therefore reduce throughput substantially.

This comparison assumes arrival times that are exponentially distributed. This would be similar to a kitting process, or can be assumed to model the receipt of orders into the system. Raw material inventory to support this system is not included in the comparison; however, it will be the same in both systems. The buffer prior to the initial process step represents a buildup of kits, which is greater in the serial line.

While the initial comparison between serial and parallel processes leads to distinct advantages in inventory and lead time for the parallel system, the last column in Table 1 show how some situations may favor a serial line. If, by subdividing the process, economies of scale can be realized, then individual assembly step cycle times may be improved. This may result in a shorter lead-time and lower inventory than in a parallel system. While manufacturing and quality consultants have lately argued against F. W. Taylor's scientific management theories, there may be times when the assembly process is very complex, and advantages in cycle time can be gained by subdividing it. This may be due to special skills needed in different parts of the process, special tooling, jigs, or fixtures that require setup and therefore increase cycle time when used at a single station, or because of ergonomic advantages to breaking the assembly at specific points. Economies may also be realized in capital equipment costs, since duplication of tools and stations might be avoided or reduced.

		M/M/1 Serial	**M/M/c Parallel**		**Efficient Serial**
Number of Stations		5	5		5
Arrival Rate	(units/minute)	0.95	0.95		0.95
Total Assy Time	(minutes)	5	5		4
Assy Time per Station	(minutes)	1	5		0.80
Service Rate per Sta.	(units/minute)	1.00	0.20		1.25
Utilization		0.95	0.95		0.76
Lead Time	(minutes)	100	23		17
Avg Inv	(units in WIP)	95	21		16

TABLE 1 : QUEUING ANALYSIS OF SERIAL AND PARALLEL STRUCTURES

3.1.3.2 Variation between Assemblers

Individual assemblers will work at different speeds, and accomplish tasks at different rates. While standardized processes and effective training programs can help minimize the amount of inter-assembler variation, it cannot be fully eliminated. An operating plant can collect and analyze data that will help determine the magnitude and effects of this variation. However, in a factory design effort such as the one conducted at Celestica, the inter-assembler variation may be unknown. The factory design should therefore be robust enough to handle an expected amount of this type of variation, and standardized procedures and training programs should be developed in order to minimize its effect. The recruitment and hiring process should also attempt to match skills with required work, in order to ensure a high level of performance with a minimum of variability.

As stated, data on this type of variability may not be available in the design process. Data from comparable factories may give reasonable estimates of this variability, but may not be available for similar products if these products are new to the company, as was the case at Celestica. However, this information should be easily attained and analyzed after the factory is in operation. In order to take advantage of the actual data when it is collected, the design should allow enough flexibility to change the design parameters that are affected by this type of variability.

In an electronics assembly plant such as Celestica's, there are very few processes that require large amounts of machine operation. The design parameter most affected by the variability between assemblers is the number of assemblers or stations required to meet a desired capacity. The physical design should be flexible enough to handle changes in the relative number of assemblers at different stages in the process.

This flexibility is more easily obtained in a parallel structure. As will be discussed in Chapter 5, throughput may be more easily maintained if a line is structured from lowest capacity to highest. If a serial line is used, the breakdown of assembly steps will be designed in order to either balance the line or achieve a desired increase in capacity at stations downstream of the bottleneck. Variation between assemblers may change the optimal line configuration, which can change on a shift-to-shift basis, or when employees are rotated, added or reduced. In a parallel structure, by contrast, the variance between assemblers will affect the aggregate throughput of the assembly process, which may require additional or fewer parallel stations, but will not require a redesign of the process. It seems then that a parallel structure provides greater flexibility in adapting to variation between assemblers.

However, while a parallel structure is more tolerant of variation between assemblers, a serial structure may result in less variability since the process can not support it. The interaction between assemblers in a serial line may effect a "regression to the mean," which will result in lower total variability, but either a higher or lower aggregate throughput than a parallel line. The assembler interaction effects, which will be affected by the training of assemblers, and management systems and metrics, should be considered as the design team decides between a parallel and a serial process.

3.1.3.3 Sub-process Variation

Sub-process variation is the difference in processing time for different steps within the assembly process. This variation occurs because of the discrete nature of the steps within the overall assembly process. While the previously discussed sources of variation are random, sub-process variation is caused by the design of the process and thus is controllable. If the overall assembly process takes t minutes to complete and there are n sub-processes, then the ideal time for each sub-process is t/n. However, because sub-processes represent some combination of discrete tasks, it is likely that each sub-process takes $t/n + \varepsilon_i$, where ε_i represents a positive or negative variation from the average. This difference in processing times can result in blocking some stations and starving others, if there are finite buffers within the line. This will result in increased work-in-process inventory and reduced throughput. A process which contains many relatively simple tasks will be more easily broken in to steps of a similar duration, and will be more adaptable to a serial line. An assembly process which contains complex individual tasks, such as complicated wiring or difficult placement of parts, will most likely have a lot of sub-process variation and would thus be more suited to a parallel structure.

3.1.3.4 Product Variation

Product variation occurs when more than one product is assembled on the same assembly line. The effect of this variation is similar to sub-process variation, except that it occurs dynamically. Similar to sub-process variation, this variation is a function of the design of the process and is thus controllable rather than random.

For an example of this type of variation, consider a three-step sequence for assembling products A and B. For product A, all 3 steps may have exactly the same average cycle time (i.e. the line is perfectly balanced.) Suppose product B is identical to product A except that one additional memory card is installed in step 2. Due to the addition of the time required to install this card, step 2 for product B will now be longer than step 2 for product A. Whenever there are units of product B at step 2, cycle times will differ between stations 1 and 2 and between stations 2 and 3, causing line imbalance. The variation causing this imbalance occurs only when product B is being assembled; when the line is full of product A, it is still perfectly balanced. Thus the variation between sub-processes will be partially determined by the product mix being produced on the line at any point in time.

3.1.3.5 Effects of Variation

Any of the above types of variation seem to make a serial line less efficient than a parallel line. It would appear then that four conditions must be satisfied to justify using a serial line:

1. Efficiencies, due to learning or scale effects, must be increased by subdividing the assembly process.

2. Variation between assemblers must be minimized (through training and documentation)
3. Sub-process variation should be nearly eliminated (a balanced line)
4. Product variation must be minimal (a dedicated line)

Prior to discounting completely the serial line, the assumptions in the above analysis should be revisited. Recall that the service rate was assumed to be distributed exponentially. This assumption implies that the service time of a particular unit is completely independent of history and of external forces. However, both the dynamics of the serial line and the learning process may invalidate this assumption, and provide benefits to a serial operation not found in a parallel structure.

3.1.4 Line Dynamics

The M/M/1 and M/M/c queue analysis above assumes that the service rate at a station is independent of history and of external forces. However, both of these may have a significant effect on the throughput of a given station.

If a service rate is exponentially distributed, then the probability that a unit will be completed in the next instant after time T_1 is the equal to the probability that a unit will be completed in the next instant after time T_2. In reality, an assembler who averages about 10 minutes to complete an operation will probably work faster if he's just taken 12 minutes assembling a specific unit, for fear that he is holding up the line. Thus it would seem that the service rate at a station may depend on history, and not be a true Markovian process as described above. Similarly, an assembler may work faster if he knows that the next station is idle, again invalidating the assumption of an independent process. In a serial line, the effect of this may be that the line speed is maintained by workers "pushing" and "pulling" material through the line, enabling a higher throughput than in a parallel system in which these forces may not exist. The factory design team will need to estimate the magnitude of these effects when determining the structure of the assembly process.

3.1.5 Quality

The effect of line structure on product quality may favor either structure, depending on the predicted behavior of the assemblers. In a serial assembly line, the processes are broken down into smaller steps than in a parallel structure. After each operation is complete, the next assembler in the sequence has the opportunity to quickly review the efforts of the previous assembler(s), and may be able to detect defects before the unit reaches the audit or test phases. Thus a serial line may result in a lower defect rate, and may enable defects to be detected earlier in the process, thereby reducing the cost of rework required by minimizing the amount of disassembly necessary to repair the defect.

By contrast, in a parallel assembly process a defect introduced in the initial stages of assembly may be overlooked or unknown to the assembler, and it therefore might not be detected until the test process has begun. However, an assembler may be more conscious of quality in that he or she is responsible for an entire unit. Individual pride and accountability may serve to motivate assemblers to pay more attention to detail. In a serial process, individual assemblers may feel less accountable for the quality of the finished product.

The judgement of the design team will again be required to determine which of these effects is expected to be greater. Factors affecting the magnitude of these effects include:

1. Length of the assembly process – in a parallel structure, a longer assembly process may increase the likelihood of defects being introduced.
2. Manufacturability of the product design – an assembly process that precludes the introduction of defects will decrease the impact of these effects.
3. Skills – training and experience may lead to a lower defect introduction rate or a higher/earlier detection rate.

4. Motivation – the motivation and pride of the assemblers may affect the level of defects introduced.

3.1.6 Equipment

The structure of the assembly process may in part be determined by the equipment required. If part of the assembly process requires the use of specialized machinery, a serial line may be the only effective way to organize assembly. This may be due to limitations in floor space based on the size of the equipment, its availability or its cost. In these cases, a hybrid structure may be desirable. For example, if the product/process favors a parallel structure except for a single step that requires dedicated, expensive machinery, parallel processes on both the input and output side of the machine may be the optimal structure. Obviously, the processing required, capacity of the machine and inventory required for support will all be factors in this design decision.

3.1.7 Demand Variability

If the demand for a product or group of products is highly variable, and the cost of additional assembly stations is high, the use of a serial line may be the most advantageous. As demand increases for a product, assemblers could be added to the serial line to increase the throughput, with very little or no additional capital costs. In a process like the computer final assembly at Celestica, the adding workers to the line would require redefining the work instructions, re-balancing the line for the new number of assemblers. They would also require additional hand tools and perhaps some additional bins for hardware. In a parallel line, by contrast, additional throughput will require additional workstations for the added assemblers. If these workstations are not available or are costly, the parallel structure will be disadvantaged. Work instructions will not need to be updated in a parallel structure. Similarly, decreasing throughput in a serial line may be as simple as removing assemblers from the line (and updating the work instructions.) In a parallel structure the material distribution process may be affected, and valuable floor space might be filled with unutilized equipment. With variable demand, therefore, the cost of implementing changes to the serial line procedures should be weighed against the capital cost of additional workstations in a parallel line. If workstations are expensive or unavailable, a serial line may be favored.

3.2 Dedicated vs. Multi-product Lines

As discussed above, a dedicated (single product) serial line may minimize the throughput and inventory effects of variability, and be desirable for a specific product based on quality, equipment or other considerations. Obviously, if a serial line is dedicated to a specific product, the demand for that product must be large enough to justify the existence of the line. If the volume of demand for individual units is not sufficient for maintaining dedicated lines, then a serial line would be required to service a mix of products. As was discussed above in the variability section, differences in the assembly times for different members of a product family will create bottlenecks in the line, reducing the throughput as compared to a parallel system assembling the same products. Therefore, if there are many different products with low demand per product, a parallel process should be reviewed. If a single product or configuration has a significant expected minimum demand level, a serial process may be preferred with a dedicated line servicing that product.

Chapter 4 discusses some of the inventory implications of parallel and serial lines. If the demand level for a specific process is such that a dedicated line can be maintained, there will be advantages not only in the assembly process, as detailed above, but in material delivery and inventory as well.

3.3 Summary

There are obviously many factors that influence the decision of whether to structure the assembly process in serial or in parallel. There is no "one size fits all" answer; individual circumstances will dictate which is more effective for a given product

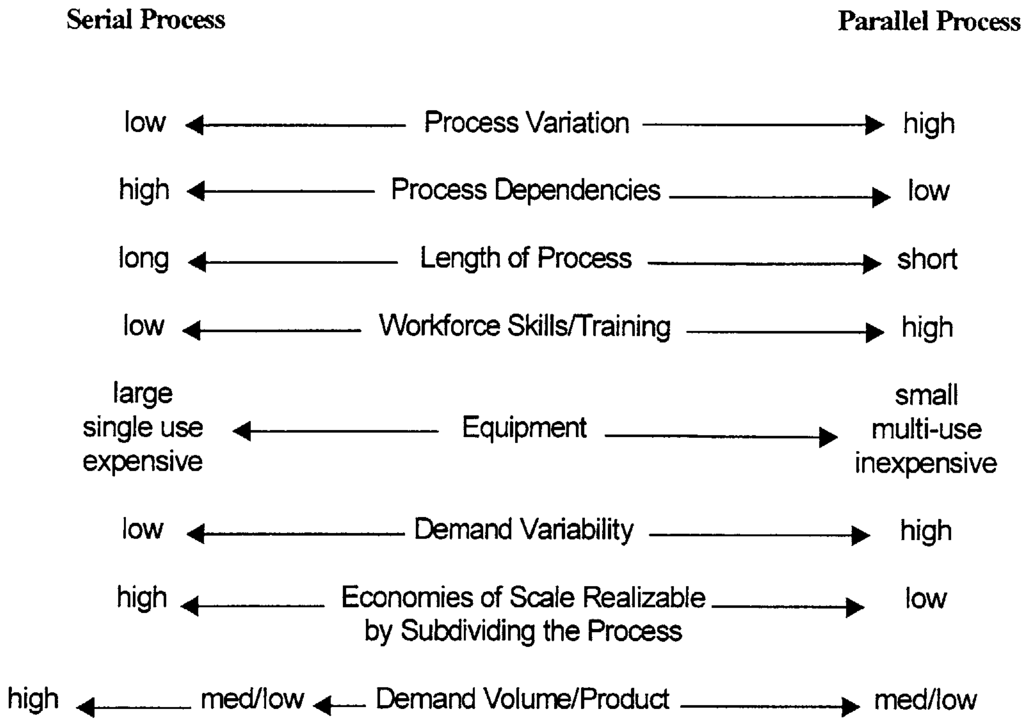


FIGURE 3: FACTORS AFFECTING ASSEMBLY STRUCTURE

or products, in a specific environment for an individual plant. Figure 3 depicts some of the relationships between the factors in the decision, and the recommended structure.

3.4 The Celestica Design

When determining the desired structure for the Celestica computer assembly factor, most of the above factors were taken into account. Although some specific data were not available, analysis of similar plants and knowledge of the planned process enabled an effective analysis to determine the optimal structure.

- Process variation: The hand assembly process at similar factories was measured, and the standard deviation of the assembly time was about 20% of the mean. Since product variety was expected to increase dramatically after the initial production ramp-up, the process variation was expected to increase, favoring a parallel assembly structure.

- Process Dependencies: The dynamics of an assembly line favored a serial process. However, the increase in quality and accountability of a parallel process outweighed these advantages.
- Length of Process: The assembly time of each unit, regardless of configuration, was expected to be less than 15 minutes. This time is short enough to allow individual assemblers to complete an entire unit without significantly reducing the total cycle time or increasing the probability of defects.
- Workforce Skills/Training: The labor force in the area and the relative attractiveness of the computer assembly plant environment would give Celestica the ability to employ highly skilled assemblers. Also, periodic training and management-by-fact (metrics) would maintain and enhance this high level of skills.
- Equipment: The assembly process required only hand tools, and workstations were low-cost multi-purpose fixtures adaptable to all products.
- Demand Variability: Based on data in the customer contract, demand variability was expected to be very high: +/- 20% within a given week. This variability was due to the inherent variability in the personal computer market.
- Demand Volume/Product: Forecasts from their customer indicated that demand for any individual product would be medium; there was no single product or small group of products which would account for any significant portion of the demand on a regular basis.

Comparing the points above to Figure 3 validates Celestica's decision to incorporate a parallel assembly structure in the plant. The flexibility in facilities layout and ability to react to changing demand were the key factors in this decision. Preliminary data from the first five months of actual production show that this decision was probably the correct one: throughput is very close to forecast, quality is high, and customer satisfaction exceeds all expectations.

Chapter 4 *Material Positioning*

The method by which material would be delivered to the assemblers is closely related to the assembly process decisions. In the electronics assembly industry, there are two primary methods for delivering material to the assembly floor: kitting and line-side stocking. The sections below will discuss each of these, their relative costs and benefits, and situations that favor one method over the other.

4.1 Kitting

In a kitting process, material is stored centrally. When an individual order arrives, enough material for one batch of production is "picked" from the storage area, by the use of a pick list generated from the order's Bill of Materials. This "kit" is combined in a tote or other device to hold the material, and contains only those parts required for one batch of a specific configuration of product.

4.2 Line-side stocking

If line-side stocking is used, parts are stored in relatively large quantities at their point of use. Thus if an assembly station is used for assembling 10 different configurations of product, the parts required for each of those configurations would need to be stored at that station. The local storage quantity should be large to ensure that the assembler has enough parts of each type on hand to assemble any configuration that may be required.

Issues to be addressed in determining the appropriate method of material delivery include security, obsolescence and poor material quality, process control, inventory accuracy and transaction costs, inventory levels and delivery cost.

4.3 Security

Maintaining all stores of inventory in a central location allows a measure of security in the control of the physical inventory. If there are valuable parts that need to be protected from theft, or very fragile parts that should be protected from breakage or disturbance, there can be significant advantage to maintaining fewer storage areas throughout the plant. If line-side stocking is used, then security measures need to be put into place next to each of the assembly stations where the fragile or expensive parts are to be stored. Kitting, on the other hand, allows for storage in a single, protected environment, and thus provides for more secure storage of these parts.

4.4 Obsolescence / Material Quality

In an industry like the personal computer industry, obsolescence of parts can cause rework of assemblies, test failures, excess inventories and poor customer relationships. It is imperative that obsolete parts be controlled and removed from production inventories as soon as possible. By maintaining a single source of raw material inventory for production, and issuing parts to the shop floor only when orders are released, the use of obsolete parts can be minimized. Obsolete parts can be removed from the kitting location as soon as Engineering Change Orders are processed. This is much more difficult with dispersed inventory locations, as would be the case if line-side stocking were used.

In a similar manner, reducing the areas where raw material is stored reduces the possibility that poor quality parts are used in final products. If a delivered lot of hard drives were found to be bad, for example, they could all be removed from the kitting and warehouse areas fairly simply. If line-side stocking were used, on the other hand, material control or quality personnel would have to screen parts at a variety of locations around the factory to ensure that poor quality parts weren't used. This could cause delays or production line shut downs until all of the bad parts could be accounted for, and could also cause rework if bad parts were assembled into units destined for the customer.

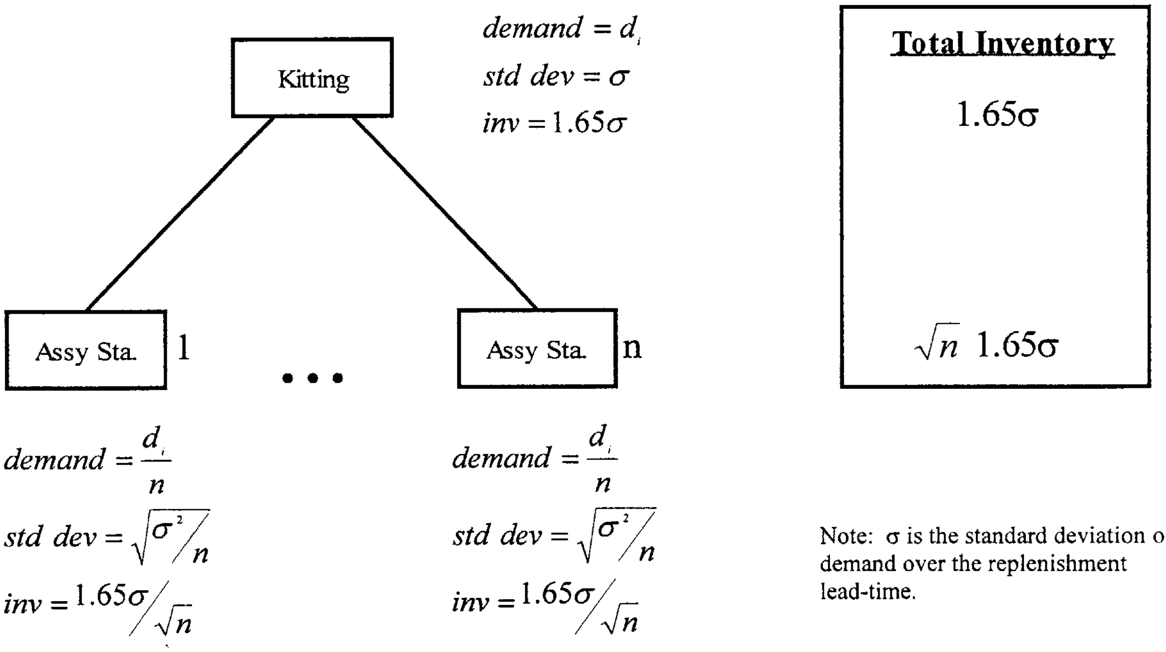
4.5 Process Control

Kitting provides a measure of process control that is not available with line-side stocking. When manufacturing many different products of similar but different configurations, it is imperative that some measure of control be used to ensure that only the proper parts for each unit's desired configuration are used. While a thorough test routine provides some measure of control, current testing practices in industry are not robust enough to ensure that all parts are correct for the unit's configuration. Utilization of a kitting process provides two levels of configuration control: the kitter is responsible for putting the correct number of the correct parts into the kit. At the assembler's station, the assembler provides an additional check to ensure that the right parts are in the kit. Also, because the tote should be empty at the end of the assembly process, the kitting and assembly processes together help ensure that all required parts are in the assembly, and only the right parts are included. An equal number of opportunities for selecting incorrect parts exists in both a kitting and a line-side replenishment system. In a kitting system the kitter is responsible for selecting the parts that make up the kit, while in line-side replenishment the assembler selects the parts as he assembles them. However, in a kitting system, the probability that an error makes it through assembly is reduced because the assembler essentially performs an audit of the parts in the kit. When line-side stocking is employed, it is possible through operator error to include wrong parts, exclude parts, or install parts not desired for the configuration of the specific unit. There is no check of the parts in the machine until the unit is in test.

4.6 Inventory Accuracy / Transaction Cost

Dispersed inventory locations provide a greater number of transactions required to track inventory movement throughout the plant. Also, cycle counting and/or physical inventory procedures would require periodic counting of the inventory maintained at each assembly station, and any other inventory locations throughout the factory. By contrast, use of a centralized kitting area reduces the number of inventory locations and the number of transactions required to update an inventory control system, thereby ensuring greater inventory accuracy and reduced transaction costs.

4.7 Inventory



Note: σ is the standard deviation of demand over the replenishment lead-time.

FIGURE 4: RAW MATERIAL INVENTORY

Reduction of raw material inventory is a major advantage in using a kitting system for material positioning. As can be seen from Figure 4, the safety stock required in a line-side stocking system would be $\sqrt{n}$ times greater than in a kitting system, where n is the number of stations at which inventory is stored. This rule-of-thumb is based on the following assumptions:

1. Demand is normally distributed
2. Inventory is kept at a point high enough to ensure a certain service level of supply (in this case, we are using 95%)

3. Demand is equally distributed among each of the *n* stations
4. The replenishment time is the same in both systems (and equal to 1 in the example of Figure 4)
5. Replenishment frequency is the same for both systems

A significant point to note in this analysis is that *n* refers to the number of storage locations for a single part, each servicing demand. If there are dedicated stations or lines for assembling units with unique parts, then *n* in this case is 1, and there is no difference between kitting centrally and stocking on the line in terms of inventory level.

4.8 Inventory Delivery Costs

Both methods of material delivery discussed have advantages and disadvantages in terms of cost. If a kitting system is used, parts must be delivered from the central warehouse (or vendor) to the kitting area. They are then picked into the individual kits, and the kit must be moved to the assembly station. When line-side stocking is used, the parts are delivered from the warehouse directly to the station(s) requiring them. The parts are then picked when needed by the assembler. No kit construction or movement is required.

When line-side stocking is the means for material delivery, delivery of parts from the warehouse to the assembly station(s) will require *n-1* more deliveries than if kitting were used. The cost of these deliveries could be very high if there are many stations assembling each product. The total cost depends on the distance from the warehouse to the assembly stations, and the layout of the plant. For example, if a part can be delivered to all stations at the same time during each replenishment cycle, and if the warehouse is centrally located, then the cost of delivery may not be significantly greater than delivering to a central kitting location.

The process of picking parts from a storage location to a kit is similar in both situations. Although a distinct kit is not produced with line-side stocking, the amount of effort required for an assembler to gather individual parts from their bins is approximately the same as the effort required to build a kit.

Delivering the kit to assembly incurs a movement cost in a kitting system that is not incurred in line-side stocking. The location of the stations, time between deliveries and size of the deliveries will all affect these costs.

A kitting system will generally require higher capital costs to set up the kitting racks, carousels, and/or material handling systems. These costs will generally be higher than the cost associated with the smaller storage bins required for line-side replenishment.

4.9 Product Flexibility

Because parts are stored centrally, a kitting system provides the ability to respond more quickly to part and product changes. Locations and instructions need only be updated for the kitting area, while in line-side stocking instructions and locations at each storage location require updating. The nature of the product at Celestica necessitates frequent additions and changes to the bill of materials for assembled products, and new product introductions occur quite frequently. In this situation a kitting system provides an advantage in the ability to quickly add or remove components from the shop floor, with limited effect on the individual assembly station and instructions.

4.10 Choosing the Right Method

The method of material delivery will depend on the structure of the assembly process. If assembly is completed in a single serial line, line-side stocking will be most efficient since there will only be one delivery location for each part. Because of the single location, security and obsolescence can be addressed in the same manner as in a kitting system. Inventory levels will be the same, since n=1. The cost of movement will be less than in a kitting system, due to the absence of the kit movement to the line. Based on the information systems available on the line, the inventory accuracy and transaction costs should not be distinctly different than in a kitting system. Process control can be addressed by ensuring that each successive assembler inspects or reviews the partially completed unit he receives from his upstream neighbor. In general, then, a dedicated or multi-product line will be better served by line-side stocking than with kitting. However, if security, obsolescence, and inventory accuracy can not be handled on the line in a cost-effective manner, kitting may provide a better alternative even though the material movement costs are higher. Also, if the level of demand requires multiple serial lines, kitting should again be reviewed as a possible material delivery method due to its inherent advantages when $n>1$ (i.e. when parts are stored in multiple locations on the shop floor).

Kitting is generally a more effective means of positioning material in a parallel assembly structure. A parallel structure will generally be chosen when product mix is high and individual product volume is low, or when demand for individual products is very volatile. Because the level of inventory is directly related to the demand for parts at the individual stations, the variability caused by these factors makes the cost of inventory in line-side stocking prohibitive. Further, the ability to provide security more easily, to mitigate the risk of obsolescence, and to reduce transaction costs and inventory inaccuracy make kitting much more attractive than line-side stocking in a parallel assembly plant.

There are, however, some parts that may be better suited to line-side stocking in a parallel layout. Specifically, those items that have low risk of obsolescence and are low cost may be stored in large quantities on the line with very little effect on total inventory costs. Parts in this category are those generally referred to as "C" parts in a traditional "ABC" analysis – hardware, common labels, etc. Since these items are generally small, stocking these on the line has the added advantage of minimizing the risk of stopping the line because a part was dropped, lost, or damaged. Figure 5 shows a summary of part characteristics that make parts suitable for different delivery schemes, and the relative performance measures of the two delivery methods discussed.

Kitting **Line-Side Stocking**

high ← Security Requirements → low
high ← Risk of Obsolescence → low
high ← Part Cost → low

PART SUITABILITY

low ← Inventory Delivery Costs → high
high ← Material Handling Costs → low
high ← Process Control → low
high ← Product Flexibility → low

DELIVERY METHOD PERFORMANCE

FIGURE 5: COMPARISON OF MATERIAL DELIVERY METHODS

4.11 The Celestica Design

During the initial stages of the plant design at Celestica, kitting was selected as a method of ensuring good process control, security of the high-value raw material inventory, and mitigating the risk of component obsolescence.

- Security Requirements: Many of the components used in the final assembly of personal computers are expensive, and availability is critical. Thus for microprocessors, motherboards, memory, disk and CD-ROM drives, maintaining security was a critical factor in the material positioning decision.
- Risk of Obsolescence: Personal computer technology continues to change rapidly. When choosing a material positioning strategy, it was therefore critical for Celestica to ensure that obsolete parts could be located quickly and removed from production,

and that raw material inventories were minimized to reduce the financial risk of obsolescence.

The reduced cost of inventory in a kitting system outweighed the increased material handling costs. More importantly, however, the degree of process control and flexibility in supporting a changing product line that are afforded by a kitting system were key factors in the decision to implement kitting. "Wrong part" defects in assembly were at only 20% of the expected rate during initial production runs, and the kitting process was effective in maintaining a continuous flow of kits to the assembly stations.

Chapter 5 *Designing Capacity*

Once we have designed the structure of the manufacturing processes, we must determine the capacity of each of the different processes. The nature of the final assembly process is such that there is inherent variability in each sub-process. Reducing this inherent variability is an essential objective of many improvement efforts such as the currently popular "Six Sigma" program from Motorola. Even the most successful programs will not be capable of eliminating variability completely, however, and thus we should design the capacity and buffers in order to overcome this variability and ensure we can meet our throughput goals.

5.1 The Theory of Constraints

The Theory of Constraints (TOC), as developed by Eliyahu Goldratt (Goldratt and Cox 1984, Goldratt and Fox 1986, Fogarty, Blackstone and Hoffman 1991, Gardiner, Blackstone and Gardiner 1994), proposes five focusing steps for analyzing and improving manufacturing:

1. Identify the system's constraint(s)
2. Decide how to exploit the system's constraint(s)
3. Subordinate everything else to the above decision
4. Elevate (if necessary) the constraint
5. If, in the previous steps, a constraint has been eliminated (i.e. it is no longer the system constraint), go back to step one...but do not allow inertia to become the constraint

One major implication of the above process is that the presence of a single constraint is assumed. The existence of a constraint may be argued, and probably can't be proved or disproved. However, in a hand assembly process, the variability inherent in a labor-intensive process nearly guarantees that there will be a bottleneck. Continually predicting its location and protecting its throughput then become the challenge for the factory management. The factory design team has the ability to choose the location of the bottleneck, or to design a "balanced" factory, allowing variation to determine the location(s) of the bottleneck(s).

5.2 TOC in Factory Design

The five focusing steps above are intended to assist in better management of an existing plant. The use of Theory of Constraints in initial factory design has not been documented well, to my knowledge. When queried on the subjected, the Avraham Goldratt Institute (led by Eli Goldratt and a depository of Theory of Constraints knowledge) was not aware of any developments or publications on using TOC in the factory design process.

In attempting to apply the Theory of Constraints in the factory design process, two major areas should be addressed:

1. Location of the bottleneck
2. Subordinating the other operations to the bottleneck

5.2.1 Bottleneck Location

The first focusing step in the Theory of Constraints is to identify the bottleneck. Since the existence of a bottleneck within the factory is inevitable, the design process should include analysis of the optimal place for the bottleneck. The location of the bottleneck will depend on such things as the nature of the processes, capital equipment requirements, overall process flow, capacity measurement, and flexibility. The following characteristics are desirable in a bottleneck, and can be used to determine where to locate the bottleneck within the factory:

1. Measurability

2. Predictability (low variability)
3. Capacity flexibility
4. Value
5. High relative cost
6. Early position in the factory process (usually)

The Theory of Constraints describes time on the bottleneck as the most valuable resource in the factory. The bottleneck should be buffered from variation in the remainder of the processes, by either inventory and/or excess capacity buffers. Because the capacity of all operations will be based on the capacity of the bottleneck, the process at the bottleneck should be both measurable and predictable.

Demand will likely have some amount of variation. The ability to match the capacity of the facility to the expected or realized demand will enable the factory to minimize the amount of finished goods inventory required to meet demand. This will also help avoid the expense of carrying excess capacity in times of reduced demand.

The location of the bottleneck should also correspond to the value the factory adds to the product. Since the bottleneck is the most valuable resource in the factory, it should represent a valuable step in the process. A bottleneck that can be considered "non-value added" should not last long as the bottleneck; improvement efforts throughout the factory should seek to eliminate such steps so that the process contains a sequence of events that each create or add value to the product.

The bottleneck should be located where capacity is expensive. Since all other steps in the process are subordinated to the bottleneck, they will necessarily have some idle time. The bottleneck is the single step in the process where idle time will be minimized, and thus the cost of the factory will be minimized if the most expensive step is chosen. This could be the step with the longest cycle time (requiring the greatest number of human resources), the step with the most skill required (expensive human resources) or the most capital intensive location (expensive equipment utilization.)

Finally, the bottleneck is probably best located near the beginning of the process. The Theory of Constraints advocates a shop floor scheduling routine known as "Drum-Buffer-Rope." Realizing that the capacity of the bottleneck represents the overall capacity of the plant, orders and material should be released to the floor at the pace of the bottleneck. The bottleneck step is therefore the "drum" of the process, setting the rhythm of the rest of the process. Placing the bottleneck close to the start of the process will reduce the amount of distortion of the order release pace, facilitating more accurate scheduling. The "rope" is the means by which the order release pace is passed from the constraint (bottleneck) to the beginning of the process. A "kanban" or pull system can act as this rope, as can a number of manual or electronic processes or software programs. Finally, the "buffer" refers to the fact that the bottleneck should be protected from variability in the rest of the process. Idle time on the bottleneck represents waste in the process. In order to avoid this waste, the bottleneck should be protected from being starved by upstream processes, and from being blocked by those downstream. This protection can be in the form of inventory or capacity buffers. Capacity buffers are provided by excess capacity at non-bottleneck process steps. The incremental cost of each will determine the most cost-effective combination of inventory and capacity to be used in buffering the bottleneck.

The previous discussion applies mainly to processes such as the computer final assembly process at Celestica. In other processes, such as wafer fabrication, process yield may determine that the optimal location of the bottleneck is farther downstream. Since time on the bottleneck is the most expensive resource in the plant, the bottleneck should be positioned such that succeeding steps have high yields, so that material which has used bottleneck time is not scrapped.

5.2.2 Subordinating Other Operations

During the design process at Celestica, one of the major difficulties encountered in implementing the Theory of Constraints in the factory design process was determining how to subordinate the other processes to the bottleneck. In order to ensure that the bottleneck remains the constraint, it is necessary to provide capacity or inventory buffers at other steps in the process so as not to block or starve the bottleneck. Both inventory and additional capacity have costs associated with them. They also affect the throughput of the system differently. Through our research, we were unable to locate a single methodology that would enable us to determine the most efficient means of protecting the bottleneck. Discussions with other people who had used or studied the Theory of Constraints led us to use additional capacity at successive process steps of between 2% and 10%. An analytical means of determining the appropriate levels of inventory and excess capacity is needed. The following section describes a queuing model which may be useful in determining appropriate capacity levels throughout the process in order to balance flow. This method should enable the factory design team to minimize the total expense of the plant (inventory and capacity) while enabling the aggregated throughput to remain approximately equal to the capacity at the constraint.

5.2.2.1 A Queuing Model

Queuing theory provides a good method for analyzing the effects of inventory and capacity on throughput. A network of M/M/1 queues as discussed in Chapter 3 provides a useful model for a general analysis. In this case, the entire final assembly process (see Figure 1) will be considered as a serial process. Each of the process steps can be considered an individual M/M/1 queuing system, with its preceding buffer. Note that the assumptions of section 3.1.3.1 apply.

In analyzing the effect of capacity and inventory, a cost model must be developed in order to measure the performance of the input parameters. For the simple model shown in Table 2, the total labor cost and carrying cost of average inventory were used to optimize the capacity increase in the system. Inputs to the model include the average cycle time at each station, the arrival rate of orders, the annual cost of an employee (which should include both salary and benefits,) and the carrying cost of one unit of inventory. This carrying cost is equal to the material cost of a unit multiplied by an interest rate. The interest rate is the cost of capital of the company plus the cost of storage and handling for the inventory, expressed as a percentage of its cost.

In this model, costs and rates in the upper left, as well as mean cycle times, are fixed. The capacity increases at each process step are the decision variables, which are varied by the optimization routine. The overall objective is to minimize the total cost (in the lower right.)

Capacity/Inventory Cost Model **M/M/1**

Salary	$20,000
Unit Cost	$ 1,000
Interest Rate	25%
Arrival Rate	1.8

				Decision Variables					
Process	***Cycle Time***	***Service Rate***	***ρ***	***Capacity Increase***	***Workers***	***Avg Inventory***	***HR Cost***	***Inv Cost***	***Total Cost***
Assembly	12	1.84	0.98	2.41%	22.1	41.6	$442,392	$ 10,392	$ 452,785
Test	8	1.85	0.97	0.53%	14.8	33.9	$296,485	$ 8,485	$ 304,971
HiPot/Cosm.	2	1.87	0.96	0.95%	3.7	25.5	$ 74,828	$ 6,365	$ 81,193
Pack	6	1.88	0.96	0.50%	11.3	22.5	$225,606	$ 5,621	$ 231,228
Localize	2	1.91	0.94	1.38%	3.8	17.0	$ 76,243	$ 4,243	$ 80,485
Audit	1	1.92	0.94	0.62%	1.9	15.3	$ 38,358	$ 3,817	$ 42,175
Consolidate	2	1.93	0.93	0.50%	3.9	14.1	$ 77,100	$ 3,530	$ 80,629

Objective	Total Cost	$1,273,465

TABLE 2: CAPACITY/INVENTORY COST MODEL (M/M/1 QUEUE NETWORK)

The model uses the general case of the M/M/1 queue (Nahmias 1997, pp 478-479) to calculate the average inventory between each step, based on the utilization. These calculations are based on:

Utilization: $\rho=\lambda/\mu$

Average Inventory: $L=\rho/(1-\rho)$

The arrival stream (λ) for each step is equal to the exogenous arrival stream (1.8 in the example) since the system is in steady state. Service rate is calculated from the service rate of the previous step and the capacity increase. The number of workers required at each step is determined by the calculated service rate and the mean cycle time. Note that in this analysis the number of workers is not constrained as an integer. In actual use, this constraint would obviously be required. Human resource cost is the number of workers required times the annual salary, and inventory cost is the average annual inventory times the unit cost times the interest rate. The total cost is equal to the sum of all of the human resource costs and inventory costs. This model assumes infinite buffer sizes in the queuing analysis. Finite buffer size queuing models are more complex, and might be analyzed effectively as Markov chains. Gershwin (1994) uses Markov chains to analyze transfer lines of unreliable machines. A similar method should be developed for hand assembly processes, where variability of service times drives system performance rather that failures and repairs of machines. Developing a model such as this is beyond the scope of this thesis.

Although the model above assumes infinite inventory buffer space and Poisson processes, it is useful for developing intuition about the effect of utilization on the inventory levels, and the relative costs of personnel and inventory in such a process.

A primary result of the above model is that no optimal capacity increase exists that can be applied throughout the process. The most cost-effective increase at each step will depend on the capacity (service rate or designed throughput) of the previous step, the cost of holding inventory, and the incremental capacity cost. The incremental cost is the primary reason for the different optimal increases throughout the process. A step that takes one worker 10 minutes to complete has an average service rate of 0.1 units/minute/worker, and costs $200,000 (10 workers) for each additional unit/minute of capacity. On the other hand, a step that has a cycle time of 1 minute requires only $20,000 (1 worker) to realize an additional 1 unit/minute increase. Because of these differences, the inventory between process steps affects the optimal capacity increase differently at different steps. For the 10 minute step described above, inventory is relatively cheap compared to capacity, and therefore the recommended capacity increase is small. For short steps, the capacity is less expensive, so the optimal increase will usually be larger.

The reason increases in capacity and/or inventory are required is variability. As was discussed in previous sections, there are many causes for variation, but they can only be overcome by a combination of inventory, excess capacity, and variation reduction programs. In order to better see the effects of variation, the model was modified to use a GI/G/1 queue network (General independent arrivals, general service and 1 server.) While the M/M/1 queue is useful to show relationships between capacity and inventory, it does not apply many situations. A more useful method is the approximation of the GI/G/1 queue as used in Table 3.

The model is essentially the same as the M/M/1 model in Table 2. Calculations of the performance measures of the queues are based on the following approximations:

SCV_a = squared coefficient of variation for interarrival times
SCV_s = squared coefficient of variation for service times

Expected waiting time in queue: $D = [\rho/(1-\rho)]*[1/\mu]*(SCV_a+SCV_s)/2$
Average inventory: $L = \lambda*[D + 1/\mu]$
SCV for the departure stream from a queue: $SCV_d = (1-\rho^2)SCV_a + \rho^2 SCV_s$

The decision variables (capacity increases) and objective (total cost) remain the same. The average inventory at each step and the SCV of the arrival stream to a process is calculated from the downstream SCV of the previous process (SCV_d.)

Because this model takes into account the variance (SCV in the model is the squared covariance – variance divided by the mean squared), it can be used to investigate the effects of variation. Realizing that when SCV=1, this model is the same as an M/M/1 queuing model, we can see the effect of cutting the standard deviation in half in Table 3 below. Because the variation is much lower, the optimized total cost is significantly lower than in the original model, and the inventory accumulated in the buffers is also well below the maximum allowed. In order to better predict the requirements for capacity buffers and inventory to ensure the bottleneck is protected and throughput is maintained, it is important to forecast or analyze the variation in cycle times, as well as the mean. Focussing on variation later in improvement programs will also help to reduce the total cost of capacity and inventory, and produce more reliable results with shorter lead times.

Capacity/Inventory Cost Model **GI/G/1**

Salary	$ 20,000
Unit Cost	$ 1,000
Interest Rate	25%
Arrival Rate	1.8

						Decision Variables					
Process	***Cycle Time***	***SCV$_a$***	***Serv. Rate***	***SCV$_s$***	ρ	***Capacity Increase***	***Workers***	***Avg Inv.***	***HR Cost***	***Inv Cost***	***Total Cost***
Assembly	12	0.1	1.81	0.10	0.99	0.76%	21.8	14.1	$435,276	$ 3,520	$ 438,796
Test	8	0.1	1.82	0.10	0.99	0.17%	14.5	11.7	$290,685	$ 2,927	$ 293,612
HiPot/Cosm.	2	0.1	1.82	0.10	0.99	0.38%	3.6	8.6	$ 72,949	$ 2,139	$ 75,088
Pack	6	0.1	1.82	0.10	0.99	0.00%	10.9	8.6	$218,846	$ 2,147	$ 220,993
Localize	2	0.1	1.83	0.10	0.98	0.54%	3.7	6.3	$ 73,340	$ 1,585	$ 74,925
Audit	1	0.1	1.84	0.10	0.98	0.30%	1.8	5.6	$ 36,779	$ 1,401	$ 38,180
Consolidate	2	0.1	1.84	0.10	0.98	0.00%	3.7	5.6	$ 73,558	$ 1,405	$ 74,963

Objective Total Cost $1,216,557

TABLE 3 : CAPACITY/INVENTORY COST MODEL (GI/G/1 QUEUE NETWORK)

5.3 Suggested Further Research

As is clear from these models, there does not appear to be a single optimal capacity increase level for a complete system. The increase at each step will depend on the variation in the process, the buffer size, the cycle time and the costs of personnel and inventory. Further, because of the many types of variation within the final assembly process, queuing models do not address all of the issues that will affect the optimum capacity levels.

The Theory of Constraints is based on sound principles, and is well respected within manufacturing. However, there appears to be very little known about some of the specifics in implementing TOC, especially in the area of factory design. Both of the topics addressed in this thesis – locating the bottleneck and subordinating other operations to it – require more research in order to assist in the design process. Questions to be answered include:

- Should the factory be designed with a specific bottleneck? Where should it be located? Are there analytical methods to determine the proper bottleneck location and throughput? What are the cost effects of the location of the bottleneck and the accuracy of its capacity measurement?

- How should inventory and capacity be used to protect the bottleneck? Specific, analytical methods should be developed to replace the gross-level model above. These methods should be useful to the design team in determining optimal capacity levels for different operations within the plant.

5.4 The Celestica Design

While most of the topics addressed above were discussed in the Celestica factory design process, no analysis was completed to determine the appropriate level of excess capacity to plan in the factory. Variation was not predicted in any detail. As is clear from this and other sections, understanding the sources and magnitudes of variation in the process is critical to designing for minimum costs while providing maximum flexibility and protection against the Law of Murphy.

Chapter 6 *Summary*

The design of a factory is different from all other projects in manufacturing. When designing a plant, assumptions and estimates must be made in the face of uncertainty in the final design of the product, the design of the process, and the demand for the products. With little or no historical data to guide their decisions, the design team must develop a structure that is robust enough to handle these uncertainties, yet cost effective and efficient. The Celestica design team did an excellent job of using their many years of accumulated knowledge in a closely related industry, research, analysis, and teamwork to quickly design and implement an innovative world-class manufacturing facility. In utilizing a cross-functional team to develop a vision and high-level guidelines prior to the detailed design, Celestica's management ensured that an effective balance between experience and creativity could be maintained in order to meet their cost, quality and delivery objectives for both the design project and the final product. Leveraging this process, and the knowledge of those many people who participated in the design effort will ensure the future competitiveness of Celestica as a leader in contract manufacturing.

As discussed in the body of this thesis, most of the decisions made in the design effort are interdependent, and most must be discussed and developed simultaneously. The structure of the overall process is linked to the structure of the assembly lines in the final assembly plant. Choices regarding material and assembly structure are interrelated, and therefore these decisions should be made in conjunction with each other. Capacities must be designed to ensure that the required throughput will be guaranteed, while at the same time minimizing both the cost of fixed investment and the variable costs of production.

Understanding the variation in human functions, in the process, the materials and demand is key to developing an effective design, and ensuring that the plant is flexible enough to meet both the needs of the customer and the return on investment required. Earlier and more in-depth analysis of these types of variation will assist in making future design decisions, and better understanding their effects. For example, while we gathered data and estimates of the cycle times in the final assembly and testing steps, the variability in those times was either estimated or ignored. By better understanding the variation expected due to uncontrollable forces, and the controllable variation related to the process and product mix, more analytical decisions could have been made with regards to assembly, material positioning and capacity. Based on review of the factors affecting and affected by these decisions, I believe the choices made were the correct ones. However, a better understanding of these sources of variation and their expected magnitude would have enabled the team to better predict the effect of demand and product design uncertainties, and ensure that the factory structure that was designed was flexible and robust enough to handle these future changes.

In conclusion, the factory design process is a process of making decisions based on assumptions and estimates. Research, benchmarking, simulation and construction of representative products within factory models could help quantify some of the effects of variation, and lead to a more robust and effective design. Flexibility in the design process and in the factory design will help ensure that the resulting plant can maintain competitiveness and profitability in a changing environment. Celestica's success in rapidly designing and building a cost-effective high-volume manufacturing plant demonstrates the effectiveness of this flexibility in both the design process and the factory design.

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