

INSTITUTO TECNOLÓGICO Y DE ESTUDIOS
SUPERIORES DE MONTERREY

CAMPUS MONTERREY

DIVISION DE INGENIERIA Y ARQUITECTURA
PROGRAMA DE GRADUADOS EN INGENIERIA



TECNOLÓGICO
DE MONTERREY.

METHODOLOGY TO GENERATE IMPROVEMENT
IDEAS AND PRIORITIZE THE OPPORTUNITIES FOR
ENHANCEMENTS, RESULTING FROM LEAN
MANUFACTURING IMPLEMENTATION

TESIS

PRESENTADA COMO REQUISITO PARCIAL PARA
OBTENER EL GRADO ACADEMICO DE:

MAESTRO EN CIENCIAS
ESPECIALIDAD EN SISTEMAS DE MANUFACTURA

POR:

FELIPE DAVID CASTRO UGALDE

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**TECNOLÓGICO
DE MONTERREY®**

**Methodology to generate improvement ideas and prioritize the opportunities
for enhancements, resulting from Lean Manufacturing implementation**

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**DIVISIÓN DE INGENIERÍA Y ARQUITECTURA
PROGRAMA DE GRADUADOS EN INGENIERÍA**

Los miembros del comité de tesis recomendamos que el presente proyecto de tesis presentado por el Ing. Felipe David Castro Ugalde sea aceptado como requisito parcial para obtener el grado académico de:

**Maestro en Ciencias
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DEDICATORIA

A Luisa, mi esposa. Tú eres la fuerza que me empuja a seguir, así como el complemento que me hacía falta. Gracias por todo tu apoyo y paciencia; gracias por infundirle a mi vida ese dinamismo; gracias por estar a mi lado y hacer desde siempre la gran diferencia en mi día a día.

A mi futuros bebés, pues todo mi afán de superación y crecimiento está fundamentado en las ganas de ofrecerles todas las oportunidades que yo tuve.

A mis papás, Pilar y Felipe, por todo su impulso, ayuda y enseñanza. Gran parte de lo que ahora soy ha sido aprendido de ustedes. La constancia, tenacidad, trabajo arduo y honradez, de ti Papá. La entrega, cariño y apoyo incondicional, de tí Mamá. Mi respeto, admiración y cariño es suyo.

AGRADECIMIENTOS

A todos mis maestros, de los que no sólo he aprendido cuestiones técnicas, sino también, toda una filosofía de entrega, esfuerzo constante y alegría por compartir su vida.

A mi asesor, el Dr. José Luis González Velarde, por todo su apoyo y guía durante este tiempo. Sus enseñanzas fueron parte fundamental para mi desarrollo en áreas nuevas.

Al Dr. Gabriel Barraza Enríquez, por su sinceridad y sus muy acertados comentarios. Gracias por su apoyo y compromiso conmigo. Su enfoque práctico ha sido siempre de gran utilidad.

A Mario Ramos, mi tutor los últimos años, de ti he aprendido que para ser exitoso, hay que esforzarse y enfocarse, pero sobre todo, tener una visión de negocio que sea ajena a objetivos particulares o localistas.

A todos mis amigos, en especial a Kike, Isaac y Calín, por estar presentes cuando necesité de ellos y por brindarme la mano tantas veces para seguir adelante.

A todas las personas que han tocado mi vida llenándola de bendiciones, alegrías y aprendizaje. Sin ellos no sería lo que hoy soy.

A todos ustedes, mil gracias...

Felipe Castro

ABSTRACT

This study proposes a methodology to make educated decisions that will help to generate improvement ideas and prioritize the opportunities for enhancement found during the application of Manufacturing Excellence (Lean Manufacturing). The methodology will be based on the utilization of a manufacturing line model, in conjunction with a sensitivity analysis. Based on the results of the sensitivity study it can be determined which areas to focus on and which ideas have the higher contribution on the performance metrics of the line.

The methodology follows these steps:

1. Perform Process Mapping.
2. Create Model.
3. Populate/Verify Model.
4. Identify Current Performance.
5. Run Sensitivity Analysis.
6. Analyze Results, Prioritize & Propose.

In order to found this methodology, this study also covers the factory physics principles that explain the relationships between the different parameters of the manufacturing lines that play a fundamental role on the behavior of a manufacturing system.

The proposed methodology will be applied on a contactor's manufacturing line at Schneider Electric (SE) to test and verify the hypothesis. SE is focus only on two markets worldwide, electrical distribution and automation/control. There are 84,000 employees around the world with presence in more than 130 countries (150 manufacturing facilities worldwide). The main brands are Square D (electrical distribution, automation/control), Merlin Gerin (electrical distribution) and Telemecanique (automation/control).

After the practical case, the hypothesis, "the utilization of the methodology and tools proposed to evaluate and prioritize the improvements will increase the effectivity of the actions taken and the expected benefits", is demonstrated to be correct.

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THESIS CONTENT.

In order to introduce the thesis antecedents and reasons to pursue this study, Chapter 1 covers Schneider Electric's Manufacturing Excellence (ME) description, reasons to implement ME & the ME implementation process that is being followed. Also, this chapter includes the justification, objective, hypothesis and benefits to be obtained through the application of this thesis. This chapter finalizes with the presentation and description of the methodology proposed.

Chapter 2 introduces Lean Manufacturing and its antecedents. It also covers the Just in Time production system at Toyota and Lean Manufacturing Basics. The chapter finalizes with the benefits to be obtained through lean implementation, a comparative study between traditional vs. lean systems and a brief implementation guide with specific success factors.

Chapter 3 describes two important tools to be used on this study, the Value Stream Mapping that will be linked to the lean methodology and the Sensitivity Analysis that will guide the decision making process during the application of the proposed methodology.

Chapter 4 presents the relations that exist between all the parameters that play a role on the behavior of manufacturing systems. Introduces the Factory Physics principles and describes the equations and scenarios to evaluate the how lean is a system. This chapter also covers a section where the variability interactions are shown via the VUT equations.

Chapter 5 develops the practical case applying the methodology presented on chapter 1 to a practical case, a contactor's manufacturing line within Schneider Electric. To finalize the chapter the results and conclusions are presented, together with directions for future research.

The appendices cover all the detailed information about the Value Stream Mapping of the line, the current status of the line, the data that was generated during modeling and testing, the detailed sensitivity analysis data and graphs. Also covers the former ideas proposed prior to the methodology proposed and includes some reference material to value stream mapping, factory physics principles summary and a lean manufacturing glossary.

Chapter 1.

1. ANTECEDENTS & JUSTIFICATION OF THE STUDY.

“Perfection of means and confusion of goals seem to characterize our age”.
– Albert Einstein (Hopp, Spearman, 2000).

This chapter presents a brief introduction of the company, the description and the reasons to pursue Manufacturing Excellence. The chapter finishes with the antecedents of the thesis, the justification, the hypothesis and the benefits to be obtained after the thesis.

1.1. Schneider Electric and Manufacturing Excellence.

Schneider Electric (SE) is the only company exclusively focused on its two particular businesses: Electrical Distribution and Automation & Control. At a time when electrical, automation and communication technologies are converging; this strong specialization enables the Group to occupy a leading international position.

SE is the leader on the electrical distribution sector (70% of the sales) and has the second place on the automation and control market (31% of sales). Currently there are 84,000 employees around the world, 17,000 in Canada, USA and Mexico. There is company's presence in more than 130 countries with more than 150 manufacturing facilities worldwide. Also SE has a sales force of 9,000 sales offices around the world.

The main brands are Square D (electrical distribution, automation and control), Merlin Gerin (electrical distribution) and Telemecanique (automation and control).

Schneider Electric (SE) defined that the implementation of the Manufacturing Excellence program will support the competitive strategy, “excellence in operation”, that will guide the company towards the achievement of the challenges included on the company's initiative called NEW 2004 - New Electric World 2004.

Manufacturing Excellence (ME) is an improvement process that comprises mainly lean manufacturing principles but also includes other tools like value stream mapping, 5S, “kaizen”, “poka yoke”, SMED and six sigma.

Manufacturing Excellence is used throughout Schneider Electric to reduce non-value added time, or waste, in the product's value stream. The value stream is the flow of a production order; from the customer, through order management, engineering and manufacturing, including the flow of raw material and components from suppliers, all the way through shipment and receipt of the product by the customer (Pesavento, 2002).

ME is intended to search for the technical process limits or constraints in order to minimize the time spent by the products to flow through the manufacturing process. The implementation of Manufacturing should identify and reduce wasted effort, in-process inventory and working capital in the system. Other overhead costs are also reduced as a result of this analysis.

Also, ME is not about people working harder. After its implementation, value-add time is often the same, but the ratio of non value-add time to total lead-time can be highly reduced. So freeing up some time to be focus on value-added activities. In all cases, time on tasks improved due to less time spent chasing parts and problems and process setup. By reducing waste, it is possible to shorten lead times, reduce manufacturing costs, lower inventory and increase throughput.

This improvement process has helped SE to meet its customers' needs better by allowing them to make changes later in the production process. The process has also improved ergonomics for the employees, optimized floor space to make room for future growth and helped the company to develop a culture of continuous improvement (3L Comitee, 2003).

ME also strengthens SE's vision of Total Order Lead Time (TOLT) the front end of Manufacturing Excellence. TOLT reviews the order process, i.e. the entire proposal-based business process, from initial quotation to final commissioning of the equipment, from a customer perspective to determine where the process can be improved (Pesavento, 2002).

1.2. Reasons to pursue Manufacturing Excellence.

We are in a fast evolving environment as consumers, expecting to get what we want, adapted to our specific needs, at internet speed. Customers are no different, they want intelligence in the order entry process, short lead-times for customized products, late change capability, dependable delivery – all at the lowest possible cost. In addition, shareholders want improved profitability with reduced working capital and employees want to work safely, and have the tools and resources needed to perform their jobs (Pesavento, 2002; 3L Comitee, 2003). Through Manufacturing Excellence, Schneider Electric will be safer, faster, better, with improved quality and less costly, resulting in highly committed customers, stakeholders and employees.

1.3. Implementing Manufacturing Excellence.

The first step to implement Manufacturing Excellence is to perform a diagnostic (in-depth review), with the purpose of determining the technical process limits or constraints and identifying opportunities to reduce or eliminate waste (Starnes & Wells, 2002). As part of the initial diagnostic, the current state value stream map

with existing information is captured. Then, the future state value stream map (avoiding and minimizing any waste) is developed. In order to evolve from current to future state, an action plan to move forward from current to future state is set and executed. Then a new future state value stream map is drawn up and the former steps are repeated to assure continuous improvement.

During diagnostic, some opportunities for improvement will include: line balancing, layouts, the implementation of constant daily output, material handling techniques, scheduling, inventory management, setup and changeover techniques and more rigorous utilization of performance metrics throughout the facility (Starnes & Wells, 2002).

ME is a continuous improvement effort; therefore, the changes are never finished. The objective is to train and empower the people to continuously find ways to drive improvements after the initial implementation phase is over. In order to be successful, companies need to include continuous improvement, in all areas, as a way of life.

The first review is 10 to 12 weeks after the start of the implementation phase. At this first review, 60%-70% of the physical changes will require to be completed (Edison, 2002).

This process (ME) can be stressful, but necessary. In the words of Dave Petratis, Schneider Electric's President and Chief Operating Officer of the North American Operating Division, we are in a "street fight" to be competitive and profitable (Starnes & Wells, 2002). Schneider Electric success depends on moving fast in all initiatives. Radical change is necessary to attain world-class performance (Edison, 2002).

1.4. Justification of the thesis.

"If you keep doing what you've always done, how come do you expect the outcomes to be different" (Crawford, 2004).

Once the current state is mapped, the next step is to find opportunities for improvement, the more the better. Then the dilemma of where to start from will appear. What areas are the most important to focus on? Which idea will get the highest improvement with the minimum effort? With scarce resources (people and money), these must focus on the opportunities that obtain the best results in the shorter time.

Currently, savings are used as the major prioritization criteria to determine which idea should be implemented first. However, the impact of the different parameters that play a role in the production chain is not well understood. Also

relate savings with ideas is not easy, and more if the total impact of the idea on the production process is not clearly understood.

Manufacturing Excellence has been applied to different areas in a mechanical way, not really understanding which opportunities will generate the greater impact on the performance of the line and therefore on the savings. Also, during implementation the process to assign a priority (determined by savings) to the opportunities is not easy to follow. Due to this shortsighted vision the efforts may be focused on opportunities that are not the highest contributors but only on the “apparent” best ideas, thus sub-optimizing the real savings that can be obtained for the organization.

The implementation, by itself, brings good results, but understanding the relations that exist between the different parameters that affect the performance of a production line can potentiate the benefits. This knowledge will lead to focus the resources to the main contributors thus increasing the benefits obtained and reducing the time to get them.

1.5. Objective of the thesis.

The objective of this study is to propose a methodology to make educated decisions that will help on the generation of improvement ideas and the prioritization of the opportunities for enhancement found during the application of Manufacturing Excellence (Lean Manufacturing).

The methodology will be based on the utilization of a manufacturing production line model, in conjunction with a sensitivity analysis. In order to test the hypothesis the study will focus on a practical case in the contactors' area of Schneider Electric in the Monterrey facility. A contactor is an electro-mechanical device to interrupt the electricity flow once a control signal is applied to it.

Some benefits that can be obtained through the application of a structured and founded methodology to lean implementation are:

- Increase the knowledge of the fundamentals and relations between the different parameters involved in lean manufacturing.
- Assign the resources in the most efficient way in the areas where the best rewards can be obtained.
- Reduce cost and increase productivity, maximizing at the same time the results and reducing the expenses.
- Share the results with the rest of the organization to maximize the impact and benefits for the implementation of Manufacturing Excellence within Schneider Electric.

1.6. Hypothesis to be tested.

The utilization of this methodology, based on the application of Sensitivity Analysis to generate and prioritize improvement ideas, will increase the effectivity of the actions taken and the benefits obtained.

To evaluate if the hypothesis is correct, the results obtained with the sensitivity analysis (SA) and the former actions taken (result of VSM & Brainstorming) will be compared to identify if the prior actions taken were aligned to the SA. Based on this comparison, it can be identified if the analysis showed valuable information to generate ideas and prioritize the opportunities for improvement.

1.7. Proposed Methodology.

The use of a structured method to follow during the implementation of any new idea can determine the success or the failure of this. Following a scientific approach assures that the study can be replicated to achieve the same results elsewhere, thus propagating the knowledge. The following sections introduce the methodology proposed for this study, this is somehow related to the DMAIC process (Define Measure Analyze Improve Control).

1.7.1. Perform Process Mapping.

In order to improve any process, it is required to quantify the current state, gathering the input information including all data related to stations' performance (process time, yield, maintenance information, variability, number of machines, etc.).

1.7.2. Create Model.

In order to model the behavior of a production line the Cycle Time Calculator, an Excel worksheet, was used. The tool is based on the application of VUT Equations in a sequential manner thus propagating the behavior to the downstream stations. The required inputs are arrival rate, variability and jobs between setups. For each workstation, process times, variability, mean time to failure (MTTF), mean time to repair (MTTR) are recorded. Based on the calculations, the last station reflect the cumulative effect of each station on the behavior of the production line in terms of the most important performance measurements such as Throughput, Work in Process and Cycle Time. The model was created with this worksheet and adjusted to reflect the two feeder lines and the existing relations between its workstations.

1.7.3. Populate/Verify Model.

All the input information gathered during the process mapping is fed to the model to verify that the behavior was according to the inputs and that no error was made when stating the relations between stations (no discrepancies or non-continuities were shown on the model).

1.7.4. Identify Current Performance.

To pursue an improvement process, the first step is to determine the current performance. In order to identify if the current process is lean or not, the behavior of the current system can be compared with the Worst Case, Practical Worst Case and Best Case. Based on where the current process is located, compared to the baseline Practical Worst Case, it can be determined if the system is lean or not and also how much improvement can be expected from lean manufacturing implementation.

1.7.5. Run Sensitivity Analysis.

Using the line model, an ordinary sensitivity analysis was run to determine the impact of all the different input parameters to the line performance measures. This study was done varying the original values and recording the results of this variation on each performance parameters. With this data, spider charts were created to show how much impact the variation of one input has on the output (in this case the original parameters were varied +/- 15%, in steps of 2.5%).

1.7.6. Analyze Results, Prioritize & Propose.

With the sensitivity analysis results the most important areas can be identified and prioritized, based on their affectance of the outputs. With this information "educated" improvement ideas can be generated that are going to impact directly to the top contributors of the output parameter to improve. Also, this information can be used to rate or prioritize the ideas already generated by the team, using the impact on the outputs as the priority parameter. Once prioritized these ideas can be monetarized to determine the savings involved with the implementation of the idea. In order to determine the impact of the different parameters to be changed, a "what-if" scenario can be run.

Chapter 2.

2. LEAN MANUFACTURING.

As mentioned earlier, Manufacturing Excellence is an improvement process that comprises mainly lean manufacturing principles but also includes other tools as value stream mapping, 5S, "kaizen", "poka yoke", SMED and six sigma.

In concordance, this chapter covers an introduction to lean manufacturing, states the evolution it's been subjected to, describes the main principles it is founded on and shows some benefits that can be obtained as result of the implementation.

2.1. Introduction.

The meaning of the word "lean" is related to anything containing little or no fat, anything that contains little excess or waste. In the context of manufacture the meaning expands to describe any manufacturing process that lacks of waste.

Opposed to the meaning of lean, "muda" is a Japanese word that stands for waste. Muda is any human activity that absorbs resources but creates no value. It can be inventory, rework, scrap, transportation, non-required processes, movement of employees, people waiting on others or products that doesn't meet customer expectations.

Based on these definitions, Lean Manufacturing can be defined as: "A systematic approach to identify and eliminate waste (non-value-added activities) through continuous improvement by flowing the product at the pull of the customer in pursuit of perfection" (Womack & Jones, 1996).

The goal of lean manufacturing is the elimination of waste in every area of production to incorporate less human effort, less inventory, less time to develop products, and less space to become highly responsive to customer demand while producing top quality products in the most efficient and economical manner possible. Essentially, a "waste" is anything that the customer is not willing to pay for.

A key difference in lean manufacturing is that production can and should be driven by real customer demand. Instead of producing based on inaccurate forecasts, lean manufacturing can produce what is required, with shorter lead times. Instead of using forecasts to push product to market, the product is pulled from customers' demand, through a system that is set up to quickly respond.

Lean organizations are capable of producing high-quality products economically in lower volumes and bringing them to market faster than traditional mass producers (not lean). A lean organization can make twice as much product with twice the quality and half the time and space, at half the cost, with a fraction of the normal work-in-process inventory. Lean management is about operating the most efficient and effective organization possible, with the least cost and zero waste (Womack & Jones, 1996).

2.2. Antecedents / History.

Even though Lean Manufacturing is the latest word in manufacturing circles, it is not especially new. It derives from the Toyota Production System or Just In Time (JIT) Production, Henry Ford's system and other predecessors. The lineage of Lean Manufacturing and JIT Production goes back to 1799 with Eli Whitney and the concept of interchangeable parts (Strategos Inc.). This section presents the evolution from early concepts through lean manufacturing, the information follows the ideas presented by Strategos Inc.

2.2.1. Early Developments.

Around 1799, Eli Whitney developed his concept of interchangeable parts when he took a contract from the U.S. Army for the manufacture of muskets for an unbelievably low price.

For the next 100 years, manufacturers primarily focus on individual, non-related, processes & technologies. As products moved from one discrete process to the next through the logistics system, few people were concerned with what happened between processes, how multiple processes were arranged within the factory and how the chain of processes functioned as a system.

The previous conditions changed in the late 1890's with the work of early Industrial Engineers who originated the idea of "eliminating waste", a key fulcrum of JIT and Lean Manufacturing. Frederick W. Taylor, through "Scientific Management", began to look at individual workers and work methods, developing time study and standardized work. Frank Gilbreth added motion study and process charting. Process charts focused on all work elements including those non-value-added elements, which normally occur between the "official" elements. Lillian Gilbreth brought psychology into the mix by studying the motivations of workers and how attitudes affected the outcome of a process.

2.2.2. The Ford System.

Starting about 1910, Henry Ford and Charles E. Sorensen tailored the first comprehensive manufacturing strategy. They took all the elements of a manufacturing system (people, machines, tooling, and products) and arranged them in a continuous system for manufacturing the model T automobile. Henry Ford is considered, by many, to be the first practitioner of JIT and lean manufacturing (Strategos Inc.).

Ford's success inspired many others to copy his methods. But most of them did not understand the fundamentals so they didn't succeed. With the appearance of labor unions and customers that request product variety, the Ford system began to break down and Henry Ford refused to adapt the system to the changes.

2.2.3. Just In Time and the Toyota Production System.

The allied victory of World War II and the massive quantities of material behind it caught the attention of Japanese industrials. They studied American production methods with particular attention to Ford practices and the Statistical Quality Control practices of Ishikawa, Edwards Deming, and Joseph Juran.

At Toyota Motor Company, Taiichi Ohno and Shigeo Shingo, began to incorporate Ford production, Statistical Process Control (SPC) and other techniques into an approach called Toyota Production System or Just In Time (JIT). They also recognized the central role of inventory in the manufacturing systems.

The Toyota people recognized that the Ford system had contradictions and shortcomings, particularly with respect to employees. Toyota soon discovered that factory workers had to contribute more to the manufacturing process (not only muscle power), thus culminating in team development and cellular manufacturing.

Another key discovery in JIT, involved product variety. The Ford system was built around a single, never changing product. Shingo worked on setup and changeover time reduction, obtaining small batches of different products with an almost continuous flow like the original Ford concept, thus introducing a flexibility that Henry Ford thought he did not need.

All of this took place between 1949 and 1975. It spread, to some extent, to other Japanese companies. When the productivity and quality gains became evident to the outside world, American executives traveled to Japan to study this success history. They brought back, mostly, the superficial aspects thus most early attempts to emulate Toyota failed because they were not integrated into a complete system and because few understood the underlying principles (Strategos Inc.).

During this time period, Norman Bodek first published the works of Shingo and Ohno in English, transferring this knowledge and building awareness in the Western world. Also, Robert Hall and Richard Schonberger wrote books on the subject that also helped to spread this knowledge.

2.2.4. World Class Manufacturing.

By the 1980's some American manufacturers, such as Omark Industries, General Electric and Kawasaki, were successful with these methods (Strategos Inc.).

Consultants started the JIT Production campaign with terms as: World Class Manufacturing (WCM), Stockless Production, Continuous Flow Manufacturing (CFM), Demand Flow Technology (DFT) and many other. Thus helping to build a knowledge base and experience accessible to many companies to pursue this change in their organizations.

2.2.5. Lean Manufacturing.

In 1990 James Womack wrote a book called "The machine that changed the world". He coined the term "Lean Manufacturing" to describe the process obtained through the evolution of automotive industry. The essential elements of Lean Manufacturing, do not substantially differ from the techniques developed by Ohno, Shingo and the people at Toyota.

Currently, Lean Manufacturing is being applied in companies in many countries, thus knowledge and experience base is expanding rapidly.

2.3. Just-in-time (JIT) Basics.

By the 1970s the Japanese manufacturers were evolving a new style of manufacturing that ignited the economic growth in Japan. This new philosophy, clearly focused on conservation, has its roots in the space and resource limitations that Japanese people confront every day.

Toyota is without any doubt the greatest contributor to the JIT revolution. Asking & Goldberg (2000) states that the success of JIT at Toyota is settled on an effective strategy based on:

1. Kanban-based pull production;
2. Elimination of waste as a guiding philosophy;
3. Faith in the value and importance of quality;
4. "Kaizen" or continuous improvement as a day to day operating strategy;
5. Belief in the value and utilization of human resources;
6. Emphasis on reducing setup times for machines;
7. Integration of suppliers and material acquisition into the process;
8. Efficient, cellular layouts with balanced material flow.

Ohno (1991) together with Hopp & Spearman (2000) suggested that Toyota's system pillars were JIT and automation. JIT is based on the concept of a supermarket, where the customers get what they want, at the time they require and in the quantity that they need. Automation refers to automation with the human touch, it is, several automated machines that are foolproofed (Poka-Yoke) so they can be "supervised" by a single operator.

Hopp and Spearman (2000) present the absolute ideal of Edwards (1993) by describing the JIT in terms of the seven zeros, which are required to achieve zero inventories.

- Zero Defects: To avoid delays due to defects stopping production (Quality at the source).
- Zero (Excess) Lot Size: To avoid “waiting inventory” delays (Lot size of one).
- Zero Setups: To minimize setup delay and facilitate small lot sizes.
- Zero Breakdowns: To avoid stopping tightly coupled operations.
- Zero (Excess) Handling: To promote flow of parts.
- Zero Lead Time: To ensure rapid replenishment of parts (zero inventories).
- Zero Surging: Necessary in system without WIP buffers (production smoothing volume and mix).

The implementation of the zero surging will cause some lost flexibility to manage unscheduled urgent orders, cancellations of machine failures. In order to counter this there are several options that will increase the flexible response within the “inflexible” JIT system as capacity buffers, setup reduction, cross training and plant layout.

Capacity buffer is the term used to designate that some time of the day won't be assigned to production. This “free” time will be used to deal with demand shortfalls and urgent orders processing. If this time is not required, the people can go home or do another thing.

In order to increase flexibility on the production, the machines require being capable to change from one product to another easily and in no-time. So Setup Reduction (Single Minute Exchange Die – SMED) is applied everywhere when feasible. To implement SMED, the first step is to identify the operations that are internal (activity that is required to run on the machine) and try to convert them as much as possible to external (activities that can run out the machine). Also eliminate the adjustment process and abolishing any setup.

Applying cross training is another way to add flexibility because it allows capacity to float to smooth the flow. Besides it has the benefits of reducing boredom, fostering big picture thinking and increasing new ideas generation.

Finally, plant layout also contributes to increase flexibility by using U-shaped cells that promotes multi-machine operator due to maximum visibility and minimum walking.

An important tool to realize JIT is “kanban”, Japanese word that stands for signboard or card and is the name of the flow control system developed by Toyota. The system is considered a pull system that controls the flow of materials in the plant using “permission” cards. When there is an empty space in the stockpoint, it becomes the production order the upstream station for producing a replacement of the product/part. This order is downstreamed through the different stations to start production on those stations.

Pull systems authorize work releases based on system status. They are inherently demand driven and control the WIP levels. Pull systems are inherently make-to-stock. On the other hand, push systems schedule work releases based on demand. They are inherently due-date driven and observe the WIP levels. Push systems are inherently make-to-order.

The basic differences between pull and push are production authorization and flow direction of the information, these differences are shown on figure 2.1. On a pure push system the authorization, usually a forecast, is given to the first station and the direction of order information flows towards the end of the line. On the contrary, in a pure pull system, the production authorization is given to the last station, usually as a result of a customer request, and the information flow goes to the prior station, and then it cascades to the first station.

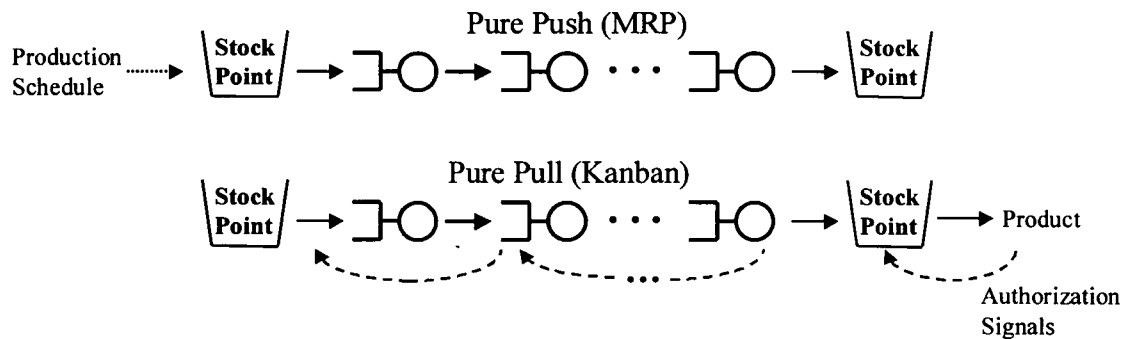


Figure 2.1 Push vs. Pull

Most manufacturing systems are not pure push nor pure pull systems, but a combination of both. The push/pull interface divides a production process into push and pull segments. Selecting the right location of the interface can help to obtain some advantages of the pull system while retaining the customer driven character of push. One way to accomplish this is by late customization so the initial workstations behave like a pull system (make-to-stock) and the stations closer to the customer as push (make-to-order). The basic tradeoff is responsiveness vs. inventory (time vs. money, speed vs. flexibility). Moving the interface closer to customer increases responsiveness but usually at the expense of inventory.

2.4. Lean Manufacturing Basics.

Lean manufacturing is lean because it provides a way to do more and more value with less and less while coming closer and closer to providing customers with exactly what they want (Womack & Jones, 1996).

Based on the proposal made by Womack & Jones (1996) Lean Manufacturing is a philosophy that can be implemented based on the application of five principles:

1. Precisely specify value by specific product,
2. Identify the value stream for each product,
3. Make value flow without interruptions,
4. Let the customer pull value from producer, and
5. Pursue perfection (focus on waste avoidance).

2.4.1. Specify Value.

Value can only be defined by the ultimate customer. It is only meaningful in terms of a specific product that meets the customer's needs at a specific price at a specific time. Therefore, the first step to implement lean manufacturing must start with a conscious attempt to precisely define value in term of specific products with specific capabilities offered at specific prices through a dialogue with specific customers. If not done following these guidelines, it becomes in muda, due that providing the wrong good or service the right way, i.e. with the correct methods, is waste.

2.4.2. Identify the Value Stream.

The value stream is the set of all the specific actions required to bring a specific product from the concept to the hands of the customer, passing through design, production, order processing, product manufacturing and logistics. To map the product stream, avoid thinking in terms of machines and departments, instead map the actions required to obtain the product. It is important to keep in mind that there are three types of steps to consider: a) steps that unambiguously create value, b) steps that create no value but are unavoidable with current technology, and c) steps that create no value and can be avoidable. There are eight basic types of muda, sort in order of importance are wait, transport, inventories, excess processing, make defective products, overproduction, motion and underutilization of people.

To increase the benefits obtained from lean manufacturing implementation it is required to go beyond the firm and share information within the entire stream (downstream, i.e. suppliers: and upstream, i.e. customers). This free-flowing communication will help to identify the opportunities to diminish the waste in the entire chain and not only within the factory.

2.4.3. Make Value Flow.

Once the first two steps are completed and the wasteful steps are eliminated, then value-creation steps need to flow. In order to accomplish this, the initial focus is the elimination of the batch-queue thinking, because it only increases the wait time and in consequence the cycle time. The focus needs to be on creating continuous flow on the current process to manufacture the object, that will ensure an efficient and lean process, thus increasing the flexibility and diminishing the response time to the customers. Then the traditional boundaries (machinery, departments, tasks, etc.) need to be ignored and all impediments to the continuous

flow are eliminated. Finally the work practices and tools are analyzed to eliminate roadblocks and improve flow.

Also, to get continuous flow every machine and worker must be completely capable. That is, they must always be in the proper condition to operate precisely when needed and every parts made must be exactly right. To get to this point, the employees will require cross training in every task and the machines must be made available all the time by the use of some techniques as Total Productive Maintenance (TPM). The work must be rigorously standardized and the use of poka-yoke, or mistake proofing, to avoid any chance of defective material to go to the next process. For time reduction in tooling changes the implementation of SMED technique will be necessary.

“Takt time” is another important concept to consider when making the value flow, it sets the rhythm of the production based on the rate of sales to meet customer requirements. Takt time (units per second) is calculating by dividing the customer demand rate per shift into the available working time per shift. This time can show the current status of your workstations and highlight any opportunity for improvement. Also it is a good tool to identify the unbalance of the line. To balance a line the part process time of each station needs to be less than the takt time.

Supermarkets are used when continuous flow is not possible and batching is necessary. A supermarket is a pull system that is placed between two processes to avoid predicting next station demand. The supermarket works like a limited size inventory that serves to supply material to downstream stations, but also, once a low inventory level is reached, it sends a production authorization signal to the upstream station that fills the stock back.

The pacemaker is the station that sets the production rate to the upstream stations, i.e. it is the workstation that is scheduled and the first to have continuous flow process. All work from stations that follow the pacemaker need to flow and no supermarkets or pull stations are located after the pacemaker.

Some guidelines (Rother & Shook, 1999) that may be considered to increase flow are the following:

- Produce to the takt time.
- Develop continuous flow (one piece at a time) wherever possible.
- Use supermarkets to control production where continuous flow is not feasible.
- Send schedule only to pacemaker for generating pull and flow.
- Distribute production of different products to pacemaker evenly over time (level production mix).
- Create “initial pull” by releasing small consistent increments of work at the pacemaker (level production volume).

- Develop the ability to make “every part every day” (shorten changeover times, SMED technique).

2.4.4. Let Customer Pull.

In the past the production was based on estimations and forecasted data, so basically the companies were *pushing* product to the customer, sometimes when it was not even required. Instead of producing using “predicted needs” the customer needs to tell what they want. This is, the customers need to *pull* the product from the production system as needed, not the other way. Pull in the simplest term means that no one upstream should produce until the customer downstream asks for it.

2.4.5. Pursue Perfection (focus on waste avoidance).

Once the application of the four initial principles starts, a constant necessity to keep reducing time, effort, cost, space and errors will appear. The reason is that making things flow faster exposes hidden muda in the stream value that is required to be eliminated to continue moving towards lean, waste-less processes. The application of these five principles is a virtuous cycle of improvements thus aiming for “kaikaku” (radical improvement), when there is constant improvement the target is now “kaizen” (continuous incremental improvement).

Accordingly to the “Introduction of Lean” developed by MAMTC, the types of wastes that are important to be considered in a lean manufacturing system include:

Overproduction: is to produce more than demanded or produce it before it is needed. It is visible as storage of material. It is the result of producing to speculative demand. Overproduction means making more than is required by the next process, making earlier than is required by the next process, or making faster than is required by the next process. Causes for overproduction waste include:

- Just-in-case logic
- Misuse of automation
- Long process setup
- Uneveled scheduling
- Unbalanced work load
- Over engineered
- Redundant inspections

Waiting: is the time a product is located at the station before it is processed. All waiting time for a machine to process should be eliminated. The principle is to maximize the utilization/efficiency of the worker instead of maximizing the utilization of the machines. Causes of waiting waste include:

- Unbalanced work load
- Unplanned maintenance
- Long process set-up times
- Misuses of automation

- Upstream quality problems
- Unleveled scheduling

Inventory or Work in Process (WIP): is material between operations due to large lot production or processes with long cycle times. Causes of excess inventory include:

- Protecting the company from inefficiencies and unexpected problems
- Product complexity
- Unleveled scheduling
- Poor market forecast
- Unbalanced workload
- Unreliable shipments by suppliers
- Misunderstood communications
- Reward systems

Processing waste: is any step that is not required to comply with customer requirements, or rework as a result of poor quality. It should be minimized by asking why a specific processing step is needed and why a specific product is produced. All unnecessary processing steps should be eliminated. Causes for processing waste include:

- Product changes without process changes
- Just-in-case logic
- True customer requirements undefined
- Over processing to accommodate downtime
- Lack of communications
- Redundant approvals
- Extra copies/excessive information

Transportation: is any material movement between stations. It does not add any value to the product. Instead of improving the transportation, it should be minimized or eliminated (e.g. forming cells). Causes of transportation waste includes:

- Poor plant layout
- Poor understanding of the process flow for production
- Large batch sizes, long lead times, and large storage areas

Motion: is the translation of the workers, machines, and transport (e.g. due to the inappropriate location of tools and parts). Not necessary motions should be eliminated. Instead of automating wasted motion, the operation itself should be improved. Causes of motion waste include:

- Poor people/machine effectiveness
- Inconsistent work methods
- Unfavorable facility or cell layout
- Poor workplace organization and housekeeping

- Extra "busy" movements while waiting

Making defective products: is producing non-quality goods. It is pure waste. Prevent the occurrence of defects instead of finding and repairing defects. Causes of processing waste include:

- Weak process control
- Inadequate process capability
- Poor quality
- Unbalanced inventory level
- Deficient planned maintenance
- Inadequate education/training/work instructions
- Product design
- Customer needs not understood

Underutilizing people: is not taking advantage of people's abilities. Causes of people waste include:

- Old guard thinking, politics, the business culture
- Poor hiring practices
- Low or no investment in training
- Low pay, high turnover strategy

2.5. Benefits of applying Lean Manufacturing.

Based on the experience of MAMTC and its document "Benefits of Lean", the implementation of Lean Manufacturing will help to find ways to achieve a number of benefits. The following figures are some references of the results that can be obtained with the application of Lean Manufacturing.

The application of the lean principles can help any organization to improve the performance of the manufacturing lines, increase the utilization of manufacturing floor, improve product quality, reduce manufacturing time, speed up response time and the elevate safety levels within the facility. Some reductions that can be obtained though lean implementation are:

- Manufacturing Lead Time 50 - 90%
- Floor Space Requirements 5 - 30 %
- Inventories 60 - 80%
- Work-in-Process 60 - 80%
- Errors reaching customer 40 – 50%
- Job-related injuries 40 – 50%
- Time to market 40 – 50%

Also within the lean thinking environment the organizations can expect to increase the performance of manufacturing lines. Some performance increases likely to obtain are:

- First-Pass Yields 50 - 100%
- Throughput 40 - 80%
- Productivity 75 - 125%
- Flexibility with minimum investment
- Quality (errors can be caught before producing a lot of pieces)

Besides the already described improvements, the implementation of lean thinking changes the behavior of systems and people. This mind set change is responsible of other improvements that are result of the continuous improvement search. Some of these additional benefits of lean transformation are:

- Reduced scrap and waste
- Cross-trained employees
- Reduced obsolescence
- Lower overall costs
- Self-directed work teams
- Lead time reduction
- Longer machine life
- Improved customer communication
- Improved vendor support and quality
- Allows more strategic management focus
- Increased shipping and billing frequencies

2.6. Traditional production vs. lean production.

For years manufacturers have created products in anticipation of having a market for them. Operations have traditionally been driven by sales forecasts and firms tended to stockpile inventories in case they were needed. A key difference in Lean Manufacturing is that it is based on the concept that production can and should be driven by real customer demand. Instead of pushing product to market, it's pulled there through a system that's set up to quickly respond to customer demand (MAMTC).

Lean organizations are capable of producing high-quality products economically in lower volumes and bringing them to market faster than mass producers. A lean organization can make twice as much product with twice the quality and half the time and space, at half the cost, with a fraction of the normal work-in-process inventory. Lean management is about operating the most efficient and effective organization possible, with the least cost and zero waste (MAMTC).

Some of the most important differences concerning the organizational characteristics are summarized on the table 2.1.

	Traditional Production	Lean Production
Business Strategy	Product-out strategy focused on exploiting economies of scale of stable product designs and non-unique technologies	Customer focused strategy focused on identifying and exploiting shifting competitive advantage.
Customer Satisfaction	Makes what engineers want in large quantities at statistically acceptable quality levels; dispose of unused inventory at sale Prices	Makes what customers want with zero defect, when they want it, and only in the quantities they order
Leadership	Leadership by executive command	Leadership by vision and broad participation
Organization	Hierarchical structures that encourage following orders and discourage the flow of vital information that highlights defects, operator errors, equipment abnormalities, and organizational deficiencies.	Flat structures that encourage initiative and encourage the flow of vital information that highlights defects, operator errors, equipment abnormalities, and organizational deficiencies.
External Relations	Based on price	Based on long-term relationships
Information Management	Information-weak management based on abstract reports	Information-rich management based on visual control systems maintained by all employees
Cultural	Culture of loyalty and obedience, subculture of alienation and labor strife	Harmonious culture of involvement based on long-term development of human resources
Production	Large-scale machines, functional layout, minimal skills, long production runs, massive inventories	Human-scale machines, cell-type layout, multiskilling, one-piece flow, zero inventories
Operational capability	Dumb tools that assume an extreme division of labor, the following of orders, and no problem solving skills	Smart tools that assume standardized work, strength in problem identification, hypothesis generation, and experimentation
Maintenance	Maintenance by maintenance specialists	Equipment management by production, maintenance and engineering
Engineering	"Isolated genius" model, with little input from customers and little respect for production realities.	Team-based model, with high input from customers and concurrent development of product and production process design

Table 2.1 Traditional vs. Lean - Organizational Characteristics

Also, due to the intrinsic behavior of each system, there are important differences on the manufacturing methods between a lean production system and a traditional system. These differences are the main transformation required to convert a traditional manufacturing system into a lean production system. The most important differences in the production methods are summarized on table 2.2.

	Traditional Production	Lean Production
Production schedules are based on...	Forecast — product is pushed through the facility	Customer Order — product is pulled through the facility
Products manufactured to...	Replenish finished goods inventory	Fill customer orders (immediate shipments)
Production cycle times are...	Weeks/months	Hours/days
Manufacturing lot size quantities are...	Large, with large batches moving between operations; product is sent ahead of each operation	Small, and based on one-piece flow between operations
Plant and equipment layout is...	By department function	By product flow, using cells or lines for product families
Quality is assured...	Through lot sampling	100% at the production source
Workers are typically assigned...	One person per machine	With one person handling several machines
Worker empowerment is...	Low — little input into how operation is performed	High — has responsibility for identifying and implementing improvements
Inventory levels are...	High — large warehouse of finished goods, and central storeroom for in-process staging	Low — small amounts between operations, ship often
Inventory turns are...	Low — 6-9 turns pr year or less	High — 20+ turns per year
Flexibility in changing manufacturing schedules is...	Low — difficult to handle and adjust to	High — easy to adjust to and implement
Manufacturing costs are...	Rising and difficult to control	Stable/decreasing and under control

Table 2.2 Traditional vs. Lean - Manufacturing Methods.

2.7. How to implement Lean Manufacturing.

In order to successfully implement Lean, the most difficult step is to get started by overcoming the inertia present in any company. It is also necessary a change agent plus the lean core knowledge, a crisis that serves as leverage for change, a value-stream mapping, and finally a quick determination to “kaikaku” the value-creating activities in order to produce rapid results that will encourage the organization to continue the lean journey.

There is a risk, when searching for lean transformation, in order to successfully implement lean thinking, it is necessary to strive against the inertia and proceed with the changes. Lean thinking will break a lot of barriers, increase transparency of processes, improve communication between departments, and so on. But it is required that the team responsible to implement lean within the factory/processes have the attitude and the support to break all traditional rules and become a change agent. This has to be done carefully in order to avoid becoming a tyrant, it

requires a strong leader that shares the vision with the people of being promoting a set of ideas which have enormous potential to benefit everyone.

The information presented on table 2.3 is a summary of the phases and steps required to implement lean within any organization (Womack & Jones, 1996). Also is a column that states the approximate time when this phases/steps are taken.

Phase	Specific Steps	Time Frame
Get started	Find a change agent. Get lean knowledge. Find a lever. Map value streams. Begin kaikaku. Expand the scope.	First six months
Create a new organization	Reorganize by product family. Create a lean function. Devise a policy for excess people. Devise a growth strategy. Remove anchor-draggers. Instill a perfection mind set.	Six months through year two
Install business systems	Focus on three or four lean activities per year Relate pay to firm performance. Implement transparency. Initiate policy deployment. Introduce lean learning. Find right-sized tools.	Years three and four
Complete the transformation	Apply these steps to suppliers and customers. Develop global strategy. Transition from top-down to bottom up improvement.	By end of year five

Table 2.3 Time frames for the Lean Leap

2.7.1. Get started.

2.7.1.1. Find a Change Agent.

The person, in charge of pursuing the change in mentality within the organization, will be responsible to push to the limits, question the current state and give results. The ideal mentality for the change agent is a make-something-happen, otherwise the lean seed will fall in sterile soil and die. The agent will require all the support from the organization and help from a team of direct-reports to execute the actions and share the vision to the entire organization.

2.7.1.2. Get the Knowledge.

It will also be necessary a person that master not only the theory but have some on hand practice applying and implementing the core concepts of lean, it may or not be the change agent. In order to do this there are several options, first someone inside the organization can be developed, someone from outside can be

brought permanently or a consultant that works with the change agent can be hired. Keep in mind that this person will be responsible to change the whole way of thinking about the company. In order to get the required support from upper management, it is required that everyone on this level master the core lean thinking principles and participates actively on the implementation and improvement activities.

2.7.1.3. Find a lever by seizing/creating the Crisis.

If the organization is in crisis plan and execute to get lean, this situation will highly increment the speed of results obtained through the implementing of lean. In a stable company, it may take to get to the same level at least 3 times more. Within stable organizations, crisis can be created, one way is to focus on a small part of the business that is on trouble (maybe a department, a product line, etc.). Also finding a lean competitor that pushes the organization to move forward can help to create a controlled crisis. Attaching a lean customer or a lean supplier to the manufacturing chain can also helps, and finally create a crisis that boosts the company in the right direction (take desperate lean actions to survive).

2.7.1.4. Map the Value Streams.

Once the leadership, the knowledge and the sense of urgency are in place, it's time to identify the current value streams and map them (family by family and step by step). In order to improve the system, thinking outside the walls of the company can be beneficial, including the suppliers and customers to the equation can help to get the best of the mapping process. Value needs to be defined by the client, not by the organization. Looking at the stream from the eyes of the end user and identifying what processes, steps really add customer-value can greatly increase the benefits obtained from lean implementation.

2.7.1.5. Begin with Important and Visible Activities.

In order to enroll in a virtuous spiral it is necessary to start as quickly as possible with a specific activity that is performing very poorly and that is important to the firm. In this way, it's sure that a lot of opportunities to improve will be found and the results will push the organization to continue the quest for lean.

2.7.1.6. Demand Immediate Results.

The most critical feature of lean is immediate feedback. The team needs to be able to see things changing. This is essential in order to create the psychological sense of flow in the workforce and the momentum to change within the organization.

2.7.1.7. As soon as Momentum is gained, expand the Scope.

Once the first results are obtained and the organization is enrolled in the lean action, other projects are required to start and other areas need to continue the implementation of lean. It is important to focus on three to four lean tasks each year and the implementation plan for next actions, otherwise it will be overwhelming and some results may not be achieved.

2.7.2. Create a new organization.

One of the main errors when implementing lean manufacturing is to think that if the implementation of the first activity is successfully finished, it is required just to duplicate that into other activities. In order to continue the evolution the organization needs to route the flow of value and keep the stream from stagnating again. Also, the resources being freed up during implementation, need to be utilized somewhere within the facility or supporting lean activities.

2.7.2.1. Reorganize by Product Family.

In order to align the processes with the lean philosophy, the reorganization by product family and value-stream is required. The reorganization of support functions (marketing, finance, engineering, purchasing, etc.) needs to be aligned in product families.

2.7.2.2. Create a Lean Promotion Function.

Dismantling the “muda” in the manufacturing processes will free people up that need something to do. It can be beneficial the creation of a lean promotion function that will be focus on logistics, continual education, periodic evaluation of results and continuous improvement. Also combining this lean promotion function with quality assurance can be helpful, because both areas are in the search of the same objective, diminish errors (“muda”) so value can flow easily.

2.7.2.3. Deal with Excess People.

With lean implementation, the human effort will be reduced at least in half. But, in order to successfully implement lean and avoid any sabotage, the vision that lean implementation is not cutting jobs is required to be shared. If the organization is on a level that is critical to do so, determine the level and resize prior to lean implementation. Then start implementing lean and keep all the current jobs. Any excess human effort should be relocated to the lean promotion function or elsewhere in the organization. It is really important to keep the jobs, otherwise the implementation will lose all the people's support.

2.7.2.4. Devise a Growth Strategy.

Is not a good idea to plan growing the margins via lean by cutting jobs, instead the available people can support a new growth strategy that uses this resources at the same pace as they are freed up.

2.7.2.5. Remove the Anchor-Draggers.

Identify possible management members that won't buy the lean idea and challenge them to accept it or leave. This may sound radical but don't taking this action will increase the risk of losing support from the people. If someone doesn't align to the lean movement, this person will be looking and highlighting any mistake, also the people below him won't support lean deployment.

2.7.2.6. Continue improving & persist on moving forward.

It's important to realize that this is a continuous path. There are always areas to improve even in areas already transformed by the lean initiative. Management needs to migrate from running activities in a steady state and avoiding variances to eliminate the root causes of variances. Keep in mind that will be some movement backward but the total movement will be forward. Avoid sending the opposite message if there is any mistake in pursue of perfection.

2.7.3. Install business systems.

Once there is some momentum and some redesign is done within the organization, lean transformation needs to be made self-sustaining. The first step is to define a mechanism to prioritize what is more important to focus the resources on those activities. Also defining a reward system and a lean training method that encourages the people to keep following the lean track is required. Current tools require to be analyzed and redesigned to be inserted easily within the value stream.

2.7.3.1. Create a Lean Accounting System.

To keep track of how the profits are being improved, the accounting system needs to migrate to a value-stream/product system that clearly identifies if cost or value is being added.

2.7.3.2. Relate pay to firm performance.

To encourage the people to keep the lean transformation and to reward their effort, the addition of a bonus to the salaries that is tied directly to the profitability of the company can boost their commitment and participation.

2.7.3.3. Implement transparency.

Benchmarking the internal performance, especially the rate of improvement is vital to share the results with everyone involved on the value-stream in real time.

2.7.3.4. Introduce lean learning.

Teach all the levels of the organization in lean techniques. But the training to the workforce needs to be done by the line managers that need to be taught in operational skills. These line managers will be teaching the workforce the tools that they will need during the implementation.

2.7.3.5. Find right-sized tools.

In order to be more flexible, evaluate current tools (machines, management systems, test equipment, etc.) and determine if they are the right ones. Think opposite to the standard thinking and determine the tools that will

permit smooth flow within the product family, and permit to switch over instantly between products to avoid batches.

2.7.4. Complete transformation.

Somewhere around three to four years from the start, the complete transformation will be achieved. The next step is to expand this initiative to suppliers and distributors and make them lean too.

2.7.4.1. Apply these steps to suppliers and customers.

Most of the product's cost is not within the limits of the company, in most cases only one quart to one third of the local costs are controlled within the facility. To impact the sixty or so of the reminding, the suppliers and customers need to be convinced to take the lean leap. The promotion team can be shared and the savings split with them as well as the knowledge that will help them to improve their margins. Then suggest them that they need to pass this to theirs as well.

2.7.4.2. Develop global strategy.

Lean will help not only to cut cost down, but it also will increment customer service levels by cutting time to market development, improving the quality, increasing the flexibility and providing customers with what they really want.

2.7.4.3. Transition from top-down to bottom up improvement.

At the beginning the improvement process will work top-down because the necessity is to change the way the employees think by demonstrating the talk. Once the employees understand they will become proactive and managers will need to transform into coaches. This transition is key to a self-sustaining organization.

2.8. Keys to implement Lean successfully.

MAMTC in the "Introduction of Lean" states some considerations to a successful implementation of lean:

Prepare and motivate people.

- Widespread orientation to continuous improvement and quality.
- Train and recruit workers with appropriate skills.
- Create common understanding of the need to change to lean.

Employee involvement.

- Push decision making and system development through the people who does the job.
- Trained and truly empowered people.

Share information and manage expectations.

- Establish achievable goals.

Identify and empower champions, particularly operations managers.

- Remove roadblocks (i.e. people, layout, systems).
- Make it both directive yet empowering.

Atmosphere of experimentation.

- Create an environment of trust where the ultimate goal is to learn lessons from previous experiences (mistakes).
- Willingness to take risks.

Installing "enlightened" and realistic performance measures, evaluation, and reward systems.

- Do away with rigid performance goals during implementation.
- Measure results and not number of activities/events.
- Tie improvements, long term, to key macro level performance targets (i.e. inventory turns, quality, delivery, overall cost reductions).

The need to execute pilot projects prior to rolling culture out across the organization.

- After early wins in operations, extend across entire organization.

Chapter 3.

3. VALUE STREAM MAPPING & SENSITIVITY ANALYSIS.

This chapter covers a brief introduction to Value Stream Mapping (VSM), a powerful visual tool to depict the different states of a process (current and future). In the appendix A there is an example of a VSM and the description of the icons can be consulted on appendix H. Also this chapter introduces the Sensitivity Analysis (SA) that will be used to determine the highest contributors to the performance.

3.1. Value Stream Mapping.

3.1.1. Description.

VSM depicts all the steps to manufacture a product including the design process, from the concept to the launch of the product. VSM is a tool that can help to visualize the flow of material and information through the system. A value stream is a powerful visual tool to specify all the actions (both value added and non-value added) required to manufacture a product -from raw material to the customer- (Rother & Shook, 1999).

Value Stream Mapping can be a powerful aid to obtain the following results:

- Helps to visualize the flow of material and information
- Helps to identify any waste within the stream.
- Ties material flow and information flow.
- Helps to develop the future state of the line, by developing how the flow should operate.

3.1.2. Process to build a VSM.

In order to build a VSM, the first step is to place customer data (including frequency of shipments), then all the icons and data that represent the processes required to manufacture the product are included. The icons are linked representing the material flow from one station to other. At the same time the inventory level between stations and supermarkets is recorded and represented on the map. The supplier information is also depicted (including frequency of receptions). The information flow is also added to the VSM. Finally, the timeline at the bottom of the map that shows the relation of the value-add time and the wait time (inventory related) is included.

Rother & Shook (1999) proposed some considerations to keep in mind while doing a VSM in order to improve the process. Some of them are:

- Start with a quick overview (walk) through the entire value stream.

- Collect current-state information while walking along the pathways of material and information flows yourself.
- When mapping, begin at the shipping end and work upstream.
- Take the times yourself don't trust on existing information.
- Map the whole value stream yourself to get a clear idea of the whole.
- Don't focus on the form is better to focus on the content, map the process right on the floor, then clean it up.

3.1.3. Purpose of a VSM.

VSM is a great tool to improve processes because it can easily depict the current state. In order to be successful the main focus should be the big picture, not just the individual processes, thus improving the whole, not just sub-optimizing the parts.

The first step is to draw the current value stream map with the information on the shop floor. Then plan for the future state map (identifying and eliminating the sources of waste). Finally make an implementation plan that will guide the manufacturing line from the current state to the future state. Once this future state is reached, a plan for a new future state needs to be developed, thus helping to continuous improvement. The goal is to have a chain of individual processes that are linked to customer needs by continuous flow or pull (Rother & Shook, 1999).

Some guidelines that can be used to determine future state mapping are:

- Determine the takt time.
- Determine if the finished goods will be built to supermarket for customer to pull or directly to shipping. Determine where to place the supermarket.
- Where to use continuous flow processing?
- Which process is the pacemaker? Schedule production.
- How to balance production mix?
- How to balance the production volume?
- What process improvements will be necessary?

3.2. Sensitivity Analysis.

Sensitivity Analysis (SA) is the study of how the variation in the output of a model (numerical or otherwise) can be apportioned, qualitatively or quantitatively, to different sources of variation - inputs – (Marshall, 1994).

3.2.1. Description.

Sensitivity analysis can be used to determine how robust is the model to the variation of each of the inputs, thus providing a powerful tool to maximize or minimize (depending on the desired result) the impact on the response. It is also used to increase the confidence in the model and its predictions, by providing an understanding of how the model response variables respond to changes in the inputs (Breierova & Choudhari, 2001).

3.2.2. Sensitivity Analysis Types.

Depending on the results and the inputs that are modified to determine the behavior of the model, there are several types of sensitivity analysis that can be performed:

- **Perturbation Analysis:** Simultaneous and independent changes in any parameter in either direction (over or under estimation) for each parameter that maintain the optimal basis. This provides the largest set of perturbations.
- **Tolerance Analysis:** Simultaneous and independent changes expressed as the maximum allowable percentage of the parameter's value in either direction (over or under estimation) for each parameter that maintains the optimal basis. This provides a range of values for each parameter.
- **Individual Symmetric Tolerance Analysis:** Simultaneous and independent equal changes expressed as the maximum allowable percentage of the parameters' value in both directions (over and under estimation) for each parameter that maintains the optimal basis. This provides a range of values for each parameter with the current value at its center.
- **Symmetric Tolerance Analysis:** Simultaneous and independent equal changes expressed as maximum allowable percentage of the parameter's value in both directions (over and under estimation) for all activity that maintain the optimal basis. This provides one single range of values of uncertainty for all parameters.
- **Parametric Analysis:** Simultaneous changes of dependent parameter values from their nominal values that maintain the optimal basis. This provides the maximum magnitude of change for values of dependent parameters.
- **Ordinary "Classic" Sensitivity Analysis:** One change-at-a-time in any parameter value that maintains the optimal basis. This provides a range for the change of any specific parameter value, holding all others at their nominal values.

3.2.3. Reasons to run a Sensitivity Analysis.

A mathematical model is defined by a series of equations, input factors, parameters, and variables aimed to characterize the process being investigated. Any input is subject to many sources of uncertainty including errors of measurement, absence of information and poor or partial understanding of the driving forces and mechanisms. This imposes a limit on the confidence in the response or output of the model.

Decision-makers and business-analysts may conduct sensitivity analysis to determine the following:

- the model resemblance with the process under study (quality of model),
- factors that mostly contribute to the output variability,
- the region in the space of input factors for which the model variation is maximum or minimum,
- interactions between factors.

3.2.4. Process to perform a Sensitivity Analysis.

Sensitivity analysis is usually performed as a series of tests in which the modeler sets different parameter values to see how a change in the parameter causes a change in the dynamic behavior of the response. By showing how the model behavior responds to changes in parameter values, sensitivity analysis is a useful tool in model building as well as in model evaluation. Usually a set of parameters is varied, one at a time, in a certain percentages from the nominal values. Then all the results are recorded and plotted to determine which parameter has the greater contribution to the output.

Sensitivity analysis can also indicate which parameter values are reasonable to use in the model. If the model behaves as expected from real world observations, it gives some indication that the parameter values reflect, at least in part, the “real world.”

Sensitivity tests help the modeler to understand the dynamics of a system and make educated decisions accordingly.

Chapter 4.

4. FACTORY PHYSICS.

"I often say that when you can measure what you are speaking about, and express it in numbers, you know something about it; but when you cannot express it in numbers, your knowledge is of a meager and unsatisfactory kind; it may be the beginning of knowledge, but have scarcely, in your thoughts, advanced to the stage of Science, whatever the matter may be".

- Lord Kelvin

This chapter presents the relations that exist between all the parameters that play a role on the behavior of manufacturing systems. Introduces the Factory Physics principles and describes the equations and scenarios to evaluate the leanliness of a system. This chapter also covers a section where the variability interactions are shown via the VUT equations.

4.1. Description.

Factory Physics is the foundation to understand manufacturing operations that relates fundamental manufacturing measures such as cycle time, throughput, capacity, work-in-process, inventory, and variability. It provides a mean to quantify the behavior of the manufacturing systems. It covers the Laws for Manufacturing that help managers understand Factory Physics and use these techniques to improve performance in their factories. It also provides a systematic description of the underlying behavior of manufacturing systems. With this knowledge, managers are able to use any manufacturing productivity strategy better.

Accordingly to Hopp & Spearman (2000), understanding the factory physics of a manufacturing system, enables managers and engineers to:

- Identify areas of leverage for improving existing systems.
- Design effective new manufacturing control systems that are consistent with, instead of contrary to, their natural tendencies.
- Design more effective supply chains.
- Achieve "lean" manufacturing without sacrificing manufacturing efficiency.
- Design more effective supply chains.
- Make the tradeoffs needed to coordinate policies from disparate areas into an environment of continual improvement.

4.2. Definitions.

Any science requires a frame to work, together with a set of concepts and definitions of terms in order to be shared in an effective way. Otherwise, two persons may be talking about the same concept with two different names or talking about different subject with the same name. The most important concepts and their definitions are presented on table 4.1.

Concept	Definition
Workstations	A collection of one or more identical machines.
Parts	A component, sub-assembly, or an assembly that moves through the workstations.
End Items	Parts sold directly to customers, relationship to constituent parts defined in bill of material.
Consumables	Any material used in process but do not become part of the product that is sold.
Routing	Sequence of workstations needed to make a part.
Capacity (r_i)	An upper limit on the throughput of a line or station. Most stations / lines need to work below capacity, otherwise they become unstable. $r_i = 1/t_i$
Order	Request from customer.
Job	Transfer quantity on the line.
Throughput (TH)	For a line, throughput is the average quantity of good (non-defective) parts produced per unit time.
Inventory Turns (turnover ratio)	A measure of inventory usage efficiency. Total yearly throughput divided by average inventory.
Work in Process (WIP)	Inventory between the start and endpoints of a product routing.
Cycle Time (CT)	Time between release of the job at the beginning of the routing until it reaches an inventory point at the end of the routing.
Bottleneck Rate (r_b)	Rate (parts/unit time or jobs/unit time) of the process center having the highest long-term utilization.
Raw Process Time (T_0)	Sum of the long-term average process times of each station in the line.

Table 4.1 Factory Physics Definitions

4.3. Basic Factory Dynamics.

The most important performance measures of a production line are defined by the following questions:

- How much it can produce? (Throughput),
- How many products are in process? (WIP), and
- How long does it take to finish a single part? (Cycle Time).

The relation of these parameters is one of the fundamentals of the manufacturing science and is called: Little's Law: $WIP = TH \times CT$, so same throughput can be obtained with large WIP and long CT or small WIP and short CT.

Another important concept to highlight is Bottleneck Rate (r_b) because it determines the maximum capacity of the line. If feasible, it is the main target to be improved because increasing bottleneck rate increases throughput and diminishes cycle time. Improvement of throughput and cycle time can also be obtained by tuning non-bottleneck stations, if enhancing the performance of the bottleneck is not feasible.

The Critical WIP (W_0) also determines the performance of the line, it is defined as the WIP level in which a line having no congestion would achieve maximum throughput (i.e., r_b) with minimum cycle time (i.e., T_0). $W_0 = r_b T_0$

In order to determine how lean is a process, first it is defined a baseline that separates bad behavior from good behavior, thus determining how far from lean manufacturing is the process under study. For this purpose the same process is subjected to the best case (no variability, no randomness) and the worst case (maximum variability, no randomness). This will establish the limits of the behavior of the manufacturing line (both very difficult to achieve in "real life" situations), but there is still an element missing, the line that divides fat from lean. In order to create this guideline, the same process will be subjected to other set of parameters in a scenario called the practical worst case (variability, maximum randomness) because any system showing a worst behavior is a target for improvement. The summary of the cases' conditions is shown on table 4.2.

Variability (having lack of uniformity) exists when the time to process a parts is not constant (best case - all parts have the same process time, worst case - the first part takes n-times the processing time and the others zero, practical worst case - all parts have the same process time). Randomness (having no specific pattern) exists when all manufacturing states (distribution of parts in the stations) are equally probable (best case and worst case – only some states are possible, practical worst case – due to machine failures or any other disruption all the states are feasible to occur).

Scenario	Variability	Randomness
Best Case (BC)	No	No
Worst Case (WC)	Maximum	No
Practical Worst Case (PWC)	Yes	Maximum

Table 4.2 BC, WC & PWC Conditions.

4.3.1. Best Case (BC).

Best Case Law (no randomness, no variability): yields the minimum cycle time and maximum throughput for each WIP level.

$$CT_{\text{best}} = \begin{cases} T_0, & \text{if } w \leq W_0 \\ w / r_b, & \text{otherwise.} \end{cases} \quad TH_{\text{best}} = \begin{cases} w / T_0, & \text{if } w \leq W_0 \\ r_b, & \text{otherwise.} \end{cases}$$

4.3.2. Worst Case (WC).

Worst Case Law (no randomness, highest variability): maximum queuing, minimum throughput and maximum cycle time.

$$CT_{\text{worst}} = w T_0 \\ TH_{\text{worst}} = 1 / T_0$$

4.3.3. Practical Worst Case (PWC).

Practical Worst Case Definition (highest randomness, variability): variability such that all WIP configurations (states) are equally likely.

$$CT_{\text{PWC}} = T_0 + \frac{w-1}{r_b} \quad TH_{\text{PWC}} = \frac{w}{W_0 + w - 1} r_b,$$

These three cases are depicted in figure 4.1. These graphs show how Throughput and Cycle Time behave on each case for a specific WIP level.

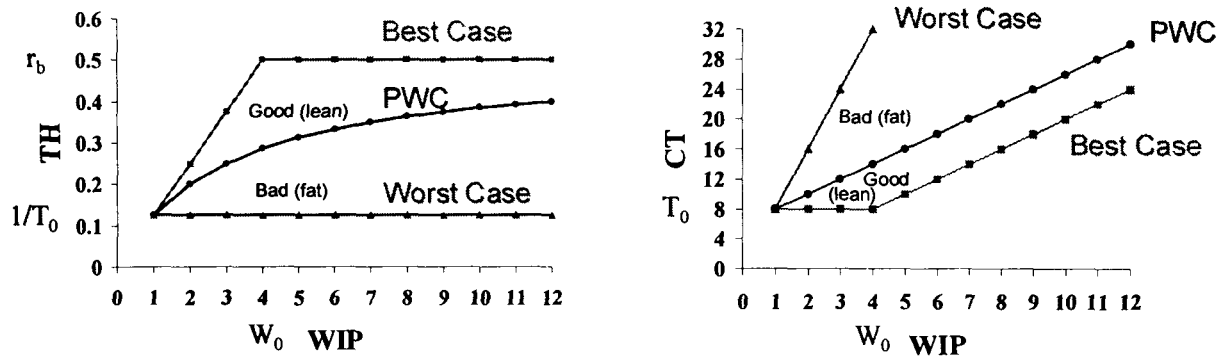


Figure 4.1 TH and CT - BC, WC & WPC

4.4. Variability Basics.

This section presents the variability basics together with some factory physics laws and corollaries based on the work developed by Hopp & Spearman (2000). Variability is defined as the quality, state, or degree of non-uniformity or changeability. Its importance relies in that any increment of variability always

degrades the performance of a production system (Variability Law). Variability is anything that causes the system to depart from regular, predictable behavior. There are several sources of variability as setups, workspace variation, machine failures, differential skill levels, materials shortages, engineering change orders, yield loss, customer orders, rework, product differentiation, operator unavailability, material handling, etc.

Variability is propagated throughout the line, thus variability early in a routing increases cycle time more than equivalent variability later in the routing (Variability Placement Corollary). So any variability within the system will be buffered by some combination of inventory, capacity or time (Variability Buffering Law). One countermeasure to diminish the impact of variability on the performance of the line is flexibility because it reduces the buffer size required (Buffer Flexibility Corollary).

The performance of an assembly station is degraded by increasing the number of components being assembled, non-uniform arrivals of components and the lack of coordination between component arrivals (Assembly Operations Law).

The most prevalent causes of variability in manufacturing environments can be categorized as:

- Natural (small variations in operators, machines, material, etc.)
- Random outages
- Setups
- Operator availability
- Scrap & Rework

Variability can be measured using the coefficient of variation that is defined as the standard deviation divided by the mean. Figure 4.2 shows the different values this parameter can have together with a qualitative description of the level of variability.

$$c = \frac{\sigma}{t} = \text{coefficient of variation, CV}$$

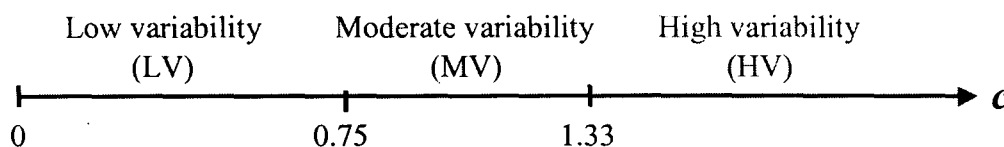


Figure 4.2 Variability Ranges

Natural variability is the variability inherent in natural process time, which excludes random downtimes, setups, or any other external influences. When talking about manual processes there is typically more variability than in automated processes.

Preemptive variability is caused by unscheduled downtimes that can greatly inflate the mean and coefficient of variation of effective process times. To take into account this, there is a necessity to know how much time the process is running or its availability (A). There is something important to notice, in terms of variability and effects on process performance, it is better to have a process that fails frequently but is quick to repair, than a process that fails rarely but takes a lot of time to repair (it is not the natural way of thinking, though).

Nonpreemptive variability represents downtimes that will inevitably occur but when they occur, can be controlled. Setups, worn tooling change, preventive maintenance, breaks and shift changes are examples of nonpreemptive downtimes.

Another source of variability is quality problems due that they cause rework. More rework implies more variability, more variability causes more congestion, more WIP and greater cycle time. The way to treat rework is similar to the one used with nonpreemptive variability.

When dealing with a situation that have more than a single type of variability, the formulas shown on table 4.3 need to be consecutively applied to accumulate the effects of them and calculate the effective process time, standard deviation and coefficient of variation.

Situation	Natural	Preemptive (unscheduled)	Nonpreemptive (scheduled)
Examples	Reliable Machine	Random Failures	Setups; Rework
Parameters	t_0, c_0^2	$t_0, c_0^2, m_f, m_r, c_r^2$	$t_0, c_0^2, N_s, t_s, c_s^2$
t_e	T_0	$t_0 / A, \quad A = \frac{m_f}{m_f + m_r}$	$t_0 + \frac{t_s}{N_s}$
σ_e^2	$t_0 c_0^2$	$\left(\frac{\sigma_0}{A}\right)^2 + \frac{(m_r^2 + \sigma_r^2)(1-A)t_0}{A m_r}$	$\sigma_0^2 + \frac{\sigma_s^2}{N_s} + \frac{N_s - 1}{N_s^2} t_s^2$
c_e^2	C_0^2	$\frac{\sigma_e^2}{t_e^2} = c_0^2 + (1 + c_r^2) A (1 - A) \frac{m_r}{t_0}$	$\frac{\sigma_e^2}{t_e^2}$

Table 4.3 Summary of Formulas

Where:

- t_e = mean effective process time
- σ_e^2 = squared effective standard deviation
- c_e^2 = squared effective coefficient of variation
- σ_r^2 = squared repair time standard deviation
- c_r^2 = squared repair coefficient of variation
- m_f = mean time to failure (time between failures)
- m_r = mean time to repair (time spent to repair)
- N_s = number of parts between setups, reworks, etc.

Variability of single stations can affect the behavior of other stations in a line by means of another variability called flow variability. Flow refers to the transfer of jobs between workstations. The link required to characterize the entire line is to determine the flow between stations. The first step is to determine the behaviors of the arrivals of jobs, then the job is processed and modified by the variability within the workstation and finally the departure becomes in the arrival for the next station. The first descriptor is the arrival rate ($r_a = 1/t_a$), in order for the workstation to keep up with arrivals, the capacity needs to exceed the arrival rate. The arrivals also have normal variation thus having a standard deviation and the coefficient of variation.

The propagation of variability between stations can be defined as a conjunction of input parameters and the fraction of time the station is busy (utilization, u), this is depicted on figure 4.3. If a station increases u without making any other changes, average cycle time will increase in a highly nonlinear fashion (Utilization Law).

$$c_d^2 = 1 + (1 - u^2)(c_a^2 - 1) + \frac{u^2}{\sqrt{m}}(c_e^2 - 1)$$

where m is the number of machines and $u = \frac{r_a}{r_e} = \frac{r_a t_e}{m}$

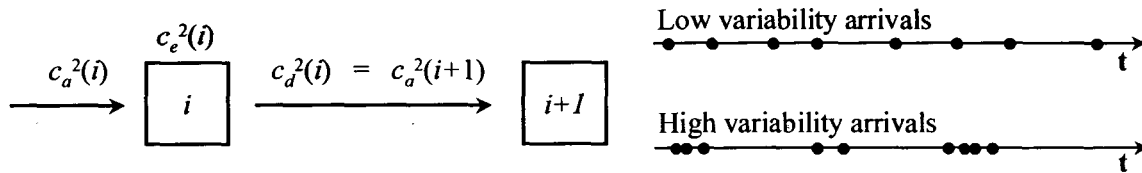


Figure 4.3 Variability Propagation

When there are multiple inputs the c_a will tend to 1 (MV). Also, flow variability out of a high utilization station is determined primarily by process variability at that station. On the other hand, flow variability out of a low utilization station is determined primarily by flow variability into that station.

4.5. Variability Interactions – VUT Equation, Queuing.

The contribution of variability within the stations is only a small fraction of the processing time, usually is between 5 to 10 percent of total cycle time. The majority of the extra time is spent in waiting for various resources. In order to model the waiting behavior the queuing theory; that combines an arrival, a process and a queue to model a line; can be used (Hopp & Spearman, 2000).

Any station can be described with 5 parameters:

r_a = the rate of arrivals in jobs per unit time ($t_a = 1/r_a$ = the average time between arrivals).

c_a = the CV of inter-arrival times.

m = the number of machines.

r_e = the rate of the station in jobs per unit time = m/t_e .

c_e = the CV of effective process times.

Some measures that present the manufacturing line performance are:

u = utilization of station = r_a/r_e .

CT_q = expected waiting time spent in queue.

CT = expected time spent at the station (queue plus process time).

WIP = average WIP level (in jobs) at the station.

WIP_q = expected WIP (in jobs) in queue.

The performance relationships between the parameters are:

$CT = CT_q + t_e$

$WIP = r_a \times CT$

$WIP_q = r_a \times CT_q$

Knowing CT_q , WIP , WIP_q and CT can be calculated.

Kendall's Classification (A/B/m/b) is used to characterize a station, where A describes the distribution of interarrival times, B describes the distribution of process times, m states the number of machines at the station and b is the maximum number of jobs that can be on the system (if it is a blocking system). The classification is shown on figure 4.4.

Typical values for A & B are: M: exponential (Markovian) distribution $c=1$, G: completely general distribution & D: constant (deterministic) distribution.

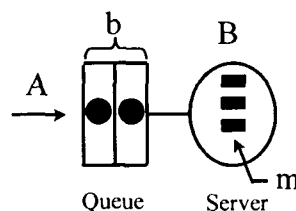


Figure 4.4 Kendall's Classification

The CT_q equation can be separated into three terms that are dimensionless. The variability term V , an utilization term U , and a time term T . That's why the Kingman's equation is also called the VUT equation.

$$CT_q \approx V \times U \times t$$

4.5.1. Non-blocking Model. G/G/m.

This model is considered an open model because the queue has no limitations to grow. As utilization approaches to one, the queue grows to infinity.

$$CT_q \approx V \times U \times t$$

$$\approx \left(\frac{c_a^2 + c_e^2}{2} \right) \left(\frac{u^{\sqrt{2(m+1)}-1}}{m(1-u)} \right) t_e$$

4.5.2. Blocking Model.

A blocking model is limited on the size the queue can be, once the model reaches the limit denoted by b , the arrival process stops. That's why it is called a closed model and it is closer to reality because there is always a limit on space, time, inventory, etc.

4.5.2.1. M/M/1/b Model.

Formulas valid for utilization different of 1.

$$WIP(M/M/1/b) = \frac{u}{1-u} - \frac{(b+1)u^{b+1}}{1-u^{b+1}}$$

$$TH(M/M/1/b) = \frac{1-u^b}{1-u^{b+1}} r_a$$

$$CT(M/M/1/b) = \frac{WIP(M/M/1/b)}{TH(M/M/1/b)}$$

$$\text{where } u = t_e(2)/t_e(1)$$

$$\text{For } u=1 \text{ WIP} = b/2, \text{ TH} = (b/(b+1)) * r_e$$

4.5.2.2. G/G/1/b Model.

Formulas valid for utilization less than 1.

$$WIP_{nb} \approx \left(\frac{c_a^2 + c_e^2}{2} \right) \left(\frac{u^2}{1-u} \right) + u$$

$$\rho = \frac{WIP_{nb} - u}{WIP_{nb}}$$

$$TH \approx \frac{1 - u\rho^{b-1}}{1 - u^2\rho^{b-1}} r_a$$

$$WIP < \min\{WIP_{nb}, b-1\}$$

4.5.3. Batch Processing.

There are two types of batching, one is process batch and the other is transfer batch. Process batch can be serial (number of jobs between setups) or parallel (number of jobs run together). Transfer batch is the number of parts that accumulate before being sent to the next station. But process and transfer batches don't require to be the same, thus lot splitting is a tool to minimize the cycle time.

Process times for batches are less variable than single part processing because the batching tends to average the effect of single parts processing. It is a great tool for quality control because of variability control, but in other instances, batching has also counter-effects that may offset any benefits from lower variability.

$$c_0(batch) = \frac{c_0}{\sqrt{n}}$$

In stations with batch operations or with significant changeover times as process batch size becomes larger, cycle time grows proportionally with batch size (Process Batching Law).

Serial batching (split is considering parts being sent as soon as processed).

$$CT_{nonsplit} = CT_q + s + kt$$

$$CT_{split} = CT_q + s + \frac{k+1}{2}t$$

Parallel batching ("true" batching).

$$CT = \frac{k-1}{2ku} t_b + \left(\frac{c_a^2/k + c_e^2}{2} \right) \left(\frac{u}{1-u} \right) t_b + t_b$$

Transfer batching (between 2 stations).

$$CT = CT_{single} + \frac{k-1}{2u(1)}t(1) + \frac{k-1}{2}t(2)$$

Where:

s = setup time

k = batch size

t = time to process a single part

t_b = time to process the batch

CT_{single} = cycle time of a system without batching

u(i) = utilization of station i.

t(i) = process time at station i

The average cycle time at a station is made up of the following components:
cycle time = move time + queue time + setup time + process time + wait-to-batch time + wait-in-batch time + wait-to-match time.

The average cycle time in a line is equal to the sum of the cycle times at the individual stations less any time that overlaps two or more stations.

Chapter 5.

5. PRACTICAL CASE. CONTACTOR LINE AT SCHNEIDER ELECTRIC.

This chapter develops the practical case applying the methodology presented on chapter 1 to a practical case, a contactor's manufacturing line within Schneider Electric. To finalize the chapter the results and conclusions are presented, together with directions for future development.

5.1. Description of the Contactor's Line.

The contactor's manufacturing line is a manual assembly line that consists of 12 different operations and is fed by two manufacturing lines that supply sub-assemblies at different locations of the main line. The two feeder lines are the Coil Assembly Line with 7 stations and the Magnet Assembly Line with 6 stations. These lines not only produce assemblies for the main line, but also to supply for resale (spare parts). The rest of the parts are supplied by the receiving area of the facility and distributed to each station as required. A diagram of the manufacturing line is shown on figure 5.1.

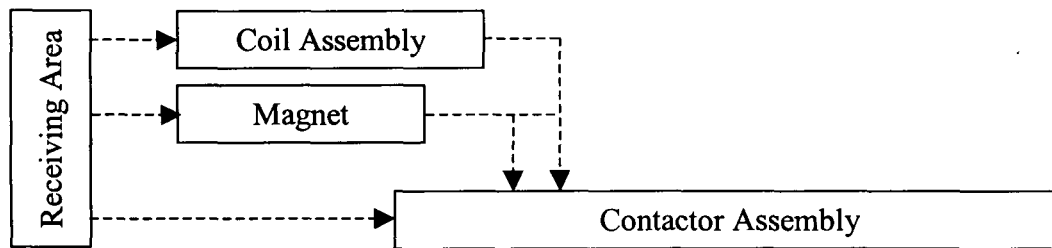


Figure 5.1 Diagram of contactor's manufacturing line

The line manages a mixed volume of different product families that are 2-pole, 3-pole and 4-pole contactors. Also there is a mix of coil voltages and contactor capacities 30, 40 and 60 Amperes. The line has 14 associates working on the main line and 16 working on the feeder lines.

The feeder lines need to work only one shift (8 hrs./shift) in order to supply enough material to the main line. The contactor line need to work 2 shifts, otherwise the daily average production target (1574 pieces) can not be accomplished.

Figure 5.2 is an exploded assembly of a 3-pole family that comprises more than 80 percent of the total production of the line. There are several parts involved and a specific order to assemble the part.

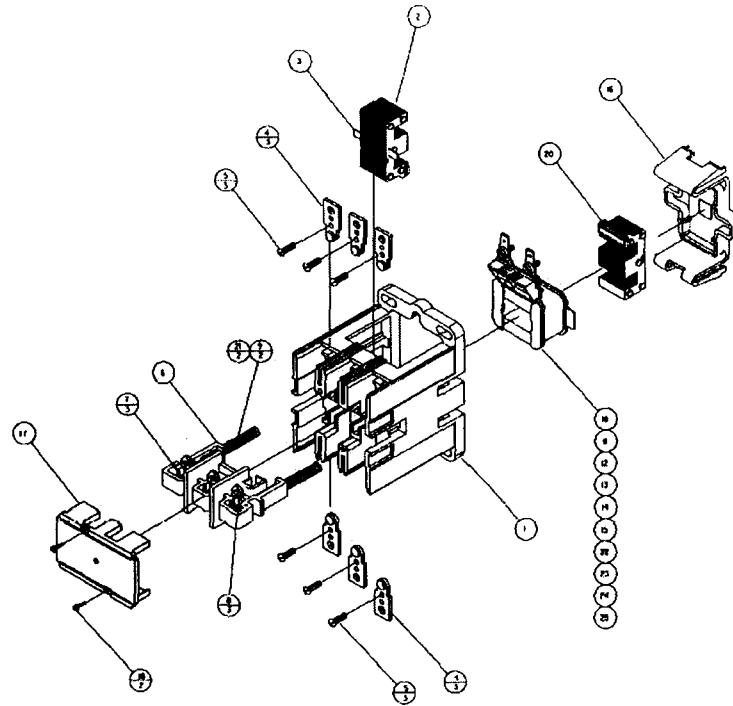


Figure 5.2 Exploded view of contactor

5.2. Methodology

The proposed methodology, to make educated decisions that will help on the generation of improvement ideas and the prioritization of the opportunities for enhancement found during the application of Lean Manufacturing, was presented on chapter 1, section 1.7. The following steps are the summary of this methodology:

1. Perform Process Mapping.
2. Create Model.
3. Populate/Verify Model.
4. Identify Current Performance.
5. Run Sensitivity Analysis.
6. Analyze Results, Prioritize & Propose.

5.3. Development & Results.

5.3.1. Perform Process Mapping.

The first step was to determine the current status of every assembly station within the production line. In order to get all the information, a team reviewed the manufacturing line beginning at the reception of materials, including all the stations of the main manufacturing line and the feeders, and finalizing at the shipment area. During this review the pertinent data and the inventory for each station was recorded. Once the information was gathered, it was populated into a value stream map (VSM), and finally, the information flow was depicted on the map.

The VSM showed the inputs, outputs and the process steps to convert raw material to finished goods (contactors). Figure 5.3 shows the VSM of the process, a detailed VSM can be consulted on the appendix A.

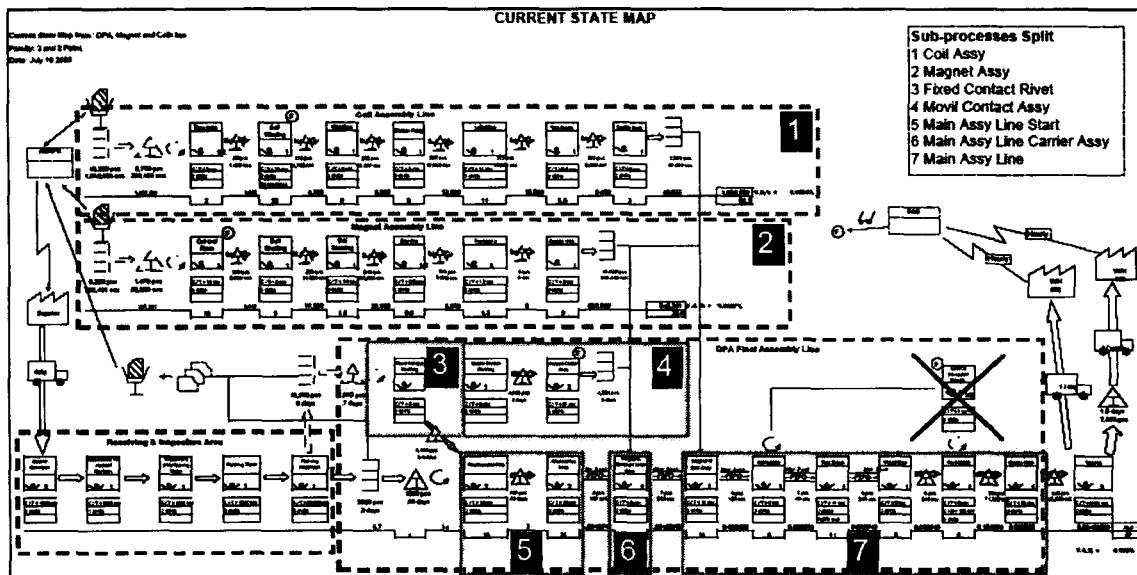


Figure 5.3 Representation of the line - VSM

5.3.2. Create Model.

To generate the mathematical model (deterministic considering variability propagation) for this specific production line that represents, at least in an approximate way the behavior of the real manufacturing line, an Excel based application developed by Hopp & Spearman (2000) called the Cycle Time Calculator was used. This application that is based on the VUT equations, calculates queue times, cycle times, and work in process (WIP) for a single product passing through a production line. It requires the product arrival rate and variability, and jobs between setups.

For each workstation, process times, variability, mean time to failure (MTTF) and mean time to repair (MTTR) are uploaded to the tool. The spreadsheet then calculates the resulting throughput, cycle time and WIP for the entire manufacturing line.

5.3.2.1. Adjustments to the model.

In order to facilitate the modeling of the current manufacturing system, the line was split in several sub-processes, each having its own worksheet. The criterion used to split the line was to divide the manufacturing process where multiple material flows converge to the same station (also at this stations some sub-assemblies that contain more than one similar part are integrated into a single product). The reason was to facilitate the integration of the model and avoid a lot of modifications on the worksheets. Also at these points (convergence points), it is required to decide which is the arrival flow (and variation) that limits the production.

To calculate the arrival rate for each sub-process, the demand of contactors, is multiplied by the number of identical pieces (instances) that are required to complete each end product (this will be modified once all the sub-assemblies are integrated into the product). Once each worksheet is complete, they were linked together to get the behavior of the entire manufacturing line. To link them, the departure rate and its variability are copied to the successor (downstream) worksheet as the arrival rate and its variability.

Where more than one flow converge to a station, it is required to select the minimum flow that arrives, because it limits the “complete” assemblies the line can produce. To consider that multi-instances will become a single product once assembled, before defining which flow is the minimum, each flow is divided by the number of instances it was multiplied before so the comparison considers only how many products can be completed with the available parts.

At the end, in order to obtain the cumulative CT and WIP, all individual cumulative figures from the worksheets are added and this represents the cumulative CT and the cumulative WIP.

As an example lets assume that there are 6 fixed contacts and 3 movable contacts on each 3-pole contactor. If the demand is 100, the production of fixed contacts has to be 600 and the movable contact sub-process requires to produce 300 parts. Lets assume that there were problems on the line and only 540 fixed contacts were produced. When these flows are going to be integrated into the end product, we need to determine which is the one that will limit the production. So instead of comparing 540 with 300 we need to compare $540/6=90$ with $300/3=100$ to determine that in this case we can only complete 90 assemblies of 100.

The Coil Assembly and Magnet Assembly lines stayed the same (no multiple flows converge on these sub-processes), but the main line was split in 5 sub-process on the stations where a sub-assembly is received. This split is shown on figure 5.3 with the white number within the black squares. The complete model of the manufacturing line can be consulted on the appendix B.

In order to model the line, with all its variations and considering the different families, a weighted average of the number of parts (with more than one instance) was done. Table 5.1 contains the production mix of families, in terms of number of poles and amperages, as the average weekly sales (AWS) and the daily production. Due to manufacturing similarities, the families are grouped by number of poles. Example, there are 4 fixed contact on a 2-pole (4%), 6 on a 3-pole (79%) and 8 on a 4-pole (17%) but due to the volumes involved, the weighted average is 6.2. Then the demand of contactors is multiplied by 6.2 and becomes the arrival rate at the station that produces that multi-instance part. Once this flow converges to the main line, this flow is divided by 6.2 (as explained before) to reflect that those pieces are going to be integrated into the main assembly to become a single product. This process was repeated with all the sub-processes that produced multi-instance parts.


Catalogue / Family	AWS	AWS/5 daily
DPA 3P 20-30 AMP	1850.97	370.19
DPA 3P 40 AMP	1099.87	219.97
DPA MODULE 3P 20-40 AMP	809.29	161.86
DPA 3P 50-60 AMP	743.69	148.74
DPA MODULE 3P 20-40 AMP WITH RIVETED CONTACTS	688.25	137.65
DPA 4P 20-30 AMP	539.35	107.87
DPA 4P 20-30 AMP	539.35	107.87
DPA 2P 40 AMP	243.16	48.63
AWS/5 total		1573.1


Table 5.1 Product mix on contactor line

Analyzing the mix of the product families in average weekly sales (AWS) in a given month, as shown on table 5.1, it can be determined that 2-pole (2P) is 4% of total production, 3-pole (3P) is 79% and finally 4-pole (4P) comprises 17%. So almost 80% of the total production are 3-pole contactors. Based on the demand of the contactors for the different families, the daily production required to meet the demand is 1573.1 (1600 pieces approximately). Due that yield in the stations is not always perfect (there is some scrap involved), this daily production needs to be increased up to 1700 pieces at the beginning of the line to deliver at least 1600 pieces. So the first pass yield is around 94 percent, this is, an average of 6 percent of scrap is produced within the manufacturing line. This number doesn't consider that some of the scrap is reworked and reintegrated to the line, so at the end the number of pieces is going to increase a little.

5.3.2.2. Cycle Time Calculator Tool

This application, that is based on the VUT equations, calculates queue times, cycle times, and work in process (WIP) for a single product passing through a production line. You specify product arrival rate and variability, and jobs between setups. For each workstation, you specify process times and variability, mean time to failure (MTTF), mean time to repair (MTTR). The spreadsheet will calculate the resulting throughput, cycle time and WIP for the entire manufacturing line.

As an example the calculation of the first station will be presented. Taking as a reference the table 5.2 that is the modified worksheet to show the formulas introduced on chapter 4. These equations calculate the performance of this station. The fields highlighted in gray  are inputs required by the system, the last section contains the outputs or performance metrics of the station.

It is important to note that the fields highlighted in gray and enclosed with double lines  were modified from the original version to obtain additional info (in this case the utilization) or to adjust the model to the requirements (for multi-instances adjustment or the decision when multiple flows converging to the station).

The first step is to input the data obtained from the VSM. And then the worksheet calculates the different variables that are indicated on table 5.2. The most important figures are the utilization and the performance metrics of this particular station.

In this case the arrival rate is 212.5 parts per hour that meets the demand of 1700 parts a day (considering 1 shifts of 8 hours). The coefficient of variation is zero because the demand is considered fixed. Then the natural process time (0.001 hr.) and variation (moderate = 0.75) are uploaded, together with the number of machines (0.5 operators). Due that most of the restrictions are in the personnel and not in the machines most of the times when talking about machines we are referring to operators at the station.

Then the fail and repair times are included, in this case it is considering that the machine or the station is presenting a problem so the operator can't perform the job. Based on this data, the effective process time (0.001) and its variation (0.822) are calculated. The model considers that process batch is the same as transfer batch. In case of batching the size, the setup time and its variation need to be uploaded to the worksheet. Based on the already loaded data the utilization of the station can be calculated, in this particular case it is very low (0.286).

MEASURE:		Thru hole
Arrival Rate (parts/hr)	r_a	212.500
Arrival CV	c_a^2	0.000
Natural Process Time (hr)	t_0	0.001
Natural Process SCV	c_0^2	0.750
Number of Machines	m	0.5
MTTF (hr)	m_f	2400
MTTR (hr)	m_r	4
Availability	$A = m_f / (m_f + m_r)$	1.000
Effective Process Time (failures only)	$t_e = t_0 / A$	0.001
Eff Process SCV (failures only)	$c_e^2 = c_0^2 + 2 * (1 - A) * A * m_f / t_0$	0.822
Batch Size	k	1
Setup Time (hr)	t_s	0.000
Setup Time SCV	c_s^2	1.000
Arrival Rate of Batches	r_a / k	103.094
Eff Batch Process Time (failures+setups)	$t_e = k t_0 / A + t_s$	0.001
Eff Batch Process Time Var (failures+setups)	$\sigma_e^2 = k(t_0^2 c_0^2 / A^2) + (2 m_r (1 - A) k t_0 / A) + c_s^2 t_s^2$	0.000
Eff Process SCV (failures+setups)	$c_e^2 = \sigma_e^2 / t_e$	0.822
Utilization	$u = r_a t_e / m$	286
Departure SCV	$c_d^2 = 1 + (1 - u^2) * (c_a^2 - 1) + (c_e^2 - 1) * (u^2 / \text{SQRT}(m))$	1.171
Yield	y	1.000
Final Departure Rate	$r_a y$	103.094
Final Departure SCV	$y c_d^2 + (1 - y)$	1.195
OUTPUTS (PERFORMANCE METRICS)		
Utilization	$u = r_a t_e / m$	286
Throughput	$TH = r_a y$	103.094
Queue Time (hr)	$CT_q = t_e * ((c_a^2 + c_e^2) / 2) * (u^{\text{SQRT}(2(m+1))-1}) / (m * (1 - u))$	0.000
Cycle Time (hr)	$CT_q + t_e$	0.002
Cumulative Cycle Time (hr)	$\sum_i (CT_q(i) + t_e(i))$	0.002
WIP in Queue (jobs)	$r_a CT_q$	0.050
WIP (jobs)	$r_a CT$	0.345
Cumulative WIP (jobs)	$\sum_i (r_a(i) CT(i))$	0.345

Table 5.2 Cycle Time Calculator Formulas

Then the yield is uploaded and the final departure rate and its variation are calculated. These two terms are very important because they serve as the arrival inputs of the next station. In this way, the variability is propagated to the downstream workstations.

Finally the performance metrics are calculated as the throughput (103.094 pieces per hour), the waiting time (G/G/m model queue), the cycle time and the WIP. When there are more than one station, the cumulative cycle time and WIP are calculated as the sum of the individual values of each station.

These same steps are applied to each station and at the end the results are the performance metrics of the entire manufacturing line. As can be seen on the last section of appendix B (contactor line model).

5.3.3. Populate/Verify Model.

Once the model was built it required to be tested to determine if it behaved the right way, otherwise the improvements that will result from the analysis may not match the reality once applied to the manufacturing line. In order to do this, the information from the VSM (appendix A) was fed into the model as shown on appendix B and as demonstrated on Table 5.2.

The verification was done, for the entire manufacturing line, in term of rate of production (which was adjusted to meet the output required), in term of cycle time and verifying that the inputs of each station were correct. Also, each station's behavior was analyzed, looking for data that highlighted any problem on the model (as overload stations, too low utilization, increase of WIP, low throughput, etc.).

Based on real performance of the line at that moment, it was determined that the Cycle Time was around 20 minutes, based on the results of the model shown on appendix B, the cumulative Cycle Time is 0.377 hours (22 minutes). So the results on the Cycle Time in the model are only 10% higher than reality. Also as mentioned earlier the Throughput was adjusted and the production rate of the line was met as well.

Using these criteria, it was determined that the model was showing similar results than the manufacturing line, thus the manufacturing line behavior could be modeled using this approach.

5.3.4. Identify Current Performance.

Figures 5.4 and 5.5 show the performance curves for the Best Case, Worst Case and the Practical Worst Case. They were calculated and plotted at each WIP, accordingly to the concepts presented on Chapter 4. Also table 5.3 presents a summary of the performance metrics (throughput and cycle time) of these three cases based on current WIP levels.

Once all the input data was uploaded to the model the results were compared with the Worst Practical Case (WPC) to determine how the process was performing and how much improvement can be achieved with small investments and changes. To determine the current behavior, it is required to know the WIP and both the TH and CT, with these data the current behavior can be displayed on the charts.

If the process is below the baseline set by the WPC then there are a lot of opportunities for improvement. On the other hand if the process is way up the WPC the improvements expected are limited.

As shown on table 5.2 and figures 5.4 and 5.5, the performance, of the current line, is below the PWC in both Cycle Time and Throughput. Current process throughput (101 pieces/hr.) is around 50% of the PWC, and Cycle Time (0.377 hrs.) is 25% greater than the PWC. Based on this, some opportunities for improvement without big investments should be found. Also the maximum utilization of any station, i.e. the bottleneck, is 0.955 located on the station Carrier Assy of the Movil Contact Assy sub-process.

Schneider Electric's Contactor Line Results

	pieces/day	Station	Line
Demand (Input)	1700		
Max. Utilization	u	0.955 Carrier Assy	Movil Contact Assy
Final Throughput	TH	101 pieces/hr	
Final Throughput	TH	804 pieces/shift	1609 pieces/day
Cumulative Cycle Time (hr)	$S_i(CT_a(i)+t_c(i))$	0.377 hrs.	
Cumulative WIP (jobs)	$S_i(r_a(i)CT(i))$	84 pieces	

	Best Case	Practical WC	Worst Case	
CT	0.241	0.301	5.302	hrs.
TH	348	279	16	pieces/hr

Table 5.3 Contactor line results

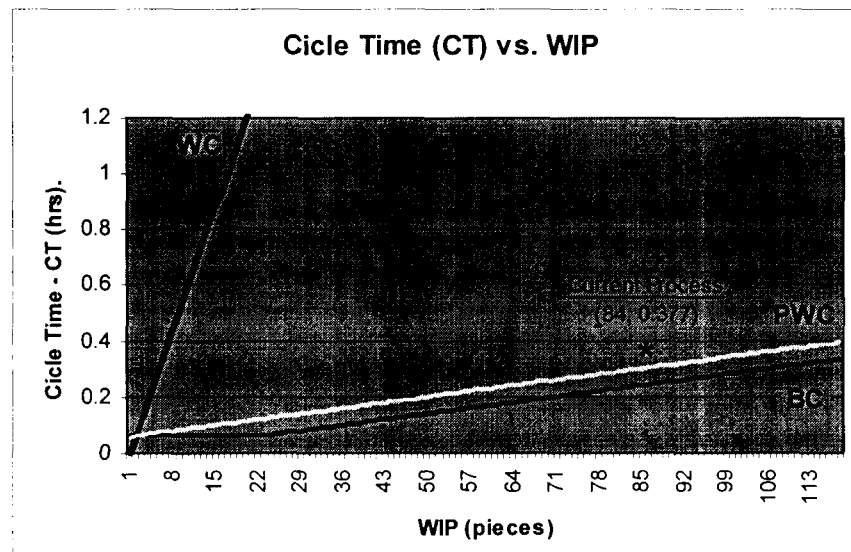


Figure 5.4 CT vs. WIP – Current status

It is important to notice that the closest the utilization is to 100%, the WIP and CT will increase in a highly non-linear fashion within the system, thus becoming unstable, because the WIP and CT grow infinitely and the results calculated by the spreadsheet are not correct. This is one reason to monitor the maximum utilization within the model. In reality, the WIP and CT won't growth to infinity, but an accumulation of material will be seen on the production line. Also in reality, this utilization can be managed by extra-time, help from other stations, etc.

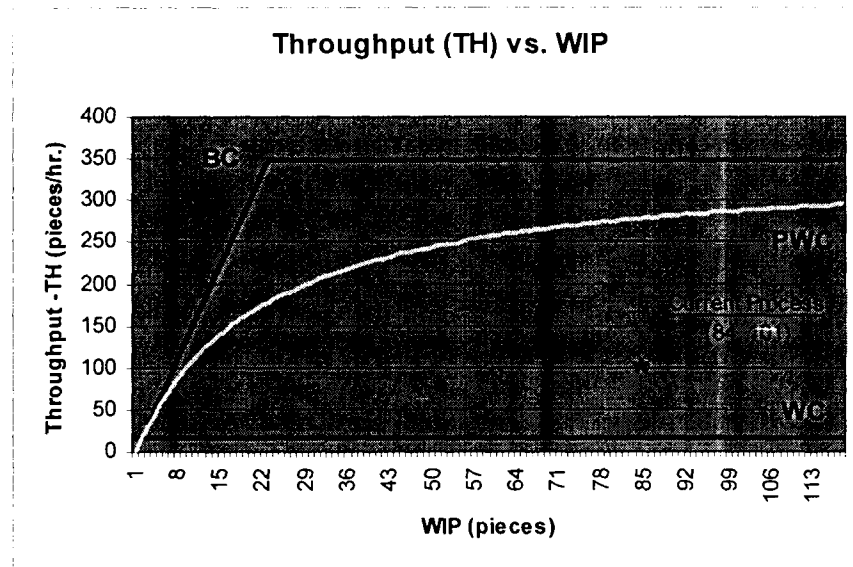


Figure 5.5 TH vs. WIP – Current status

5.3.5. Run Sensitivity Analysis.

Once the model is created and verified, then the analysis of the data can be initiated. The sensitivity analysis focuses on the input data that can be modified within each station. Each of these inputs were varied +/- 15% in steps of 2.5 % in order to determine their individual contribution to the outputs (Throughput, Cycle Time and WIP) and the changes on the responses were recorded. On table 5.4 some results of varying the parameter c_0^2 for TH and CT are shown.

Line	Station	Parameter	85%	88%	90%	93%	95%	98%	100%
Throughput									
1	Coil As:	1	c_0^2	100.5375	100.5375	100.5375	100.5375	100.5375	100.5375
Cycle Time									
1	Coil As:	1	c_0^2	0.3771	0.3771	0.3771	0.3771	0.3771	0.3771

Table 5.4. Sensitivity Analysis Calculation

As an example, the original value of parameter c_0^2 was 0.75 and the TH with this value was 100.5375 pieces per hour. Then this parameter is reduced in 2.5 % (0.7312) and the new TH is recorded (100.5375), then we decrease an additional 2.5 % (0.7129) and again the TH is recorder (100.5375). We continue this process until we cover the range of +/- 15%. In this example, we can determine that the TH is not sensible to the reduction of the parameter c_0^2 . Then we continue with the next step that is varying the parameter again, but recording the CT and finally the WIP. At the end we are going to have a table with all the output variations (TH, CT and WIP) as a result of the input changes.

After varying all the parameters once at a time and recording each output, the information obtained from the sensitivity analysis was sorted to identify the inputs that cause the greater impact on the outputs based on the direction of improvement (less is better, or more is better). Appendix D, shows the sensitivity analysis sorted by station, and appendix E contains the results sorted by priority.

As show on figures 5.6, 5.7 and 5.8, together with the tables 5.5, 5.6 and 5.7; once the data from the sensitivity analysis was gathered, spider charts, to show in a graphical manner the extent of the contribution of each parameter, were created. When looking at the spider chart the lines that have the greatest slope are to be considered because these are the most important contributors to the output. Remember that can be contributors in two directions, parameters that when increased diminish the outputs, and also the ones that when increased increase the outputs as well. The analysis will consider only the ones that impact in the direction of improvement, i.e. increase Throughput, and reduce Cycle Time and WIP.

When a line changes its trend too abruptly, this is a sign that there is a decision involved on this particular station (when more than one flow converges to a single station the smaller flow determines how many “complete” products can be manufactured). The change corresponds to the point where the contribution of this particular input equals the impact of other input involved on the decision. After this point, any additional changes won’t affect because another station will take the role as main contributor.

When an input parameter is increased to a value that causes the station to have an utilization equal or greater than one (the system becomes unstable causing WIP and CT to grow infinitely), the graphs show a peak that increases to infinity. In reality, the WIP and CT won’t growth to infinity, but an accumulation of material will be seen on the production line. Also, this overutilization can be managed by extra-time, help from other stations, etc.

5.3.5.1. Throughput.

In order to pursue improvement we need this parameter to increase its value, so producing more finished products in a certain time. Based on the results from the spider chart shown on figure 5.6 and the data extracted from appendix E (sensitivity analysis sorted by priority) we can determine the following:

- The main parameter that controls the throughput is the arrival rate (not included on the graph). The only limitation is to keep all utilization values less than one (stable system).
- Only one input parameter has impact on the Throughput, any workstation yield.
- The behavior of the yield within the same sub-process is the same for all workstations. They impact the result in the same way.
- Without moving the arrival rate the only parameters that can increase up to certain level the throughput are the yields of any station on Main Assy Line and Coil Assy Line.
- The highest contributors are any yield of the Main Assy Line.
- The second highest contributors, limited to grow up to 101.5, are the stations of Coil Assy Line. The limit is determined on the value that makes this flow become greater than the other flows converging to Main Assy Line, such that the decision to choose the smaller flow doesn't consider this factor anymore.

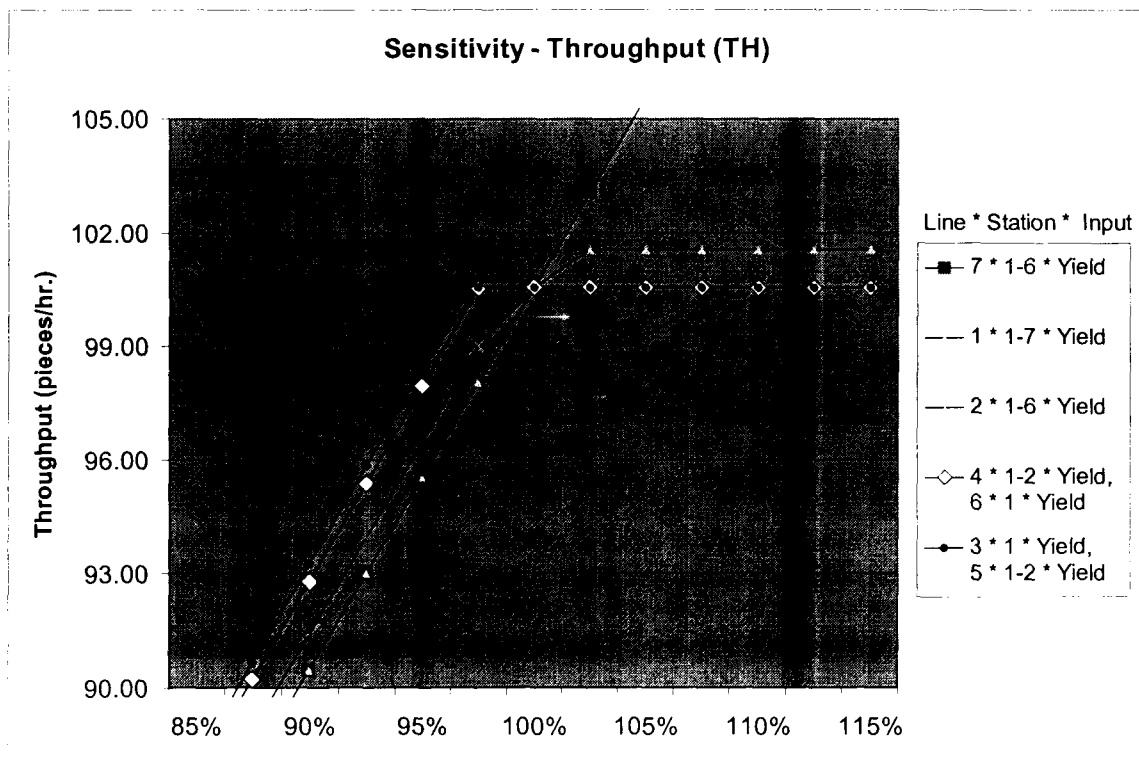


Figure 5.6 Sensitivity Analysis for Throughput

- Other yields affect only when they decrease their current yield, but not when it is increased; it is, they can limit the number of “complete” assemblies but not increase them.
- The higher the number of instances that go into the product the smaller the impact of the yield in the results (decreasing direction, i.e. when the original value is reduced in a certain percentage). There is a “delay” in the decreasing direction response proportional to the number of instances that goes into the product that flow.

Figure 5.6 summarizes the results obtained after varying all the input parameters to determine its impact on the Throughput. The improvement direction for throughput is to increase it. In order to relate the input parameter with a characteristic curve, it is necessary to refer to the appendix E, where the information about the sensitivity analysis is sorted accordingly to the impact in the improvement direction. Table 5.5 shows the data related to figure 5.6.

Line	Static	Param	85%	88%	90%	93%	95%	98%	100%	103%	105%	108%	110%	113%	115%
Throughput															
7 Main As	4	y	85.46	87.97	90.48	93.00	95.51	98.02	100.54	103.05	105.56	108.08	110.59	113.10	115.62
7 Main As	1	y	85.46	87.97	90.48	93.00	95.51	98.02	100.54	103.05	105.56	108.08	110.59	113.10	115.62
7 Main As	2	y	85.46	87.97	90.48	93.00	95.51	98.02	100.54	103.05	105.56	108.08	110.59	113.10	115.62
7 Main As	3	y	85.46	87.97	90.48	93.00	95.51	98.02	100.54	103.05	105.56	108.08	110.59	113.10	115.62
7 Main As	5	y	85.46	87.97	90.48	93.00	95.51	98.02	100.54	103.05	105.56	108.08	110.59	113.10	115.62
7 Main As	6	y	85.46	87.97	90.48	93.00	95.51	98.02	100.54	103.05	105.56	108.08	110.59	113.10	115.62
1 Coil As	1	y	85.46	87.97	90.48	93.00	95.51	98.02	100.54	101.56	101.56	101.56	101.56	101.56	101.56
1 Coil As	2	y	85.46	87.97	90.48	93.00	95.51	98.02	100.54	101.56	101.56	101.56	101.56	101.56	101.56
1 Coil As	3	y	85.46	87.97	90.48	93.00	95.51	98.02	100.54	101.56	101.56	101.56	101.56	101.56	101.56
1 Coil As	4	y	85.46	87.97	90.48	93.00	95.51	98.02	100.54	101.56	101.56	101.56	101.56	101.56	101.56
1 Coil As	5	y	85.46	87.97	90.48	93.00	95.51	98.02	100.54	101.56	101.56	101.56	101.56	101.56	101.56
1 Coil As	6	y	85.46	87.97	90.48	93.00	95.51	98.02	100.54	101.56	101.56	101.56	101.56	101.56	101.56
1 Coil As	7	y	85.46	87.97	90.48	93.00	95.51	98.02	100.54	101.56	101.56	101.56	101.56	101.56	101.56
2 Magnet	3	y	86.32	88.86	91.40	93.94	96.48	99.02	100.54	100.54	100.54	100.54	100.54	100.54	100.54
2 Magnet	1	y	86.32	88.86	91.40	93.94	96.48	99.02	100.54	100.54	100.54	100.54	100.54	100.54	100.54
2 Magnet	2	y	86.32	88.86	91.40	93.94	96.48	99.02	100.54	100.54	100.54	100.54	100.54	100.54	100.54
2 Magnet	4	y	86.32	88.86	91.40	93.94	96.48	99.02	100.54	100.54	100.54	100.54	100.54	100.54	100.54
2 Magnet	5	y	86.32	88.86	91.40	93.94	96.48	99.02	100.54	100.54	100.54	100.54	100.54	100.54	100.54
2 Magnet	6	y	86.32	88.86	91.40	93.94	96.48	99.02	100.54	100.54	100.54	100.54	100.54	100.54	100.54
6 Main As	1	y	86.32	88.86	91.40	93.94	96.48	99.02	100.54	100.54	100.54	100.54	100.54	100.54	100.54
4 Movil C	1	y	87.63	90.21	92.79	95.36	97.94	100.52	100.54	100.54	100.54	100.54	100.54	100.54	100.54
4 Movil C	2	y	87.63	90.21	92.79	95.36	97.94	100.52	100.54	100.54	100.54	100.54	100.54	100.54	100.54
3 Fixed C	1	y	88.07	90.66	93.25	95.84	98.43	100.54	100.54	100.54	100.54	100.54	100.54	100.54	100.54
5 Main As	1	y	88.07	90.66	93.25	95.84	98.43	100.54	100.54	100.54	100.54	100.54	100.54	100.54	100.54
5 Main As	2	y	88.07	90.66	93.25	95.84	98.43	100.54	100.54	100.54	100.54	100.54	100.54	100.54	100.54

Table 5.5 Sensitivity data for Throughput

5.3.5.2. Cycle Time.

In order to pursue improvement, the cycle time needs to decrease its value, so increasing the production of finished goods. Based on the results from the sensitivity data of the appendix E (sensitivity analysis sorted by priority) and the spider chart, figure 5.7 we can determine the following:

- The highest contributor is the process time of station 2 belonging to line Movil Contact Assy.

- The second largest impact is obtained by decreasing the yield of the station 1 of the line Movil Contact Assy. This may sound strange but it is only a reflection of the status of the following station. Reducing the yield decreases the arrival rate and the utilization of the following station, and due that the utilization is close to one (0.955), the result is less waiting time on queue, less WIP and thus less cycle time.
- The third is increasing the number of similar machines in the station 2 of the line Movil Contact Assy that states that there is a capacity restriction on this station. Increasing the number of machines basically splits the processing time by n, where n is the number of machines.
- These three inputs are responsible for more than 50% of the total variation that can be obtained considering all the inputs.
- The most important input parameters for the sensitivity analysis are the process time, the yield and the number of machines. This influence greatly depends on the line where the input is located.
- The lines with most influence on the Cycle Time are Movil Contact Assy, Main Assy Line, and Coil Assy (Some parameters have more influence than others).

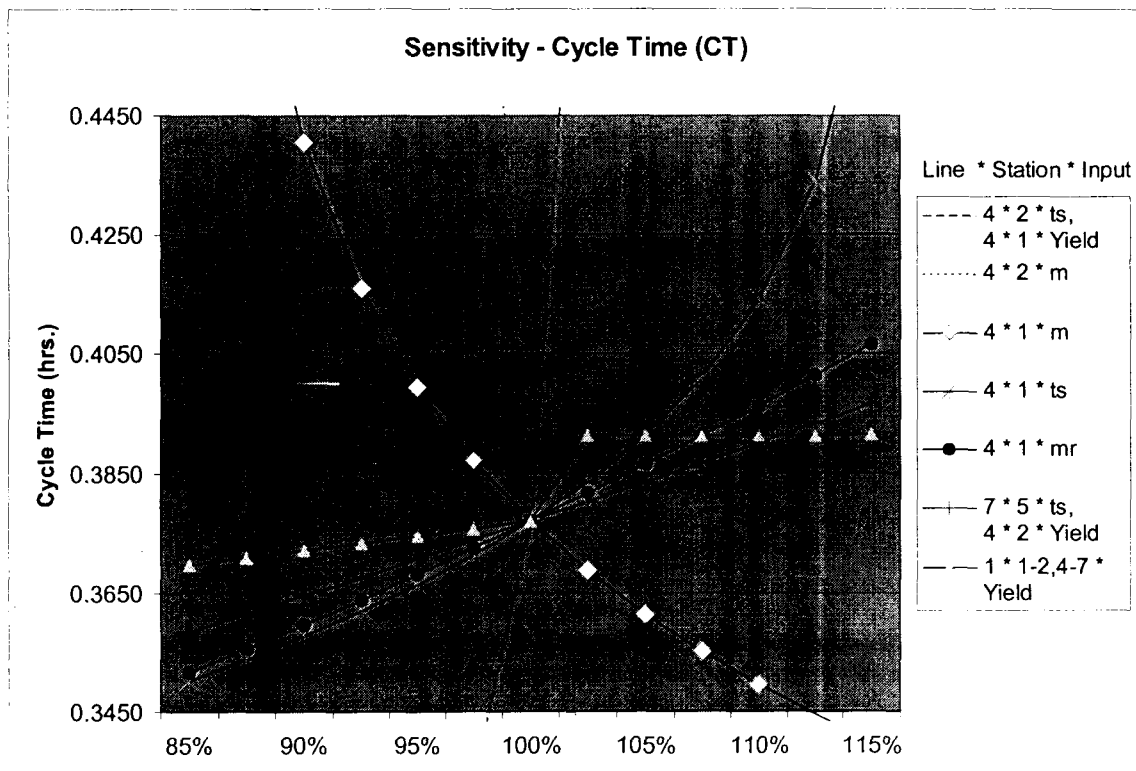


Figure 5.7 Sensitivity Analysis for Cycle Time

Figure 5.7 summarizes the results obtained after varying all the input parameters to determine its impact on the Cycle Time. The improvement direction for Cycle Time is to decrease it. In order to relate the input parameter with a characteristic curve, it is necessary to refer to the appendix E, where the information about the sensitivity analysis is sorted accordingly to the impact in the improvement direction. Table 5.6 contains the data for figure 5.7.

Line	Static Param	85%	88%	90%	93%	95%	98%	100%	103%	105%	108%	110%	113%	115%
Cycle Time														
4 Movil C	2 t ₀	0.2833	0.2875	0.2932	0.3013	0.3135	0.3343	0.3771	0.5152	Infinity				
4 Movil C	1 y	0.2848	0.2890	0.2945	0.3023	0.3140	0.3337	0.3771	0.5089	Infinity				
4 Movil C	2 m					Infinity	0.5228	0.3771	0.3351	0.3152	0.3037	0.2962	0.2909	0.2871
4 Movil C	1 m	0.6160	0.4841	0.4403	0.4161	0.3996	0.3871	0.3771	0.3687	0.3614	0.3551	0.3495	0.3445	0.3400
4 Movil C	1 t ₀	0.3501	0.3538	0.3577	0.3619	0.3664	0.3714	0.3771	0.3835	0.3913	0.4011	0.4143	0.4340	0.4691
4 Movil C	1 m _r	0.3516	0.3555	0.3596	0.3638	0.3681	0.3725	0.3771	0.3817	0.3865	0.3914	0.3964	0.4015	0.4067
7 Main As	5 t ₀	0.3585	0.3615	0.3646	0.3676	0.3708	0.3739	0.3771	0.3803	0.3835	0.3867	0.3900	0.3934	0.3967
1 Coil As:	1 y	0.3682	0.3696	0.3710	0.3724	0.3739	0.3754	0.3771	0.3919	0.3926	0.3934	0.3942	0.3951	0.3961
1 Coil As:	2 y	0.3682	0.3696	0.3710	0.3724	0.3739	0.3754	0.3771	0.3919	0.3926	0.3933	0.3942	0.3951	0.3961
1 Coil As:	3 y	0.3681	0.3695	0.3709	0.3724	0.3739	0.3754	0.3771	0.3918	0.3925	0.3933	0.3941	0.3950	0.3960
1 Coil As:	4 y	0.3681	0.3695	0.3709	0.3724	0.3739	0.3754	0.3771	0.3917	0.3924	0.3930	0.3938	0.3946	0.3955
1 Coil As:	5 y	0.3697	0.3709	0.3721	0.3733	0.3745	0.3758	0.3771	0.3912	0.3913	0.3913	0.3913	0.3914	0.3914
1 Coil As:	6 y	0.3697	0.3709	0.3720	0.3732	0.3745	0.3758	0.3771	0.3912	0.3912	0.3912	0.3912	0.3912	0.3912
1 Coil As:	7 y	0.3691	0.3704	0.3716	0.3729	0.3743	0.3756	0.3771	0.3912	0.3912	0.3912	0.3912	0.3912	0.3912

Table 5.6 Sensitivity data for Cycle Time

5.3.5.3. Work in Process.

In order to pursue improvement, the WIP needs to decrease its value, so increasing the production of finished goods and decreasing the inventory. Based on the results from the sensitivity data of the appendix E (sensitivity analysis sorted by priority) and the spider chart, figure 5.8 we can determine the following:

- The greatest impact is the yield of station 1 belonging to line Movil Contact Assy.
- The process time of station 2 of the Movil Contact Assy is the second more important contributor.
- Increasing the number of machines of station 2 of the Movil Contact Assy also contributes to decrease Work in Process.
- These three input parameters are responsible for more than 60% of the total response variation due to all inputs.
- The most important input parameters for the sensibility analysis are the process time, the yield and the number of machines. This influence greatly depends on the line the input belongs to.
- The lines with most influence on the Work in Process are Movil Contact Assy and Coil Assy (Some parameters have more influence than others).

Figure 5.8 summarizes the results obtained after varying all the input parameters to determine its impact on the Work in Process. The improvement direction for WIP is to decrease it. In order to relate the input parameter with a characteristic curve, it is necessary to refer to the appendix E, where the information about the sensitivity analysis is sorted accordingly to the impact in the improvement direction. Table 5.7 shows the data for figure 5.8

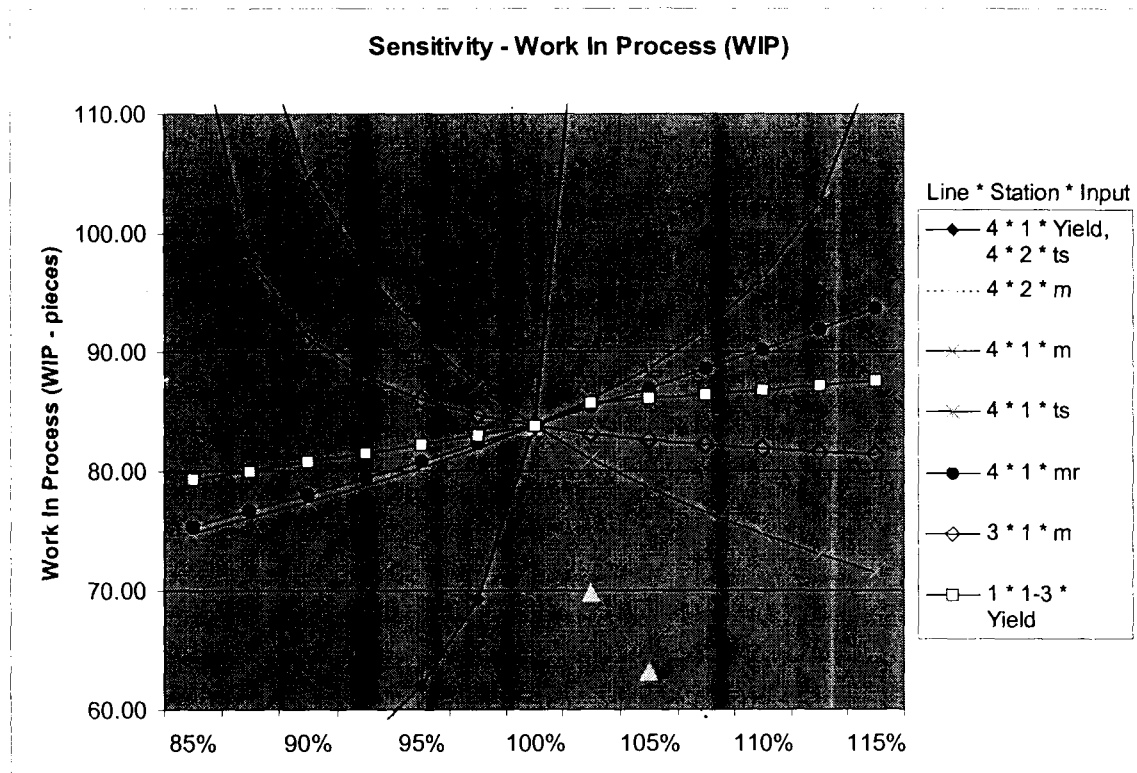


Figure 5.8 Sensitivity Analysis for Work in Process

Line	Station	Param	85%	88%	90%	93%	95%	98%	100%	103%	105%	108%	110%	113%	115%
Work in Process															
4 Movil C:	1	y	50.261	52.100	54.421	57.525	62.015	69.335	83.810	129.744	Infinity				
4 Movil C:	2	t ₀	52.631	54.039	55.934	58.615	62.687	69.593	83.810	129.738	Infinity				
4 Movil C:	2	m					Infinity	150.000	83.810	69.848	63.243	59.409	56.914	55.169	53.884
4 Movil C:	1	m	163.287	119.414	104.845	96.781	91.298	87.149	83.810	81.015	78.614	76.514	74.651	72.983	71.478
4 Movil C:	1	t ₀	74.843	76.072	77.375	78.768	80.279	81.942	83.810	85.968	88.550	91.799	96.181	102.744	114.413
4 Movil C:	1	m _r	75.337	76.653	78.008	79.401	80.833	82.302	83.810	85.356	86.941	88.564	90.225	91.924	93.662
3 Fixed C:	1	m	119.739	97.948	91.204	87.925	85.989	84.713	83.810	83.138	82.620	82.208	81.874	81.598	81.366
1 Coil As:	1	y	79.332	80.034	80.752	81.487	82.241	83.014	83.810	85.726	86.050	86.395	86.763	87.159	87.586
1 Coil As:	2	y	79.632	80.285	80.953	81.638	82.341	83.065	83.810	85.677	85.950	86.245	86.563	86.908	87.285
1 Coil As:	3	y	79.731	80.367	81.018	81.687	82.374	83.081	83.810	85.656	85.910	86.184	86.483	86.809	87.167

Table 5.7 Sensitivity data for Work In Process

5.3.6. Analyze Results, Prioritize & Propose.

The results obtained from the sensitivity analysis can be used in two different ways. The first one is to focus on the most important input parameters that improve the performance, and generate ideas that modify those inputs to achieve system enhancement. The second is evaluating existing ideas whose impact is compared to the most sensible parameters to determine the importance of this ideas (prioritization). Based on the results of the sensitivity analysis, a set of ideas to improve the most important input parameters can be generated.

Output	Input	Priority	Ideas
Throughput	Yield of Testing (Station 3) from Main Assy Line	1	Improve testing capacity by increasing the voltage and reducing the cycle time to avoid second testing. Change the probes to improve contact to avoid false rejects.
Throughput	Yield of Visual Inspection (Station 3) from Main Assy Line	1	Train inspector to avoid false rejects and provide visual aids and tools to improve visual inspection. Implement do-check in the line.
Throughput	Yield of Testing (Station 6) from Coil Assy	2	Improve incoming inspection for material quality.
Throughput	Yield of Winding (Station 2) from Coil Assy	2	Make a plan for preventive maintenance to avoid disruption during process. Train associates to avoid rework/scrap

Table 5.8 General ideas to improve Throughput based on SA

Output	Input	Priority	Ideas
Cycle Time	Process time of Carrier Assy (Station 2) from Movil Contact Assy	1	Reduce time using fixtures that improve process and access. Increase labor (from not fully utilized station). Redesign to facilitate assembly.
Cycle Time	Yield of Contact Rivet (Station 1) from Movil Contact Assy	2	Improve next station performance. This is only a reflection of the near to one utilization of downstream station. Increase personnel, time or improve fixturing to reduce cycle time.
Cycle Time	No. Machines of Carrier Assy (Station 2) from Movil Contact Assy	3	Implement fixturing to minimize process time and increase capacity of the station.

Table 5.9 General ideas to improve Cycle Time based on SA

Output	Input	Priority	Ideas
Work in Process	Yield of Contact Rivet (Station 1) from Movil Contact Assy	1	Improve machine performance and train the associate to avoid rework/scrap.
Work in Process	Process time of Carrier Assy (Station 2) from Movil Contact Assy	2	Reduce time using fixtures to improve manufacturing. Increase labor (from not fully utilized station). Redesign to facilitate assembly.
Work in Process	Machine number of Carrier Assy (Station 2) from Movil Contact Assy	3	Improve fixturing to minimize process time and increase capacity of station.

Table 5.10 General ideas to improve Work in Process based on SA

The following ideas were generated during the value stream mapping not considering the sensibility analysis results, these are summarized on the appendix G. Some of them will be linked to the process parameter they are targeting to improve and the priority assigned by the sensitivity analysis.

Objective		Value Stream Objective	Sensibility Analysis	
			Parameter	Priority
Improve profitability in contactors final assembly.	1	Reduce the process inventory in "Contact riveting assy" process	WIP / Space	---
	2	Define the optimum process inventory (buffer) in "Contact riveting assy"	WIP / Space	---
	3	Reduce the # of person and shift in riveting process. (2 m/c)	Utilization	*** May Increase CT
	4	Analyze if it's feasible SMED in 2 riveting process	mr	CT 6 WIP 6
	5	Reduce the # of person in "Contact assembly" process.	Utilization	*** May Increase CT
	6	POKA YOKE fixture in "Contact assembly" process (avoid contact assy mistake)	Yield	TH None
	7	Reduce the supermarket inventory in terminals and silver rivets (actual 1.6 weeks, analyze optimum weeks)	WIP / Space	---

Table 5.11a Previous Ideas ranked accordingly to SA - Contact Assy

Objective		Value Stream Objective	Sensibility Analysis	
			Parameter	Priority
Improve profitability in contactors final assembly	8	Reduce the supermarket inventory in block 31149-057-01 (analyze optimum weeks)	WIP / Space	---
	9	Reduce the # of person in "Accessories assembly" & "Contact carrier assy" process.	Utilization	OK
	10	Implement ONE PIECE FLOW from "Assembly contact" to "Packaging"	CT	---
	11	Analyze to remove at minimum the WIP in line.	WIP / Space	---
	12	Move the "Contact carrier assy" next to "Magnet Assy" process.	WIP	---
	13	Analyze redesign the block and terminal to avoid process mistake (POKA YOKE design)	Yield	TH None CT 28 WIP 24
	14	Reduce to 1 station the "contact carrier and magnet assy", "Coil and Clip assy" and "Labels"	t0	CT 15, 41 WIP35, 14
	15	Improve DPA, magnetics and coils layout.	Space	---
	16	Evaluate install label automatic feeder. Join with test equipment.	t0, yield	TH None CT 32, 20 WIP 4, 18
	17	Evaluate the movement of automatic packaging m/c from 132 to DPA packaging station	t0, c02	CT 7, 6 WIP 22, 6
	18	SMED in packaging station (actual 124 sec)	Mr	CT 7 WIP 9
	19	Evaluate eliminate final inspection to process inspection	t0	CT 1 WIP 6
	20	Reduce 1 station the Test and Visual Insp.	t0	CT 37 WIP 3
	21	Implement record completion in packaging assy (lift tables, signal light to shipping department)	WIP, Space	---

Table 5.11b Previous Ideas ranked accordingly to SA - Contact Assy

Objective		Value Stream Objective	Sensibility Analysis	
			Parameter	Priority
Improve profitability in Magnet Assembly line	1	Reduce the # of person in "Cut and place" process.	m	*** May Increase CT CT 12 WIP 4
	2	Implement cellular station in "riveting assy" and "shade coil riveting"	t0	CT 24 WIP 12
	3	Implement batch lot size of 35 between "cut and place" and "riveting assy" stations.	Batching	---
	4	Implement KANBAN system between Magnetic line and DPA line (current 2.5 days of inv.)	WIP, CT	---
	5	Reduce to 1 shift operations	Utilization	OK
	6	Implement KANBAN system between final inventory and DPA assy line.	WIP, CT	---

Table 5.12 Previous Ideas ranked accordingly to SA - Magnet Assy

Objective		Value Stream Objective	Sensibility Analysis	
			Parameter	Priority
Improve profitability in Coils Assembly line	1	Reduce the supermarket inventory in (actual 5.8 weeks, analyze optimum weeks)	WIP, Space	---
	2	Analyze mix and times per coils models to define optimum batch lot	Batching	---
	3	Implement system to identify types of coils in process line.	Yield	TH 7 Limited CT 11 WIP 7
	4	Add 1 person in label station to reduce cycle time	t0	CT 34 WIP 32
	5	Implement KANBAN system between Coils and DPA line (current 12.7 hours)	WIP, CT	---

Table 5.13 Previous Ideas ranked accordingly to SA - Coil Assy

Based on these results we can determine that some of the greater contributors to the performance of the line are being addressed, but some of them are missing. Also some of the ideas may decrease the performance of the system in terms of CT and WIP (the utilization of some stations will go near or greater than one, i. e. unstable operation). On the contrary, with the sensitivity information we can address the most important parameters without generating a lot of ideas and investing the time to evaluate them.

5.3.7. Conclusions (Practical Case).

Accordingly to the development of the practical case, we found that following the methodology can help to reproduce the study in other situations. The first step is the simplest one, to get as much information from the manufacturing line as possible. To do this we use the Value Stream Mapping tool that pictures the different processes and the relations between them.

As the methodology confirms, one of the most important steps is the model creation and the consecutive verification that it behaves as close as the manufacturing line. In this case the manufacturing line model, in terms of Cycle time, over-estimates de Cycle Time by 10%. Another parameter that was verified, for the entire line, was the throughput to identify if the line can produce what usually does in the reality, in this case the model was adjusted so the production was met. Based on this results we can determine that the information provided by the model will be helpful to take some decisions, due that there is a good approximation of the behavior found on the manufacturing floor.

The model behaves, close enough, and the reasons of the discrepancies are that the model has several limitations, restrictions and simplifications. The most important restriction is that this model is deterministic, whilst the manufacturing processes are not. The simplification of using only a weighted averages for the arrival rate is another factor that can increase this difference. Other factor that may contribute to this difference is the flexibility of the people in the line that somehow increases the productivity when it is required or supports other workstations. Aligned to this there is a behavior that during the day the performance is increased up to a maximum and then it lowers as close as the time to leave is approaching, thus increasing the variability in the system. Also, the difference can be address by the inherent variation in process times, even though some variation is being taken into consideration by the coefficient of variance, the model continues to be deterministic.

Model creation can be accomplished in other ways, it can be a mathematical model result of a design of experiments or it can be a simulation model that can take into consideration the variability of the manufacturing systems.

The tool as demonstrated can be very helpful to get a better understanding of a manufacturing system, and also is a simple enough tool to use without too much experience. So the price paid for this simplicity is the accuracy of the results, as shown by the results this difference is only 10% for Cycle Time.

In order to determine the current status of the manufacturing line, it is compared with the Best Case, the Practical Worst Case and the Worst Case. The result obtained in this case (lower in TH and CT to the performance of the PWC), assures that the system can be improved without too much trouble or expenses. If

the system performance is above the PWC, the improvement is still feasible, but there will be less opportunities than in this case.

The single most important tool used on the practical case is the Sensitivity Analysis. The core of this methodology lies on this tool, that is used to identify the input parameters that are the most important to the performance of the system. This is a fairly easy tool to apply, but in this case we are talking of more than 150 input variables which gives a total of 1500 iterations for each performance parameter. At the end, the tool is iterating 4500 times to cover TH, CT and WIP. In order to simplify this analysis a macro was developed to run this iterations and report the results of the performance metrics for each change.

Once the data was obtained, it was analyzed and prioritized to help on the decision making process. Otherwise it is only a long list of values that are difficult to manage. One way to manage this data is using a graphical approach as the one used on the analysis, the spider charts are intuitive to use in order to determine the impact of each parameter, basically we focus on the slope of the curves. It is important to notice that some charts are not continuous and one of the reasons is that some grow to infinity because the utilization reaches one in a station. Other reason is that due to there are decisions to select the minimum flow, sometimes increasing or decreasing a variable makes it greater than the other flows and then it stops its contribution.

Based on the results we can determine that the most important parameters to increase TH are first the arrival rate (in this case was not considered to avoid minimizing the rest of the contributions to a very low level). The other parameters that are very important are the individual yields of the stations.

For CT, the parameters that improve it, as expected, are time related or utilization related. In this case a parameter appear (as shown on figure 5.7) that was not obvious, it was the yield. Thus decreasing the yield contributes to diminish the Cycle Time. Although this is mathematically feasible, it is not a path to follow on the manufacturing arena, because it means that the line will produce scrap parts to improve CT. The real reason behind this anomalous behavior is that the downstream operation from this one is highly utilized (it's running close to one), so because this it has a loss of queue and therefore a long waiting time to be processed. So the real action to take is to somehow release some capability of the downstream station and improve with this the CT.

In the case of WIP, the parameters that affect the results are similar to the ones in CT, as a matter of fact the same case with the yield arises in this parameter as well, and the reason is the same as the one explained on the former situation. The other parameters are the number of machines and the processing time, this is related to minimize the utilization and thus the queue which is WIP.

As stated on section 5.3.6 the sensitivity data can be used in two ways, to generate ideas that are truly focus to address the main contributors and to evaluate ideas already generated. In this particular case evaluating ideas, demonstrate that some of the high contributors are address but not all of them. So there is less effort when generating the ideas based on the sensitivity analysis than evaluating ideas that may or may not address the top contributors.

Based on the sensitivity analysis we can generate ideas that will target those inputs that will assure the greatest impact on the results. Due that most of the impact to the performance metric (TH, CT and WIP) is determined by a couple of parameters (3-4), we can generate 5 ideas on how to improve them, resulting in 15 to 20 ideas to be generated and evaluated. If we consider 20 minutes to generate and evaluate each idea it will take at most 400 minutes (approximately 6.6 hrs.).

On the other hand, if we don't have the sensitivity analysis, there are in this case 150 inputs that can be modified for each performance metric (TH, CT and WIP). If we generate only 2 ideas, it will result in a massive number of ideas to be generated and evaluated (300). If we consider 20 minutes to generate and evaluate each idea it will take at most 6000 minutes (approximately 100 hrs.). Besides due to the lack of information about which is parameter is more important, all the decisions will be based on "experience" and all the improvement planned may not be achieved.

Based on these two scenarios we can determine that with the sensitivity analysis the effort required to achieve better results is more than 15 times less than without the guide of the sensitivity analysis. We can also translate this effort to savings, considering the salary of the team in both cases. In the same manner, the improvement on the results, when applying the sensitivity analysis, to make educated decisions, can be demonstrated in further research.

5.4. Conclusions.

The utilization of a structured methodology that includes the sensitivity analysis can increment the knowledge and understanding about the system. With this knowledge and the identification of the most important parameters to improve the system, we can minimize the effort to enhance the manufacturing line. Also, the results obtained can be increased, because the organization can focus all the resources (money and people) where they are important.

The model creation is one of the most important steps of this methodology. If the model doesn't depict the reality within certain margin, the results can be misleading and the improvements may not be obtained. This is the reason to include an additional step to verify the model within the methodology. Even though at the beginning it may appear that the model creation takes some time and

experience to be developed, this time is greatly pay off when the results of the sensitivity analysis guide the decision making process.

It's important to keep in mind that the sensitivity analysis proposed is the classic one, where you vary only one parameter at a time. It may be a good research theme to investigate if other sensitivity analysis type that vary several parameters at the same time can achieve better results due to the intrinsic interaction between the manufacturing parameters.

The hypothesis to be tested in the thesis was “the utilization of the methodology and tools proposed to evaluate and prioritize the improvements, will increase the effectivity of the actions taken and the expected benefits”.

To evaluate if the hypothesis is correct, the results obtained with the sensitivity analysis (SA) and the former actions taken (result of VSM & Brainstorming) were compared (tables 5.11, 5.12 and 5.13) to identify if the prior actions taken were aligned to the SA. Based on this comparison, it can be identified if the analysis showed valuable information to generate ideas and prioritize the opportunities for improvement. Also there is a great difference in the effort required to get the results with and without following the methodology that includes the sensitivity analysis.

Based on the information presented on this chapter, and supported by the sensitivity analysis we can determine that even though some of the top contributors were addressed when implemented without the methodology, not all of them are taken care of. Besides the knowledge of the sensitivity analysis results can help to make “educated decisions” instead of brainstorm “wild guesses” based on experience. Experience is a great tool to generate valid ideas that really contributes to the performance of the line, but the shortcoming is that not all the people has it, and it takes time to grow it. Also it is not easy to quantify the impact before making any change, but once created a model it can be used, to run a “what-if” scenario and determine the change in the behavior of the line without making any physical change.

The use of the methodology serves a double purpose, first educates the people on the behavior of the manufacturing lines and second provides a great tool to improve its performance towards lean manufacturing.

Finally, and based on the information presented the thesis:

“The utilization of the methodology and tools proposed to evaluate and prioritize the improvements, can *indeed* increase the effectivity of the actions taken and the expected benefits” can be taken as valid.

5.5. Further developments.

Keeping in mind that the sensitivity analysis used is the classic approach, only varies one parameter at a time. It may be a good research theme to investigate if other type of sensitivity analysis, that vary several parameters at the same time, can achieve better results (due to the intrinsic interaction between the manufacturing parameters). These results can be compared to the ones obtained in this study to identify how different they are and quantify the differences. At the same time a validation will be required where the top parameters can be evaluated on a dummy manufacturing line to determine if they behave in the expected way by the two analyses. Based on these results it can be estimated how different the approaches are and which gets a better results, and which is obtains the best results in terms of productivity (time spent vs. accuracy of results).

Other study that can derive from this is related to the “optimization” of the results. Once the first SA results are obtained, top parameters can be used to run an optimization process based on a parametric sensitivity, i.e. simultaneous variation of top parameters in steps, to determine best combination to “optimize” results. Also this study can verify, if the results are aligned to the manufacturing process behavior. Even more, the “optimization” can be run not only one metric (TH, CT & WIP) at a time, but trying to improve all three at the same time.

The model used on this study is deterministic (but take into account some variations), so it can be expanded to a stochastic approach or to a simulation tool that determines the sensitivity analysis results. These results can be compared with the ones obtained in order to determine, not only how different they are, but to compare them to real manufacturing line behaviors.

One limitation of the current proposal is that lacks of standard parameter to compare and prioritize the ideas that are not performance metrics related like space reductions, inventory, scrap, rework, layout changes, etc. In order to improve the comparison, the use of approximate savings generated can be helpful. In this manner, all the ideas can be prioritized using the same criteria. This study can be based on the development of the rules to follow to transform performance metric improvement into savings in a standardized way.

Finally these results and further studies can be applied to other areas as well. In design, as an example, the application of this methodology can help to identify clearly, opportunity areas to improve. In this environment, the most important part is to define how to model the entire design process, due to its highly variable in scopes and requirements. The same applies to other areas where special adaptations of the concepts and ideas will be required.

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APPENDICES

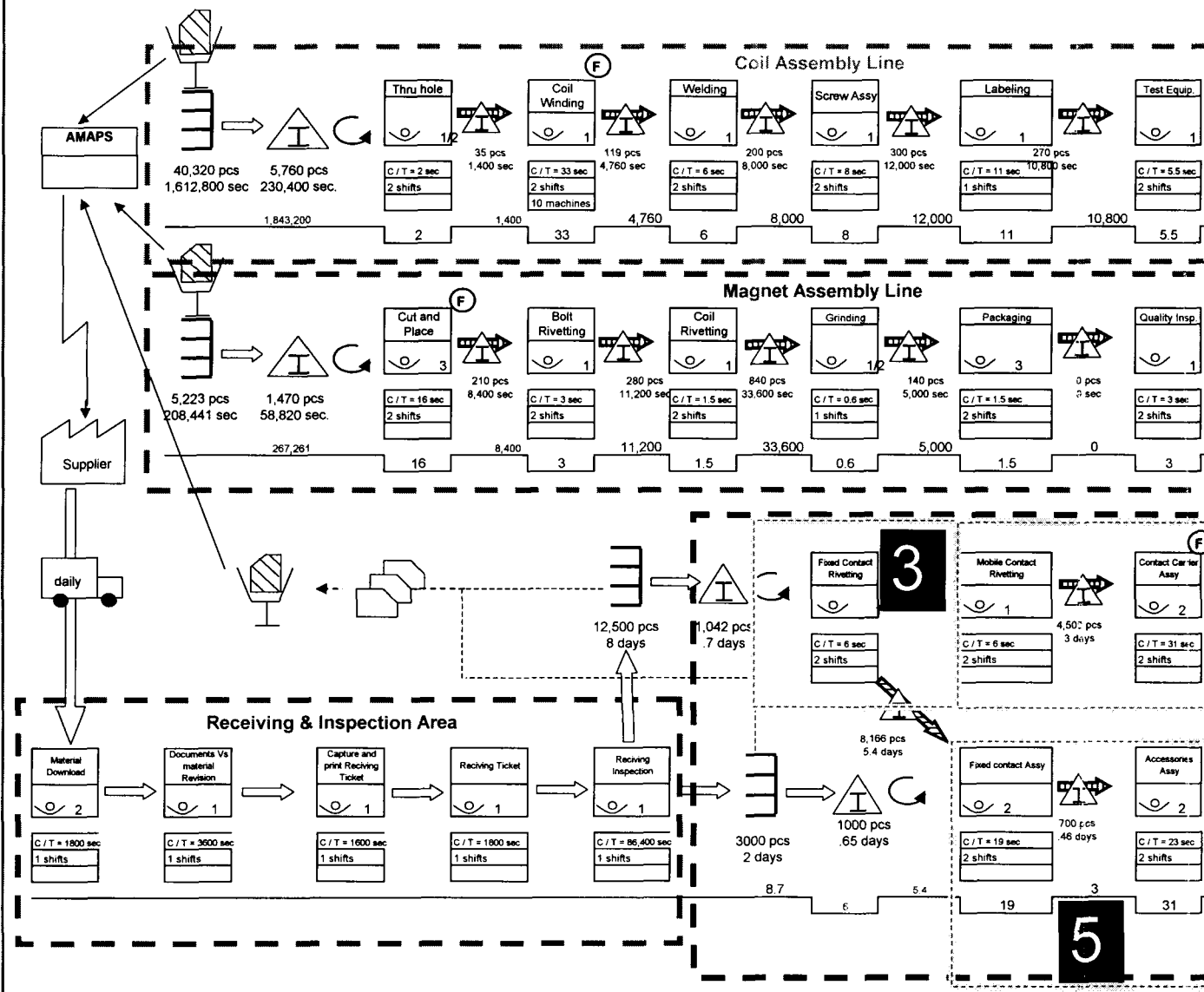
APPENDIX A.
Contactor Line – VSM

CURRENT S

Current State Map from: DPA, Magnet and Coils line

Family: 2 and 3 Poles

Date: July 19 2002



- 1 Coil Assy
- 2 Magnet Assy
- 3 Fixed Contact Rivet
- 4 Movil Contact Assy
- 5 Main Assy Line Start
- 6 Main Assy Line Carrier Assy
- 7 Main Assy Line



APPENDIX B.
Contactor Line – Model

1 Coil Assembly

Shifts		1	1	1	1	1	1	1
Hrs. / Shift		8						
MEASURE:	STATION:	Thru hole	Coil winding	Welding	Screw Assy	Labeling	Test	Quality Insp.
Arrival Rate (parts/hr)	r_a	212.500	212.500	210.375	210.375	210.375	210.375	208.271
Arrival CV	c_a^2	0.000	1.928	1.935	1.797	1.578	1.348	1.300
Natural Process Time (hr)	t_0	0.00055556	0.00916667	0.00166667	0.00222222	0.00305556	0.00152778	0.00083333
Natural Process SCV	c_0^2	0.750	0.750	0.750	0.750	0.750	0.750	0.750
Number of Machines	m	0.5	10	1	1	1	1	1
MTTF (hr)	m_f	2400	230	5000	5000	600	2400	5000
MTTR (hr)	m_r	4	2	0.5	0.5	0.5	0.5	0.5
Availability	A	0.998	0.991	1.000	1.000	0.999	1.000	1.000
Effective Process Time (failures only)	t_e	0.001	0.009	0.002	0.002	0.003	0.002	0.001
Eff Process SCV (failures only)	c_e^2	24.670	4.479	0.810	0.795	1.022	0.886	0.870
Batch Size	k	1	1	1	1	1	1	1
Setup Time (hr)	t_s	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Setup Time SCV	c_s^2	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Arrival Rate of Batches	r_b/k	212.500	212.500	210.375	210.375	210.375	210.375	208.271
Eff Batch Process Time (failures+setups)	$t_b = kt_0/A + t_s$	0.001	0.009	0.002	0.002	0.003	0.002	0.001
Eff Batch Process Time Var (failures+setups)	$k^2 \sigma_0^2 / A^2 + 2m_r(1-A)kt_0/A + \sigma_s^2$	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Eff Process SCV (failures+setups)	c_b^2	24.670	4.479	0.810	0.795	1.022	0.886	0.870
Utilization	u	0.237	0.196	0.351	0.468	0.643	0.321	0.174
Departure SCV	c_d^2	1.928	1.935	1.797	1.578	1.348	1.300	1.287
Yield	y	1.000	0.990	1.000	1.000	1.000	0.990	0.990
Final Departure Rate	$r_b * y$	212.500	210.375	210.375	210.375	210.375	208.271	206.189
Final Departure SCV	$yc_d^2 + (1-y)$	1.928	1.926	1.797	1.578	1.348	1.297	1.284
Utilization	u	0.237	0.196	0.351	0.468	0.643	0.321	0.174
Throughput	TH	212.500	210.375	210.375	210.375	210.375	208.271	206.189
Queue Time (hr)	CT_q	0.006	0.000	0.001	0.003	0.007	0.001	0.000
Cycle Time (hr)	$CT_q + t_e$	0.007	0.009	0.003	0.005	0.010	0.002	0.001
Cumulative Cycle Time (hr)	$\sum_i (CT_q(i) + t_e(i))$	0.007	0.016	0.019	0.024	0.034	0.036	0.037
WIP in Queue (jobs)	$r_b CT_q$	1.330	0.002	0.260	0.532	1.509	0.170	0.040
WIP (jobs)	$r_b CT$	1.448	1.967	0.611	1.000	2.152	0.492	0.213
Cumulative WIP (jobs)	$\sum_i (r_b(i) CT(i))$	1.448	3.415	4.025	5.025	7.177	7.669	7.882
0.643	Labeling	Thru hole	Coil winding	Welding	Screw Assy	Labeling	Test	Quality Insp.
327								

2 Magnet Assy

Shifts		1	1	1	1	1	1
Hrs. / Shift		8					
MEASURE:	STATION:	Cut & place	Bolt rivet	Coil rivet	Grinding	Packaging	Quality Insp.
Arrival Rate (parts/hr)	r_a	425.000	425.000	422.875	418.646	416.553	416.553
Arrival CV	c_a^2	0.000	0.344	0.521	1.273	2.362	2.358
Natural Process Time (hr)	t_0	0.00444444	0.00083333	0.00041667	0.00016667	0.00041667	0.00083333
Natural Process SCV	c_0^2	0.750	0.750	0.750	0.750	0.750	0.750
Number of Machines	m	3	1	1	0.5	3	1
MTTF (hr)	m_f	5000	2400	200	1200	5000	5000
MTTR (hr)	m_r	0.5	1	1	2	0.5	0.5
Availability	A	1.000	1.000	0.995	0.998	1.000	1.000
Effective Process Time (failures only)	t_e	0.004	0.001	0.000	0.000	0.000	0.001
Eff Process SCV (failures only)	c_e^2	0.772	1.749	24.512	40.617	0.990	0.870
Batch Size	k	1	1	1	1	1	1
Setup Time (hr)	t_s	0.000	0.000	0.000	0.000	0.000	0.000
Setup Time SCV	c_s^2	1.000	1.000	1.000	1.000	1.000	1.000
Arrival Rate of Batches	r_a/k	425.000	425.000	422.875	418.646	416.553	416.553
Eff Batch Process Time (failures+setups)	$t_e = kt_0/A + t_s$	0.004	0.001	0.000	0.000	0.000	0.001
Eff Batch Process Time Var (failures+setups)	$k^2\sigma_0^2/A^2 + 2m_r(1-A)kt_0/A + \sigma_s^2$	0.000	0.000	0.000	0.000	0.000	0.000
Eff Process SCV (failures+setups)	c_e^2	0.772	1.749	24.512	40.617	0.990	0.870
Utilization	u	0.630	0.354	0.177	0.140	0.058	0.347
Departure SCV	c_d^2	0.344	0.521	1.273	2.362	2.358	2.179
Yield	y	1.000	0.995	0.990	0.995	1.000	1.000
Final Departure Rate	$r_a * y$	425.000	422.875	418.646	416.553	416.553	416.553
Final Departure SCV	$yc_d^2 + (1-y)$	0.344	0.523	1.270	2.356	2.358	2.179
Utilization	u	0.630	0.354	0.177	0.140	0.058	0.347
Throughput	TH	425.000	422.875	418.646	416.553	416.553	416.553
Queue Time (hr)	CT_q	0.001	0.000	0.001	0.002	0.000	0.001
Cycle Time (hr)	$CT_q + t_e$	0.005	0.001	0.002	0.002	0.000	0.002
Cumulative Cycle Time (hr)	$\Sigma_i(CT_q(i) + t_e(i))$	0.005	0.006	0.008	0.010	0.010	0.012
WIP in Queue (jobs)	$r_a CT_q$	0.282	0.204	0.477	0.806	0.001	0.298
WIP (jobs)	$r_a CT$	2.171	0.558	0.654	0.876	0.174	0.645
Cumulative WIP (jobs)	$\Sigma_i(r_a(i)CT(i))$	2.171	2.729	3.383	4.259	4.433	5.078
0.630	Cut & place	Cut & place	Bolt rivet	Coil rivet	Grinding	Packaging	Quality Insp.
675							

3 Fixed Contact Assy

Shifts		2
Hrs. / Shift	8	
MEASURE:	STATION:	Fixed Contact Rivet
Arrival Rate (parts/hr)	r_s	658.750
Arrival CV	c_s^2	0.000
Natural Process Time (hr)	t_0	0.00166667
Natural Process SCV	c_0^2	0.750
Number of Machines	m	1.33
MTTF (hr)	m_f	200
MTTR (hr)	m_r	0.5
Availability	A	0.998
Effective Process Time (failures only)	t_e'	0.002
Eff Process SCV (failures only)	$c_e'^2$	2.243
Batch Size	k	1
Setup Time (hr)	t_s	0.000
Setup Time SCV	c_s^2	1.000
Arrival Rate of Batches	r_s/k	658.750
Eff Batch Process Time (failures+setups)	$t_e = kt_0/A + t_s$	0.002
Eff Batch Process Time Var (failures+setups)	$k^2\sigma_0^2/A^2 + 2m_r(1-A)kt_0/A + \sigma_s^2$	0.000
Eff Process SCV (failures+setups)	c_e^2	2.243
Utilization	u	0.828
Departure SCV	c_d^2	1.423
Yield	y	1.000
Final Departure Rate	$r_s \cdot y$	658.750
Final Departure SCV	$yc_d^2 + (1-y)$	1.423
Utilization	u	0.828
Throughput	TH	658.750
Queue Time (hr)	CT_q	0.007
Cycle Time (hr)	$CT_q + t_e$	0.008
Cumulative Cycle Time (hr)	$\sum_i (CT_q(i) + t_e(i))$	0.008
WIP in Queue (jobs)	$r_s CT_q$	4.322
WIP (jobs)	$r_s CT$	5.422
Cumulative WIP (jobs)	$\sum_i (r_s(i) CT(i))$	5.422
0.828	Fixed Contact Rivet	Fixed Contact Rivet
798		

4 Movil Contact Assy

Shifts		2	2
Hrs. / Shift	8		

MEASURE:	STATION:	Contact Rivet	Carrier Assy
Arrival Rate (parts/hr)	r_a	332.563	332.563
Arrival CV	c_a^2	0.000	2.986
Natural Process Time (hr)	t_0	0.00166667	0.00861111
Natural Process SCV	c_0^2	0.750	0.750
Number of Machines	m	0.67	3
MTTF (hr)	m_f	400	5000
MTTR (hr)	m_r	1	0.5
Availability	A	0.998	1.000
Effective Process Time (failures only)	t_e'	0.002	0.009
Eff Process SCV (failures only)	$c_e'^2$	3.735	0.762
Batch Size	k	1	1
Setup Time (hr)	t_s	0.000	0.000
Setup Time SCV	c_s^2	1.000	1.000
Arrival Rate of Batches	r_a/k	332.563	332.563
Eff Batch Process Time (failures+setups)	$t_e = kt_0/A + t_s$	0.002	0.009
Eff Batch Process Time Var (failures+setups)	$k \cdot \sigma_0^2 / A^2 + 2m_r(1-A)kt_0/A + \sigma_s^2$	0.000	0.000
Eff Process SCV (failures+setups)	c_e^2	3.735	0.762
Utilization	u	0.829	0.955
Departure SCV	c_d^2	2.986	1.051
Yield	y	1.000	0.995
Final Departure Rate	$r_a \cdot y$	332.563	330.900
Final Departure SCV	$yc_d^2 + (1-y)$	2.986	1.050
Utilization	u	0.829	0.955
Throughput	TH	332.563	330.900
Queue Time (hr)	CT_q	0.023	0.109
Cycle Time (hr)	$CT_q + t_e$	0.025	0.118
Cumulative Cycle Time (hr)	$\sum_i (CT_q(i) + t_e(i))$	0.025	0.143
WIP in Queue (jobs)	$r_a CT_q$	7.773	36.257
WIP (jobs)	$r_a CT$	8.329	39.121
Cumulative WIP (jobs)	$\sum_i (r_a(i) CT(i))$	8.329	47.450
	0.955	Carrier Assy	Contact Rivet
	348		Carrier Assy

5 Main Assy Line Start

Shifts		2	2
Hrs. / Shift		8	
MEASURE:	STATION:	Fixed C Assy	Accessories
Arrival Rate (parts/hr)	r_a	106.250	106.250
Arrival CV	c_a^2	1.423	1.377
Natural Process Time (hr)	t_0	0.00527778	0.00638889
Natural Process SCV	c_0^2	0.750	0.750
Number of Machines	m	2	2
MTTF (hr)	m_f	5000	5000
MTTR (hr)	m_r	0.5	0.5
Availability	A	1.000	1.000
Effective Process Time (failures only)	t_e'	0.005	0.006
Eff Process SCV (failures only)	$c_e'^2$	0.769	0.766
Batch Size	k	1	1
Setup Time (hr)	t_s	0.000	0.000
Setup Time SCV	c_s^2	1.000	1.000
Arrival Rate of Batches	r_a/k	106.250	106.250
Eff Batch Process Time (failures+setups)	$t_e = kt_0/A + t_s$	0.005	0.006
Eff Batch Process Time Var (failures+setups)	$k^2\sigma_0^2/A^2 + 2m_r(1-A)kt_0/A + \sigma_s^2$	0.000	0.000
Eff Process SCV (failures+setups)	c_e^2	0.769	0.766
Utilization	u	0.280	0.339
Departure SCV	c_d^2	1.377	1.314
Yield	y	1.000	1.000
Final Departure Rate	r_a^*y	106.250	106.250
Final Departure SCV	$yc_d^2 + (1-y)$	1.377	1.314
Utilization	u	0.280	0.339
Throughput	TH	106.250	106.250
Queue Time (hr)	CT_q	0.001	0.001
Cycle Time (hr)	$CT_q + t_e$	0.006	0.007
Cumulative Cycle Time (hr)	$\sum_i (CT_q(i) + t_e(i))$	0.006	0.013
WIP in Queue (jobs)	$r_a CT_q$	0.068	0.115
WIP (jobs)	$r_a CT'$	0.628	0.794
Cumulative WIP (jobs)	$\sum_i (r_a(i) CT(i))$	0.628	1.422
	0.339	Accessories	Fixed C Assy Accessories
	313		

6 Main Assy Line Carrier Assy

Shifts	2	
Hrs. / Shift	8	
MEASURE:	STATION:	Magnet & Co
Arrival Rate (parts/hr)	r_a	104.138
Arrival CV	c_a^2	2.179
Natural Process Time (hr)	t_0	0.00166667
Natural Process SCV	c_0^2	0.750
Number of Machines	m	1
MTTF (hr)	m_f	5000
MTTR (hr)	m_r	0.5
Availability	A	1.000
Effective Process Time (failures only)	t_e'	0.002
Eff Process SCV (failures only)	$c_e'^2$	0.810
Batch Size	k	1
Setup Time (hr)	t_s	0.000
Setup Time SCV	c_s^2	1.000
Arrival Rate of Batches	r_a/k	104.138
Eff Batch Process Time (failures+setups)	$t_e = kt_0/A + t_s$	0.002
Eff Batch Process Time Var (failures+setups)	$k^2 \sigma_0^2 / A^2 + 2m_r(1-A)kt_0/A + \sigma_s^2$	0.000
Eff Process SCV (failures+setups)	c_e^2	0.810
Utilization	u	0.174
Departure SCV	c_d^2	2.137
Yield	y	1.000
Final Departure Rate	$r_a * y$	104.138
Final Departure SCV	$yc_d^2 + (1-y)$	2.137
Utilization	u	0.174
Throughput	TH	104.138
Queue Time (hr)	CT_q	0.001
Cycle Time (hr)	$CT_q + t_e$	0.002
Cumulative Cycle Time (hr)	$\sum_i (CT_q(i) + t_e(i))$	0.002
WIP in Queue (jobs)	$r_a CT_q$	0.054
WIP (jobs)	$r_a CT$	0.228
Cumulative WIP (jobs)	$\sum_i (r_a(i) CT(i))$	0.228
0.174	Magnet & Contact Carrier Assy	Magnet & Co
600		

7 Main Assy Line

Shifts	2	2	2	2	2	2
Hrs. / Shift	8					

MEASURE:	STATION:	Magnet & Cd	Nameplate	Test	Visual Insp.	Packing	Quality Insp.	
Arrival Rate (parts/hr)	r_a	103.094	103.094	103.094	102.063	101.043	101.043	
Arrival CV	c_a^2	1.284	1.203	1.195	1.475	1.462	1.384	
Natural Process Time (hr)	t_0	0.00388889	0.00138889	0.00305556	0.00138889	0.00166667	0.00031111	
Natural Process SCV	c_0^2	0.750	0.750	0.750	0.750	0.750	0.750	
Number of Machines	m	1	1	1	1	1	1	
MTTF (hr)	m_f	5000	5000	200	5000	5000	5000	
MTTR (hr)	m_r	0.5	0.5	1	0.5	0.5	0.5	
Availability	A	1.000	1.000	0.995	1.000	1.000	1.000	
Effective Process Time (failures only)	t_e'	0.004	0.001	0.003	0.001	0.002	0.000	
Eff Process SCV (failures only)	$c_e'^2$	0.776	0.822	3.990	0.822	0.810	1.071	
Batch Size	k	1	1	1	1	50	1	
Setup Time (hr)	t_s	0.000	0.000	0.000	0.000	0.033	0.000	
Setup Time SCV	c_s^2	1.000	1.000	1.000	1.000	0.750	1.000	
Arrival Rate of Batches	r_s/k	103.094	103.094	103.094	102.063	2.021	101.043	
Eff Batch Process Time (failures+setups)	$t_e = kt_0/A + t_s$	0.004	0.001	0.003	0.001	0.117	0.000	
Eff Batch Process Time Var (failures+setups)	$k*\sigma_0^2/A^2 + 2m_r(1-A)kt_0/A + \sigma_s^2$	0.000	0.000	0.000	0.000	0.001	0.000	
Eff Process SCV (failures+setups)	c_e^2	0.776	0.822	3.990	0.822	0.069	1.071	
Utilization	u	0.401	0.143	0.317	0.142	0.236	0.031	
Departure SCV	c_d^2	1.203	1.195	1.475	1.462	1.384	1.384	
Yield	y	1.000	1.000	0.990	0.990	1.000	0.995	
Final Departure Rate	r_a*y	103.094	103.094	102.063	101.043	101.043	100.537	
Final Departure SCV	$yc_d^2 + (1-y)$	1.203	1.195	1.470	1.457	1.384	1.382	
Utilization	u	0.401	0.143	0.317	0.142	0.236	0.031	
Throughput	TH	103.094	103.094	102.063	101.043	101.043	100.537	
Queue Time (hr)	CT_q	0.003	0.000	0.004	0.000	0.028	0.000	
Cycle Time (hr)	$CT_q + t_e$	0.007	0.002	0.007	0.002	0.144	0.000	
Cumulative Cycle Time (hr)	$\Sigma_i(CT_q(i) + t_e(i))$	0.007	0.008	0.015	0.017	0.161	0.161	Cumulative
WIP in Queue (jobs)	$r_a CT_q$	0.276	0.024	0.380	0.027	2.785	0.001	
WIP (jobs)	$r_a CT$	0.677	0.167	0.697	0.169	14.574	0.033	Cumulative
Cumulative WIP (jobs)	$\Sigma_i(r_a(i)CT(i))$	0.677	0.845	1.542	1.710	16.284	16.317	83.799
	0.401	Magnet & Coil Assy	Magnet & Coil Nameplate	Test	Visual Insp.	Packing	Quality Insp.	
	257							

APPENDIX C.
Contactors Line – Results

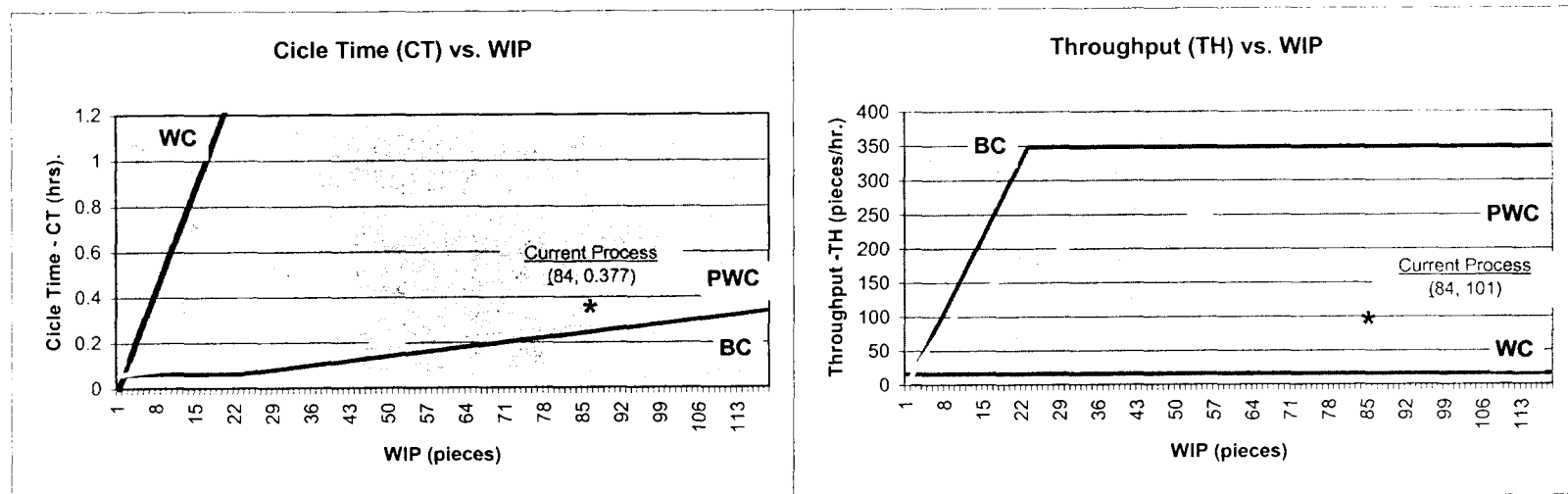
Schneider Electric's Contactor Line Results

	pieces/day	Station	Line
Demand (Input)	1700		
Max. Utilization	u	0.955	Carrier Assy Movil Contact Assy
Final Throughput	TH	101	pieces/hr
Final Throughput	TH	804	pieces/shift 1609 pieces/day
Cumulative Cycle Time (hr)	$S_i(CT_a(i)+t_c(i))$	0.377	hrs.
Cumulative WIP (jobs)	$S_i(r_a(i)CT(i))$	84	pieces

Performance vs. PWC	
Throughput	Below
Cycle Time	Below

	Best Case	Practical WC	Worst Case	
CT	0.241	0.301	5.302	hrs.
TH	348	279	16	pieces/hr

Utilization (maximum/line)		0.643	0.630	0.828	0.955	0.339	0.174	0.401
r_b (Bottleneck rate)	348	327	675	798	348	313	600	257
Station	Carrier Assy	Labeling	Cut & place	Fixed Contact I	Carrier Assy	Accessories	Magnet & Cont	Magnet & Coil
Line	Movil Contact	Coil Assy	Magnet Assy	Fixed Contact I	Movil Contact	Main Assy Line	Main Assy Line	Main Assy Line

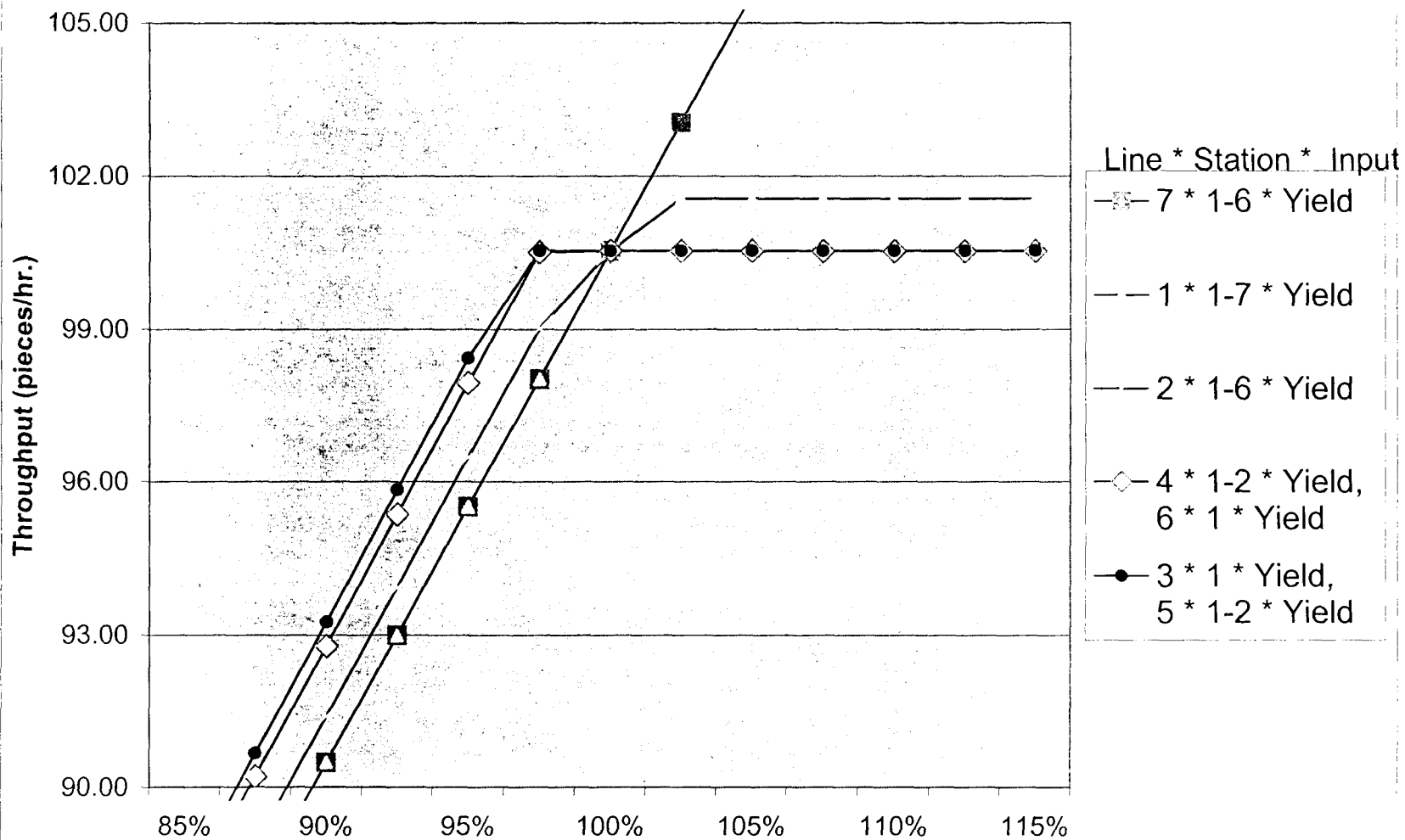


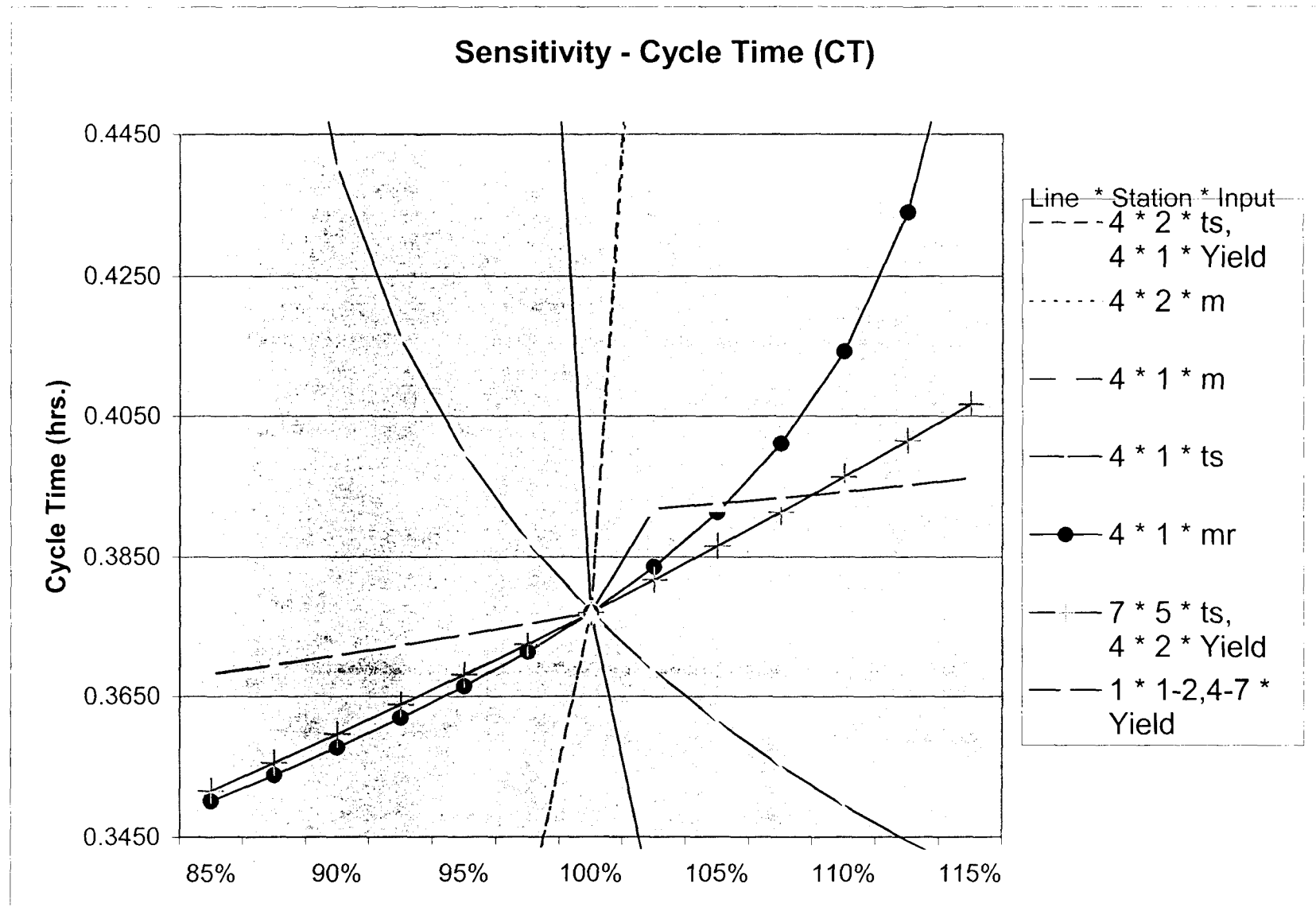
APPENDIX D.
Sensibility Analysis – Results by Stations

APPENDIX E.
Sensibility Analysis – Results by Priority

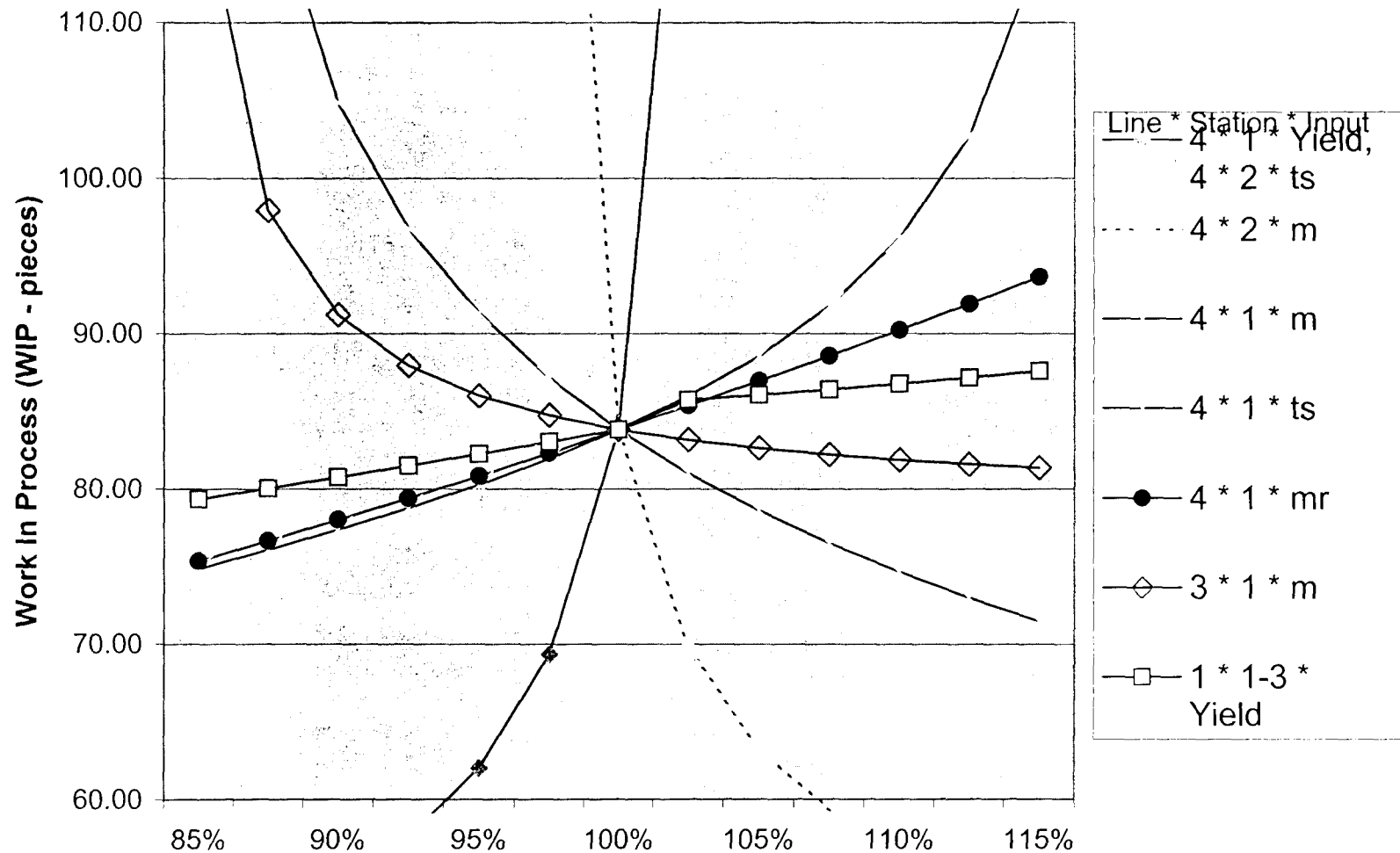
APPENDIX F.
Sensibility Analysis – Graphs

Sensitivity - Throughput (TH)





Sensitivity - Work In Process (WIP)

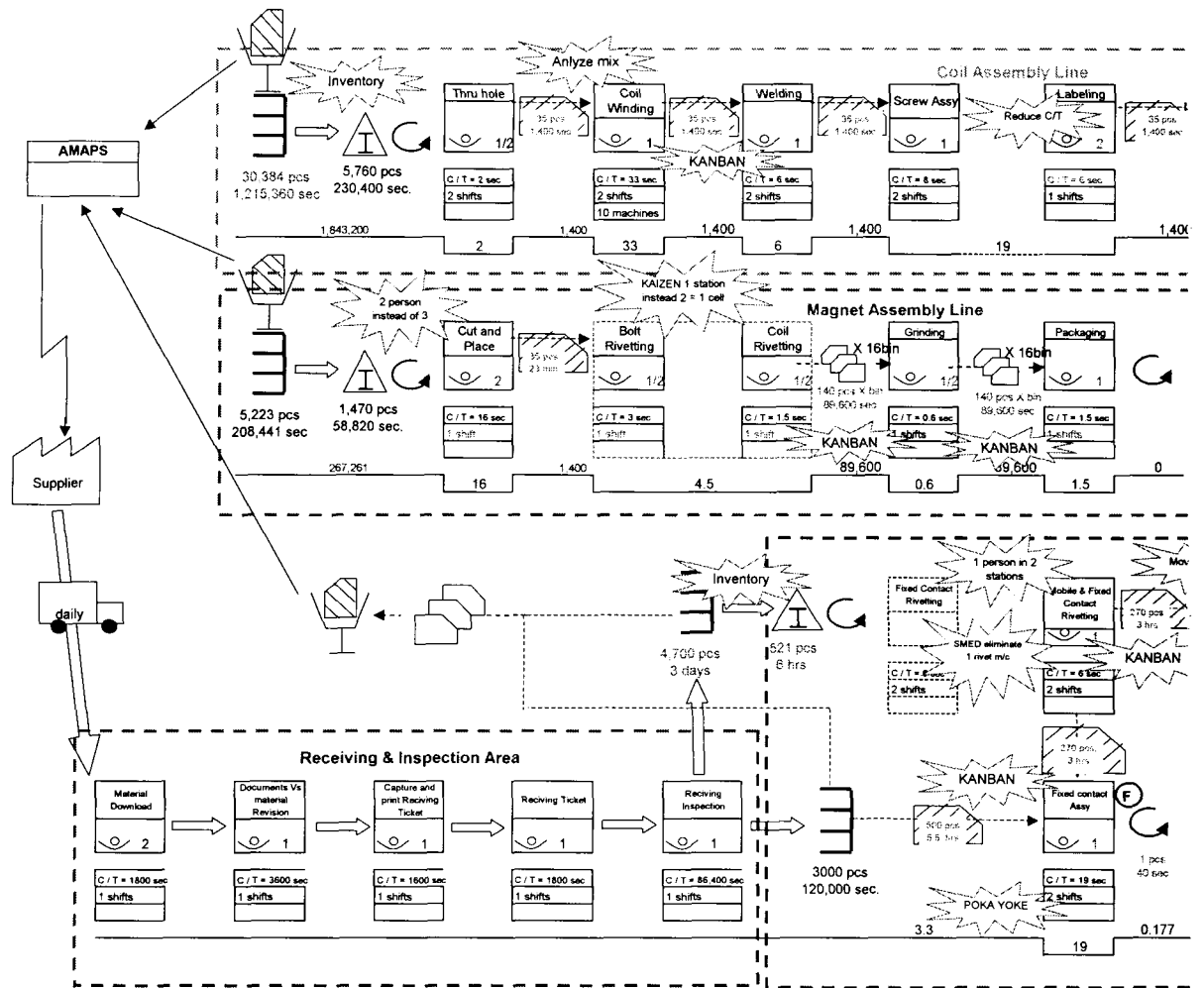


APPENDIX G.
Sensibility Analysis – Prior Ideas VSM

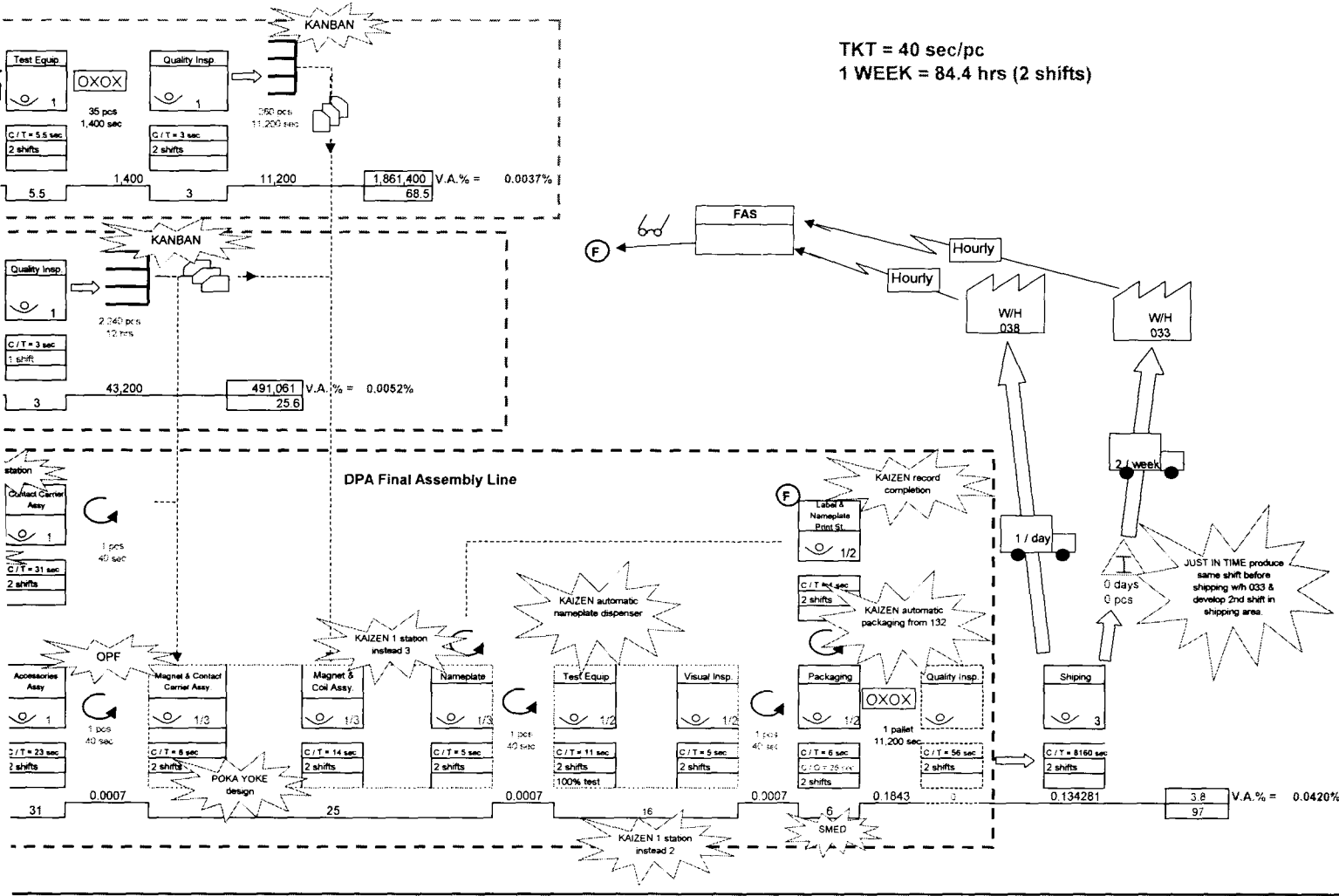
Current State Map from: DPA, Magnet and Coils line

Family: 2 and 3 Poles

Date: July 19 2002



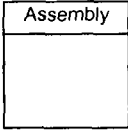
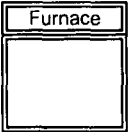
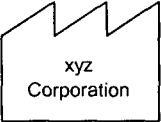
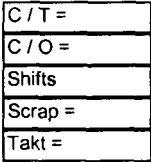
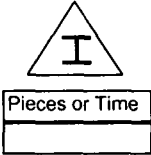
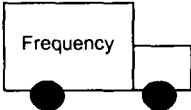
FUTURE STATE MAP



DATE:	07/19/2002						
FACILITY MANAGER:	Joe Blanck						
VS MANAGER:							
Product Family Buisness Objective	VS LOOP	Value Stream Objective	GOAL (measurable)		2002 MOI		
					July	August	September
Improve profitability in DPA contactors final assembly.	1	Reduce the process inventory in "Contact riveting assy" process	1 shift inv.	PLAN	→		
				REAL			
	2	Define the optimum process inventory (buffer) in "Contact riveting assy"	3 hrs.	PLAN	→		
				REAL			
	3	Reduce the # of person and shift in rivetting process. (2 m/c)	1 person 1 shift	PLAN	→		
				REAL			
	4	Analyze if it's factible SMED in 2 rivetting process	1 m/c instead of 2	PLAN	→		
				REAL			
	5	Reduce the # of person in "Contact assembly" process.	1 person	PLAN	→		
				REAL			
	6	POKA YOKE fixture in "Contact assembly" process (avoid contact assy mistake)	0 % defects	PLAN	→		
				REAL			
	7	Reduce the supermarket inventory in terminals and silver rivetts (actual 1.6 weeks, analyze optimum weeks)	3 or less weeks	PLAN	→		
				REAL			
	8	Reduce the supermarket inventory in block 31149-057-01 (analyze optimum weeks)	1 week or less	PLAN	→		
				REAL			
	9	Reduce the # of person in "Accesories assembly" & "Contact carrier assy" process.	1 person	PLAN	→		
				REAL			
	10	Implement ONE PIECE FLOW from "Assembly contact" to "Packaging"	1 piece maximum as buffer	PLAN	→		
				REAL			
	11	Analyze to remove at minimum the WIP in line.	1 shift / reduce minimum 30% space in line	PLAN	→		
			REAL				
12	Move the "Contact carrier assy" next to "Magnet Assy" process.	0 inventory between this station and final assy line	PLAN	→			
			REAL				
13	Analyze redesign the block and terminal to avoid process mistake (POKA YOKE design)	0 % defects	PLAN	PLE report if the change don't reduce will be pending.			
			REAL				
14	Reduce to 1 station the "contact carrier and magnet assy", "Coil and Clip assy" and "Labels"	Tak time = 26	PLAN	→			
			REAL				
15	Improve DPA, magnetics and coils lay-out.	Reduce maximum space	PLAN	→			
			REAL				
16	Evaluate install label automatic feeder ti test equipment	0 % defects / blance label operation and test eq. Cycle time	PLAN	→			
			REAL				
17	Evaluate the movement of automatic packaging m/c from 132 to DPA packaging station	0 % defects / eliminate manual operations	PLAN	→			
			REAL				
18	SMED in packaging station (actual 124 sec)	Change over = 25 sec.	PLAN	→			
			REAL				
19	Evaluate eliminate final inspetion to process inspection	Eliminate operation	PLAN	→			
			REAL				
20	Reduce 1 station the Test and Visual Insp.	Eliminate operation	PLAN	→			
			REAL				
21	Implement record completion in packaging assy (lift tables, signal light to shiping dep)	0 inventory in shiping area	PLAN	→			
			REAL				

YEARLY VALUE STREAM PLAN							WRITTEN	CHECKED	APPROVED	
HLY SCHEDULE			PERSON IN CHARGE	RELATED IND. & DEPTMTS	REVIEW SCHEDULE		ADVANCE %			
October	November	December			REVIEWER	DATE	25	50	75	100
			J.C. Peña							
			C. Gutierrez							
			J.C. Peña							
			C. Gutierrez							
			J.C. Peña							
			C. Gutierrez							
			A. Chang							
			A. Chang							
			J.C. Peña							
→			C. Gutierrez							
			G. Solis							
			C. Gutierrez							
cost, will not apply right now. This activity			E. Rocha							
			C. Gutierrez							
→			C. Gutierrez							
			C. Gutierrez							
			C. Gutierrez							
			C. Gutierrez							
			C. Gutierrez							
			F. Garza							
			C. Gutierrez							
			J.C. Peña							

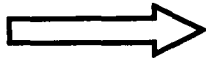
APPENDIX H.
Value Stream Map – Icons

Material Icons	Represents	Notes
	Manufacturing Process	One process box equals an area of flow. All processes should be labeled. Also used for departments.
	Shared Manufacturing Process	
	Outside Sources	Used to show customers, suppliers, and outside manufacturing processes.
	Data Box	Used to record information concerning a manufacturing process, department, customer, etc.
	Inventory	Count and time should be noted.
	Truck Shipment	Note frequency of shipments



Movement of
production material by
Push

Material that is produced and moved
forward before the next process
needs it; usually based on a
schedule.



Movement of finished
goods to the customer

Max. 20 pieces
--FIFO-->

Transfer of controlled
quantities of material

Indicates a device to limit quantity
and ensure FIFO flow of material
between processes. Maximum
quantity should be noted.



Supermarket

A controlled inventory of parts that is
used to schedule production at an
upstream process.



Withdrawal

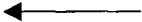
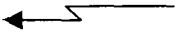
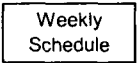
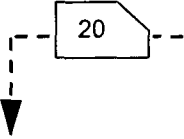
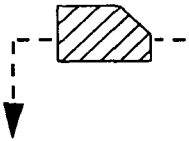
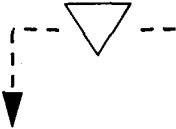

Pull of materials, usually from a
supermarket.

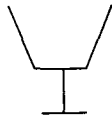


Move by Forklift



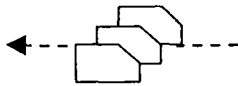
Boat Shipment

Information Icons	Represents	Notes
	Manual Information Flow	As production schedule or shipping schedule.
	Electronic Information Flow	Via electronic data interchange.
	Information	Describes an information flow.
	Production Kanban	Kanban path on dotted lines. The "once-per-container" kanban. Card or device that tells a process how many of what can be produced and gives permission to do so.
	Withdrawal Kanban	Kanban path on dotted lines. Card or device that instructs the material handler to get and transfer parts.
	Signal Kanban	The "one-per-batch" kanban. Signals when a reorder point is reached and another batch needs to be produced. Used where supplying process must produce in batches because changeovers are required.
	Sequenced-Pull Ball	Gives instruction to immediately produce a predemied type and quantity, typically one unit. A pull system for subassembly processes without using supermarket.

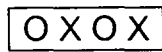


Kanban Post

Place where kanban cards are collected and held for conveyance.

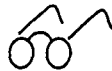


Kanban Arriving in Batches







Lead Leveling

Tool to intercept batches of kanban “
and level the volume and mix of
them over a period of time.



"Go See" Production
Scheduling

Adjusting schedules based on
checking inventory levels.

General Icons	Represents	Notes
	Kaizen Lightening Burst	Highlights improvement needs at specific processes that are critical to achieve the value stream vision. Can be used to plan kaizen workshops.
	Buffer or Safety Stock	
	Operator	Represents a person viewed from above.
	Quality Problem	

APPENDIX I.
Factory Physics Principles

Factory Physics Principles

Little's Law: The fundamental relation between WIP, CT, and TH over the long-

$$\text{WIP} = \text{TH} \times \text{CT}$$

term is:

so same throughput can be obtained with large WIP, long CT or small WIP, short CT.

Critical WIP (W_0): WIP level in which a line having no congestion would achieve maximum throughput (i.e., r_b) with minimum cycle time (i.e., T_0).

$$W_0 = r_b T_0$$

Best Case Law (no randomness, no variability): The Best Case yields the minimum cycle time and maximum throughput for each WIP level.

$$\text{CT}_{\text{best}} = \begin{cases} T_0, & \text{if } w \leq W_0 \\ w / r_b, & \text{otherwise.} \end{cases} \quad \text{TH}_{\text{best}} = \begin{cases} w / T_0, & \text{if } w \leq W_0 \\ r_b, & \text{otherwise.} \end{cases}$$

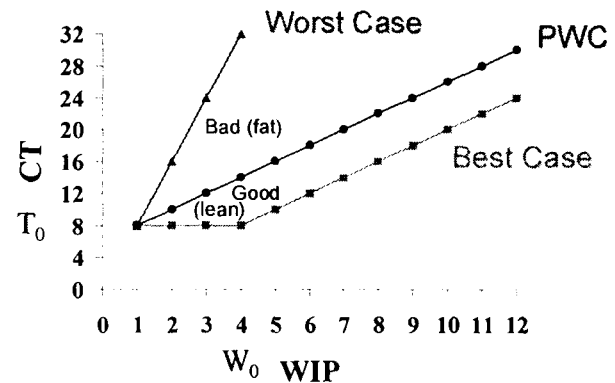
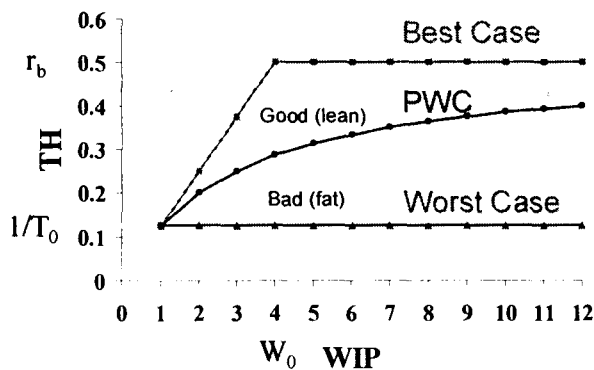
Worst Case Law (no randomness, highest variability): imagine marked job experiences maximum queuing

$$\text{CT}_{\text{worst}} = w T_0$$

$$\text{TH}_{\text{worst}} = 1 / T_0$$

Practical Worst Case Definition (highest randomness): variability such that all WIP configurations (states) are equally likely

$$\text{CT}_{\text{PWC}} = T_0 + \frac{w-1}{r_b} \quad \text{TH}_{\text{PWC}} = \frac{w}{W_0 + w - 1} r_b,$$



Law (Labor Capacity): The maximum capacity of a line staffed by n cross-trained operators with identical work rates is
 $TH_{max} = n/T_0$

Law (Variability): Increasing variability always degrades performance of a production system.

Corollary (Variability Placement): In a line with where releases are independent of completions, variability early in a routing increases cycle time more than equivalent variability later in the routing.

Law (Variability Buffering): Variability in a production system will be buffered by some combination of:

1. inventory,
2. capacity,
3. time.

Corollary (Buffer Flexibility): Flexibility reduces the amount of variability buffering required in a production system.

Law (Conservation of Material): In a stable system, over the long run, the rate out of a system will equal the rate in, less any yield loss, plus any parts production within the system.

Law (Capacity): In steady state, all plants will release work at an average rate that is strictly less than the average capacity.

Law (Utilization): If a station increases utilization without making any other changes, average cycle time will increase in a highly nonlinear fashion.

Law (Process Batching): In stations with batch operations or with significant changeover times:

1. The minimum process batch size that yields a stable system may be greater than one.
2. As process batch size becomes larger, cycle time grows proportionally with batch size.
3. Cycle time at the station will be minimized for some process batch size, which may be greater than one.

Law (Move Batching): Cycle times over a segment of a routing are roughly proportional to the transfer batch sizes used over that segment, provided there is no waiting for the conveyance device.

Law (Assembly Operations): The performance of an assembly station is degraded by increasing any of the following:

1. number of components being assembled,
2. variability of component arrivals,
3. lack of coordination between component arrivals.

Definition (Station Cycle Time): The average cycle time at a station is made up of the following components: cycle time = move time + queue time + setup time + process time + wait-to-batch time + wait-in-batch time + wait-to-match time

Definition (Line Cycle Time): The average cycle time in a line is equal to the sum of the cycle times at the individual stations less any time that overlaps two or more stations.

Law (Rework): For a given throughput level, rework increases both the mean and standard deviation of the cycle time of a process.

Law (Lead Time): The manufacturing lead time for a routing that yields a given service level is an increasing function of both the mean and standard deviation of the cycle time of the routing.

Law (CONWIP Efficiency): For a given level of throughput, a push system will have more WIP on average than an equivalent CONWIP system.

Law (CONWIP Robustness): A CONWIP system is more robust to errors in WIP level than a pure push system is to errors in release rate.

Law (Self-Interest): People, not organizations, are self-optimizing.

Law (Individuality): People are different.

Law (Advocacy): For any program, there exists a champion who can make it work, . . . at least for a while.

Law (Burn-out): People get burned out.

Law (Responsibility): Responsibility without commensurate authority is demoralizing and counterproductive.

Performance Measures: Throughput, WIP, Cycle Time, Service

APPENDIX J.
Lean Manufacturing Glossary

Glossary.

Changeover Time	When a given work center is changing production from one part to another, it represents the amount of time from making the last good piece of unit A to the start of production of the first good piece of unit B. Also known as set-up time .
Consignment Inventory	Inventory, generally finished goods, that are in the possession of the customer or in a nearby warehouse, but remain the property of the manufacturer by agreement of those in possession.
Constraint	A work center or machine that lacks capability or capacity to produce a part within the necessary TAKT time.
Daily Rate	The number of a particular product required to be made on a certain day, based upon customer demand.
Demand at Capacity	The highest targeted daily volume of output of units that is planned to be achieved by the flow line.
Demand Flow Technology (DFT)	Copyrighted term of JclT Institute. See Flow Manufacturing .
Dual Card Kanban	A signal to the resupply cell to set up and run a quantity of parts needed at the Flow Line.
Flex Fences	Negotiated boundaries of production volume fluctuation, agreed upon by customers, suppliers and production. It is based upon marketing requirements, production flexibilities, supplier capabilities and total product cycle time .
Flexible Workforce	All employees are qualified to perform not only their current operation, but at least one operation before and one operation after their operation.
Flexing	When idle, an operator moves to an area where work is needed.
Flow Manufacturing	Delivering a product or service that the customer has asked for, when the customer asks for it, by using management by sight and employee involvement, on a continuous flow line. Not by piles of reports, parts, and schedules.
Flow Technology (FT)	See Flow Manufacturing .

In-Process Kanban (IPK)	The signal to the previous operator that a part or component is needed. In effect, this signal directs the previous operation when to work (IPK is empty) and when not to work (IPK is full).
Kanban	A communication signal used to pull products and materials through the manufacturing process.
Kanban Card	The signal that indicates the replenishment size and delivery location for replenishment material.
Kanban Sizing	The quantity of each part which should be brought to the work area whenever a new supply of that part is needed.
Labor Weighted Time	The weighted average cycle time in a given process, calculated from the processing time and proportional amount of each product passing through the work center.
Line Balancing	Grouping together (and splitting up) tasks from the Sequence of Events into time segments equal to or less than the Takt (Operational Cycle Time)
Linearity	The percentage deviation of planned daily production vs. Actual production. It is a primary Flow Manufacturing measure.
Manufacturing Cycle Time	See Total Product Cycle Time .
Mixed Model Analysis	A tool which analyzes each work center on a production line to assess their ability to support operational TAKT time requirements with a proposed mix of daily production.
Mixed Model Process Map (MMPM)	A tool which groups products into families based upon similarity of processes and machines.
Non-replenishable Kanban	Typically used for high dollar (1) custom products, (2) one-time customer orders, or (3) infrequent material demand. A non-replenishable Kanban is NOT replenished when emptied.
Non-Value Added	Any activity performed that, in the viewpoint of the customer, does not represent an increase in utility as the part is transformed in to a finished product or service. These activities might include material movement, inspection, etc. The goal of flow manufacturing is to eliminate all non-value added activities in the providing of a good or service. Compare Value Added .
Operational Cycle Time	See Takt Time .

Operational Method Sheet (OMS)	A document which pictorially describes: (a) The quality checks to be performed before each step; (b) The work content in each operation; and (c) Verification of the work content before passing the part to the next operation.
Product Synchronization	Shows the relationship of manufacturing processes that must come together to produce the finished product. Also known as 'Product Sync'.
Pull Manufacturing	The production or withdrawal from inventory of items only as demanded for use or to replace those taken for use. Material is not issued until signaled from the user.
Push Manufacturing	The production or withdrawal from inventory of items as required by a given schedule or order document.
Raw-In-Process Inventory (RIP)	all raw and in-process materials that are at supply points in or close to production line or feeder process (excludes material in the stockroom).
Resupply Cell	Work center that is producing or supplying product to a downstream internal customer. Generally identified on a kanban as the source for replenishment material.
Rework Loop	An element of a Product Synchronization which identifies manufacturing rework.
Sequence of Events (SOE)	A detailed list of all of the tasks, quality and safety criteria and time required to manufacture a product or a part. Each step is categorized as either Setup, Run or Move.
Set-up Time	When a given work center is changing production from one part to another, it represents the amount of time from making the last good piece of unit A to the start of production of the first good piece of unit B. Also known as changeover time .
Single Card Kanban	A signal to the resupply area or directly to the supplier indicating that a purchased part / material is needed. The "Card" references the actual resupply information (attached to the Kanban container).
Single Minute Exchange of Dies (SMED)	The concept of set up and changeover times being less than ten minutes. This discipline is essential to successful flow of material in a mixed-model line.
Supplier Pull	A methodology whereby: (a) The supplier receives accurate forecast; (b) The factory triggers delivery of material based on consumption and desired inventory levels; and (c) The supplier delivers quality material on the date requested.

Takt time	The targeted rate (in minutes, hours or days) at which a part or product comes off the line to meet customer demand. Also known as Operational Cycle Time .
Total Product Cycle Time (TPCT)	The work content (Setup, Run, Move) through the longest path (of the Product Sync) to build a product. Also known as Manufacturing Cycle Time .
Under Capacity Planning	The daily planning of resources (people and machines) not required to meet the daily rate . It includes such elements as cross-training, continuous improvement, safety, and preventative maintenance.
Value Added	Any activity performed that, in the viewpoint of the customer, represents an increase in utility as the part is transformed in to a finished product or service. The goal of flow manufacturing is to eliminate all non-value added activities in the providing of a good or service. Compare Non-Value Added .
Wait/Work Board	A scheduling board at the resupply cell used to accumulate Kanban cards. When the specified number of cards is accumulated, they are moved to the work side of the board. This signals the cell to set up and produce the parts in the specified quantity in a first-in / first-out manner.
Zero Working Capital	An effect of Flow Manufacturing whereby the finished products are produced and sold and paid for before the raw materials are paid for. In essence, the materials of production are 'free', because you are paid for the finished product before you pay for the raw material. A very short Total Product Cycle Time and very low Work-in-Process inventories are required to achieve Zero Working Capital.

