Redesigning a Mass Manufacturing System to Achieve Today's Manufacturing System Objectives

David S. Cochran and **Yong-Suk Kim**

Production System Design Laboratory

Mechanical Engineering Department

Massachusetts Institute of Technology

Cambridge, MA 02139, USA.

H. Carl and **Martin H. Weidemann,**

Technical University of Aachen (RWTH-Aachen)

Aachen, Germany

Abstract

In world where product life cycles are decreasing, and customers are demanding they receive high quality products in a timely manner; traditional 'mass' based production techniques based on hard automation are becoming uncompetitive. Mass production systems are unable to accommodate frequent model changes in an economic and timely fashion. One promising alternative to solving these problems is a linked-cell manufacturing system. In this paper, the design processes of a 'lean' manufacturing plant that will replace the current 'mass' type plant of a major automotive supplier are presented. Design decision criteria associated with these conversion processes are illustrated according to a set of '*lean manufacturing principles*'. Financial justification is achieved by comparing the two systems in terms of operating costs.

***Keywords**: Cellular Manufacturing System**,* *Lean Manufacturing, Manufacturing System Design Decomposition, Cost Analysis, and Automotive Industry*

1. Introduction

In today's highly competitive market, manufacturers are expected to provide their products in a short order lead time with high quality standards, while keeping the price under a given market price [1], [2]. In addition, the ever-changing tastes of a volatile market ask for frequent product model changes, requiring modification of existing manufacturing systems. In this context, a manufacturing system is expected to achieve high quality, short throughput time and the flexibility to adapt to unexpected future changes such as demand volume or new product design, without losing cost competitiveness in the market place.

There is vast literature available describing elements and principles of lean manufacturing, such as Just-In-Time (JIT), Kanban, and Poka-yoke [2], [3], [4]. However, few describe *what* kind of system problems these lean elements solve and *how* those problems and lean elements are interrelated. Because of that, relatively few firms have been able to reach a high level of performance such as has been achieved at Toyota.

The industrial engineers of a major supplier in the automotive industry were faced with exactly this problem when searching for an alternative manufacturing system design, which could fulfill the requirements of their customers, who expect Just-In-Time (JIT) delivery and rapid implementation of sudden product changes. Together with the Production System Design Laboratory (PSD) at Massachusetts Institute of Technology (M.I.T.), a project was established to design a “lean” alternative to the current manufacturing system.

The alternative design was based on the Manufacturing System Design Decomposition (MSDD), which is a framework developed by Cochran et al., to understand and teach the objectives and means of manufacturing system design associated with ‘lean’ principles [5], [6]. The design that was developed considers the constraints and requirements of the current production system and its customers.

Two manufacturing systems are compared in this paper. It is shown that the alternative manufacturing system has other advantages such, as short response time, which cannot be evaluated by cost alone.

2. Problem Definition

The alternative cellular manufacturing system has been designed for the production of a housing, which is an aluminum block with a large number of holes. To manufacture one part requires up to 173 milling, drilling and tapping operations with a cycle time ranging from 6 seconds to 22.5 seconds for each operation, on six faces of the block. This housing has to be produced in 17 different variants. The peak demand for this product has been about 100,000 pieces per month.

In current production (Figure 1 and Figure 2), the machining centers equipped with tombstone fixtures are used to fulfill this task. These machining centers are five axis CNC machines with three spindles, which can process three parts in parallel. The tombstone fixture can hold twelve parts at once (Figure 3).

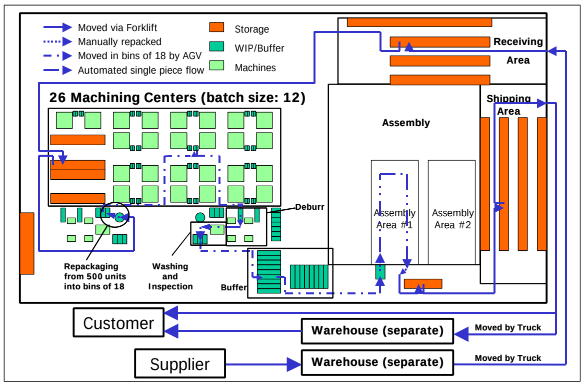

Figure 1. Current Plant Layout and Material Flow

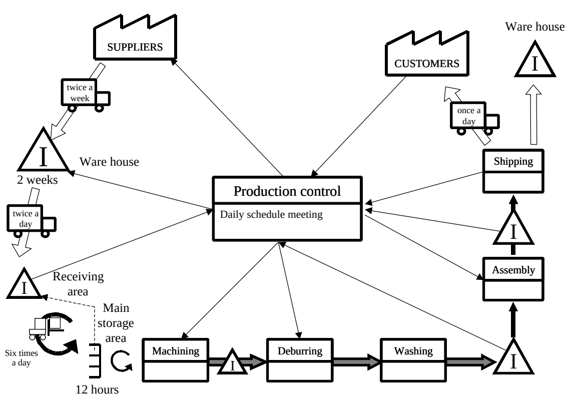

Figure 2. Value Stream Map of the Current Production

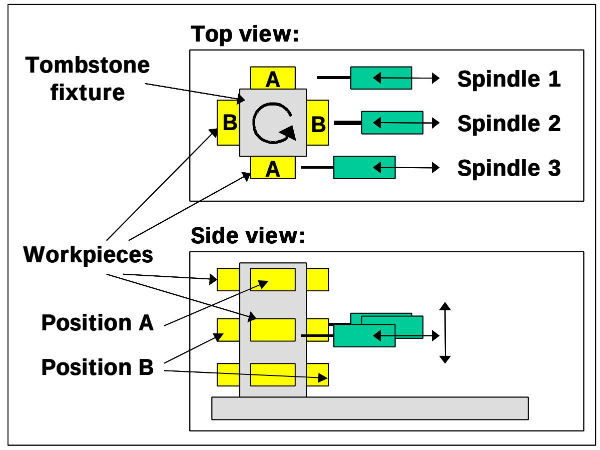

Figure 3. Tombstone Fixtures

The machining centers were chosen to accommodate high product variety. The manufacturing engineers are able to write only one CNC program for each type of housing. Furthermore, the tombstone fixtures hold twelve parts at a time. These fixtures were implemented to ensure positioning accuracy without re-clamping parts in the fixtures. Nevertheless, this objective was not achieved completely. The parts must be re-fixtured at least two times. First, six raw housings are fixtured in position A in Figure 3 during the first machine cycle. Then the half-machined parts are refixtured to position B in Figure 3 during the second machine cycle, while raw housings are fixtured in position A, again. Machine cycle time is about 25 minutes.

Therefore, the cycle time per part is about 4 minutes and 15 seconds (six finished parts per each machine cycle).

In current production, four machining centers are grouped together with one operator, who is also responsible for inspecting the finished parts. One part out of each load is inspected for possible defects. The most common defect is due to a “chip in spindle” problem during drilling operations. If a defect is detected, at least the whole load of twelve parts is scrapped. The next load is likely to be scrapped as well, because the machine is already processing the next load of parts while the previous load is being inspected. The scrap rate of current production is approx. 3.5%, which is not acceptable.

The four machining centers are supplied by Automated Guided Vehicles (AGV), which deliver raw aluminum blocks and pick up finished parts for delivery to a central deburring and wash station. This system needs 7 operators, 4 setup and two maintenance workers per shift.

The complex nature of the setup operation makes the economic run size 200 parts in machining. Consequently, buffers are needed to compensate for this non-ideal run size for the 17 different types of products. Assembly and machining of the housings are not balanced and are operated separately. For example, the machining area is operated in three shifts but assembly is operated in two. The cycle time of assembly is about 30 seconds, while the cycle time of the machining center is about 4 minutes per part, for the deburring machine, about 50 seconds per part, and for the washing machine, about 4-5 seconds per part with a lead time of 720 seconds. Therefore, a buffer has been installed between machining and assembly that can hold 18,000 housings. About 650 housings of each type have to be in the buffer at all times to ensure that there are no delays in assembly.

3. Proposed Alternative

The design of a cellular manufacturing system has to reflect the objectives of the manufacturing system design, which are focused on the customer. The actual design process of an alternative Cellular Manufacturing System follows these steps:

1. Balancing the system to customer demand (determination of the pace).
    - Grouping of products
    - Calculating takt time
    - Design of cell layout
    - Configuration of walk loops for different takt times

2. Leveling production (producing the right mix).
    - Linking cells to assembly
    - Information system

3.1 Balancing

Balanced production means producing at the pace of customer demand.

3.1.1 Grouping of Products

A manufacturing cell is a group of machines or processes of functionally dissimilar types that are physically placed together and dedicated to the manufacture of a specific range of parts [7]. Therefore, the selection of part types for cells is an important decision factor, especially when the previous takt time calculations resulted in a decision for a multiple cell model. An acceptable equipment utilization rate or balanced machine loads can be achieved by proper selection of product types. For this kind of decision, Group Technology (GT) may be used [8], [9], [10].

The basic concept of group technology is: to identify and bring together parts that are related by similar attributes and then to take advantage of similarities to develop simplified and rationalized procedures in all stages of design and manufacture [8].

In this alternative cell design project, however, group technology is not used since grouping products is relatively simple – product A and product B. They have very different housing machining processes. Differences within individual housing families are small enough to be ignored.

3.1.2 Calculating Takt Time

A designer should first define who the customer is. In a balanced system, capacity is aligned to meet customer demand.

When estimating customer demand, the capacities of the customer's production lines are a good guide upon which to determine customer demand. Marketing analysis or analysis of production data of similar preceding products can be another good source.

In a balanced cellular manufacturing system, the demand of the external customer sets the pace of the final cell, which is most likely an assembly cell. The preceding cells should have enough capacity to produce at the same pace as the assembly cells even though variation in the form of fallout (i.e., defective parts) or downtime exists.

Knowing customer demand, the maximum volume capacity of a cell needs to be determined, considering a range of customer takt time. The maximum volume capacity of a cell is decided by the minimum takt time. The takt time is calculated by the inverse of the average forecasted customer demand over a period of time that is the available time for production (Equation 1, Figure 4).

$$Takt\ Time = \frac{available\ time / month}{average\ demand / month} \qquad (1)$$

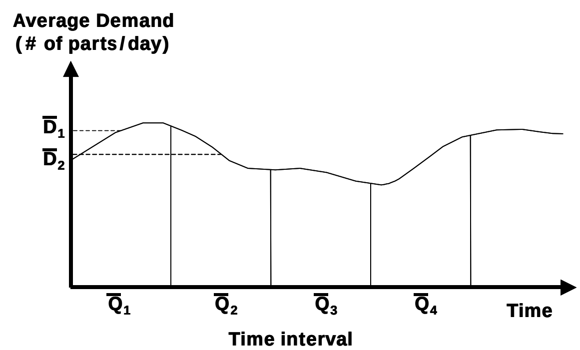

Figure 4. Customer Demand Fluctuation with Time and Average Customer Demand

However, the planned capacity of a new system also has to meet customer demand while overcoming inevitable variations within the system such as machine downtime. Therefore, actual-vs.-planned production has to be accommodated for by giving extra capacity to the new manufacturing system. Extra capacity can be built into the new system by considering a uplift factor of x% when deciding the minimum takt time [11]. A useful uplift factor is the Overall Equipment Efficiency factor (OEE) [12]. Therefore, the equation for takt time changes into the following equation:

$$Takt\ Time' = \frac{available\ time}{average\ demand} \times OEE \qquad (2)$$

Takt time' is the fastest cycle time that a cell, as a unit of capacity, is able to achieve (see Figure 5 for overall takt time ideas). In the alternative cellular manufacturing system design, an OEE of 78% was estimated, which corresponds to 60 minutes planned downtime, 85 minutes unplanned downtime and a scrap-rate of 2.5% (all per shift of 8 hours). This is a conservative estimate.

For the design of the alternative lean manufacturing system, peak demand has to be considered, because the alternative system should have enough capacity to produce adequately when peak demand occurrs. In this case the calculation of the takt time for peak demand resulted in a system takt time of 13.2 seconds per unit.

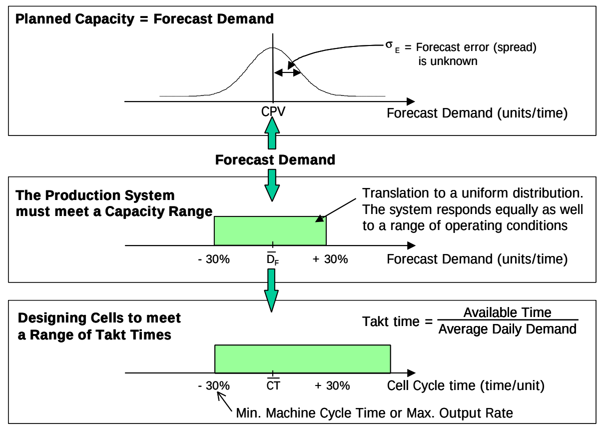

Figure 5. Customer Demand and Takt Time, and Determination of Machine Cycle Time Range

However, considering many empirical studies [13], this time is too short to maintain a low level of operational complexity because 13.2 seconds is too short a period for operator work loops. In addition, an even larger investment will be needed due to the high speed required for the machines in the cell. In this context, a plural number of cells are needed to increase the takt time to a reasonable range. The decision on the number of cells is an optimization among several factors, such as the number of machines, number of operators, and cost/complexity of machines.

Despite the complexity of this decision process, a 4-cell model is chosen since empirical evidence suggests that a takt time of less than 30 seconds causes a high level of complexity in cell operation.. In addition, a 3-cell model requires a larger number of machines than a 4-cell model. In this decision, machine complexity or number of operators is not considered since it is assumed that the major constraint lies on the initial investment to be made for the new system that is mainly affected by the number of required machines.

A 4-cell model only requires a cell takt time of 52.8 seconds per unit for peak demand. The cell takt time for the average demand is 65.6 seconds per unit. Among 4 cells, only one cell will be able to produce both product A and B because the demand for product B is much smaller than product A while product B requires more machining processes.

3.1.3 Design of Cell Layout

A cellular manufacturing system can operate at minimum takt time, when all the stations of the cells are capable of operating in less than minimum takt time. Therefore, the work content at each station should be properly designed so that the operation time is less than minimum takt time.

$$M_{CTi} \leq TT_{\min} \qquad (3)$$

where,

M_{CTi} = cycle time of the machine I

TT_{min} = minimum takt time.

When regrouping the operations, the following constraints have to be taken into consideration:

- Knowledge of the existing process
- Capabilities of machines
- Minimum takt time of cells (in this case: 52.8sec. at peak demand)

The result of regrouping the operations is reflected in the cell design. All the operations are grouped in a way that the total process time of each station including pallet change and tool change is less than 52.8 seconds.

Minimum takt time also works as a parameter for machine acquisition. Sometimes there are operations where the latest state-of-art machines process the part much faster than required by minimum takt time. In these cases, slower, simpler, and less expensive machines may be implemented while fulfilling manufacturing system requirements.

Another point to consider when purchasing machines for cells is the quick loading and unloading of parts at stations. In this study, manual loading and automatic unloading was chosen since manual loading is cost effective while automatic unloading enables the reduction of manual operation time. This way, the operator can operate as many stations as possible with as little wasted motion as possible. Furthermore, an automated pallet changer was implemented to protect workers from the high pressure cutting fluid that is used to eliminate burrs.

Considering all these points leads to a machining cell design for product B as presented in Figure 6. A parallel row configuration has been chosen to accommodate operator work loops. Grouping of operations results in 15 CNC machining stations performing different operations, three deburrer and one wash, rinse, and dry machine. In this machining cell, each CNC-machine (#1 to 15) is equipped with an automated pallet changer and hydraulic fixtures.

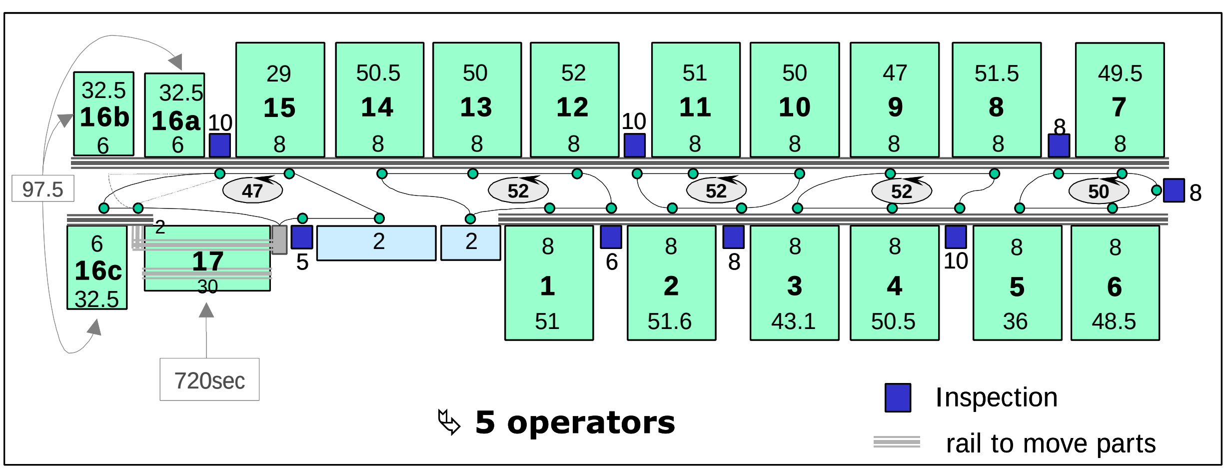

Figure 6. Proposed Machining Cell for Product B at the Peak Demand

Machining stations # 1 and 2 need highly accurate CNC machining centers since all critical operations in terms of tolerances are grouped and allocated to the first two stations. In this way, there is minimal re-clamping of the parts affecting the required tolerances of the housing. In fact, even for the existing system, parts are re-clampedand thus, it is reasonable to assume there is no problem with process capability. Operations in stations # 4, 6, 7 and 11 require high-power CNC machining centers due to the operational characteristics. All other CNC machining centers are simple 3-axis, single cycle, and automatic machining centers.

Parallel processing is implemented for the deburring operations (station #16a, b, c) that use high pressure water jets to remove the burrs. Due to the fact that the cycle time is 97.5 seconds, three deburr machines are necessary to meet minimum takt time. These operations cannot be broken down or be substituted with alternative processes since they are not yet available; therefore, parallel processing is inevitable in this case. However, a continous effort to decrease machine cycle time to less than minumum takt time is necessary.

A pipeline station is the wash, rinse and dry machine (station #17). The parts are moved through this machine on a single piece conveyer. The machine is capable of releasing one part per every 30 seconds.

The machining cell in Figure 6 is capable of machining all variants of housings. However, only 1/20 of all housings need to be processed in all of the 15 machining stations. Therefore, it makes sense to use only one cell of this type. The other three machining cells require fewer machines when re-grouping the operations needed for the rest of the housing variants. The result is a similar cell, which has 11 machining stations, 2 deburr stations and one wash, rinse, and dry machine.

3.1.4 Configuration of Operator Work Loops for Different Takt Times

The workforce is used most effectively if the operators are able to operate several stations at the same time. This separation of operators from machines is possible when operators are trained to operate multiple machines, and operator work-loops are well defined. Operator work-loops requires minimized walk loop time, which is possible when the stations / machines are located close to each other. Parallel or U-shaped row configuration with minimized machine width, helps to minimize the operator walk time. An operator’s movement in lean cells is often designed to be counter-clockwise to avoid extra motion, because the vast majority of people are right-handed and thus, it is easy for operators to use their right hand to load a machine [3], [4].

Another advantage of work-loops is that they can be adjusted according to production volumes. Simply by designing different standard work-loops for different takt times and changing the number of operators in a cell, volume flexibility of the lean cell is achieved. The ideal number of workers in a cell is given by the following equation:

$$NOR = \sum_{i=1}^{n} \frac{OCT}{TT} \qquad (4)$$

where NOR is the number of operators required in a cell. OCT is the operator cycle time, which includes the station cycle time plus walking time to the next station. TT is the cell takt time. The calculated NOR has to be rounded to the next higher integer.

Figure 6 shows the work-loop configuration at minimum takt time (peak demand). At minimum takt time 5 operators are needed in the machining cell for product B. As mentioned before, the number of operators is not a fixed value. As the takt time varies with customer demand, it changes as well. For example, for the average demand case that requires 65.8 seconds of takt time, only 4 operators are necessary to operate the cell.

3.2 Leveling

Level production enables production with a minimum of inventory. It is defined by the quantity and mix of products demanded by the final customer, within a given time interval (demand interval). An information system which controls production and links the cells to each other is indispensible for achieving this goal.

3.2.1 Linking cells to assembly

Kanban is a tool for managing and assuring JIT production [2]. It is a simple but efficient control system. Kanban is sometimes in the form of cards (Kanban cards) that communicate information between cells regarding the required production. The required product type and quantity is specified on each card.

In this case, all machining cells are supplied with raw housings from the warehouse, which can be done in one supply-loop. The assembly cells are connected to the machining cells with the help of kanbans. Each machining cell supplies only one assembly cell. There is no cross-linking. The flow of material stays clear. Mixing up of parts does not happen. The kanban used for requesting parts is called the “withdrawal kanban”. In the case of the housing, the machined housings are taken out from the standard work in process (SWIP) of the machining cell. This is also the signal calling for the machining cell to replenish the withdrawn parts. Then, a raw housing is taken out of its container at the rack for the incoming parts, and moved to the first machining center to be processed.

In this case, because there are only four different kinds of raw housings, it is possible to keep them on the rack at the machining cell. The empty containers work as a “withdrawal kanban”.

The number of kanbans has been calculated for the assembly-loops and the warehouse-loop using the following equation [14].

$$N_{container} = \frac{D \times RLD \times (1 + a)}{S} \quad (5)$$

where,

$N_{container}$ = Min. Number of containers (kanbans)

D = Demand rate (parts/sec)

RLD = Replenishment lead time (sec)

a = safety factor (considering fall out rate and other sources of variation) = 0.3

S = container size (parts/container)

In the finished housing replenishment loop, the RLD is the time taken to replenish a finished product container withdrawn by the shipping. The throughput time of the cell is {16 + 2 (parallel cycle) + 11 (washing)} * Takt Time + 13 seconds (to finisht the rest of operation) = 1921.2 seconds for the average demand. Assuming a container holds 10 products, the total replenishment time for a container is 1921.2 + 9 * Takt Time = 2513.4 seconds ~ 42 minutes.

Assuming the material handler picks up the finished products every 33 minutes, the number of containers necessary is decided to be nine per each type considering the production while the containers are away. This number can be decreased by continuous improvement to minimize the system variation and more frequent material pick up.

In the raw housing replenishment loop, it is assumed that a raw material replenishment time is 30 minutes and there are raw materials large enough to refill the containers instantly, at 10 parts per container. The total number of kanbans in this case turned out to be seven for average demand, considering production while the containers are away from the machining cell. A safety factor of 0.3 is assumed to compensate possible sources of variation, which is subject to Kaizen (continuous improvement) activity. This calculation is for product B but the number of kanbans required for product A can also be calculated in the same way.

As is shown in Figure 7, in a new system, machining cells are linked to assembly cells and operate according to takt time, which is the pace of customer demand.

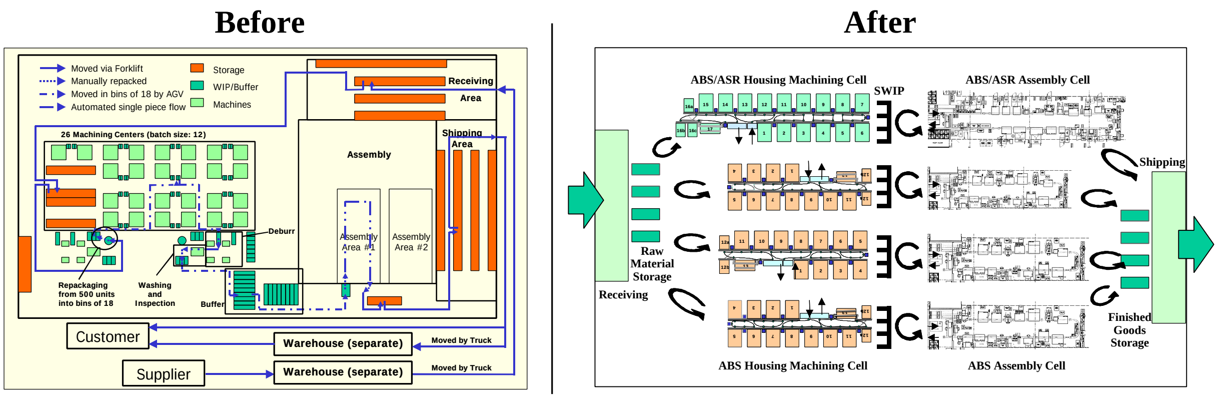

Figure 7. Current System (left) vs. Newly Proposed Linked Cell Manufacturing System (right)

3.2.2 Information system

Production should be driven by the demand of the customer. The goal is to produce and supply only the parts needed, so that the waste of over-production is eliminated.

Since the mix of a customer order varies over time, the production system must be flexible toward producing the right mix of different product types within the customer demand interval. Therefore, kanban from the customer determines what mix has to be produced and the frequency of kanbans arriving from the customer sets the mix per time interval (Figure 8).

The introduction of a true "pull" system requires a new information system to level the demand to the cells. A useful and simple tool is the Heijunka Box. The Heijunka Box controls the timing of the flow of information to the final cell in the manufacturing system. Furthermore, Heijunka controls the sequence (mix) of production. Thereby, the production of different variants has to be evenly distributed over the course of the day to ensure a just-in-time production. This even distribution is called "heijunka sequential planning." It prevents inventory and idling time of associates and machines. Heijunka controls the cycle time of information disbursement to the manufacturing system.

According to the actual customer demand, kanban cards are placed into the Heijunka Box. Each column of the box represents one time interval of the material handler's work loop and thus, adequte number of kanbans according to the amount that should be shipped during this period are placed into one column. After each time interval, kanban cards are withdrawn from the Heijunka Box and taken to the last cell of the value stream within the plant, usually the assembly cell. The material handler retrieves the number of containers corresponding to the withdrawl kanbans from the standard WIP after the assembly lines. At this time, empty containers are brought back to the assembly line and this signals production. Separate production order kanbans are implemented for ease of use. One production order kanban indicates the production of one part and thus, 10 production kanban per one withdrawl kanban will be fed back to the beginning of the assembly line since one container holds ten parts.

The Heijunka Box is filled up daily. The order of the kanban cards is determined by leveling the customer orders. Only the parts needed that day are being produced when using Heijunka. The replenishment pull system between cells ensures that parts are only available when needed.

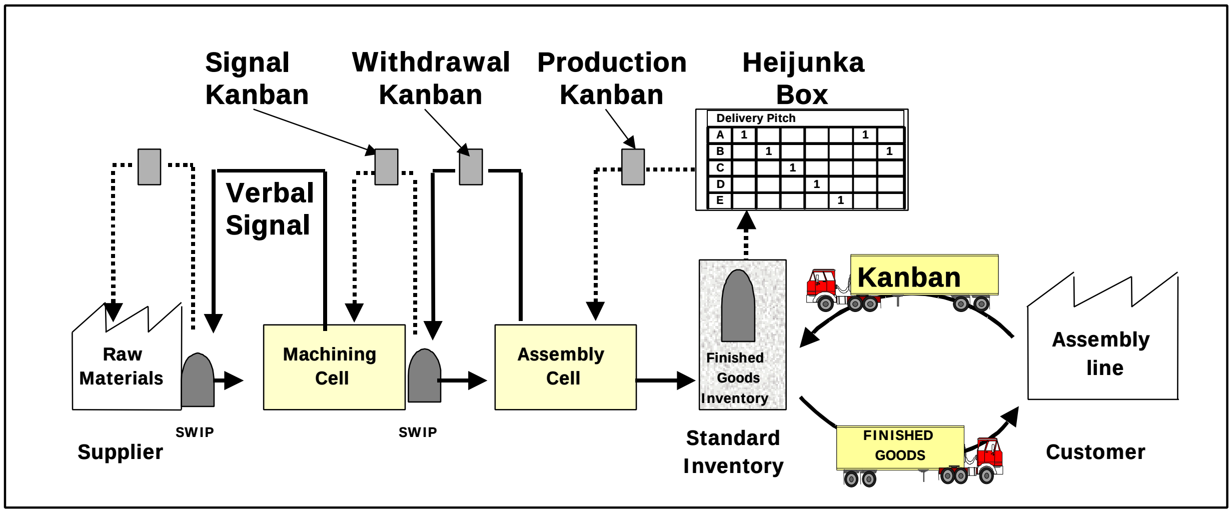

Figure 8. Pull System Controlled by Heijunka

4. The advantages of the proposed Cellular System

4.1 Quality

In the new alternative manufacturing system design, several methods are deployed to ensure predictable quality of output. First, inspection stations are placed after stations performing critical operations. Therefore, a ‘make one, inspect one, pass one’ philosophy is achieved at all critical operations [15]. This philosophy helps reduce the time it takes to find the source of and correct problems that eventually contribute to better initial quality. This can be implemented without a major increase in cost because operators are separated from machines and these additional inspection operations do not significantly affect the number of operators required for a cell.

Second, capable machines, fixtures, and equipment are selected to achieve a required level of quality at each processing step. For example, upper end machining centers that provide high horsepower and accuracy are chosen where those features are necessary. On the other hand, simpler and less expensive machines are selected for processes that require only an ordinary level of accuracy or horsepower. Hydraulic fixtures are deployed to ensure a quick loading and unloading of parts while minimizing precision loss due to frequent clamping and unclamping. In addition, all processes that require high level of accuracy are grouped together into the first and second stations, so that re-clamping little affects the required tolerances.

Third, the adopted single-piece-flow helps to reduce the scrap rate because quality is checked after one piece is processed; there are no more scraps caused by the batch process (e.g., the “chip in the spindle” case) because only one piece is processed at a time.

For these reasons, the quality of the new manufacturing system is expected to be much higher than in the current production system. Considering the current scrap rate of 3.5% and other lean manufacturing plants, a scrap rate of less than 1% is expected.

4.2 Time Reliability

Predictable time output is a basic requirement for a Just-In-Time production and distribution. Time output is affected by all relevant processes involved in the production of a part. In the proposed system, the conventional way to buffer the variation in time output, inventory, is minimized while other strategies are employed to achieve a high level of time reliability.

In a lean manufacturing system, all relevant processes are designed to meet takt time and operate in a periodic way based on takt time. This periodicity gives room to absorb the variation of each cycle time. In other words, as long as machine operations are done within takt time, reliable time output is achieved. In addition, all operations have standardized steps to follow so that reliable time output from workers are ensured. Standardized operation steps for manual operations are important because the pace of production in the cell is controlled by the operators.

Cross-training of workers with a team leader also contributes to reliable time output. It prevents production disruptions by absent or unskilled workers. When an operator is unavailable, the team leader temporarily replaces his/her position. The same strategy can be applied where an operator is behind the pace, so that other workers or the team leader in the cell, each of whom is cross-trained to help the operator to catch up to production pace.

Another indirect but very important contributing factor for time reliability is in the increased quality level. Since the production of scrap not only wastes valuable materials but also precious time, quality also affects the time reliability of a system. As discussed in the previous section, quality of the new system is expected to be enhanced by a factor of several times.

Other methods used are a standard replenishment system to ensure material availability and regularly scheduled maintenance of equipment to ensure machine reliability.

4.3 Cost and Investment

Figure 9 shows the result of a cost comparison. The costs are broken down to cost per hour. (The costs are multiplied with a constant factor for confidentiality.)

The cost of investments are determined by linear depreciation over seven years. They incorporate machines, transportation systems, warehouse equipment and the module of the MRP system responsible for scheduling. Also included are the central cooling and chip system, the first set of tooling per machine, fixtures and the gauging system.

The investment cost in the current system is much higher than that in the cellular system because the current manufacturing system uses highly capable and flexible machining centers regardless of processing requirements. The machining centers are highly underutilized when they performed operations requiring an ordinary level of accuracy or power. This capability under-utilization results in a larger investment than is necessary. In addition, a larger investment in an automated transportation system was required to shorten the throughput time of the machining area. The design is neither product orientated nor system oriented.

Compared to the existing system, the proposed cellular manufacturing system has slightly higher labor costs. This is because the design of the current system has been developed to decrease labor cost. This goal has been achieved by implementing automation extensively (see [16] for further discussion on this issue).

Inventory cost does not really matter in either system, which is different from typical lean implementation cases that report huge savings from inventory reduction (see [17], [18] for other lean implementation case studies). This is because the focus of this study is limited to one machining process of the product's metal housing, which does not take significant portion of the cost.

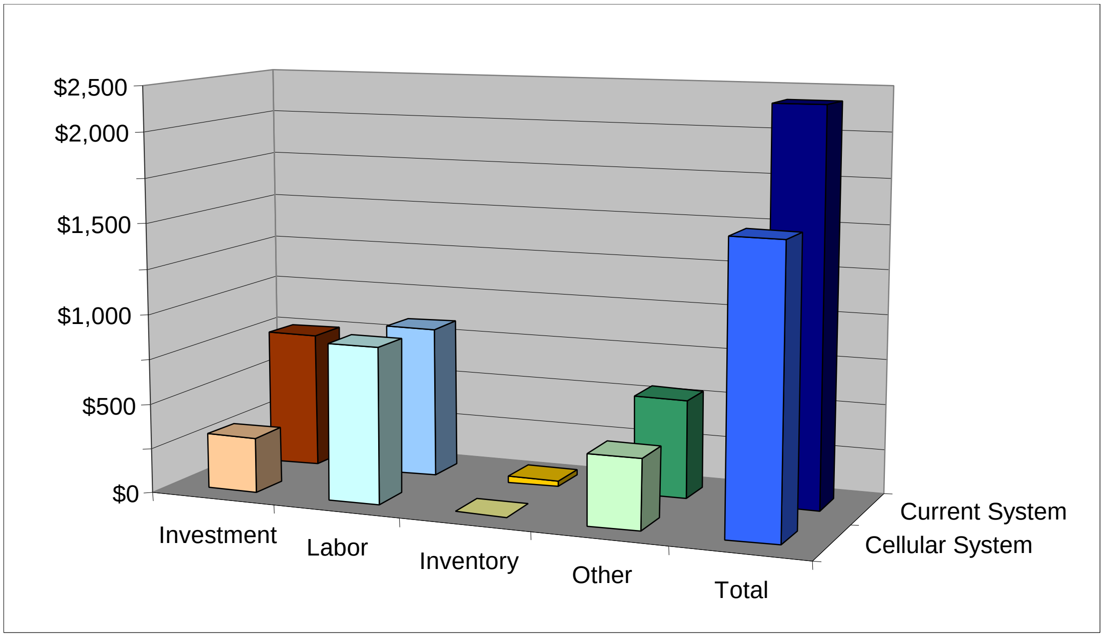

Figure 9. Cost of the Systems per Hour

The other costs are higher in the current system due to the scrap rate. "End of the line" inspections are not the best solution for a product that has to be processed so many times.

In the cost structure of the current manufacturing system (Figure 10) investment has the biggest share. Therefore, the machines and equipment need to be utilized most effectively to justify this investment.

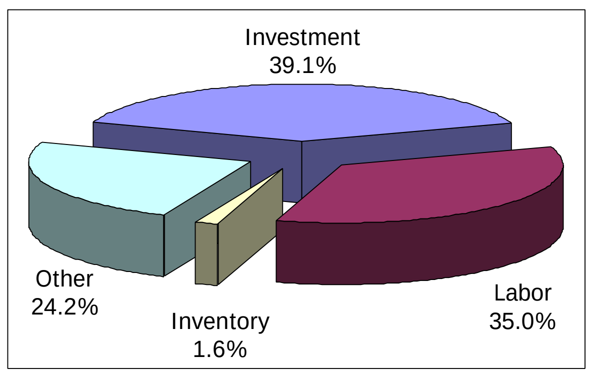

Figure 10. Cost structure of the Current Manufacturing System

The share of labor is 35%. It is still a large portion of the costs and it is clear that labor needs to used efficiently, although machine utilization has priority.

The effective use of labor becomes even more important in the cellular manufacturing system. The share of labor cost is more than half of the total cost (Figure 11).

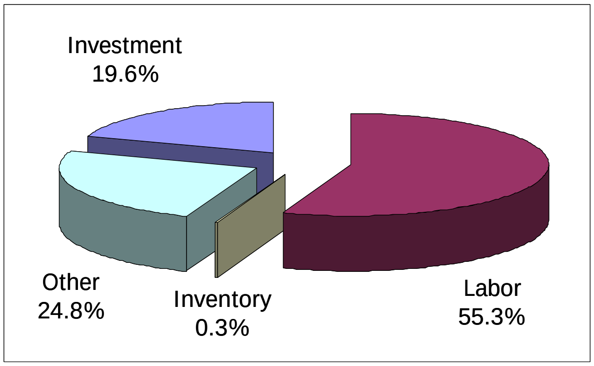

Figure 11. Cost structure of the Cellular Manufacturing system

The utilization rate of machines and equipment is not as important as in the current system due to this cost factor. If customer demand is below peak demand, then the manufacturing system does not work at minimum peak takt time and the machines are not fully utilized. This is justified due to the cost structure.

In the cellular approach the number of operators is adjusted to customer demand. This ensures the most effective use of the workforce. It is even necessary to vary the number of operators in response to customer demand. The effect is that the operating cost of the whole manufacturing system decreases when customer demand goes down. Making a profit is still possible.

5. Conclusion

The goal of the study and its cost analysis is to show how a cellular manufacturing system would perform in comparison to an existing system of mass production. It is not intended to prove that the existing system is bad or poorly designed, but to show the benefits that emerge from a cellular manufacturing system design.

The analysis of the existing system and the design of the new system have been done at the same time but separately, following the same checklist for data-retrieval in order to assure the most objective view of the systems possible.

The design of the cellular manufacturing system incorporates the ideas of lean production. It is based upon a “green field situation.” Despite this fact, the intention was to meet as many constraints of the current system as possible in order to make a feasible comparison between the current system and the proposed system. It was the goal of this project to design a cellular manufacturing system that could have been built instead of an existing one and that could be operated in a present environment, and to show its advantages over the existing system.

Lower costs are not the only advantage of the cellular system design. Even more important is the ability to respond to quality issues, to adapt quickly to changes in product design, the capability to manufacture a large variety of variants, and volume flexibility of the cellular manufacturing system.

Evaluating manufacturing systems by cost is only one way to look at them. It also depends on other aspects, such as their adaptability into production networks, which would ensure that all the advantages of the manufacturing system can be passed on within the supply-chain and to the external customer. These aspects are part of cooperative research projects between the Production System Design Laboratory (PSD) at MIT and the Research Institut for Operations Managment at RWTH Aachen.

Acknowledgement

The authors would like to thank Mr. Quinton Kum Yew Ng, Mr. Steve Hendricks, and Ms. Pat Smethurs for their editorial assistance.

6. References

1. Fine, C, *Clockspeed: Winning Industry Control in the Age of Temporary Advantage*, Perseus Publishing, Cambridge, MA, 1998.
2. Ohno, T., *Toyota Production System: Beyond Large-scale Production*, Productivity Press, Portland, OR, 1988.
3. Monden, Y., *Toyota Production System: An Integrated Approach to Just-In-Time*, 3rd edition, Engineering & Management Press, Norcross, GA, 1998.
4. Shingo, S., *A Study of the Toyota Production System from an Industrial Engineering Point of View,* Productivity Press, Portland, OR 1989.
5. Suh, N. P., Cochran, D. S., and Lima, P. C., Manufacturing System Design, *Annals of*

48th General Assembly of CIRP, Vol. 47/2/1998, 1998, pp. 627-639.

6. Carrus, B. J. and Cochran, D. S., Application of a Design Methodology for Production Systems, *Annals of the 2nd International Conference on Engineering Design and Automation*, Maui, Hi., 1998.
7. Pullen, R., A Survey of Cellular Manufacturing Cells, *The Production Engineer*, Vol. 55, No. 9, pp. 451-454, 1976.
8. Suresh, N. C. and Kay, J. M. (editors), *Group Technology and Cellular Manufacturing: A State-of-the Art Synthesis of Research and Practice*, Kluwer Academic Publisher, Boston, MA, 1998.
9. Wemmerlov, U. and Hyer, N. L., Procedures for the Part Family/Machine Group Identification Problem in Cellular Manufacturing, Journal of Operations Management, Vol. 6, No. 2, February, 1986.
10. Ham, I., Hitomi, K., and Yoshida, T., *Group Technology: Application to Production Management*, Kluwer-Nijhoff Publishing, Boston, 1985.
11. Charles, M., Cochran, D., and Dobbs, D., Design of Manufacturing Systems to Support Volume Flexibility, Proceedings of SAE International Automotive Manufacturing Conference, Detroit, MI, May 11-13, 1999.
12. Nakajima, S., *Introduction to TPM: Total Productive Maintenance*, Productivity Press, Portland, OR, 1988.
13. Cochran, D. and Dobbs, D. Mass vs. Lean Plant Design Evaluation Using the Production System Design Decomposition, NAMRI/SME, Volume 28, pp. 359-364, 2000.
14. Cochran, D., 2.812 Manufacturing System Design and Control, Lecture note, MIT, Cambridge, MA, 2000.
15. Black, J. T., The Design of a Factory with a Future, McGraw-Hill Inc., New York, 1991.
16. Cochran, D., Kim, J., and Kim, Y-S., Design of relevant performance measures for manufacturing systems, Proceedings of the 3rd World Congress on Intelligent Manufacturing Processes and Systems, Cambridge, MA, June 28-30, 2000.

17. Womack, J., Jones, D., and Roos, D., *Machine that Changed the World: The Story of Lean Production*, Harper Perennial, New York, NY, 1990.

18. Womack, J. and Jones, D., Lean Thinking: Banish Waste and Create Wealth in Your Corporation, Simon & Schuster, New York, NY, 1996.

Author Biography

Prof. David Cochran is an Associate Professor of Mechanical Engineering at the Massachusetts Institute of Technology (MIT). He founded the Production System Design Laboratory, an initiative within the Laboratory for Manufacturing and Productivity, to develop a comprehensive approach for the design and implementation of production systems. He is a recipient of the "Shingo Prize for Manufacturing Excellence." He has taught over 30 manufacturers the implementation and underlying principles of production system design. Dr. Cochran serves on the Board of Directors of the Greater Boston Manufacturing Partnership and the AMA. Prior to joining MIT, Dr. Cochran worked with Ford Motor Company. He holds a Ph.D. and B.S. degrees from Auburn University, and a M.S. degree from the Pennsylvania State University. His email address is: dcochran@mit.edu. Phone: ++1 – 617 – 258 6769. Fax: ++1 – 617 – 253 7488.

Yong-Suk Kim is a Ph.D. candidate in the Mechanical Engineering department at MIT. He holds a M.S. degree from MIT and a B.S. degree from Seoul National University. His research focuses on simultaneous design and development of manufacturing systems and products supported by an appropriate performance measurement system. His email address is: yskim@mit.edu.

Dipl.-Ing. Henning Carl is a Ph.D. candidate in the Technical University of Aachen (RWTH – Aachen). He received his diploma degree from Technical University of Clausthal, Germany.

Dipl.-Ing. Martin Weidemann is a Ph.D. candidate in the Technical University of Aachen

(RWTH – Aachen), Germany. He received his diploma degree from Technical University of Aachen (RWTH – Aachen), Germany.