COBEM 99
XV Congresso Brasileiro de Engenharia Mecânica
15th Brazilian Congress of Mechanical Engineering
22 - 26 de Novembro de 1999 / November 22 - 26, 1999 Águas de Lindóia, São Paulo,

AN APPLICATION OF AXIOMATIC DESIGN FOR DESIGN OF A MANUFACTURING CELL ON AN AUTOMOTIVE SUPPLIER INDUSTRY

Carlos Lobo
Yane Lobo
Paulo Lima
Universidade Estadual de Campinas – DEF/FEM
C. P. 6122 – 13083-970 – Campinas, SP, Brasil

Abstract. *The objective of this paper is to show an application of Axiomatic Design on the design of a manufacturing cell. The Axiomatic Design is based on the principle that it is necessary to translate the customer's desires – internal and external – into functional requirements (FR), and to translate these functional requirements into design parameters (DP). In production system design this methodology facilitates design a manufacturing system that attends the customer's needs. Another set of principles that helps to design a manufacturing cell that attends the customer's needs is Lean Manufacturing. The main problem of Lean Manufacturing was always methodological: how it must be applied, in what sequence, and how all those principles can be integrated in a production system. The Axiomatic Design that is usually applied for the product design answers these questions. With the Axiomatic Design it is possible to determine what must be implemented and in what sequence. Using the Axiomatic Design and the principles of Lean Manufacturing, the generation of waste is avoided. The combination of these two techniques makes it possible to obtain a more efficient and accurate production system design. An application of this methodology for design of a machining cell of an automotive supplier is shown.*

Key words*: Axiomatic Design, Lean Manufacturing, System Design*

1. INTRODUCTION

Nowadays customers require high quality, time delivery, and flexibility, beyond low costs, which are no longer a decisive factor for gain orders, but a necessary factor for competition. So the companies have to be aligned with the customers' desires and needs. The Axiomatic Design and the principles of Lean Manufacturing can be used like a tool to align the company with their customers. The Axiomatic Design translates the customers' desire into function requirements and the Lean Manufacturing has as a main principle value creation through waste elimination, as well as creation of the process in a continuous flow between the raw material and the final customer. This paper has the objective to show how these two tools can be used for design the manufacturing cell that attends the customers' needs. Also shown is an application of this methodology in a automotive supplier industry.

2. AXIOMATIC DESIGN

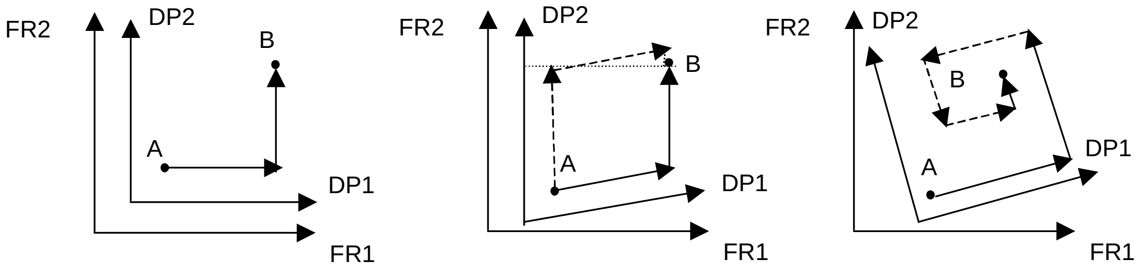
The Axiomatic Design is based on the principle of translating the customers' needs – internal or external – into functional requirements (FRs), and these into design parameters (DPs).

So the design task is guided by the customers' desires. This methodology helps the designers to find in the beginning the customers' needs, improve the traditional design that was a hard process, with many variations and drawbacks, until the best design was meet. The customers' needs are translated into functional requirements that are translated into design parameters that mean the solutions used in the design.

In order to obtain the best design, Suh (1990) states two axioms, the axiom of independence and the axiom of information, that help in the design parameters selection. The axiom of independence says that each functional requirement must be independent. When the functional requirement changes, only one design parameter must be changed, because the system is independent. The changes in one design parameter only affect its functional requirement. The second axiom establishes that the design information must be minimized. The information content is defined in terms of the logarithm of probability to satisfy the functional requirement. In this way, systems that have a low probability of success have a high content of information. With these two axioms the best design can be found.

The application of the Axiomatic Design in the manufacturing system implies, in design, everything in accord with the highest level FR that according to Suh *et. al* (1998), is maximizing the return on investment. Based on this statement the entire manufacturing system is subordinated to this FR. So the best DP for this FR is design of a production system that exactly meets this requirement, and not just use one manufacturing system that was designed to produce a different product. At this point, a process of zig-zag should be done to decompose the FRs and DPs until the whole system is designed.

Considering the independence or not of the FR, the design can be classified in three groups. Uncoupled design, that means that the FRs are entirely independent; decoupled design, that means that part of FRs are dependent; and coupled design, that means that the FRs are dependent. Figure 1 shows the design types.



	DP_1	DP_2
FR_1	X	
FR_2		X

Uncoupled Design
Independent of
Control sequence

	DP_1	DP_2
FR_1	X	
FR_2	X	X

Decoupled Design
Dependent of
Control sequence

	DP_1	DP_2
FR_1	X	X
FR_2	X	X

Coupled Design
Chaotic

Figure 1 – Design Types

In Fig. 1, the uncoupled design permits you to change the configuration from point A to point B independently. This means that you can choose the order that you will make the changes. Independent of the order, the result will be always the same. Looking at the matrix, the FRs can be solved in any order. In the decoupled case, this is no longer true. FR_1 is independent, but the solution DP_2 affects both FR_1 and FR_2. This case has a triangular matrix. If the order in the solution is not observed, it is impossible to solve the system. In the worse case, the coupled design, both FRs are affected by both DPs. In order to solve this system, many interactions should be made until the nearest solution is matched.

3. LEAN MANUFACTURING

The base of Toyota Production System (TPS) is waste elimination. The two pillars on which TPS is supported are the Just-In-Time and the autonomation (Jidoka), as shown in Fig. 2.

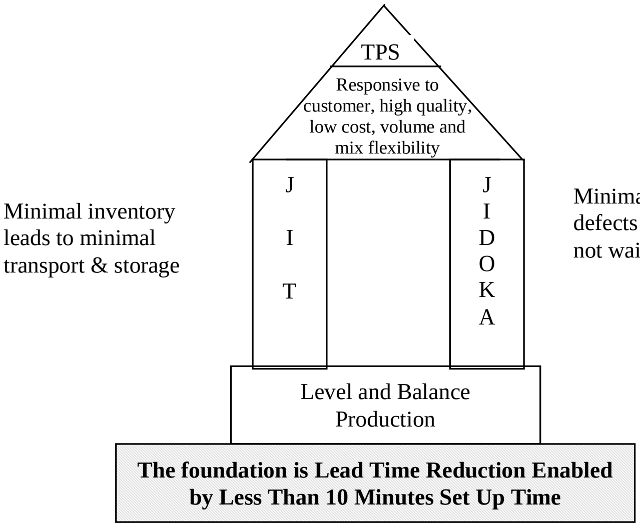


Figure 2 – Pillars of the Toyota Production System

The Lean Manufacturing (Womack *et al.*, 1990) a evolution of Just-In-Time (JIT), was introduced by Toyota, twenty-five years ago, can be defined as a manufacturing model that tries to produce correct quantities of items, when these are necessary, reducing the work in process and maximizing the productivity (Lobo, 1997). The pre-automation or autonomation in TPS completely separates the worker from the machine. A machine, after the total depreciation, can be operated at no cost. On the other hand the workers have to be paid forever. So, to reduce the cost is better to have a machine stopped than workers stopped (Shingo, 1996).

The Lean Manufacturing eliminates all unnecessary production phases, and puts the necessary production phases in a continuous flow. In addition, the correct value for the product from the point of view of the customer must be determined. Womack & Jones (1996) named this process as Lean Thinking, and proposed five principles to implement it.

3.1. To determine accurately the value of the specific product

The value only can be determined by the final customer and only is significant when it is expressed in terms of a specific product. Only the customer knows what functions the product must have and how much he wants to pay for it.

The Lean Thinking must begin by determining the value in terms of a specific product with specific functions offered by a specific price set through the dialogue with a specific customer. It is also necessary to create teamwork linked to each product family.

3.2. To identify the supply chain for each product

The supply chain is a set of all specific critical management tasks that are necessary to produce a specific product. In other words, the task of problem solution that begins in conception and ends in the product launching. The task of information management that goes from the order to the delivery. And the task of physical transformation that goes from the obtaining the raw material to the final product.

3.3. To make the value flow without interruptions

When the product and its functions are the focus of the organization, management is easier than when the organization or the machine is the focus. In this way all activities can go in a continuous flow. By aligning all essential phases in a continuous and stable flow, without useless movements, without interruptions, without batch and without queue, everything goes better. For this is necessary:

- To determine the supply chain, focusing on the real product;
- To ignore the traditional frontiers and functions, eliminating all obstacles to the continuous flow;
- To rethink the tools and practices for specific work, eliminating back flow, scrap and disruption.

3.4. To let the customer pulls the value of the product

The best way to understand the logic and the challenge of Pull Production is to start with a real customer that express a real product demand and goes in reverse, going through all necessary phases to send the product to the customer.

One that helps in this process is to determine the Takt Time, as shown in Eq. (1). The Takt Time is based on the demand, so the production works according to the customers' needs.

$$\text{Takt Time} = \frac{\text{Available Daily Time}}{\text{Average Daily Demand}} \tag{1}$$

3.5. To seek perfection

To go after the radical and continuous improvement, two techniques are necessary:

- To have a good sense of perfection. For this, the managers of supply chain need to apply the four principles of Lean Thinking;
- The managers have to decide what forms of waste they will address first.

4. CELL DESIGN

To design the cell, three aspects are important: the mix, the time and the frequency. Mix is **what** the production has to make. Time is **when** the production has to be made by. And frequency (Takt Time) is **how** the production has to make. Figure 3 shows the comparison between the production and the flow through a tube.

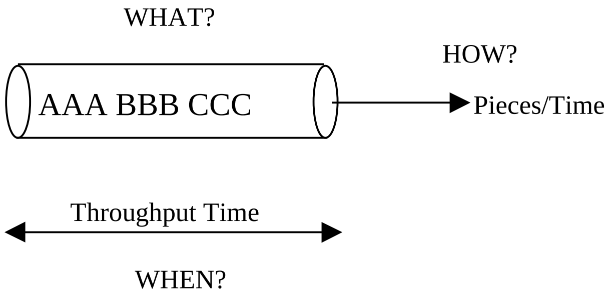


Figure 3 – Comparison between the production and the flow

Using the Axiomatic Design it is possible design the cell. In this design the functional requirements quality cost were used as system constrains. This means that during all design activity quality and cost must be considered in the decisions.

The FRs for the design of this cell were selected based on Suh *et al.* (1998). According to him, there are three FRs to be solved: Balanced Production, Leveled Production, and Synchronized Production. Balanced Production is obtained linking the cell with the customer demand using the takt time. Leveled Production is obtained leveling the production mix. Synchronized Production is obtained with a low response time.

The design matrix for these three FRs-DPs is a diagonal matrix. This makes the design a decoupled design, in other words, the cell can be implemented and controlled in a easy way if the correct sequence is observed. As shown in Table 1, the Balanced Production must be achieved first, then Leveled Production, and finally the Synchronized Production.

Table 1 – Diagonal Matrix

	Balanced Production	Leveled Production	Synchronized Production
Frequency	**X**		
Mix		**X**	
Time	**X**	**X**	**X**

The Balanced Production occurs when all operations are at the same pace, this means that the flow is in the takt time. Figure 4 shows the decomposition of the Balanced Production.

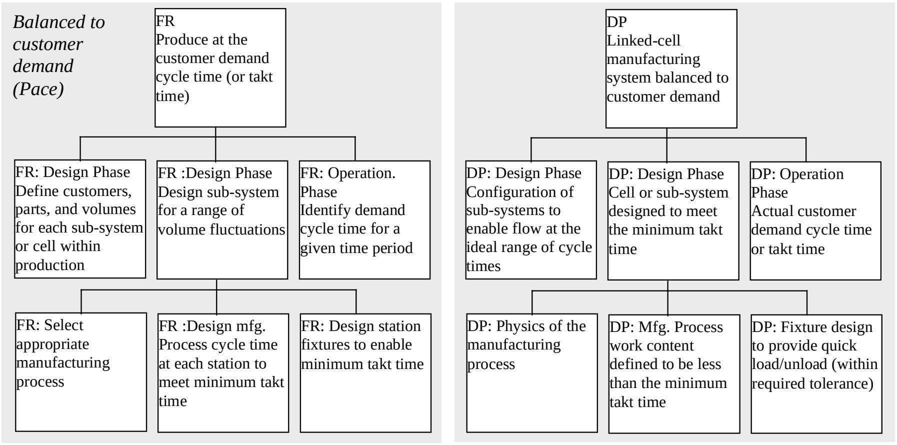


Figure 4 – Balanced Production (Suh *et al.*, 1998)

The Leveled Production is achieved when all operations produce the quantity and the mix demanded by the customer. Figure 5 shows the decomposition for the Leveled Production.

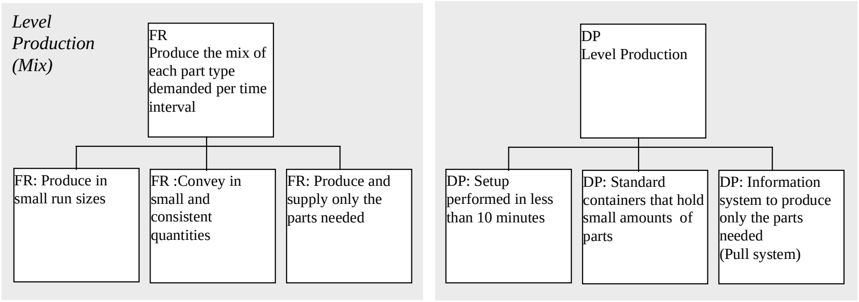


Figure 5 – Leveled Production (Suh *et al.*, 1998)

The Synchronized Production is achieved when all operations produce at the exactly same frequency, this means that the frequency demanded by the customer. Figure 6 shows the decomposition for the Synchronized Production.

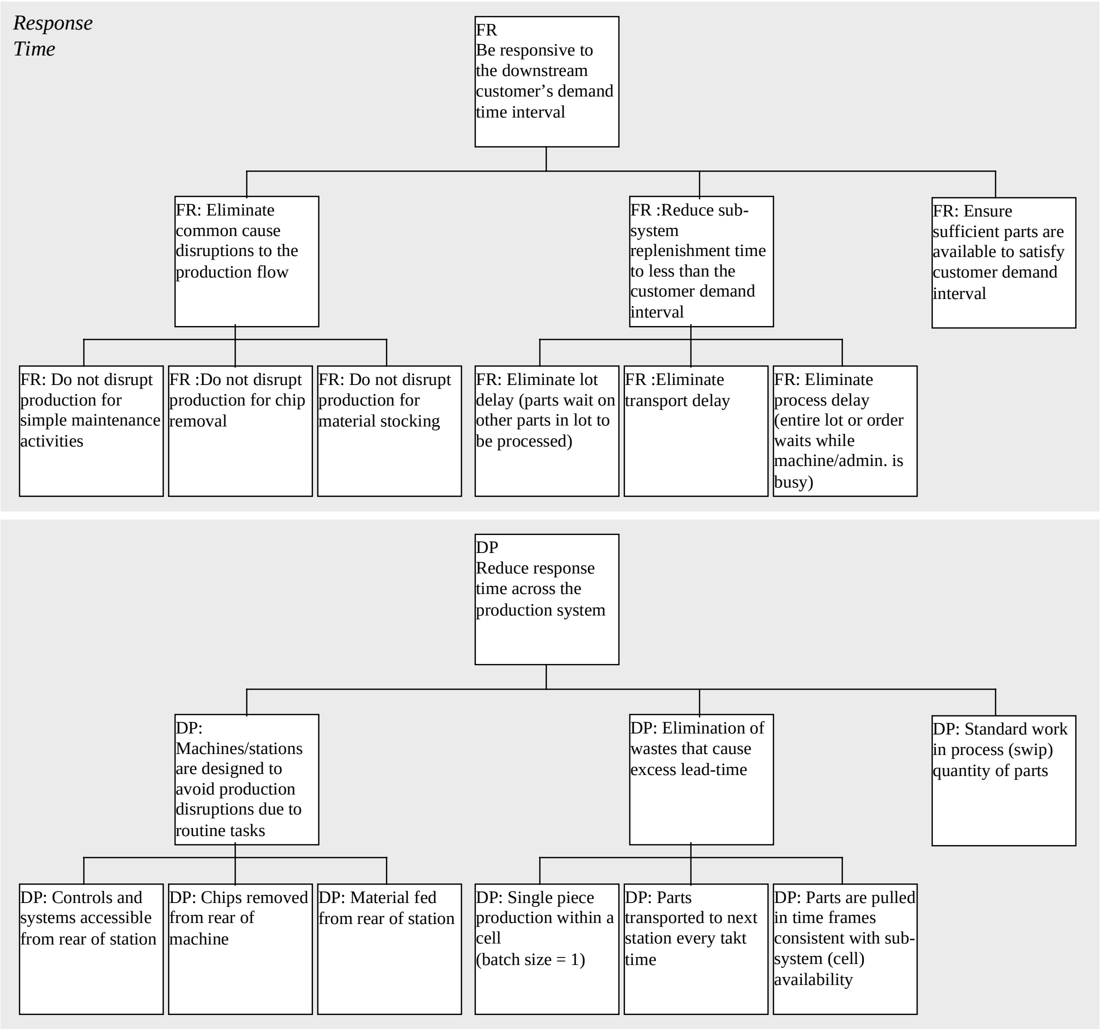


Figure 6 – Synchronized Production (Suh *et al.*, 1998)

5. CASE STUDY

In this case study the axiomatic design decomposition showed in the previous section is used to design an automobile supplier-machining cell that processes the rack bars for the steering gears. The application of each decomposition branch must be entirely done before moving to the next one. The right way to implement the design is going down and then to the right.

The rack bar is made from a steel bar of 1-inch diameter. Both ends of the bar must be turned and drilled in order to make a screw on both sides. After that, the bar has to be broached to open the tooth. Then, the bar is washed and heat threaded using an induction process. After that, it passes through a stress relief treatment for 60 minutes in a continuous flow oven and then it is straightened. Finally, after the bar is ground it is washed, audited and a piston is assembled in the middle of the bar.

The customer wants to receive diary deliveries from all models, and wants enough flexibility to decide nearly every day what he wants for the next day. This means that the cell should produce 740 parts per day with a takt time of 79 seconds in two shifts. Further, this cell has to produce three different rack bar models.

Looking at the axiomatic design in Fig. 4 the highest FR is produced at the customer demand cycle time. As stated in the DP, linking the cell to the customer makes this possible. This entire branch addresses that the cell must be balanced with the customer demand. The cell will produce every day what is demanded by the customer, and not based on a forecast. Going down the decomposition, the first FR is to identify the customer and its demand. As shown, the DP is to enable the system to produce at the ideal cycle time. As shown, this is clearly established. The second FR, to design the cell in order to support volume fluctuations, is divided in three different FRs: select the appropriate manufacturing process, design manufacturing process cycle time at each station to meet minimum takt time, and design station fixtures to enable minimum takt time. Finally, the last FR is identifying the demand during the operational phase. The DP for this FR is to produce only after the customer order the mix he wants. This was easily implemented because the cell was designed to have a low throughput time.

As explained before, this cell was entirely designed to meet the process needs. This satisfies the FR-DP that states that the appropriate process must be adopted and solution for this is to design each machine according to the cell. So, the machines were specified in this way. The washers were designed and built in-house because they only need to wash one part per time. The broach was designed to have a small capacity and a reduced setup time. So the designers decided to use a horizontal machine, much easier to install and use than the vertical one.

Looking at the FR-DP that states that each machine must meet the minimum cycle time, the solution is to define the work content in such a way that it meets the minimum cycle time. This means that the designers decided to use simple turn machines and split this operation between the machines in order to reduce the cycle time and use cheaper machines. In addition, it was decided to maintain two induction machines, instead of a bigger one, so the cycle time needed would be achieved. This bigger machine is able to produce two parts in each great cycle time. Also the grinders were specified to be simple although a high quality surface is needed. In this case, the designers decided to use two simple machines in sequence.

The last FR states that the machine fixtures should be designed to facilitate meeting the minimum cycle time. The DP for this is to design fixtures that provide quick load/unload operations. In the cell this was implemented by specifying machines that do the unload task automatically. This was decided because the unload task is easier than the load task. So the load task was designed to manual, and the unload to be automatic.

The second highest FR, shown in Fig. 5, addresses the necessity of producing the right mix of parts in each time interval as demanded. The DP for this FR is to level the production. The decomposition of this FR is divided into three FRs: producing in small lot sizes, conveying the parts in small and consistent quantities, and producing and supplying only the parts needed.

Small lot sizes are possible when the setup time is short, otherwise it is economically impossible. Short setup times are achieved using SMED techniques and designing the machines to have a quick setup. The best example of this is the design of the broach machine. Instead of having a big vertical broach, that has a very low cycle time and can produce a large number of parts per cycle, the designers decided to use a horizontal broach, that only produces one part per cycle, and has a medium-high cycle time, but has an easy and quick setup, and, most important, has an easy load/unload fixture.

The second FR, conveying the parts in small and consistent quantities, is achieved with standard small containers. This guarantees that the cell will not produce more than needed. Using small containers enables the company to deliver small lots to the customer.

Finally the third FR, producing and supplying only the parts needed, is enabled by establishing an information system that pulls the production as the customer needs.

The third highest FR, shown in Fig. 6, addresses the necessity of being responsive to the downstream customer’s demand time interval. The DP for this is to have a reduced response time across the production system. This FR also has three decomposition: eliminate common cause disruptions to production flow, reduce sub-system replenishment time to less than the customer demand interval, and ensure that sufficient parts are available to satisfy customer demand.

Eliminate common cause disruptions to production flow are avoided by designing machines that do not have to be stopped by common tasks. This FR is decomposed into three FRs: Do not disrupt production for simple maintenance activities, do not disrupt production for chip removal, and do not disrupt production for material stocking. The DPs for these FRs are respectively: controls and systems are accessible from rear of station, chips are removed from the rear of the station, and material fed from the rear of the station. Basically, these three DPs are used in the design of the machines. All of them were specified with rear chip remove and with rear maintenance. The last DP, material fed from the rear of the station, is used in the sub-assembly when the worker has to press the piston in the rack bar. The pistons came in by a fed using gravity to move it. All replenishment is made from the back of the station.

The second FR, reduce sub-system replenishment time to less than the customer demand interval, is addressed by the DP elimination of the wastes that causes excess of lead-time. This FR has three decompositions: eliminate lot delay, eliminate transport delay, and eliminate process delay. The FR, eliminate lot delay, is solved using single piece flow. This means that only one part will be produce per cycle time in all machines. The second FR, eliminate transport delay, is solved by transporting the part to next station every takt time. Finally, the FR eliminate process delay is solved by pulling the parts in times frames consistent with the cell availability.

The third FR, ensure that sufficient parts are available to satisfy customer interval, is solved by the DP that establish a standard amount of work in process – swip.

Based on these design parameters, the cell was designed. The number of workers was defined based to the takt time required. Depending on the customer demand the number of workers can be raised or reduced. This cell can operate with only one worker, and produce approximately 500 parts per day in two shits, or can use three workers, and produce approximately 1000 parts in two shifts. The number of workers gives the production capacity, and the machines have some extra capacity, especially the induction machine and the washers. The final design for the cell is shown in the Fig. 7.

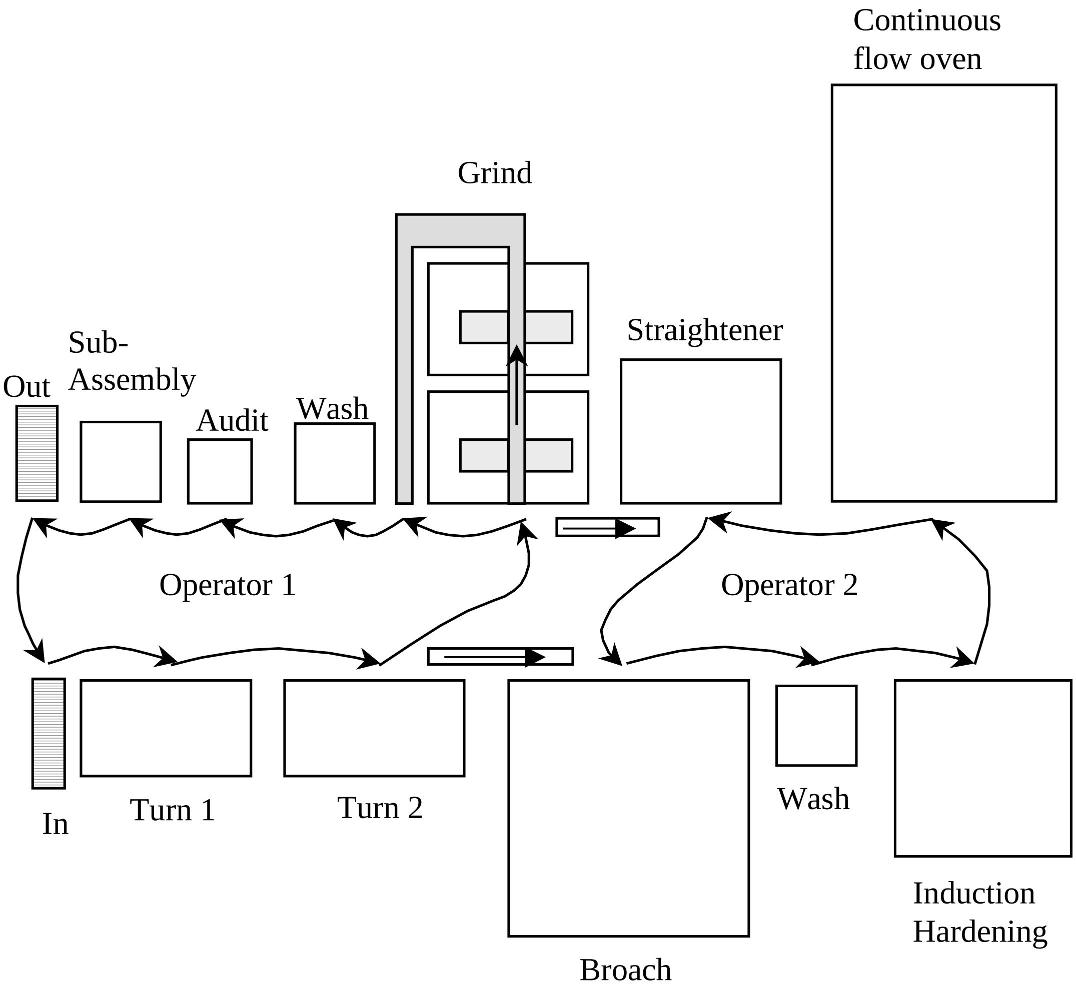


Figure 7 - Cell Design

6. CONCLUSION

In this paper the major principles of Lean Production were integrated and implemented using the Axiomatic Design and production general design. Based on this general design, specific solutions were found, and this structure also establishes the correct order to implement and control the cell. The case study shows the applicability of the Axiomatic Design in designing a production cell.

To know why and in which sequence Lean Production should be implemented is a critical success factor. Using the same principles in the wrong sequence can result at least in a low performance, and in the worse case in a production system with an unpredictable behavior. The Axiomatic Design is not only important in the correct design of the system, but also in the operational phase when the system must be adjusted in accord to the customer needs.

Acknowledgments

Fapesp that supports this research.

REFERENCES

Lobo, C., 1997, Proposta de metodologia para incremento do desempenho da manufatura através da técnica de simulação, Msc. Thesis, The University of Campinas, Campinas, Brasil.

Shingo, S., 1989, A Study of the Toyota Production System, Productivity Press.

Suh, N. P., Cochran, D. S., and Lima, P. C., “Manufacturing System Design”, (keynote paper presented at the CIRP General Assembly, in Greece, August, 1998), CIRP Annals, Volume 47, No. 2, 1998.

Suh, N., 1990, The principles of design, Oxford University Press, New York.

Womack, J. P.; Jones D. T., 1994, From lean production to the lean enterprise, Harvard business review, march-april.

Womack, J. P.; Jones D. T., 1996, Lean Thinking, Simon & Schuster, New York.

Womack, J. P.; Jones D. T., Roos D, 1990, The Machine that Changed the World, Rawson Associates, New York.