Lean Manufacturing Cell Capstone Project

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Whereas many capstone projects involve the design and fabrication of some prototype product, the emphasis of this semester-long exercise in cooperative project management is a functioning lean manufacturing work cell. Student teams begin with a set of prints to develop the process flow and fixtures required to implement the lean production of a product involving the assembly of several parts, beginning with stock materials. The design challenges are two-fold: create a lean production process and design work-holding devices required to achieve the process plan. The manufacturing cell involves integrating work stations that employ a variety of levels of automation: manually controlled drill press, two-axis CNC machining, and an articulated arm robot. Classmates perform the labor to fabricate the products utilizing a *kanban* system and work instructions created by the design teams. Each design team is required to submit a set of Production Part Approval Process (PPAP) documents which detail the component designs, process planning, quality assurance, and production control of their product.

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Background

The design of this capstone course serves the needs of an engineering technology program whose mission is to prepare management-oriented engineering technologists. Many alumni from the program work as either process engineers, process planners, product designers, or production managers. The industries vary from large equipment OEMs to custom injection molders to OEMs of advanced diagnostic equipment. This capstone course is meant to provide a project management experience that includes planning, execution, and control. The focus of the capstone is the design and implementation of a lean production cell.

Responsibility for the design and operation of a production process is a career path open to more students than that of designing individual products. Therefore, this capstone course focuses on the design of a lean production process as an alternative to the more traditional product design-oriented capstone course (Ackerman, 2007).

Lean manufacturing principles have been taught in engineering technology programs for over ten years. Lobaugh (2005) exposed students to an element of lean manufacturing by having student teams perform an analysis of lean process improvements for local companies. The value of incorporating a physical simulation of the lean production process was demonstrated by Verma (2006) using ready-made components that were assembled by student teams. Nambiar and Masel (2008) utilized production simulations with plastic blocks in a special class developed to address the requests by area employers for graduates with knowledge of lean manufacturing. The unique feature of this capstone class is the level of realism involved. Student teams design and implement a lean production work cell in which they convert standard lumber into nontrivial products. Further, alumni from the program have commented that this capstone class structure provided the best environment for them to learn practical project management skills (Reifschneider, 2010).

Capstone Course Elements

This paper will address several areas of teaching a capstone course as well as provide a detailed description of the work cell design process.

Content

The objective of the course is to teach the project management integration required to design and deploy a functioning lean manufacturing cell. There is a balance of designing a process and creating a product in this capstone course. The process planning is critical to have a work cell that is efficient at producing products. Good design of fixtures needed for work holding constitutes the product design focus in the class. In the past student design teams developed their own product ideas. They would then design the fixtures to manufacture their product. This process, however, posed two problems. First, there was a lack of parity in the product complexity across the different teams in the class. Second, the time taken during the semester for teams to finalize their prototype pushed back the start time for their process planning and fixture design. The emphasis for these teams became a product design class and not the process planning for a lean production work cell which is the intent. Consequently, the designs are now developed by the instructor before the course begins.

The key lessons in this capstone course are not only to be able to repeatedly make a quality product, but also to do this in the most timely, efficient manner possible. The goal is to develop and implement a lean manufacturing work cell.

Teams

Teams are formed by the instructor to insure complementary skills and parity across class. Students have prior knowledge of CNC and robot programming. Students choose their group assessment method. Student teams draft their own charter outlining member participation expectations and grounds for dismissal. Teams also decide how the capstone team project grade is assigned: all get the same grade or individual grades based upon identified contributions to the team project. Most teams choose the same grade option. The semester-long design project is 50% of the capstone course assessment.

Outcomes

There is a balance of process and product. Primary deliverables are an industry standard Production Part Approval Process (PPAP) document with a functioning lean manufacturing cell.

The products that are to be manufactured are primarily made of wood to reduce the cost of production and simplify the machining operations. The designs of the products are complex enough to require significant work holding problem solving and process planning to manufacture, but not so complex that ten could not be made by a team of 10 students over a two-hour period. The product is an assembly of at least six parts. The fit of components is a critical product requirement: flush surfaces and square corners. Products also have at least one moving part. In recent years products have been hinged bird nesting boxes and bird feeders. Each design team has a unique design to build, but all designs have similar levels of complexity as outlined above. The quality target is a product comparable or better to that which would be found at a retail hardware store.

Components are operated upon at various work stations: a CNC mill, a drill press, and an articulated arm robot with an air drill. These work stations represent three levels of automation: manual drill press, two-axis CNC milling, and six-axis articulated robot. Design teams are expected to incorporate all three types of work stations in their process map. The goal is to have a well balanced production flow. Students are cautioned not to over task an automated workstation because this may become the rate determining step and will actually lower production flow, which is not desirable.

Although some manual operations are expected, no work is done without proper work-holding fixtures. For example, an accurately located complex hole pattern can be drilled into a work piece without using CNC. Movable dowel pins are employed to function as adjustable datums for work holding.

As with production planning teams in industry, each design team must submit a PPAP document to summarize how well their products met the project goal.

Lean Work Cell Design Process

The design process each team undertakes to plan and implement a lean production work cell of their product is flow-charted in Figure 1. Items that are boxed in double lines with bolded text are components of the PPAP document.

Production Part Approval Process (PPAP)

This is a standard quality assurance document developed by the Automotive Industry Action Group (DaimlerChrysler Corporation, et al. 2000). It is a series of documents which need formal approval by the supplier and the customer before full production of a product can begin. Key elements of the PPAP that are included in the capstone assessment are listed below.

- Design Records, copy of customer prints.
- Inspection Prints, prints identifying dimensions to be verified for quality assurance purposes.
- First Articles, products made using production ready tooling and fixtures.
- Dimensional Results, tabular summary of how first articles compare to the Inspection Prints
- Process Flow Diagram, the production plan logic indicating every step of the manufacturing process.
- Process Failure Mode Effect Analysis (PFMEA), chart indicating what could go wrong during each type of processing operation, how severe the failure could be to the operation, and the potential cause of failure. Risk Potential Numbers are computed for each potential cause of failure. Corrective measures are identified for each work station (reference to setup prints, checks, and training) to mitigate failures. References to work station operating instructions for safe operation are included.
- Gage R & R, determination of the repeatability and reproducibility of the gages used to inspect products for quality assurance.

- Initial Process Studies, computation of process capability or PPK, based upon measured quality control features in machined components.

Comments about the lean work cell design process illustrated in Figure 1 are given below.

- Teams of four to five students are formed by the instructor to insure a complementary skill set for the technical requirements of the project.
- The design of the product a team is to manufacture is conveyed with a set of prints. These prints become the Design Records for the PPAP.
- Concurrent work proceeds to develop the process flow, solid models of the product, and construction of a prototype of the product using the Design Records.
- If the prototype appears satisfactory, then the CAD design can proceed to fixtures. If not, an engineering change request is made to adjust the product design.
- Once the basic process flow diagram is complete, then the PFMEA and a production level PERT diagram is prepared. The PERT is a flow chart of the production process that factors in operation time (milling and drilling) at each work station as well as the transport time between stations. The PERT is used to determine the critical path, or cycle time, as well as to identify the rate determining work station that sets the *takt* time of the manufacturing work cell. The *takt* time is the time interval at which successive products are released from a production cell, the primary factor determining production rate.
- The PERT is used to create a Work Flow Diagram (WFD) that illustrates how all components in the production process move through the work cell. A critical element of this diagram is the *kanban* which is a sign card system that provides a visual reference for operators to direct them when to produce and where to send their finished parts.
- Because the PFEMA addresses failure modes and issues of safety, it must be completed before fixture design can be completed.
- Complete fixture design triggers concurrent work to develop inspection prints, work instructions, and the building of fixtures. The inspection prints are used to create the Dimensional Results chart, the measure of acceptable product quality.
- Before a pilot run is made, the First Articles (first parts) made from the fixtures are compared to the inspection prints. If adjustments are required, then the PFEMA is revised, fixtures are modified, and another round of inspecting "first articles" is done until adjustments are not required.
- The Pilot Run is the first time the lean process flow is implemented to make products. Design team members perform the labor to create the pilot run products. Classmates acquire cycle time data that is used to determine the work cell flow. Assessments are made of the safety of the operations, the quality of the work instructions, and the balance of the workstation times in the work cell. High quality work instructions are needed because, during the production run, classmates of the design team will provide the labor to make products. The design team is not involved in the operation of the work cell during their production. Their task is to have designed a visual, logical process with easy to comprehend instructions so that relatively untrained employees accomplish the production of quality products in a safe and timely manner.

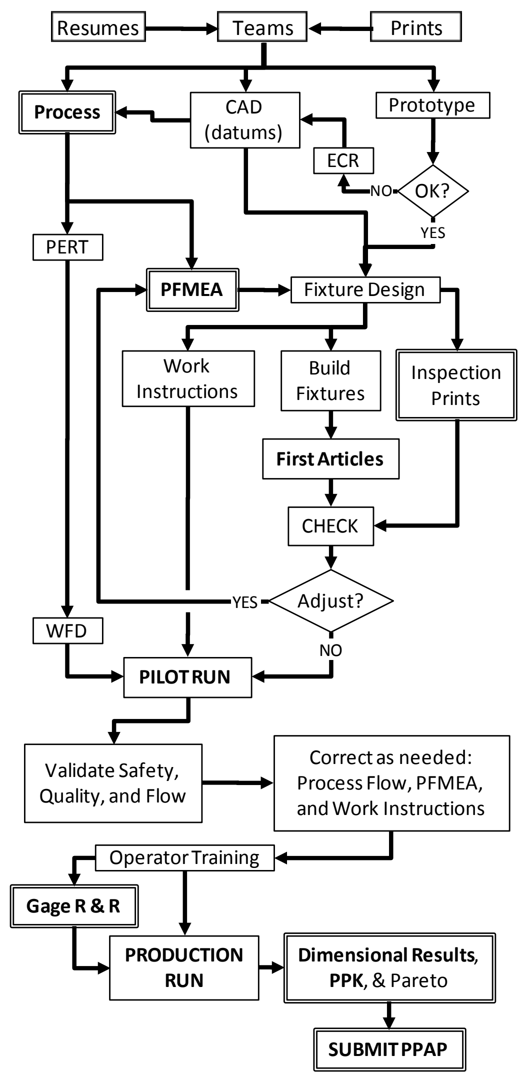

Figure 1. Lean Work Cell Design Process

- If all is well with the Pilot Run outcomes, then classmates (operators) are trained for the Production Run. Training amounts to verifying that the assigned workers can demonstrate safe operation of the machine at their work station.
- Before the Production Run begins, the design team must determine the Gage R&R with the assigned set of operators.
- The Production Run occurs during a two-hour period. Prior to the start, the design teams setup the machines: mount fixtures, set datums, place auxiliary tables and tools as needed.
- The quality assurance data, the Dimensional Results and Pareto chart data, are gathered by operators during the Production Run and given to the design team.
- The last step in the capstone project is organizing all of the PPAP documents into an excel workbook. The spreadsheet format allows prints, flow charts, and tabular data to be contained on separate worksheets. Worksheet tabs are labeled with the appropriate titles. This format is neatly organized and paperless.
- There are several milestone checkpoints throughout the course when teams are evaluated on the progress they are making toward their goal.
- Key learning objectives include: 1) designing and building effective work holding fixtures for each manufacturing step, 2) organizing the material flow through the work cell to minimize wasted motion and idle time (key lean concept), 3) controlling the production flow through proper use of tracking methods such as a *kanban*, 4) creating effective work instructions for classmates to produce the required components with little formal training, and 5) developing the habits of effective team work and project management.

Course Structure

The team design project is an integral part of the capstone course, but only 50% of the assessment. Individual assignments addressing the review topics outlined below account for 15% of the assessment.

- Lean manufacturing practice.
- Work-holding principles.
- Project management and effective teaming.
- Cost analysis: unit cost and break-even.
- The PPAP document and process.
- Midterm exam of review topics: 10%
- Final exam is Engineering Technology Sequence assessment exam: 25%

Conclusion

The creation of a lean manufacturing cell involves a good balance of learning the process of manufacturing something with the focus of making a specific product. Although students in the class are from the same academic program, the team members have select advanced skills because of the breadth of skills required to accomplish the project. In addition, the inclusion of an industry standard production qualifying document, the PPAP, gives students relevant experience they will value immediately after starting their career.

The project management accomplished in this course closely matches what most alumni experience in their early career. Many alumni found the class to be an excellent platform to learn practical project management skills because they must implement something they have designed. The course requires effective teamwork, problem solving, data collection, and the design of a process with constraints of cost, time, and quality.

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