AC 2008-100: MANUFACTURING CENTRIC UNDERGRADUATE CAPSTONE EXPERIENCE

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Manufacturing Centric
Undergraduate Capstone Experience

A Department of Industrial Technology (IT) at medium sized Midwestern University has created a two course capstone experience for its undergraduate curriculum. The cohort sequence is the culmination of the technology and required business minor sequence courses. The goal of this capstone experience is to simulate, as closely as possible, a real manufacturing enterprise.

The design of the course is based on constructionist curriculum design. An understanding of the constructionist approach to curriculum design can be seen in the writings of Jean Piaget, Jerome Bruner, and John Dewey. Both Jean Piaget and Jerome Bruner see the individual as the principle in the acquisition and construction of his or her own knowledge. Both are considered constructivists. Constructivism is a learning theory in which individuals interact with the world around them and then go through internal processes to make sense of those interactions. Both Piaget and Bruner discuss the relevance of a curriculum based on the developmental stage of the individual and the need for interaction with objects and individuals for growth. Dewey demonstrated that students gain a deeper understanding, and skills of scientific analysis buy doing or activity based or project based learning as we know it today. The design is based on various constructionist instructional design approaches and is reiterative in nature and takes in to account the stakeholders' (current students, alumni, and employers) feedback in to the revisions. This is feedback is achieved through interviews, surveys. [1,2,3,6]

In this capstone course sequence the students face technical, business, and personnel challenges and issues from the workplace such as technical problems, cost management, team dynamics, and time pressures. Nearly all aspects of manufacturing are addressed, including product design and specification, supply chain management, process design and documentation, tool design and build, lean manufacturing concepts, inventory control, cost accounting, automatic data collection, and quality assurances methodology including the application of statistical process control, various quality management tools and Six-Sigma techniques.

The students are assigned to teams - manufacturing firms for the purpose of the exercise– with an average of five students per team. Each team must design and produce a product that meets a set of criteria and within the constraints defined by the firm's Board of Directors (the professors) and the customers (the other student teams). The teams go through the steps of mock-ups, proto-type builds, process selection, tooling build, pre-production runs, and a real production run to produce at least 20 – 40 products in 6 hours (one of the constraints). Processes include, but are not limited to, plastic molding and forming, metal machining, metal casting, metal forming, and wood processing. The team that develops the product, manufacturing processes, and documentation for a specific product takes on the role of manufacturing engineers and managers during the production run and are not allowed to operate the equipment to produce the products. Other students from this class and other IT classes become the labor force and must use the materials, tooling, data collection systems, and processes as documented by the development team. Multiple document and product check points and project reviews are presented during the capstone sequence.

It must be emphasized that this is not a simulation exercise, it is real manufacturing. Student decisions have real consequences and their design and plan must work. For example, designing a product assembly fixture is not simply a CAD activity. The fixture is designed, built, tested for accuracy, reliability, capacity, repeatability of set-up, etc. and must be robust enough to handle the abuse in a production environment. The fixture must also be capable of withstanding the inevitable variability of the raw materials and parts for which it will be used. The average team will produce approximately 18 such fixtures during the course.

Students integrate various contemporary integrated manufacturing concepts during these production runs. Automatic identification and lean manufacturing concepts such as Kan Ban, Poka Yoke, Visual Controls and others are practiced. Firms must also implement statistical quality control tools and Six-Sigma techniques including various data collection, analysis, and process control methodology.

It is through this project-based experiential learning activity that learning occurs on the "production floor" as students draw on the scaffolding developed from previous course work and the new materials that are presented in the capstone courses. This course sequence has been highly rated by students, the department's industrial advisory board, and employers.

The following will present additional detail about each of the two courses in this capstone sequence. Each course has three distinct, but highly connected areas of content including lectures, manufacturing documentation (known as the manufacturing plan) and activity based learning (known as lab). Each of these areas will be discussed for each course.

Capstone Course #1, Contemporary Integrated Manufacturing (4 credit hours with 6 contact hours per week).

Lecture Content

The lecture content includes formal lectures (via PowerPoint), class discussions, team presentations, etc. The lecture content is described below:

- Introduction to Manufacturing operations including: historical overview, organizations missions, strategies and tactics, competitiveness, and productivity
- Product design: value analysis, legal, ethical & environmental issues, standardization, life cycles, concurrent engineering, design for X.
- Product documentation including: product structure, bill of materials (BOM), item master and part numbering systems, product costing.
- Project management:
- Supply chain management:
- Inventory management:
- Materials requirements planning (MRP) and enterprise resource planning (ERP):
- Just-In-Time (JIT & Lean Operations).

In addition to the above lecture content, student team present lectures on various topics including: high performance teams, legal supervision, and lean topics.

Manufacturing Plan

There is a detailed manufacturing plan developed during the two capstone course sequence. The plan is divided into several subsections including: engineering drawings, materials plan, tooling plan, production plan, quality plan, automatic identification and data capture plan and a safety plan. This plan is developed over the course of 20 weeks with four reviews before the final document is submitted (typically a four inch binder). This plan begins in the first course, however, most of the content is developed in the second course. The following is a description of the content developed during the first course.

- The engineering drawing section includes a complete set of “working drawings” of the product to be produced. This includes both CAD orthographic and isometric drawings of all parts, subassemblies and the final product.
- The materials plan includes a Multi-level Indented bill of materials [5] (see Appendix 1.1), product structure [5] (see Appendix 1.2), total materials cost spreadsheet including primary, secondary and support materials required to produce the product.

Lab Activities

Students are actively engaged in the implementation of their plan to design and develop a product which will be produced in a manufacturing setting at the end of the capstone sequence. The lab portion of this two course sequence is intended to give the students the time and tools to effectively develop the product design, tooling, processes and operational controls and strategies to prepare for this culminating event.

During the first course in this sequence, students determine the product they will be producing, develop sketches and working drawings from which a model or mock-up is produced . This model is typically produced quickly using foam board, cardboard, and other model making materials. The intent is to quickly get a physical representation of the product to confirm the design. This is an excellent method to make design issues such as aesthetics, symmetry and balance issues visible which are often difficult to identify on a two dimensional drawing. Following the model build, the team presents their product to the class and faculty for review and critique. There are two outcomes possible: accept the design as-is or with only minor changes; major redesign, including the building of a new model to be again reviewed and critiqued. Once the product is accepted, the team is released to create detailed engineering drawings and a product structure for review.

Once engineering drawings have been reviewed and accepted, the team purchases the materials required to produce a single prototype using the actual materials planned for the final product. The materials costs are also determined and the prototype and costs are presented to the class and faculty for review. It should be noted that all students must purchase one of every product produced in class so the class review is also a customer review, therefore, the class input is often quite detailed. Following this review, each team determines changes to their product before the second course begins. These changes often focus on design for manufacturability, cost reduction, process capability and capacity issues.

Capstone Course #2, Product Manufacturing (5 credit hours with 8 contact hours per week).

By the time students begin this course they have developed team camaraderie, their products have been designed, and a prototype has been produced. In addition, the product has been documented with engineering drawings, part numbers have been assigned, a Bill of Materials has been produced, and materials cost have been determined.

This course is broken into three areas of content: traditional lecture, manufacturing documentation/plan, and activity-based learning known as labs.

Lecture Content

The lecture content includes formal lectures (via PowerPoint), class discussions, team presentations, etc. The lecture content is described below:

- Overview of Automatic Identification & Data Capture technology & techniques used in industry.
- Manufacturing Tooling (jigs & fixtures) including: design, production, tooling costs including labor, materials and overhead, Poke Yoke techniques and tool set-up reduction techniques.
- Engineering Change Control including engineering Change Requests (ECR's), Engineering Change Orders (ECO's) and sub-contract work requests.
- Capacity Planning including Design vs. Effective capacity, efficiency and utilization of resources, Make/Buy decisions, and Theory of Constraints
- Work design including job design, specialization, working conditions, and ergonomics. Methods analysis is also covered in this section including time and motion studies, flow charting, and determine standard times.
- Process Selection and system design including the study and analysis of project, job-shop, batch, repetitive and continuous processes. There is also an overview of robotics and automation which is covered in-depth in another course.
- Facility layout including product vs. process layout techniques, cellular manufacturing, and a variety of facility layout tools and techniques.
- Manufacturing Costs including Cost/Volume determination (fixed costs, variable costs, and break-even point determination), Developing labor, materials and tooling cost standards, and the analysis of capital improvements costs including return on Investment, simple payback, internal rates of return, etc.
- Inventory Management & Control with the focus in this course on determining inventory levels (order quantity, safety stock, reorder point, economic order quantities, lead time, etc.) and "shop floor" inventory control including the use of KanBan's, kitting, movement, etc.
- Quality Assurance is reviewed. This topic is covered in depth in another course. The focus here is the implementation of quality tools in a manufacturing environment. These tools include: statistical control charts, run charts, Pareto diagrams, check sheets, scatter diagrams, etc.

In addition to the above lecture content, student team present lectures on various topics including: PokeYoke tooling, process set-up time reduction, aesthetic quality measurement, standard time determination, etc.

Manufacturing Plan

There is a detailed Manufacturing Plan developed during the two capstone course sequence. The plan is divided into several subsections including: Engineering Drawings, Materials Plan, Tooling Plan, Production Plan, Quality Plan, Automatic Identification & Data Capture Plan and a Safety Plan. This plan is developed over the course of 20 weeks with four reviews before the final document is submitted. The following is a description of the content of each of these sections.

- The Engineering Drawing section includes a complete set of “working drawings” of the product to be produced. This includes both orthographic and isometric drawings of all parts, subassemblies and the final product. In addition an “exploded isometric” drawing is required for all subassemblies and the final product.
- The Materials Plan includes a Bill of Materials (BOM), total materials cost spreadsheet including primary, secondary and support materials required to produce the product, and an inventory control strategy to control materials during production. This may include the use of KanBan’s, kits, totes, visual controls, etc.
- The Tooling Plan is quite substantial in both content and sheer volume. This plan covers all special tooling deigned and built by the students. Included in this plan is a complete set of engineering drawings for each tool, tool costs including materials and labor, a “tool use” document for each tool which includes tool set-up and safe and correct operation instructions.
- The Production Plan starts with the big picture of the production operation, the Operations Process Chart. In addition a detailed Standard Routing (Appendix 1.3)is developed for each part, subassembly and final product which includes step-by-step operator instruction, time standards, inspection steps, safety issues and inventory movement. These standards are then utilized to develop a capacity analysis to determine both equipment and labor requirements. There is also a shop floor flow map for each part, subassembly and final assembly indicating the actual flow through the factory [4].
- The Quality Plan is intended to answer several key questions including: What are the Key quality characteristics to be monitored? How will these be controlled to reduce or eliminate variation? How will these be check and/or measured? How will these check and measurements be documented? (control charts, check sheets, etc.) Where when and by whom in the process will the checks and measurements be made? What is the process to deal with “out of specification” problems?
- The Automatic Identification & Data Capture (AIDC) section documents to students plan to utilize AIDC techniques in the production of the product. This may include the use of bar codes, radio frequency tracking devices, etc. to monitor inventor, collect quality data, track labor, etc.
- The Safety Plan requires students to identify risks and develop a plan to reduce or eliminate these risks. The risk assessment may include mechanical, electrical and/or chemical hazards.

Lab Activities

The first lab activity in the second course begins with another review with the class and faculty. The product changes indicated above are again reviewed and once approved, the team builds prototype #2 implementing all changes. This is the final design! Any future changes must be submitted on an Engineering Change Request document and again be scrutinized by the class and faculty.

Process Selection

Once the final product design has been determined, several activities begin simultaneously. These include: process design, tool design and build, process flow, and quality control. The teams must determine the "best" processes to be used to produce the parts need for their product. They consider process capability and capacity, process time, set-up time, etc. The process flow is documented on a standard routing and details regarding set up, tooling, time standards, etc. are input to this document as they are identified.

Tooling and Quality Control

The teams also identify the need for tooling such as drill fixtures to reduce variation, increase processing speed and reduce set up time. Tooling is designed, produced, tested for accuracy, repeatability, set up, robustness, etc. As the tools and processes are being tested, quality problems often become visible. At this time the team must decide how to deal with these issues. They may consider several options including: identify and eliminate the cause of the problem, add an inspection station so the problem does not continue in the process or change the design to be able to accept the problems.

Pilot Run

During the 15^{th} and 16^{th} week of the 20 week course sequence, teams are required to make a Pilot Production Run of the product. During this time they produce at least three products following their production documentation (drawings, standard routings, etc.) and using their production tooling they have designed and produced. The intent of this activity is to confirm the design of the entire manufacturing process from process selection and capability and process documentation to material flow and quality control. Following the pilot run the activity is reviewed and critiqued by the faculty and the team. Some changes may be suggested and others may be required (such as tooling or processes with a high safety risk). The team then has about one week to make necessary changes before the actual production run is to occur.

Production Run

The culminating lab activity of this two course capstone sequence is known as the Production Run. All activities culminate to this critical activity. Typically there are 20 students in these courses including four teams of five, each with a different product they have designed. The actual production run is typically a six hour class activity plus additional work on the front and back end for the team managing the run. Each production run consists of the following activities:

- Lab (factory) set-up: The afternoon and evening before the production run, the management team takes charge of the lab/s needed for their production run. They reconfigure the lab (as allowed) including moving workstations and selected equipment. They set up all equipment, tooling and processes per their production plan as well as the inventory control system per their materials management plan. The quality control system they designed is set up including measurement and data collection locations. All safety issues must be addressed and resolved. All production documentation is also placed in the appropriate locations. This set up activity often takes eight to twelve hours.
- Production Run Activity: It must be noted that the team that designed the product and manufacturing plan is now in a leadership/engineering role and cannot perform any direct labor, material handling or quality control tasks. The team directs and controls the production run just as a manager and manufacturing engineer would control factory operations. They make work assignments, monitor process and employee performance and make adjustments as needed to produce high quality products in the time allotted. They must quickly and effectively deal with any problems that may arise during production including: safety, tooling, capacity, flow, inventory control, etc. This is real and for many students, this is the hardest they have ever had to work.
- Post Production Activity: The post production activity varies with each team. If the required number of high-quality products are completed during the time allotted, post production activity may focus only on final inspection and tool and process "tear down." If, however, the products are not completed or there are serious quality problems, the team must deal with these ASAP in order to be able to ship products at the designated time. Therefore, it is in the team's best interest to manage to run in such a way that high quality products are produced in the planned quantity during the allotted production time.
- Product Distribution: At the end of the course, each class member will pay for and receive a product from each production run. These are randomly distributed so each class member has an equal chance of obtaining the best or worst product produced. It should be noted that the faculty inspects all products and no bad products will be distributed. The best and worst products are all "good" products but do vary within an acceptable range.

Capstone Experience Wrap Up

The capstone experience concludes with a final review of product, process, and documentation by the two instructors of the courses. Feed back from the class is given to each of the teams as well. What went well and what could have been improved is the focus of this review session with each team. At this point the teams have been working through this experience for twenty weeks. It is not unusual for the teams to have 8-15 hours a week involved in these courses.

Teams often talk not only about the measurable outcomes of the course but also the less tangible aspects of the course such as truly working as a team versus previous experiences as working as a group, the difficulties of executing a work plan, the variability in workers, materials and equipment that must be dealt with. This is the type of significant learning which can be achieved with activity based learning projects such as these.[1,2,3] In this capstone sequence students demonstrate to the professors but more importantly to themselves that they can not only plan but execute their plans.

Reference list

1 Bruner, J. (1966). *Toward a Theory of Instruction*. Cambridge, London: The Belknap Press of Harvard University Press.

2 Dewey, J. (1905). *The School and Society.* New York: The University of Chicago Press McClure, Phillips & Company. (Original work published 1900)

3 Kemp, J. (1985). *The Instructional Design Process*. New York, NY: Harper & Row Publishers Inc.

4 Meyers, F. (1992). *Motion & Time Study.* Englewood Cliffs, NJ: Prentice Hall.

5 Stevenson, W. (2007). *Operations Management.* New York, NY: McGraw-Hill Higher Education

6 Wadsworth, B. (1996). *Piaget's Theory of Cognitive and Affective Development* (Fifth ed.) White Plains: Longman Publishers USA.

APPENDIX

Appendix 1.1

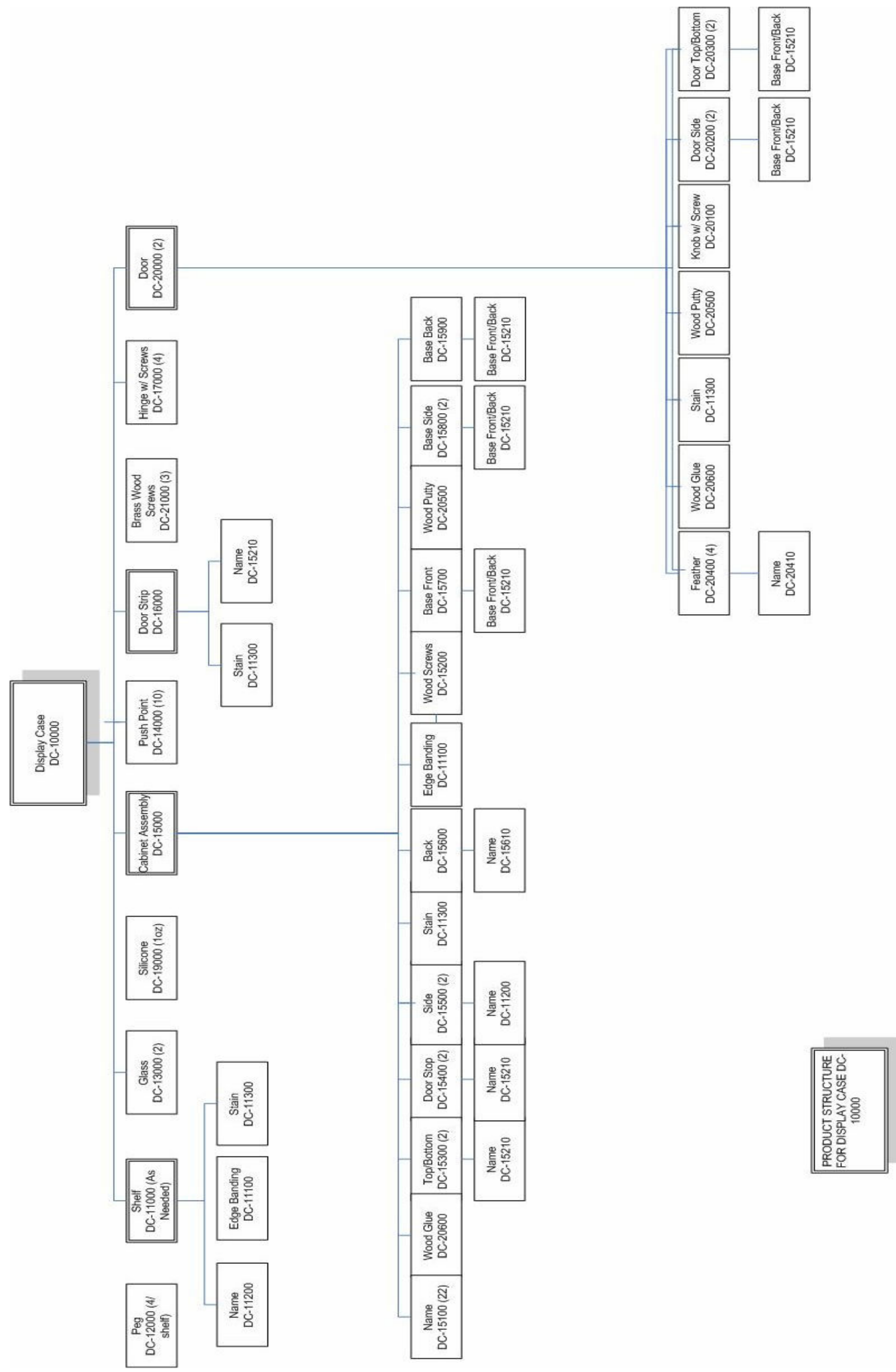
Rev #____
Date:____

Bill of Materials

Display Case

Level	Part Number	Description	Qty/Unit	Make/Buy
0	DC-10000	Display Case	1	Make
1	DC-11000	Shelf	As Needed	Make
2	DC-11100	Edge Banding	13"	Buy
2	DC-11200	1/2" Oak Plywood	84.5 in sq	Buy
2	DC-11300	Stain	As Needed	Buy
1	DC-12000	Peg	4	Buy
1	DC-13000	Glass	2	Buy
1	DC-14000	Push Point	10	Buy
1	DC-15000	Cabinet Assembly	1	Make
2	DC-15200	Wood Screws 1.5"	8	Buy
2	DC-15100	3/4" Nail	20	Buy
2	DC-20600	Wood Glue	As Needed	Buy
2	DC-15300	Top/Bottom	2	Make
3	DC-15210	Oak Stock	0.888 bd ft	Buy
2	DC-15400	Door Stop	2	Make
3	DC-15210	Oak Stock	.068 bd ft	Buy
2	DC-15500	Side	2	Make
3	DC-11200	1/2" Oak Plywood	111.13 in sq	Buy
2	DC-11300	Stain	As Needed	Buy
2	DC-15600	Back	1	Make
3	DC-15610	Oak Plywood 1/4"	214.31 in sq	Buy
2	DC-11100	Edge Banding	64"	Buy
2	DC-15700	Base Front	1	Make
3	DC-15210	Oak Stock	.182 bd ft	Buy
2	DC-20500	Wood Putty	As Needed	Buy
2	DC-15800	Base Side	2	Make
3	DC-15210	Oak Stock	.084 bd ft	Buy
2	DC-15900	Base Back	1	Make
3	DC-15210	Oak Stock	.182 bd ft	Buy
1	DC-16000	Door Strip	1	Make
2	DC-11300	Stain	As Needed	Buy
2	DC-15210	Oak Stock	.052 bd ft	Buy
1	DC-20000	Door	2	Make
2	DC-20400	Feather	4	Make
3	DC-20410	1/8" Hardboard	1 in sq	Buy
2	DC-20600	Wood Glue	As Needed	Buy
2	DC-11300	Stain	As Needed	Buy
2	DC-20500	Wood Putty	As Needed	Buy
2	DC-20100	Knob W/Screw	1	Buy
2	DC-20200	Door Side	2	Make
3	DC-15210	Oak Stock	.167 bd ft	Buy
2	DC-20300	Door Top/Bottom	2	Make
3	DC-15210	Oak Stock	.073 bd ft	Buy
1	DC-17000	Hinge W/Screws	4	Buy
1	DC-19000	Silicone	1oz	Buy
1	DC-21000	Brass Wood Screws	3	Buy

Appendix 1.2



Display Case
DC-10000
Peg
DC-12000 (4/ shelf)
Shelf
DC-11000 (As Needed)
Name
DC-11200
Edge Banding
DC-11100
Stain
DC-11300
Glass
DC-13000 (2)
Silicone
DC-19000 (1oz)
Cabinet Assembly
DC-15000
Name
DC-15100 (22)
Wood Glue
DC-20600
Top/Bottom
DC-15300 (2)
Name
DC-15210
Door Stop
DC-15400 (2)
Name
DC-15210
Side
DC-15500 (2)
Name
DC-11200
Stain
DC-11300
Back
DC-15600
Name
DC-15610
Edge Banding
DC-11100
Wood Screws
DC-15200
Base Front
DC-15700
Base Front/Back
DC-15210
Wood Putty
DC-20500
Base Side
DC-15800 (2)
Base Front/Back
DC-15210
Base Back
DC-15900
Base Front/Back
DC-15210
Push Point
DC-14000 (10)
Door Strip
DC-16000
Stain
DC-11300
Name
DC-15210
Brass Wood Screws
DC-21000 (3)
Hinge w/ Screws
DC-17000 (4)
Door
DC-20000 (2)
Feather
DC-20400 (4)
Name
DC-20410
Wood Glue
DC-20600
Stain
DC-11300
Wood Putty
DC-20500
Knob w/ Screw
DC-20100
Door Side
DC-20200 (2)
Base Front/Back
DC-15210
Door Top/Bottom
DC-20300 (2)
Base Front/Back
DC-15210
PRODUCT STRUCTURE FOR DISPLAY CASE DC-10000

Appendix 1.3

STANDARD ROUTING

Product Name: **DISPLAY CASE**
Part Name: SIDE
Part Number: DC-15500
Revision: 2
Date: 2/29/2008

Total DL Hours: 0.0699

Summary	Number
Operations	12
Transportations	8
Inspections	1
Delays	
Storages	
Total Steps	21

OP #	OPERATION O	T	I	D	S	DESCRIPTION OF OPERATION	Std Tools/Equip	Special Tooling	DL (HRS)
1		⇨				TRANSPORT 1/2" OAK PLY TO TABLE SAW			0.0006
2	○					RIP SHEET TO 7"	T-SAW/RULE		0.0081
3		⇨				TRANSPORT TO RADIAL ARM SAW			0.0019
4	○					CROSS CUT THREE PIECES TO 15-7/8"	RAS/RULE		0.0006
5		⇨				TRANSPORT TO TABLE SAW	RULE		0.0008
6	○					RAISE OR LOWER BLADE TO 1/4"	RULE		0.0047
7	○					SET BLADE 3/16" AWAY FROM GUIDE	RULE		0.0067
8	○					CUT DADO JOINT(GOOD SIDE UP)	TABLE SAW		0.0017
9		⇨				TRANSPORT TO WORK BENCH			0.0011
10	○					CUT TWO 16" PIECES OF EDGE BANDING	BLADE/RULE		0.0008
11	○					APPLY EDGE BANDING TO LONG SIDES	IRON/ROLLER		0.0017
12	○					TRIM EXCESS EDGE BANDING	BLADE		0.0006
13		⇨				TRANSPORT TO DRILL FIXTURE			0.0014
14	○					SET HOLE DEPTH WITH GAUGE		T-DC-15500-A	0.0019
15	○					DRILL 1/4" HOLES	D-PRESS/1/4" BIT	T-DC-15500-A	0.0002
16		⇨				TRANSPORT TO DRILL FIXTURE			0.0014
17	○					DRILL HINGE HOLES	DRILL-1/16" BIT	T-DC-15500-B	0.0028
18		⇨				TRANSPORT TO SANDING AREA			0.0011
19	○					SAND BOTH SIDES	SANDER		0.0308
20		⇨				TRANSPORT TO ASSEMBLY AREA			0.0011
21			□			INSPECT & RECORD ON CHECK SHEET			0.0167