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# TEACHING PRODUCTION SYSTEM DESIGN WITH THE AXIOMATIC DESIGN METHODOLOGY

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## ABSTRACT

Professors all across the world are striving to develop new and innovative teaching methods. MIT Mechanical Engineering Professor David S. Cochran has developed a course to teach production system design by exposing students to real problems in real-world factories. Through partnerships with local manufacturing companies, students learn how to solve real factory system design problems. Students benefit by learning, and the participating companies benefit from their ideas. A significant challenge for the students is defining the company's problem and the corresponding solution. Axiomatic Design is used by the students to guide their thinking and the factory-system re-design process. By studying some of the projects that have been directly implemented by the companies, we will be able to conclude that this innovative teaching and factory-system design method is an effective way to teach production and manufacturing system design.

**Keywords**: manufacturing system design, axiomatic design, teaching, problem solving process.

## 1 INTRODUCTION

Certain classes in college such as calculus or economics are best taught in the traditional way – lectures with chalk and chalkboard. However, what about those classes that teach the way factories work, the problems they face, and the rational solutions to those problems? Is it simply enough to teach the theories and equations based on a fictitious manufacturing plants? In previous attempts to teach these subjects, students learn how to calculate cycle time or takt time, and how to theoretically maximize the efficiency of production, but the results are all based on fabricated situations.

Professor David Cochran, the developer of the Manufacturing System Design and Control class at the Massachusetts Institute of Technology, believes that this is not the best way to teach the material. He has designed his class so that students could learn more about real manufacturing by working in the real factory. The focus of the class, Introduction to Manufacturing System Design (2.82/2.812), is set to implementing lean manufacturing principles into real world factories. Students gain invaluable knowledge and experience on Lean Manufacturing by participating in real projects through the relationships Prof. Cochran has developed with local Boston manufacturing companies such as United Electric Controls Corp., Tuthill, C&K, Middleton Aerospace, and Kinney Vacuum.

Students are allowed to choose one company and one project that they will work on throughout the term. Companies in various industries participate in the class and the products manufactured by the participating companies include pumps, switches, components for aircraft, and sensors. The projects include the design of manufacturing cells, setup reduction, machine design for manufacturing flexibility, and the design of factory information systems. Throughout the term, students apply what they learn from the class to create their own solutions to the real problems of the sponsoring company.

The projects provide a mutually beneficial opportunity for both the students and the participating companies. The companies benefit from the students' ideas and perspectives on the various manufacturing challenges they are exposed to. Students get a chance to face real manufacturing problems and solve them with their knowledge, so that they can gain invaluable experience in industry.

## 2 THE FACTORY AS THE LABORATORY

Manufacturing is diverse and involves attempting to achieve multiple objectives simultaneously within systems that require human decision making. Therefore, it is difficult to convey the complexity that exists within manufacturing systems in the classroom alone. For that reason, Professor Cochran has established partnerships with local Boston manufacturing companies. The goal of that partnership is a win-win for both the students and the company sponsors. The company sponsor is able to reap the benefit of the students' work in manufacturing problem solving. The students gain the benefit of learning how to solve a real manufacturing problem. Therefore, they must learn how to define and solve a problem in a meaningful way to achieve the desired result in a limited period of time. The students work with different people within the company from the vice president level to the operators level. They gain insights that many people who work within the company do not have. The students also gain knowledge from many different areas of the company including manufacturing engineering, product design, finance, material supply, sales and marketing, and even the company union representatives. Because of their exposure,

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the students learn that solving manufacturing systems problems requires not only technical knowledge but also inter-personal knowledge and skills.

## 3 CLASS ORGANIZATION

In the very early part of the course, the Vice Presidents of sponsoring companies visit MIT and give presentations regarding their company and provide an overview of the proposed projects to establish the importance of the proposed projects. It is very important to cooperate with sponsoring companies in this course. After having background information on the sponsoring companies and the proposed projects from the presentation session, the students then visit the sponsoring company and see the actual production. Then, the students select a project. The projects range from the formation of manufacturing cells, machine and fixture design for manufacturing flexibility, setup time reduction, or other specific problems. Throughout the term, students apply material from the classroom to create effective solutions for the company to consider. To make this happen, a point of contact is assigned to each project so that students can have access to the necessary information and can organize factory visits, independently. It is a key to the success of this course that the sponsoring companies open their doors to students and share the information to solve real manufacturing problems.

## 4 USING AXIOMATIC DESIGN TO DEFINE THE PROBLEM

The first problem that students usually meet is that project objectives are loosely stated by the sponsoring company. Therefore, the students must determine the true objectives and the corresponding solutions. For this purpose, the students use Axiomatic Design [Suh, 1990] as the methodology to convey the manufacturing system design problems. By stating the objectives (what problems they solve) and solving methods (how they solve the problems) in terms of functional requirements (FR) and design parameters (DP), students can establish a clear view of project goals. In addition, the decomposition process with zigzagging ensures that the design solutions are independent. (See Fig. 1).

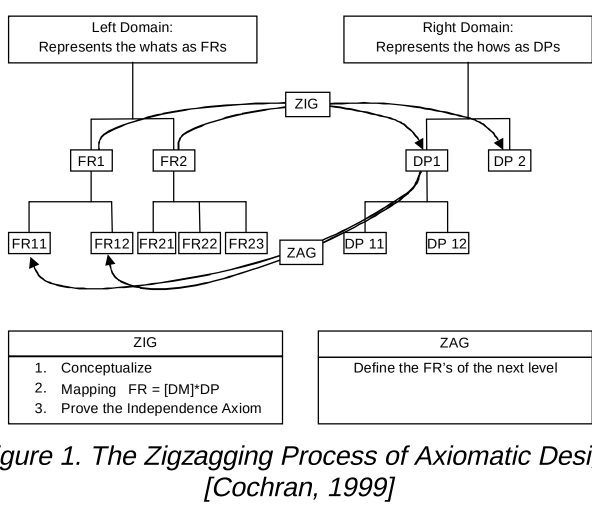


*Figure 1. The Zigzagging Process of Axiomatic Design [Cochran, 1999]*

If goal statements from companies are compared to re-defined goal statements from students that are developed based on Axiomatic Design, it is obvious that students benefit from using the Axiomatic Design methodology. As shown in Table 1 and Table 2, statements from companies are so nebulous that it is difficult to see the core of problems and imagine the possible solutions.

**Table 1. The goal statements from companies**

| Project Titles | Goal Statements from Companies |
|---|---|
| Tuthill: Design of Linked Cell Manufacturing System | Determine the internal and external customers of the plant, and calculate a takt time. Design a linked cell manufacturing system for the plant, with a clear and logical flow of both the products and the information. In other words, how can the information generated in assembly be cascaded back to the rest of the plant, allowing the takt time to be met? |
| United Electric: Wire Processing | 95% of the probes built in sensors require lead-wire assemblies, the process of measuring, cutting, jacket stripping and lead stripping is the single longest step in the production of probes. The current process is tedious and difficult to adapt to mixed lot processing. We would benefit from any technologies or systems that could reduce the process time. |
| United Electric: Miniaturize 105/120 T/B Assembly Fixture | In our TPS pilot cell, there is a fixture used to aid in the assembly of terminal blocks. This project would examine the current method and make improvements to poka-yoke (mistake-proof) and miniaturize the process. |

**Table 2. Problems with sponsor company statements**

| Sponsor Company | Unclear Objective | Unclear Solution | Comments |
|---|---|---|---|
| Tuthill. Design of Linked Cell Manufacturing System | X | X | System Design |
| United Electric Wire Processing | X | X | Sub-system Design |
| United Electric Miniaturize 105/120 T/B Assembly Fixture | X | X | Machine / Fixture Design |

However, when those statements from companies are turned into FRs and DPs by using Axiomatic Design, the objectives of projects and corresponding solutions become very clear. Next three examples will show how those two statements are different and how the Axiomatic Design approach helps students to structure their thinking processes. Examples are presented according to their level within the system: system design level, machine design level, and fixture design level.

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### 4.1 EXAMPLE 1 (SYSTEM DESIGN LEVEL): DESIGN OF LINKED CELL MANUFACTURING SYSTEM (TUTHILL) [ALBERS, ET AL., 1999]

The Kinney Vacuum division of Tuthill Corporation manufactures various types of vacuum pumps such as rotary piston, liquid ring, and dry screw pumps. 340 standard pumps and customized pumps are produced in the unionized plant in Massachusetts.

In this project, students sought the way to streamline the system for production signaling (pull) and coordination of material flow with the key upstream processes and the stockroom kitting function. The scope of this project is limited to the production of standard rotary vacuum pumps.

After getting knowledge on the current production system, the students thought of the design decomposition starting from the functional requirement of 'produce & supply only parts that are needed.' Following the zigzagging process of Axiomatic Design and checking the design matrices, they designed a new system followed by a discussion on feasible implementation of design parameters (DPs). The design decomposition of this project is as shown in Fig. 2.

Compared to the original goal statement provided by the company shown in Table 1, the design decomposition clearly shows what goals need to be achieved and how they are to be achieved in terms of 15 leaf FRs and DPs (See Table 3). Since the design is represented in a design hierarchy with design matrices, it is simple to understand the decision process and the effect of one decision to the higher level FRs.

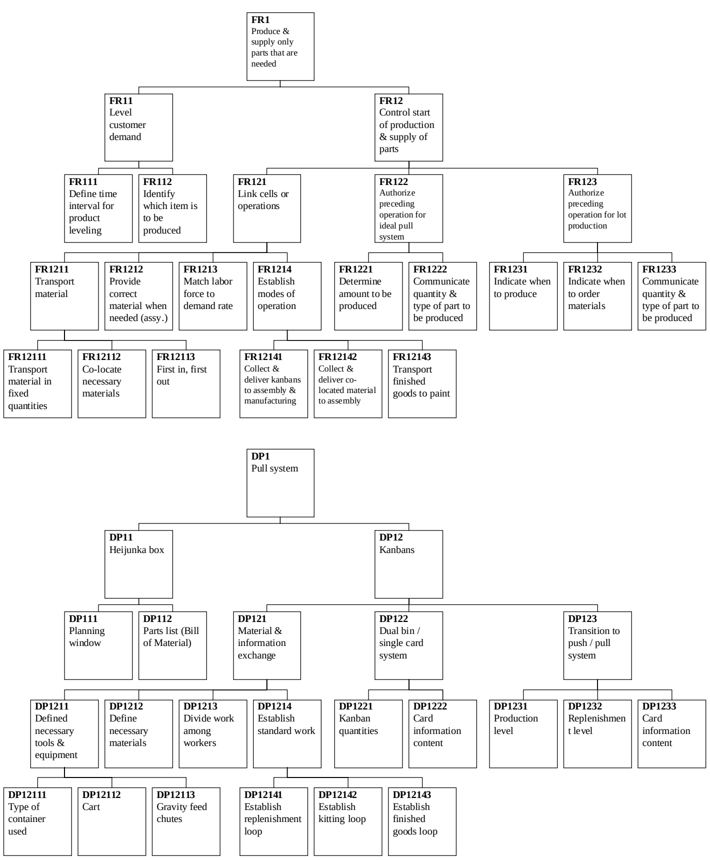


*Figure 2. The Design Decomposition of the Linked Cell System Design Project [Albers, et al., 1999]*

**Table 3. Leaf FRs and DPs of the Design Decomposition of the Linked Cell System Design Project.**

| Leaf FRs | Leaf DPs |
|---|---|
| FR111 Define time interval for product leveling | DP111 Planning Window |
| FR112 Identify which item is to be produced | DP112 Parts of list (Bill of Material) |
| FR12111 Transport material in fixed quantities | DP12111 Type of container used |
| FR12112 Co-locate necessary materials | DP12112 Cart |
| FR12113 First in, First out | DP12113 Gravity feed chutes |
| FR1212 Provide correct material when needed | DP1212 Define necessary materials |
| FR1213 Match labor force to demand rate | DP1213 Divide work among workers |
| FR12141 Collect & deliver kanbans to assembly & manufacturing | DP12141 Establish replenishment loop |
| FR12142 Collect & deliver co-located material to assembly | DP12142 Establish kitting loop |
| FR12143 Transport finished goods to paint | DP12143 Establish finished goods loop |
| FR1221 Determine amount to be produced | DP1221 Kanban quantities |
| FR1222 Communicate quantity & type of part to be produced | DP1222 Card information content |
| FR1231 Indicate when to produce | DP1231 Production level |
| FR1232 Indicate when to order materials | DP1232 Replenishment level |
| FR1233 Communicate quantity & type of part to be produced | DP1233 Card information content |

After having this design decomposition, the ways to implement leaf DPs are discussed according to the Axiomatic Design principle. For example, the leaf FR 12112, co-locate necessary materials, should be achieved by the corresponding DP 12112, Cart. The details of DP 12112 are as follows:

"This requirement [FR12112] is met by providing trays that slide to allow the parts to be co-located under the assembly cart. The assembly cart contains the fixture on which any of the pumps made in the cell can be built. Under the working surface, a tray is stored for each station in the assembly cell. The kitter fills these trays according to the instructions on the bill of materials retrieved from the heijunka box. This way, the assembler can work out of one tray at each station and have all the needed parts within each reach." [Albers, et al., 1999]

The same kind of elaboration of DPs as above is done for all leaf DPs to facilitate actual implementation of DPs. Using this elaboration, all leaf DPs were incorporated into the new

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linked-cell manufacturing system and this was the end of the design process.

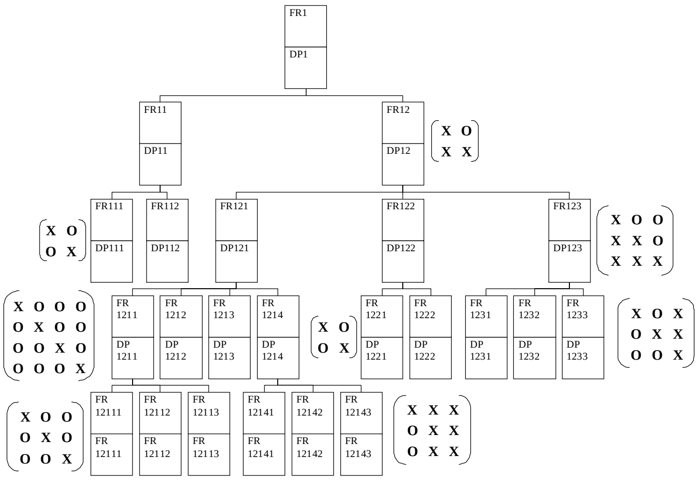


*Figure 3. The Design Matrices of the Design Decomposition of the Linked Cell System Design Project*

In this project, the design of new linked-cell manufacturing system is done by decomposing FRs and DPs in the design hierarchy while following the zigzagging principle. The final picture of the new system is proposed and shown by incorporating all leaf DPs into the new system. The proposed material and information flow of the new linked cell system is shown in Fig. 4.

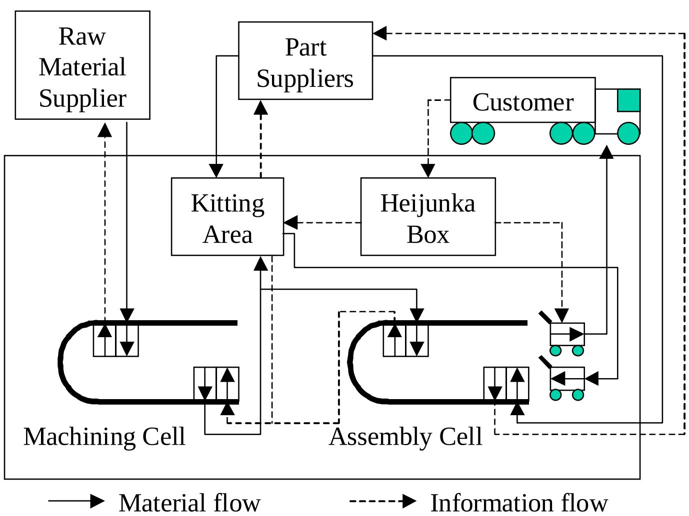


*Figure 4. Material and Information Flow of the New Linked Cell System*

## 4.2 EXAMPLE 2 (SUB-SYSTEM LEVEL): WIRE PROCESSING (UNITED ELECTRIC) [MARTINEZ, ET AL., 1998]

United Electric (UE) is a privately held company located in Watertown, Massachusetts that produces temperature and pressure gauges. UE employs about 200 people and the annual revenue is about 400 million in U.S. dollars.

In this project, students strove to transform the current batch process of wire processing into the single piece flow process. Batch production in wire process is required due to the long changeover time and lack of man/machine separation in the first three processes, so that the current wire processing does not meet 1 minute takt time. To solve this problem, students set the first FR as 'meet customer takt time' and decomposed it into lower levels. The design decomposition of this project is shown in Fig. 5.

As seen in the design decomposition of Fig. 5, the nebulous statement of the goal in Table 1 is translated into the clear goal to meet the customer takt time. Furthermore, more specified functional requirements to achieve this goal could be thought by decomposing it according to the Axiomatic Design methodology. Since the design level is subsystem (cell) level that is lower than system design, more physical design parameters are shown up such as DP113 on/off switch, DP132 Funnel guides, etc. Based on this design decomposition, students could design machines in the cell to satisfy all end level functional requirements (leaf FRs) by end level design parameters (leaf DPs) and thus actually implement them. The design matrices of this design decomposition are shown in Fig. 6.


*Figure 5. Design Decomposition of the Second Project*

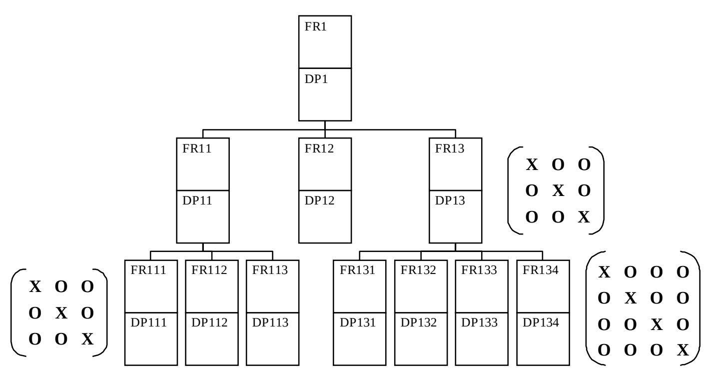


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*Figure 6. The Design Matrices of the Design Decomposition of the Linked Cell System Design Project*

## 4.3 EXAMPLE 3(MACHINE DESIGN LEVEL): 120/105 CELL – TERMINAL BLOCK FIXTURE REDESIGN (UNITED ELECTRIC) [GERACI, ET AL., 1998]

In this project, students studied one of the fixtures used in an assembly cell. The main function of the fixture is to crimp rivets using a pneumatic piston in order to fasten a terminal block and mounting plate together. The components parts that are assembled by using this fixture consist of two different types of terminal blocks (123 terminal block and standard terminal block), aluminum base plate, an insulation piece, and the two rivets used to assemble everything together. The difference between the two terminal blocks is small but substantial, so that it requires of using two different sets of top and bottom dies to crimp the rivets. This requires changeover of the die every time a different part type is to be assembled. Based on the company's goal statement in Table 1 and their observation of problems, students developed the design decomposition as shown in Fig. 7.

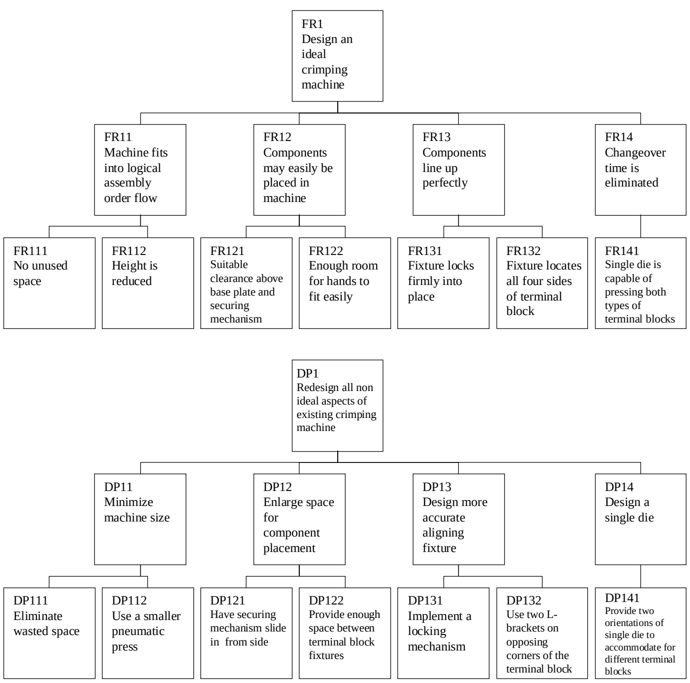


*Figure 7. Design Decomposition of the First Project*

As seen in the above design decomposition, the unclear statement of goals stated by the company, 'poka-yoke' and 'miniaturize' the process, is translated into four clear functional requirements: 1) machine fits into logical assembly order flow, 2) components may easily be placed in machine, 3) components line up perfectly, and 4) changeover time is eliminated. Furthermore, these functional requirements are further decomposed into 7 functional requirements and design parameters to achieve actual physical implementation. In that case, the rest of the design process is to implement DPs into a physical fixture design while considering the physical integration theorem of Axiomatic Design. The proposed design of new fixture is provided in Fig. 8.

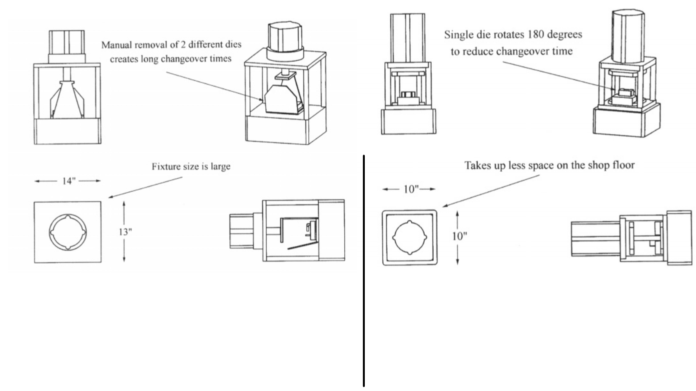


*Figure 8. The Old Fixture (left) vs. The New Fixture (right) [Geraci, et al., 1998]*

In addition to this benefit, the Axiomatic Design approach provides another important advantage as a design methodology. The sponsoring company thought that all they needed was to miniaturize the fixture and make the process mistake-proof, but the design decomposition clearly conveys that there are more design considerations that should be paid heeded. For example, one of the FRs indicate that components should be easily placed in the machine, which requires more space allocated for component placement while another FR indicates that the machine should fit into the assembly flow. This is one of the advantages of Axiomatic Design, that many different aspects of a design are considered simultaneously to achieve a higher level FR by means of a design hierarchy and design matrix. If one checks the design matrix with the above design, it can be seen that at Fig. 9, it is a decoupled design.

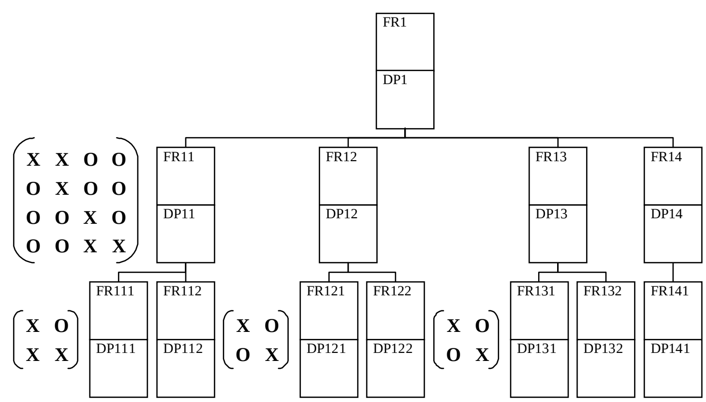


*Figure 9. The Design Matrices of the Design Decomposition of the Linked Cell System Design Project*

## 5 CONCLUSIONS

The new teaching method developed by Prof. Cochran provides a unique opportunity for students to learn about production system design. The combination of classroom instruction and real factory experience is a good way to help students to understand both the theoretical fundamentals and actual implication of production system design. The use of Axiomatic Design in the class, strengthens the decision-making process in system design and provides rigorous, explainable

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results to the industrial participants. Students are able to think of real-life manufacturing design problems and strive to tackle them. Most impressively, the students are able to see the implementation of their solutions.

This teaching method benefits two parties: the students and the community. The students who have taken this course will enter the engineering community with a different attitude toward the real factory floor due to their experience in this course. In fact, it is this experience that has led some participating companies to hire several students to continue working for them.

The community equally benefits from this new teaching method. Participating companies think of their problems in a more logical way in corporation with the students. In many cases, the companies are provided solutions to their problems. In addition, the companies learn how to tackle the production system problems and how to solve those problems with Axiomatic Design.

Axiomatic Design provides strong advantages in defining problems and finding corresponding solutions in a myriad of design processes. Students learned that it is important to always consider the objectives (functional requirements) while seeking answers (design parameters) to problems and to select DPs to ensure independence. To portray breadth and depth, this paper has illustrated the application of Axiomatic Design to the system, sub-system, and machine/fixture levels of production systems.

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