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## **AC 2011-681: INSTRUCTIONAL METHODOLOGY FOR CAPSTONE SENIOR MECHANICAL DESIGN**

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# Instructional Methodology for Capstone Senior Mechanical Design

**Abstract:** The capstone design project is a big event in every mechanical program. The capstone design project serves as a bridge to help students migrate from an academic environment to an industrial environment. Any school normally don't have the full capability to construct and physically test each capstone design project due to limited equipment, limited funds and limited time, which is the primary difference between the industrial environment and the academic environment. Due to this defect in the academic environment, there are two common major problems in lots of capstone designs. Some capstone projects couldn't provide the supporting documented analysis to answer whether components or final product were safe or not, which is not acceptable because safety is the most important design criteria. Some students didn't know how to manufacture components/assemblies of their design. In our capstone design project course, we propose, and implement the concepts of a virtual factory. In our capstone design, every student and design team own their virtual factory. Every student and design team can design and construct virtual products of their designs, and furthermore can numerically test virtual components /assemblies to make sure that safety criteria are satisfied before they start to construct their prototypes. The discussion of the virtual factory-based approach in the capstone design project will be presented in this paper. Some observations and opinions about how to instruct senior mechanical design projects based on our Capstone design course - MECH690-Mechanical Design will also be presented and shared throughout this paper. We recommend that mechanical engineering program provide every student the virtual factory when they graduate.

## 1. Introduction

One of the main activities of engineers is to design and to construct products that satisfy customers' and society's needs. One of the primary outcomes for engineering education is to train students for conducting engineering design. In ancient time, engineering students were apprentices to their Masters to learn engineering designs through real practices in real environments. Nowadays, engineering students are effectively training as apprentices under faculty Masters in engineering schools. Engineering students learn engineering design through various technical courses and different class design projects in an academic environment. The senior design project or the capstone design is the most important design project for training engineering students.

The capstone design project is a major event of every engineering education program. Students look forward to it not only because it is the chance to apply the learned knowledge & skills by converting ideas into reality through the capstone design project, but also because they want to conduct a real design in the almost-close-to industrial environment setting. Furthermore, students are looking for a bridge to help them migrate from an academic environment to an

industrial environment. Although some capstone design projects are part of real industrial design projects or directly sponsored and funded by some companies, most of capstone design projects are students-initiated and the faculty-approved design projects. Therefore, the vast majority of the capstone design projects are carried out in the academic environment setting. It is obvious that the academic environment setting is quite different from the industrial environment setting. There are two distinguished differences between them. The first difference is that any design project in industry targets a practical application which will be sold and used by customers. The real need and application is the root of industrial design projects. However, the capstone design projects are still part of training program. The second difference- the primary difference, is that any successful design project in industry is fully tested before it is released to production line for customers to purchase. But most of capstone projects are not fully tested because schools never have enough equipment, time or funds for this.

Based on our experience, some capstone design projects are ill-developed. Typical examples are:

- a) The project was constructed, but it was simple application of some learned knowledge and skills. The design team was not able to clearly state real and reasonable need for the project;
- b) After the project was completed and constructed, students could not provide the supporting documented analysis to answer whether components or final product was safe or not. This is not acceptable because the safety is the most important design criteria;
- c) After the project was designed, students didn't know how to manufacture their design. This is also not acceptable because high manufacturing cost might arise or the components might not be able to be manufactured;
- d) After the project was completed and even constructed, they did not have a full set of engineering documents.

How to instruct the capstone design project in an academic environment to prepare students for industry is always hot research topic of engineering education [1, 2, 3, 4]. There are lots of different definitions about engineering design [1, 2, 5, 6]. Any successful real design project has a lot of different features. But what are the key fundamental features of an engineering design? In our opinions, the engineering design is a process of designing and constructing safe and economic products, accompanied by a set of complete documents for full duplication of the designed products, with the desired performance and functions to satisfy customers' need. Therefore, the key fundamental features of engineering design are a need, safety, performance, manufacture-ability and a full set of engineering documents. Any capstone design project should at least satisfy these key fundamental features. In this paper, we will discuss how to instruct the capstone design project to satisfy these key fundamental features. But two most common problems b) and c) mentioned above will be the focuses of this paper. In order to help students to prevent these two common problems, we propose and summarize the new concept of a virtual factory-based approach, and introduced & implemented it in our capstone design course. Through the virtual factory-based approach, each student and design team can design; construct

virtual components, virtual assemblies and the virtual product, and numerically test virtual components and virtual assemblies of capstone design projects. Design teams were asked to build a virtual prototype and to numerically test the design safety and virtually simulated the manufacturing process to verify the manufacture-ability of the design. Therefore, students were able to provide the status of safety of the design project with supporting document and knew how to manufacture the design projects. The discussion and application of the virtual factory-based approach in the capstone design will be presented in this paper. Some observations and opinions on instructing senior mechanical design projects based on our Capstone design course - MECH690-Mechanical Design will also be presented and shared through this paper.

## 2. Program Overview

The Baccalaureate program in Mechanical Engineering Technology (BMET) at Wentworth Institute of Technology located in Boston, MA, is a cooperative education and projected-based program in which all students conduct multiple group design projects, including the capstone design project. In the BMET program, there are 2 required and 1 optional semesters of industry experience in the form of the coops. The BMET programs' technical course curriculum is listed in table 1. Some highlighted courses and the BMET program's special features are explained here.

Table 1-The BMET program's technical curriculum

Freshmen year			
MECH103 – Introduction to Engineering and Technology	MECH124 – Mechanical Graphics	MANF195 – Manufacturing Processes I	MECH163 – Mechanical Design I
Sophomore year			
MECH395 - Mechanical CAD Applications I	MECH343 - Statics	MECH255 – Thermodynamics I	MECH180 – Strength of Materials
COOP300 Pre-Cooperative Work Term in the Summer term (Optional)			
Junior year			
MECH270 – Fluid Mechanics	Elective I *– MECH290 Thermodynamics II	MECH530 – Material Science	Elective II* - MECH375 Machine Design I
COOP400 Cooperative Education in the Spring term			
Senior year			
COOP600 Cooperative Work Semester II in the Fall term			
Elective III*- MECH562 Fluid Mechanics II	MECH460 – Heat Transfer	MECH591– Instrumentation and Measurements	MECH535 – Dynamics

Elective IV*–MECH 468 Machine Design II	MECH605 – Mechanical CAD Applications II (FEA)	MECH690 – Mechanical Design Project	
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\* Only one course of several mechanical electives is shown

In freshman year, MECH124-Mechanical Graphics is designated to train students to understand the principles of views & projections, sketching and basic concepts of graphics through the use of AutoCAD. Through this course, students are able to read, understand and create engineering drawings and create some engineering drawings. In MANF195-Manufacturing Processes I, a required course in the BMET curriculum, students are trained on basic manufacturing processes and use of equipment such as manual lathe & mill, sheet metal press, and CNC machines, as well as welding. MECH163-Mechanical design I introduces students to the fundamental principles of the generic design. The five-phase design process [5] is discussed in detail and implemented to conduct all group design projects, including the capstone design projects for the BMET program students.

In sophomore year, MECH395 - Mechanical CAD Applications-I teaches students how to use Solidworks to create parametrical 3D models and provides insight into the mechanical design process through two different group design projects. The Solidworks is used as a design tool to explore and carry out the design projects. At 2010, we propose the concepts of virtual component (VC) and virtual assembly (VA) [7]. Through this course, we instruct students to create virtual component (VC) and virtual assembly (VA).

A Virtual Component (VC) [7] is defined as a 3D component model created by a CAD program such as Solidworks and stored in the digital form, which has following four attributes: (1)the 3D component model has the exact same geometries of the real component. Dimensions of 3D model are the nominal dimensions. The dimensional tolerances and geometric tolerances are specified in the 2D drawing; (2) the constitutive equation of the same material of the real component is assigned to the 3D component model, so that the 3D model has same physical behaviors of the real component under applied loadings. This is the key attribute to make the 3D model a virtual component; (3) the 3D component model is one complete item and can be used in different products as the real component. So, the same 3D component model can be used and reused again; and (4) the 2D component drawing is inherently linked to the 3D component model. The change in drawing will trigger the change in the 3D component modeling or vice versa and is called associativity. This attribute is extreme important since dimensional tolerances and geometric tolerances are defined in the drawing. The inherently linked engineering drawing can guarantee that the identical real component can be manufactured. According to the features of Solidworks and its simulation module [8, 9], the 3D component model created by the Solidworks is a virtual component [7].

The Virtual Assembly (VA) [7] is a 3D assembly model created by a CAD program such as Solidworks and stored in the digital form, which has the following four attributes: (1) the 3D assembly model consists of several virtual components which are defined by the same BOM (Bills of Materials) of the real assembly or machine; (2) virtual components in the 3D assembly model are assembled by the same geometric assembly relations as these in the real machine. For an example, outer cylindrical surface with the mating inner surface of the bearing is concentric. The side surface of the inner ring of the bearing with side surface of the shoulder of the shaft is coincident. In other words, the geometric relations and constraints among the virtual components in the 3D assembly model are the same as those in the real machine. So, the possible relative movement /positions in the 3D assembly model will be the same as those in real machine; (3) the 3D assembly model will have the same mechanical behavior as those of the real machine under the same loading conditions, that is, the 3D assembly model will have the same deflections, strains and stresses as those of the real assembly or machine under same applied loadings;(4) the 3D assembly model is inherently linked to the 2D assembly drawing. The change in assembly drawing will trigger the change in the 3D assembly modeling or vice versa. The linked assembly drawing can be used as the technical documents to assemble the identical real assembly or machine. According to the features of Solidworks and its simulation module [8, 9], the 3D assembly modeling created by Solid Works is truly a virtual assembly [7].

In senior year, MECH605 – Mechanical CAD Applications II explores how to use the simulation (Finite Element Analysis ) module of the Solidworks to numerically test the virtual component or assembly to obtain the strain/stress/deformation/damage information in order to check the status of safety and/or to provide directions for further modification [7, 10]. In this course, we only spend one week on the theory of finite element method, and then, teach students to numerically test virtual component/assembly under static loadings, thermal loading, fatigue loading and fluid loadings to get the strain/stress/deformation field. We also discuss how to numerically test virtual component/assembly to get their natural frequencies. We believe that these numerical FEA tests could cover more than 80 percentages of real tests in industries.

By the time that our students are ready to conduct the capstone design project, they not only have all the necessary knowledge, but also own a virtual factory, that can be defined as a platform through which component/product can be virtually designed, virtually constructed and numerically tested. All of this virtual component, virtual assembly/product, virtual test, and anything from the virtual factory are stored in the electronic form and can be retrieved at any time. For example, the Solidworks platform, which includes Solidworks, the simulation module and CAM module, can be treated as a virtual factory.

### 3. Instructional Methodology for Capstone Senior Mechanical Design

Although there are many different approaches for conducting engineering design, the core items of these are almost the same. The five phases of engineering design process [5] is one of these popular approaches, which are: Phase I: Needs assessment; Phase II: Problem formulation (Design specifications); Phase III: Abstraction and synthesis (Conceptual design); Phase IV: Analysis (Detailed design) and Phase V: Implementation. This five- phase engineering design process is the approach we use to guide all design projects and capstone design project at the BMET program. This concept is introduced and discussed in detail in the course MECH163 – Mechanical Design I in the freshman year. It is repeated in the course MECH395 - Mechanical CAD Applications I at the sophomore year; in the course MECH375 Machine Design I in the junior year and in the course MECH605 – Mechanical CAD Applications II (FEA) in the senior year.

#### 3.1 Summary of the weekly progress for the Capstone design project

The Capstone design project: MECH690 – Mechanical Design Project is taught during the summer term of the senior year for the BMET program. Generally, students are asked to develop possible topics for the capstone design project in advance during the spring term. The required weekly student progress for MECH690-Mechanical Design that authors used to guide the capstone design project during summer 2010 is listed at Table 2.

The MECH690-Mechanical design project is a 1-6-4 course, which means 1 hour lecture and discussion per week, with 6 group-working-together hours per week, and a 4-credit course. The time period for the project is 13 weeks. Following is the brief summary of the execution of the capstone design under authors’ supervision.

Table 2-Weekly plan for MECH690-Mechanical design project, summer 2010

Week #	Contents and expected progress
Week #1	Phase I: Assessment of needs (1) Group discussions on two possible projects ; (2) Need’s assessment
Week #2	Phase II: Design specifications (1) Search related information; (2) Define the design specifications; (3) Submit the pre-proposal of the project for instructor’s approval
Week #3 and #4	Phase III: Conceptual design- Create the alternative design options (1)Collect & search related information, (2) Generate at least three options; (3) Submit the formal proposal, (4) The first information presentation
Week #5	Phase III: Conceptual design -Strength analysis on key component/assembly (1) Create the key virtual components/assemblies; (2) Run numerical test (FEA) on the virtual components/assemblies to gain stress/strain/deformation

	information for the purpose of evaluating design options
Week #6	Phase III: Conceptual design- Cost evaluation of projects and Decision matrix (1) Estimate costs of design options , (2) Run decision matrix to decide the final design option; (3) The second informal class presentation
Week #7, #8 and #9	Phase IV: Detailed design (1) Create virtual components/virtual assemblies of the design project, (2) Use virtual components and virtual assembly to simulate the manufacturing process of components and assembling process of virtual assemblies, (3) Numerically test virtual components and virtual assemblies to check the status of safety and deformation, (4) Generate 2D component and assembly drawings which are internally linked to the virtual components and virtual assembly
Week #10, #11 and #12	Phase V: Implementation (1) Construct the prototype; (2) Prepare the complete set of engineering documents, which includes final design project report, virtual components/virtual assemblies with corresponding drawings, manufacturing routings of components and assemblies, (3) Prepare and deliver the technical poster of the design project, (4) Prepare and deliver the final formal presentation.
Week#13	Submit a DVD disk which contains full set of engineering documents.

Week #1 and week#2 were used to work on the Phase I and II: needs' assessment and design specifications. The result was the pre-proposal, which was submitted to instructor for approval. Normally, we asked students to think about the possible topics for the capstone design project one or two months in advance. At the end of week #2 after the pre-proposal was approved, design groups delivered the first information presentation in the class to share ideas and to ask for the critics and inputs. Weeks #3 to #6 were used to conduct the Phase III: Abstraction and synthesis (Conceptual design). The result was several alternatives for the design project and the final design options. Free-hand sketching was the main tool to communicate design ideas. During the conceptual design, only critical virtual components/virtual assemblies were created for numerical testing. At the end of week #6, design groups delivered the second information presentation of the project in the class to show their design options for the critics and inputs. Weeks #7 to #9 were used to conduct the Phase IV: Analysis (Detailed design). The result was full set of numerically tested prototype that consisted of virtual components and virtual assemblies. No design option was allowed to enter Phase V: implementation for constructing the prototype before the virtual components/virtual assemblies had been numerically tested and passed. The last three weeks were used to construct the prototype and to prepare the full set of engineering documents, including project report, virtual components/assemblies/drawings and manufacturing routings.

### **3.2 Observation & opinions based on the capstone design project**

The authors have the privilege of having both several-years industrial design experience and several-year teaching experience in engineering schools. In the following, some observations and opinions on instructing senior mechanical design projects based on our Capstone design course - MECH690-Mechanical Design will be presented and shared. The observation and opinions will be described and explained according the sequence of the five phases of the design processes. Then the discussion and application of the virtual factory-based approach in the capstone design will be presented in section 3.3.

#### **Phase I: Needs assessment**

Every year, only a few capstone design projects have industrial sponsors and are part of the real industrial design projects. Most of capstone design projects are without industrial sponsors and students-initiated. The root of any design project in industry is the need. Without a need, the design project cannot be set up. However, some proposals of the capstone design projects used the topics without a clear need or without a clear statement of the need. For example, one design team proposed to design & build a hydraulic turbine generator to show the generation of electricity. The project was rejected because they didn't clearly show the need behind the proposal. It is a general knowledge that hydraulic turbine generator can generate electricity. After the group proposed to design and construct a small scale hydraulic turbine generator system as school equipment to demonstrate the generation of electricity for elementary /middle school, the project was approved because the real or reasonable need was established.

In order to let students gain the experiences and feeling of real industrial project while doing the capstone project, the design proposal must clearly describe its application "need". Any design proposal without a clear applied "need" must be rejected.

#### **Phase II: Problem formulation (Design specifications)**

The design specifications are the core of a design project. All design activities start from and are focused on the design specifications. However, some design teams started the design activities and created some design options without clear design specifications. This design team began the design and completed some design activities, and then specified some design speculations based on the design options they had created. These were a very bad habit for engineering students. When this happened, the design activities should be suspended until the design specifications were fully defined.

For capstone design projects, student design team should use the design specifications to drive their design.

### **Phase III: Abstraction and synthesis (Conceptual design)**

Each design team was asked to create at least three design options before they started to choose one as the final design option. The free-hand sketching was the main tool for communicating the design ideas and expressing the design options in this stage. But the critical virtual components/virtual assemblies were created for the numerical tests through the virtual factory. For example, one design team designed the wind turbine stand system, which was to be installed on the roof of a building. The columns and the connectors between columns were the key critical components. Before they made selection, they created virtual components/assemblies and numerically tested them in their virtual factory.

### **Phase IV: Analysis (Detailed design) and the implementation of the virtual factory**

For industrial design project, the key components / assemblies and prototype are fully tested because the safety is the most important design criteria that every product must satisfy. Industrial companies can and must provide enough time, human resource and funds to run these physical tests because all of these have been planned when the design project is set up. However, for the capstone design project in the academic environment, design teams have limited time, limited funds and limited test instruments. In another words, design team normally don't have the opportunity to fully test their prototypes. Therefore, it is common phenomena that when some capstone design projects were completed and prototypes were built, students could not provide the supporting documents to answer whether their designs were safe or not. Any design project is not a real design and cannot be treated as a completed project if it cannot provide the status of safety with supporting analysis and documentation. This situation should be changed for the engineering education.

As discussed in previous section, the BMET program students who had attended MECH395-Mechanical CAD Application I and MECH605-Mechanical CAD application II, had owned their own virtual factory. In our capstone design project, each group had to create virtual components/assemblies and numerically test every component and the prototype in their virtual factory. In the virtual factory, students were asked to use the sequence of features of virtual component /assemblies to simulate the manufacturing process of the virtual component and assembling process of the virtual assembly, so that design team knew how to manufacture their design. After they virtually create their design, they were requested to numerically test key components and the prototype. They had to modify and re-modify the design if the numerical simulation (the FEA analysis) didn't pass the safety criteria. Only after the virtual components and the prototype had passed the safety criteria, they were allowed moving to the last phase-implementation for constructing the prototype.

## **Phase V: Implementation**

In the final stage: implementation, design group constructed their prototypes and prepared the full set of engineering documents listed below.

- Virtual component/assembly/drawing created by Solidworks
- Numerical simulation (FEA) results on the virtual component /assembly, which were the stress/strain/deformation/damage information of virtual components/assembly with the conclusions on the status of safety.
- Manufacturing routes for the component in which sequences of manufacturing routes (manufacturing work station) were specified.
- Manufacturing routes for sub-assembly/top assembly drawing in which sequences of assembly station were specified.
- Final project reports.

Since the virtual components / assemblies / drawings of the capstone design project are stored in the electronic form, the interface for any further modification is ready at any time if necessary. For modern industry, quick response to the market needs and change is a key for success. The concepts of the virtual factory-based approach, including virtual components, virtual assembly and numerical test and simulation can effectively serve this purpose.

### **3.3 Discussions on the virtual factory-based approach in the capstone design project**

The AutoCAD and Finite Element Analysis (FEA) are two powerful tools for engineering profession for a quite long time. The AutoCAD, such as Autodesk, can be used for creating mechanical drawing. FEA software can analyze the strain/stress on the imported component's geometry. Based on authors' teaching experience and industrial experience in the field of mechanical engineering, we proposed new concepts of the virtual component/assembly in 2010 [7], which are the combinations of AutoCAD and FEA technique in the Solidworks Platform. Based our experience in teaching the Capstone design projects, we summarize and propose, in this paper, the new concept of the virtual factory-based approach for Capstone design.

The virtual factory proposed in this paper refers to a platform where virtual mechanical component and virtual mechanical assembly can be created and saved in the digital form; the manufacturing process of a mechanical component can be simulated; the assembly process of the mechanical assembly can be simulated; and the mechanical behaviors of virtual component / assembly such as strain/ stress/ deformation/ damage under loadings can be numerically tested. There are a lot of platforms which can be used as the virtual factory, such as Solidworks platform, Pro/E platform and CATIA platform. Solidworks platform is chose to explain the concept of the virtual factory-based approach because the BMET program has used this software for years to train the BMET program students.

The virtual factory mentioned in this paper is the platform solely for mechanical component and mechanical assembly. The electrical components and systems are common in mechanical

product or system. But, the electrical components and systems cannot be simulated in this virtual factory.

The virtual factory-based approach is a new, but very powerful and useful concept for students in the academic environment. Every student or every team can own their own virtual factory. They can design & create virtual component/ virtual assembly in the digital form; can simulate the manufacturing process of the virtual component & assembly process of the virtual assembly; and numerically test the virtual component / assembly under loadings. The virtual factory-based approach can help students to prevent two most common problems b) and c) in conducting the Capstone design mentioned in the section of introduction in this paper. In other words, the application of the virtual factory-based approach in the academic environment can help student understand how to properly manufacture their components or how to properly assemble their assembly, and can help students to check the status of the safety of the component/assembly. Some examples in followings are used to demonstrate and explain these ideas.

In virtual factory, the proper sequence of the adding features of a virtual component can be used to simulate the manufacturing process of the component from the shape of raw material to the shape of the virtual component. The sequence of the adding features in the virtual component does not have to be the exact same as those in real manufacturing. However, by presenting it this way, students are forced to think about the manufacturing during the design and have a significantly better understanding of how to manufacture the component after they successfully build the virtual components. The a) of the figure 1 shows a virtual component: the cylinder plate. The b) of the figure 1 shows the sequence of adding features when it is virtually constructed. The c) of the figure 1 simulates the manufacturing process of this virtual component.

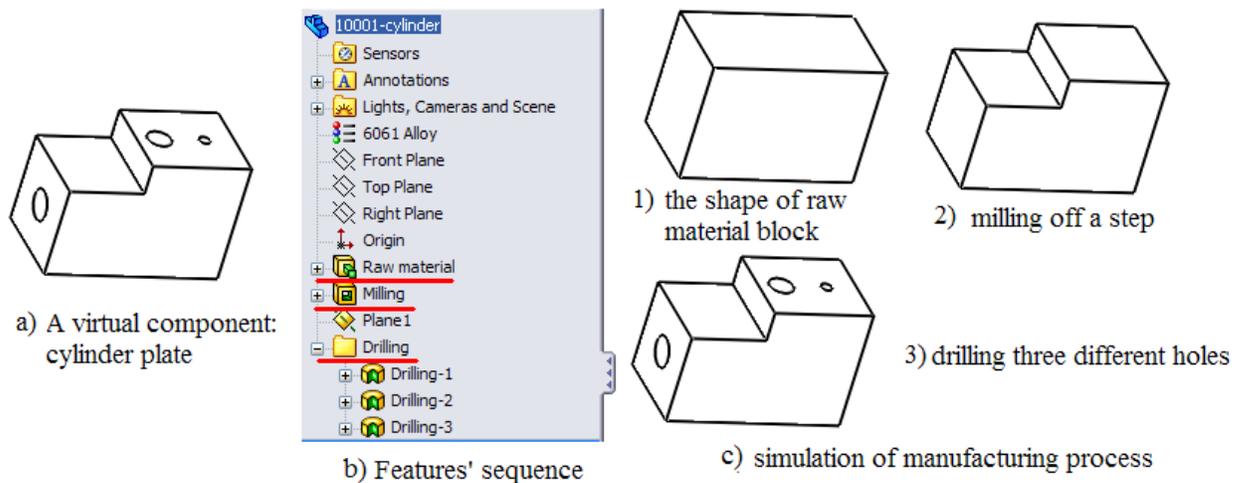


Figure 1 Features' sequence to simulate manufacturing sequence of the cylinder plate

The a) of the figure 2 shows a virtual component: the pin. The b) of the figure 2 shows the sequence of adding features when it is virtually constructed. The c) of the figure 2 simulates the manufacturing process of this virtual component.

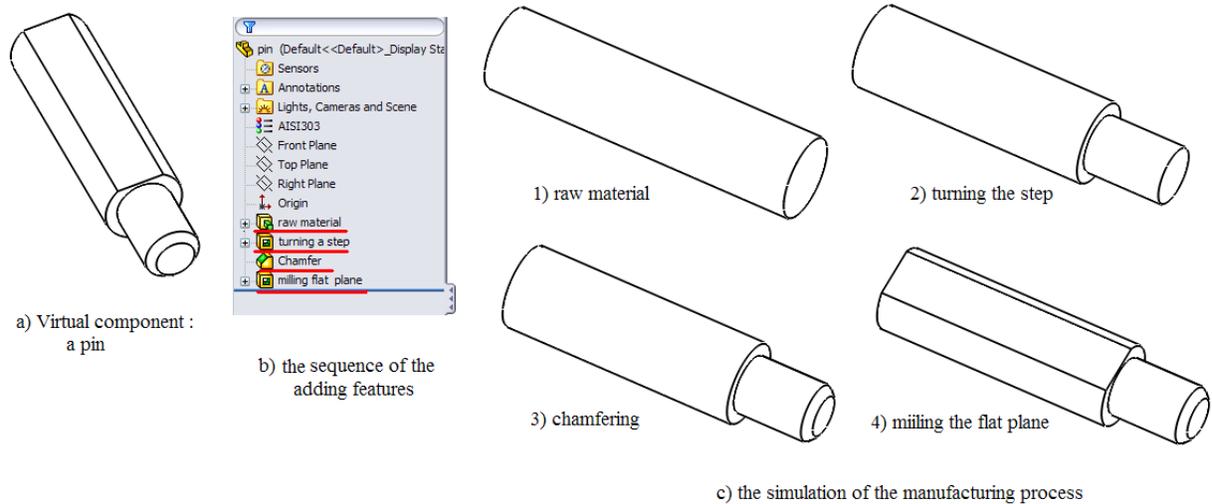


Figure 2 Features' sequence to simulate manufacturing sequence of the pin

If a student used the sequence of adding features shown in the figure 3, this student didn't know how to manufacture the pin although the final shape of the pin and drawing were the same.

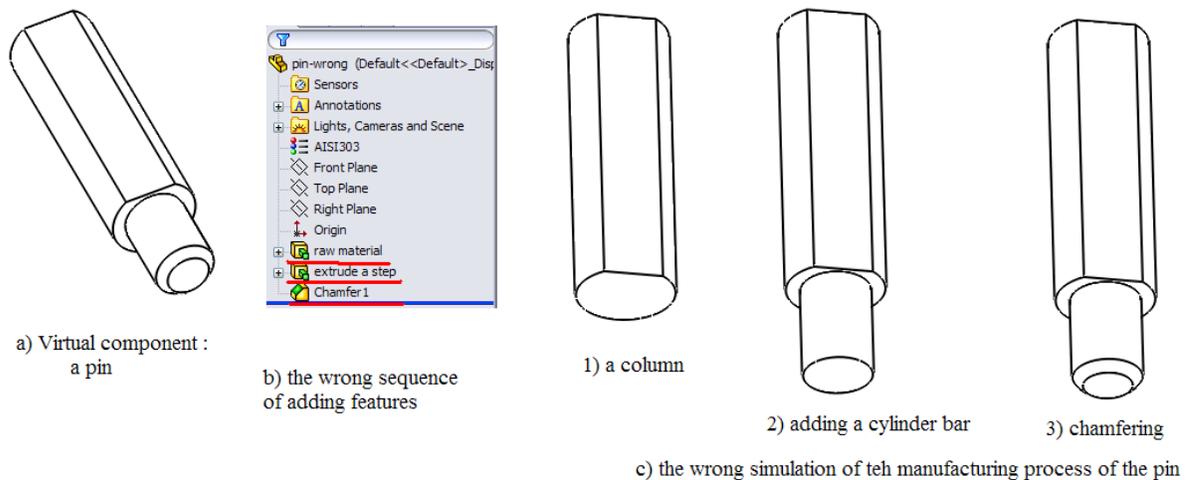


Figure 3 the wrong features' sequence for simulating the manufacturing sequence of the pin

The sequence of adding virtual components can be used to simulate the assembling process of the assembly. The a) of the figure 4 is a virtual assembly: the disk-plate assembly. The jig fixture had been designed for this sub-assembly in order to get proper assembly, in which the pivot shaft was pressed into the disk plate first and then the pivot bar was pressed into the disk plate. The b) of the figure 4 shows the sequence of adding virtual components. The c) of the figure 4 shows the simulation of the assembling process of the assembly. In the virtual factory embedded in the Solidworks platform, the functions of "Animate explode" and "Animate collapse" can be used to simulate the disassembling and assembling processes [8]. The "mates" in the virtual factory can be used to specify the relationship among virtual components on the interfaces [8].

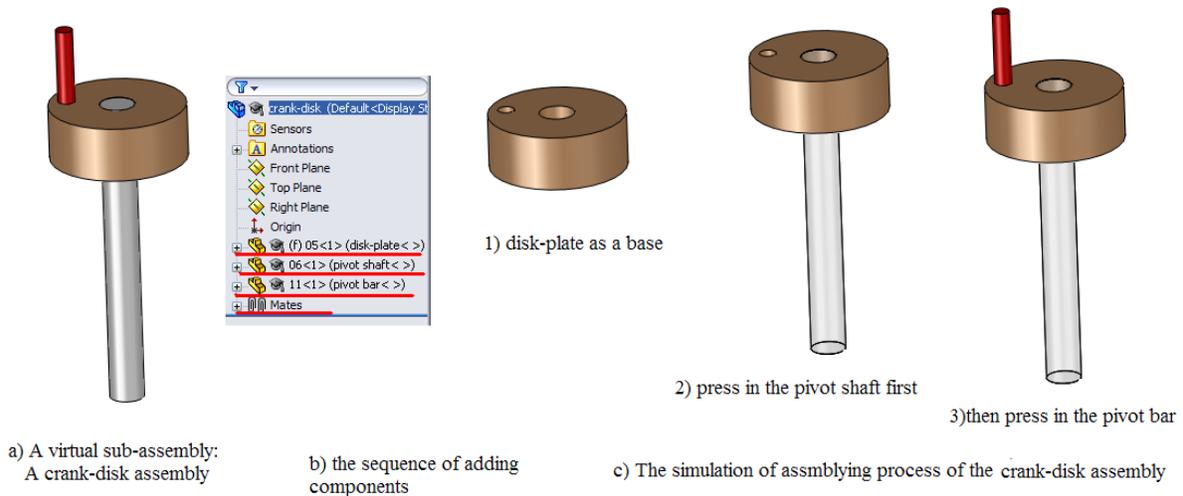


Figure 4 the sequence of adding virtual components to simulate assembling process

The most important function of the virtual factory-based approach for the capstone design is that students in the academic environment can numerically test their virtual component /virtual assembly at any time to check whether the component/assembly satisfies the safety design criteria or not. This never means that the numerical test (the FEA analysis) on the virtual component/assembly could replace the real physical test on the real prototype. The physical test on the real prototype is a must in industrial environment before it can be released to the production line. However, the numerical test (FEA analysis) on the virtual component /assembly can stop un-safe component/assembly into the production of real prototype for real physical tests. This could save huge amount money in the industrial environment. A lift arm assembly is shown in figure a) of figure 5. The b) of the figure 5 shows the numerical test result (FEA analysis), in which the “red” areas means the failure. Without the help of the virtual factory, it was extremely difficult for students to know whether the lift arm assembly would be failure or not.

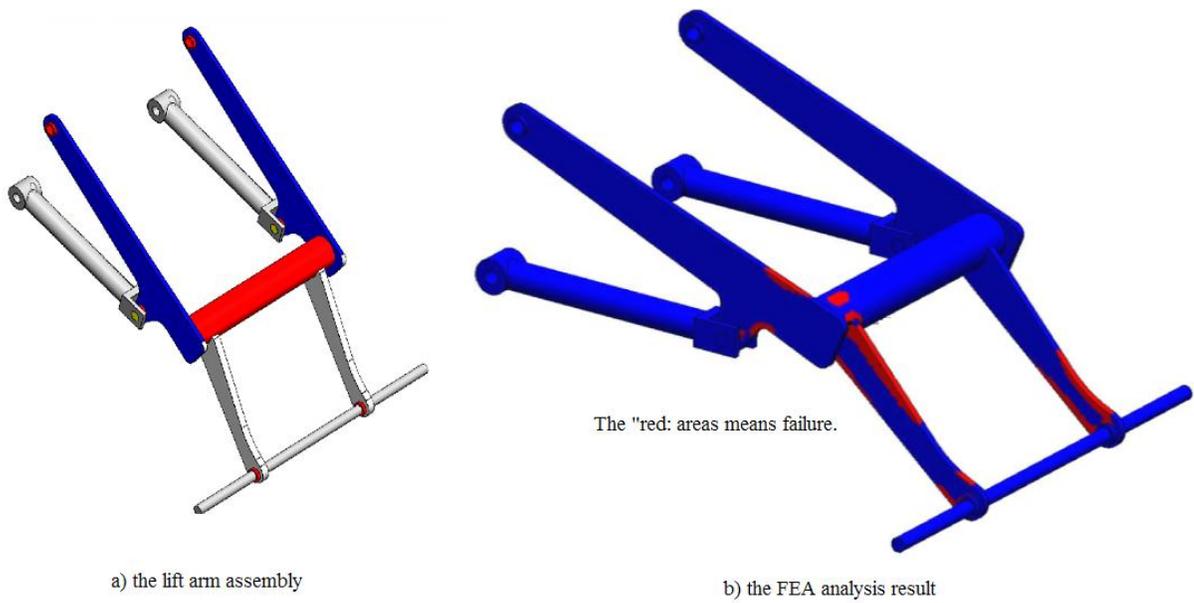


Figure 5 FEA analysis on the virtual assembly: the lift arm assembly

The numerical test on the virtual component or virtual assembly in the virtual factory can provide directions for modification and re-modification of virtual component or virtual assembly. From a) of the figure 6, the failure might cause by the small fillets in the lift arm. The figure b) of the figure 6 was the new design which was safe under the same loading.

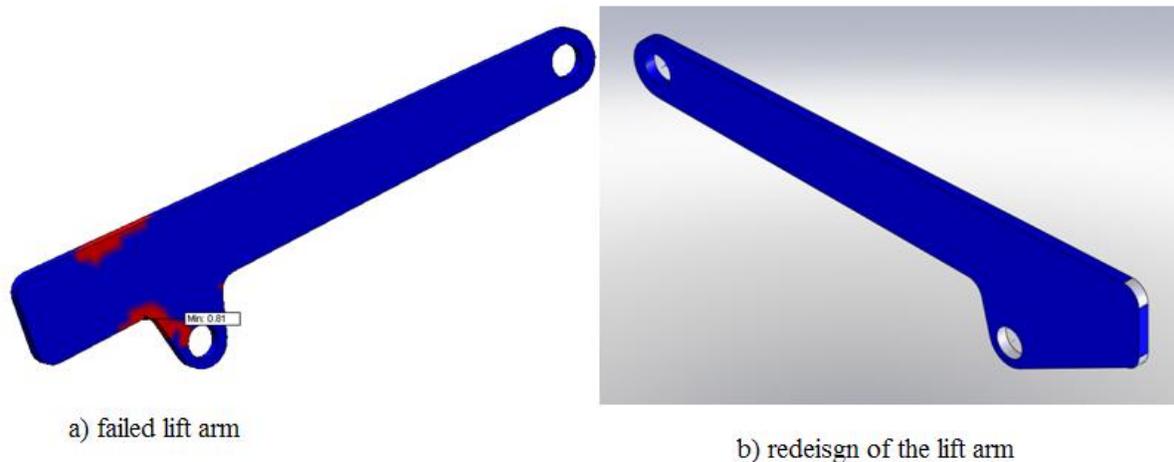


Figure 6 re-design of the virtual component: the lift arm

In summary, the virtual factory for capstone design in the academic environment is a platform in which students can design and construct virtual mechanical components/ virtual mechanical assembly; can simulate the manufacturing process of virtual component and the assembling process of virtual assembly; and can numerically test virtual mechanical components/ virtual mechanical assembly to check the status of the safety. The concept of the virtual factory-based approach can help students to have better understanding the design process and to obtain better design results in the academic environment. The numerical test (FEA analysis) in the virtual factory cannot replace the physical test on the real prototype. However, it might help to stop unsafe component /assembly into the construction of the prototype.

#### 4. Discussions and Conclusions

Engineering design is a process of designing & constructing safe and economic products, with an accompanying a set of complete documents for full duplication, with the desired performance and functions to satisfy customers' need. Safety is the most important design criteria that any product must satisfy. However, most of capstone projects are not fully tested because schools never have enough equipment, time and funds for this purpose. Nowadays, with advanced CAD software such as Solidworks, this situation can be significantly improved by the virtual factory-based approach. Through the virtual factory, while conducting the capstone design project, design team can create virtual components, virtual assemblies. Then they can numerically test these virtual components, virtual assemblies and virtual prototype to gain stress/ strain/ deformation/ damage information to check the status of safety of the design. Design team can

also simulate the manufacturing process and animate the assembling /disassembling processes of the virtual components/assemblies in the virtual factory.

We recommend that every mechanical engineering program provide every student a virtual factory in which they can create and numerically test virtual components, assemblies and prototype before they graduate. In the proposed virtual factory-based approach, students can have better understanding of engineering design and can gain better design for their capstone design.

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