AC 2011-152: TEACHING CAD MODELING USING LEGO

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Teaching CAD Modeling Using LEGO®

This paper explores the potential of using LEGO® to support teaching CAD modeling techniques to engineering technologists. There are a number of advantages to using this medium. First, LEGO® building blocks come in a wide variety of shapes from the simple standard forms to more complex special purpose blocks found in kits such as *Racers* or *MindStorms*. From a CAD modeling perspective the features used to model these blocks can therefore range from the simple *pad/pocket* type to more involved *sweeps* and *multi-section* shapes (lofts). Students can learn and practice *bottom-up* assembly modeling techniques by building models using libraries of standard blocks. They can also model custom blocks using the *design-in-context* approach. This can support creativity in generating new LEGO® kit concepts. Since LEGO® blocks and kits are easily available and affordable, it is possible for students to create a CAD model for which a physical prototype can be built. With the availability of rapid prototyping equipment (e.g. Stratasys FDM technology) or use of a service bureau, custom blocks can also be included in these prototypes. This introduces students to *Design for Manufacture* and *Assembly* concepts as these custom blocks must be designed with appropriate wall thicknesses and stiffening, and with appropriate clearances and fits to assemble to standard blocks. The ability to do this adds to the appeal that LEGO® has for many students who are well familiar with their use. Experiences from implementing a LEGO® based CAD project in a freshman course that teaches Engineering Design and Graphics will be used to underscore the benefits of using this approach.

Introduction

CAD instruction is a required part of the curriculums of many engineering and technology disciplines. In most cases it has replaced manual drafting instruction as the technique for generating engineering drawings. The state-of-the-art enables the creation of a 3D model using a feature-based parametric modeling environment. This is well suited for capturing design intent. The designer must select features, create the sketches that construct them, and specify the dimensions that control size (parameters) strategically to allow the types of changes that may occur without "breaking" the model. CAD courses introduce students to the underlying methodologies of 3D parametric modeling. These methods though implemented within different applications (e.g. SolidWorks, CATIA, Unigraphics, Inventor) can be viewed as generic building blocks for the technology. These include:

- Sketching
- Dimensioning and constraining sketches
- Decomposition of part geometry into modeling features
- Capturing Design Intent
- Assembly constraints (Bottom-up modeling)
- Design-in-Context Assembly Modeling (Top-down modeling)
- Use of standard components (Component Catalogues and Libraries)
- Generative Drafting Methods

Within an engineering or technology program that is focused on product development, an important goal is to complement instruction in the methodology and the mechanics of CAD system use with modeling realistic components whenever possible. This should at the end of the day introduce students to the concepts of *Design for Manufacture* (DFM) and *Assembly* (DFA). They should quickly come to appreciate that it is relatively easy to construct a product that may never exist as more than a digital model, but that it is another thing to create a model that must be fabricated. This is a challenging pedagogical goal particular for introductory courses where many students are not only unfamiliar with CAD technology but also lack a fundamental understanding of fabrication processes.

In this paper a new concept to CAD instruction is being proposed that utilizes LEGO® building blocks. The goal is to utilize a readily accessible and familiar product that is simple enough both in geometric structure and in the application of DFM and DFA principles so that students can readily create both a digital model and physical prototype. Students get to see their CAD models "come to life" but must take steps to ensure that the desired result is achieved.

Use of LEGO® in Engineering Education

The use of LEGO® blocks in engineering education is not uncommon. A common application involves building programmable mobile robots from LEGO®. These applications vary only in specifics and level of application. Lai-Yuen[1] and Jaksic and Spencer[2] present examples of LEGO® use in upper division courses, Mehrubeoglu[3] and Want et al.[4] present examples of LEGO® use in introductory courses, and McGrath et al.[5] and Whitman et al.[6] present examples of LEGO® use in pre-college programs to attract students to engineering and science.

A rarer application of LEGOs in engineering education is the use of virtual LEGO® environments. In addition to robotics, Lai-Yuen[1] also describes the use of a virtual assembly of LEGO® blocks to teach students concepts in micro-manufacturing. Kelley[7] describes a similar approach in which virtual LEGO® blocks are used to teach and implement Product Data Management (PDM) techniques. Pasek et al.[8] have developed automation to assemble LEGO® blocks as part of a CIM driven LEGO® Factory. This utilizes a virtual assembly of LEGO® blocks as input to process planning that sequences assembly of the LEGO® model in the factory. While these cases involve students creating virtual LEGO® assemblies, none of them include the students either designing or prototyping new LEGO® blocks as part of a creative design process that develops a new concept.

It should also be mentioned that there are a number of software tools available that can be used to build LEGO® models using standard blocks. This includes LEGO's own *LEGO Digital Designer* application[9] and *LDraw*[10]. The goal of these applications is to assist LEGO® practitioners to create and visualize their designs prior to acquiring blocks and building the model. They also generate instructions to assist in the build. They are not strictly speaking CAD applications and so are not suitable for use in a CAD curriculum. They also do not promote the modeling and fabrication of custom blocks as is proposed in this paper.

CAD Instruction that Leads to A Physical Prototype

A wide range of instructional material is now available for CAD given the proliferation and accessibility of the technology. A cursory seach at Amazon.com for example for books dealing with systems such as AutoCAD or Solidworks yields a large number of options. Numerous publishers produce texts on CAD systems and there are several that specialize in this area. Professional educational services that teach CAD also offer their materials for use as instructional purposes within university degree programs in Engineering and Engineering Technology. These materials, to different proportions, cover both the methodologies of 3D parametric modeling and the mechanics of using the interface of a particular system. They use a combination of:

- Background explanations,
- Rote exercises (follow the instructions),
- Independent exercises (do it yourself) driven by dimensioned drawings, and
- Open ended projects.

An important embedded theme for a curriculum of CAD instruction is that students should be made aware that their models need to be fabricated. To have CAD instructional material that is structured around modeling then fabrication of a physical product is challenging. Products that are complex enough geometrically to provide good practice using the CAD system can have a range of fits that make the creation of a physical prototype difficult. This says nothing of the need for skill in using fabrication processes to make a prototype. Both an understanding of fits and exposure to manufacturing processes may not be covered until after CAD instruction in a technology program.

Off-the-shelf instructional materials typically do not place a high emphasis on integrating DFM and DFA considerations into CAD modeling. It is typically open ended projects that provide the best format for encouraging students to integrate manufacturing considerations into their modeling as part of generating a physical prototype. For this purpose, CAD instruction may be combined with some exposure to CAM and CNC programming that allows students to by-pass manual fabrication. However, this leads to a very heavy course content and can distract from the focus on CAD technology as students must also learn tool path generation and CNC programming. A better solution is to utilize Rapid Prototyping (RP) technology. The time overhead in building a prototype directly from a CAD model using a process such as Fused-Deposition Modeling (FDM from Stratasys) is significantly less than the use of CAM and CNC. As part of an introductory CAD class students using RP get exposure to tool path generation (for layered manufacturing) and must make some allowances in their modeling if the prototyped component is to fit within an assembly. One limitation is that students must work with materials that are used by the RP process which are typically non-metallic e.g. ABS plastic for FDM. The physcial prototypes that students create should be functional with the material used by the RP process.

Why Use LEGO®?

An instructional methodology that encourages students to consider fabrication when modeling and that can lead to a physcial prototype is possible using products built with LEGO® blocks that are augmented with custom blocks built by RP. The following summarizes some of the advantages of using this approach.

- <u>Familiarity and Accessibility:</u>
  LEGO® is a concept that is familiar to most students. This in itself provides a connection to reality. Many exercises in off-the-shelf instructional material are not based on real components and students may not be familiar with those that are. LEGO® blocks can easily be made available to students as part of their modeling exercises, to compliment paper drawings and instructions with a physical artifact.

- <u>Supports Teaching Different CAD Modeling Techniques:</u>
  As anyone familiar with LEGO® can attest to, there is a large and ever growing set of blocks that are available. These range from the simple blocks and flats to styled pieces that are specifically designed for promoting the theme of a kit. The features present in these therefore correlate with the feature set available in a typical parametric CAD system. For example, a simple 2 x 2 block can be used to develop exercises that use the *Pad* and *Pocket* feature. In addition, the studding presents an opportunity to use the *Patterning* tool. More styled blocks that are developed to support the theme of a LEGO® kit would require the use of more advanced features such as a *Rib* (sweep) or *Multi-Section Solid* (loft) feature. Exercises in modeling various types of blocks can easily be created to support instructional objectives. LEGO® also naturally supports the instruction of assembly modeling techniques.

- <u>Supporting and Managing Creativity:</u>

  Students are typically more motivated when they are given an assignment where they can exercise creativity. Open-ended projects provide this opportunity. However, this can be a double edged sword if not properly managed. As evidenced by the vast assortment of LEGO® themes and kits that are available on the market, the LEGO® concept does generate creativity. At the same time being a modular approach to constructing a product it allows constraints to be placed by the instructor that help to manage the effort. One technique used for this is to require students to build a *Platfrom* around which their concept is to be developed. Figure 1 shows an example of a platform and a concept developed around it. *Platforms* can be constrained by the theme of the project and the number and types of blocks used. This provides control over the size and effort put into creating a model.

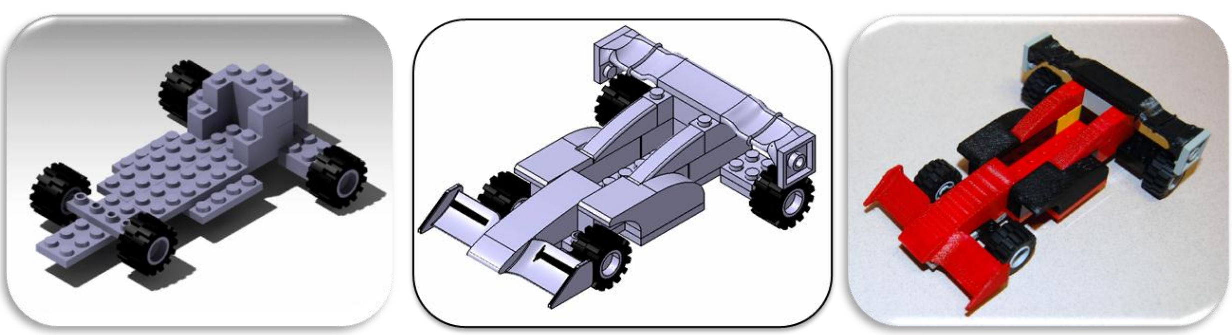

Figure 1. Platform Concept

- <u>Complementing the Virtual with a Physical Result:</u>
  Ease of access of LEGO® blocks makes creating a physcial prototype feasible. In addition the use of RP allows students to see their concepts evolve from brainstorming, through

sketches and detailing with CAD models to a physcial result. The connection between the CAD model and a final, physcial result is thus reinforced in the minds of the students.

- <u>The Ability to Incorporate Manufacturing Considerations:</u>
  Custom blocks that are developed to create a LEGO® concept must fit with standard blocks using the patented stud mechanism. This requires students to include mating features and to use appropriate dimensions and clearances on their blocks to facilitate assembly. Figure 2 shows stud and recess sizing guidelines based on the FDM RP process that are given to students for incorporation in their models. Students in the design of blocks are encouraged to include features that assist in injection molding, the process that would ultimately be used for mass production. These features include, draft, appropriate wall thickness and stiffeners. The RP process also places requirements such as the impact of orientation on surface finish. Consideration of these requirements provides an introduction to *DFM* and *DFA.*

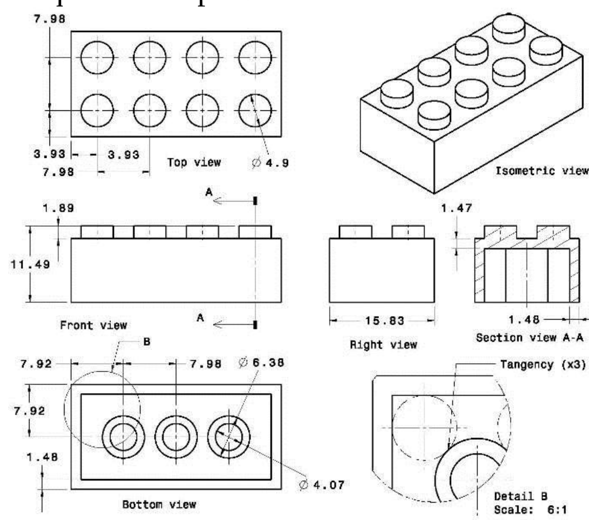

Figure 2. Dimensional Guidelines for LEGO® Stud Mechanism to mate with FDM Built Parts

- <u>Introduces Toolpath Planning:</u>
  This is a critical component of understanding machining processes. Students in Manufacturing and Plastics Engineering Technology do courses in CAM and CNC programming. The use of process planning software to create a "job" for a RP machine requires the generation of tool paths that guide the build head of the machine.

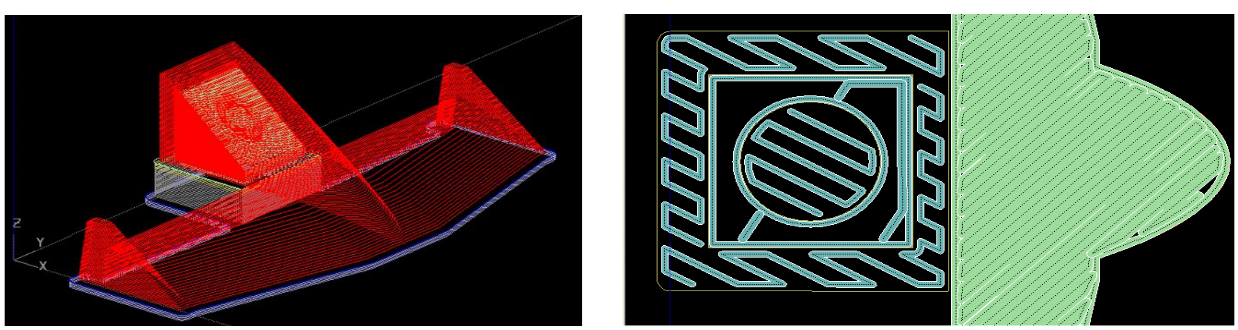

Figure 3. Tool Path Generation for FDM RP Process to Build a LEGO® Compatible Part

Though 2D and additive, students are introduced to the concept of how a tool needs to be programmed for moving it over a region to generate a shape. Figure 3 shows examples of slice boundaries and toolpath fill patterns generated by process planning software for creating ABS plastic components on a Stratasys FDM RP machine.

Strategy for Introducing LEGO® into CAD Education

A two step strategy is being adopted for integrating the use of LEGO® into the introductory CAD instruction in the Engineering Technology Department at Western Washington University. The steps are as follows:

- Develop a LEGO-Based Team Project for Introductory CAD Course (ETEC 113)
- Integrate Exercises that Require LEGO® Block Modeling into Instructional Materials

A LEGO-Based Team Project

The goal of this project is to provide an experience for students to work together in applying the design process to create a physical product. As part of the detailed design phase in the project, CAD modeling of the product is required. Fabrication involves construction of custom components from ABS plastic on RP machines and assembly with standard components. Earlier efforts at running this project led to significant variability in the quality of the results obtained from different groups. Choices of project topics included products such as CO_2 cars, flash lights and ergonomic hand tools. These were selected in part because they contain custom components made from plastic that can be fabricated using ABS on FDM machines that are available for the students to use. However, each choice had its drawbacks. Students are drawn to the "CO_2 Cars" (the races at the end of the term are always a big event) and are able to exercise significant creativity in developing their designs. However, it is difficult to ensure that each student gets to participate in modeling the design in CAD since most of the work is focused on a single custom component, the body of the car. Flashlights and ergonomic hand tools provide more substance for incorporating *DFM* and *DFA* considerations. There are also more components to model. However, they are less appealing to students. Developing designs that incorporate proper assembly features that enable custom built and standard components to come together properly in a final prototype is hard to consistently control.

A LEGO-based project has replaced these earlier efforts and is undergoing refinement in current offerings of ETEC 113. The steps that must be completed by each team in arriving at these results include:

- Conceptual Design
- Final Design Selection and Refinement
- Integration of DFM and DFA Requirements
- Detailed Modeling of Custom Blocks
- Process Planning of Custom Blocks
- Fabrication of Custom Blocks on an FDM RP Machine
- Assembly of the Prototype
- Documentation Generation

Figure 4. Examples of Student Project CAD Modeling and Prototyping

Figure 4 gives some additional examples of student work from this course. Illustrated are examples of platforms, final detailed CAD assembly models and the assembled prototypes with custom blocks. Figure 5 shows examples of concepts for these designs that were developed as part of the process that is followed.

The results show that the reasons identified previously to use a LEGO® approach are in fact justified. This is particularly true in achieving a process where a CAD model leads to a physical prototype, a necessity that will be reinforced in many other courses that students will take in their programs at Western Washington University and also in their workplace upon graduation. Further, the students are introduced to the importance of considering manufacturing in their design work and that modeling and fabrication are two steps in a much larger product development effort that includes more abstract activities such as conceptualization, ranking and refinement. More details of the experiences running this project can be found in a previously published paper[11].

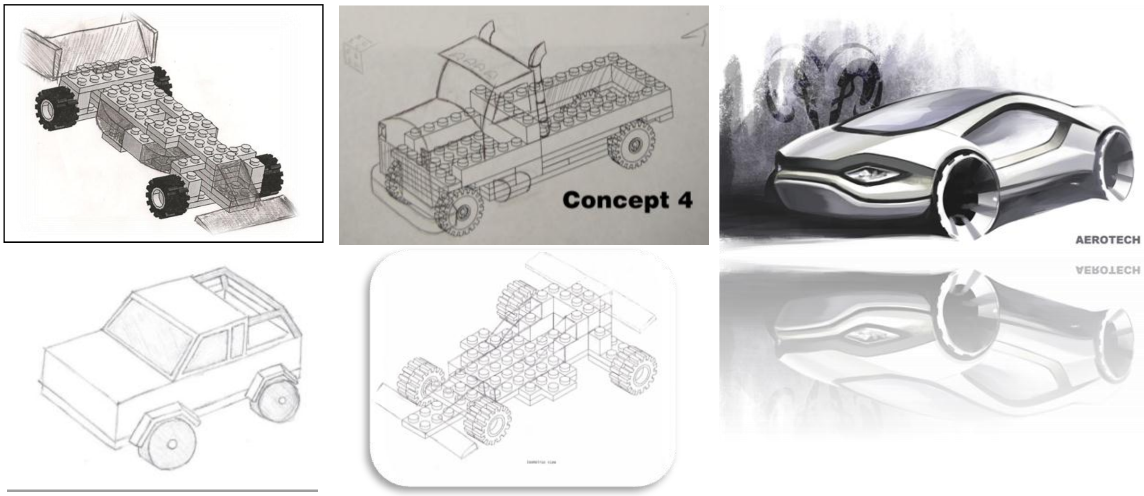

Figure 5. Examples of Concepts from Which Design Were Developed

Current offerings of ETEC113 are incorporating some refinements to the project that are designed to improve the final result and overall experiences of the students. These are:

- Provide Sample LEGO® Kits as Examples and Sources of Building Blocks: The prior strategy was to provide each team with a set of standard blocks and wheels that they could configure to build their platform. However, this left too much room for teams to decide on size and shape of their final concept. In some cases this resulted in non-LEGO like results with oversized or over stylized custom blocks. With three LEGO® Racer kit samples, each group will get to see the optimal size and style of the custom blocks they should create. Further they will be able to mix and match these blocks in developing the platform that their concept will be built around. Teams will also be allowed to use the more generic blocks that many have access to. Over eagerness will be tempered by the requirement that all blocks used must be modeled. A library of CAD models for standard blocks and wheels already exists for this purpose. It is hoped that this refinement will help improve consistency and the level of detail in custom blocks and the overall final assembly.

- Include Independently Graded Individual Activities in the Project: Team projects are often carried by one or two individuals who do the majority of the work. While this may be a true reflection of what happens in the real world, it is important that students are taught the importance of full participation and contribution to a project's success. To achieve this goal several deliverables of the team project will require individual effort that will be graded for each student. These are:

    - Concept Generation and Sketching: Each student will be required to generate three concepts of his or her own based on the theme agreed upon by the group. For each concept a sketch is to be created to convey the idea. With teams of four, this will lead to a pool of twelve concepts that can be used in the final concept selection and refinement phases of the project.

- Modeling of Custom Blocks: It is required that custom blocks should include use of advanced modeling features (*rib/slot* and *multi-section solid* features). This is an open-ended exercise is using these tools that should be experienced by all students. Teams should attempt to distribute the modeling of these blocks amongst members in a way that is equitable. However, ultimately it will be each student's responsibility to ensure that his or her work is on par with his or her peers. If necessary the same block may be modeled by more than one person to achieve this goal.
- Drawing Generation for Custom Blocks: This gives each student the experience of creating a drawing from their 3D block models. Given the advanced features this is more challenging that simple part modeling.

Feedback from Students

To test the acceptance of this approach to students in the ET programs requiring CAD, a series of questions have been prepared and given to students in different sections. The following table summarizes responses from one section (19 responses out of 23) to seven key questions. It can be seen that students place a high value on knowing how to make things (questions 1, 5, 6 and 7). There is strong agreement that the LEGO® based project is a good approach for achieving a physical result (question 4) and for deepening understanding of how manufacturing influences design (question 1). Students also appreciate both the creativity that the project provides (question 4) and that it provides them the opportunity to incorporate advanced modeling features in their designs (question 2). One area where there appears to be more uncertainty is on whether the LEGO® approach adequately supports learning of CAD and is preferable to other approaches. This is understandable, since without exposure to earlier project approaches it is difficult for them to appreciate the challenges and limitations they present.

Table 1. Students Responses to Use of LEGO® for CAD Instruction

		SA	A	N	D	SD
1	How did the group project help you understand the importance of Design for Manufacture and Design for Assembly principles?	2	17	0	0	0
2	Do you feel that the group project provided a good opportunity for you to use advanced modeling features such as Rib/Slot and multi-section solid features?	7	10	1	1	0
3	The use of LEGOs adequately supports the development of your understanding of CATIA and it would not be preferable to work on a product with more engineering significance?	1	8	6	1	0
4	The use of LEGOs supports being creative in developing and refining design concepts?	9	10	0	0	0
5	The use of the LEGO approach Is a good technique for ensuring that a functioning prototype is the result?	5	10	4	0	0
6	The creation of a physical prototype is important to your sense of accomplishment in completing the group project?	14	15	0	0	0
7	Being able to use the department's FDM machines for building custom blocks is an important facet of your experiences in completing the group project?	10	8	1	0	0

SA-Strongly Agree; A - Agree; N - Neither Agree or Disagree; D - Disagree; SD - Strongly Disagree

LEGO® Block Modeling Exercises in Instructional Materials

The ET department is currently in the process of developing new instructional materials for ETEC 113. To guide students through the use of different feature types, LEGO® block exercises can be highly instructional. Examples of the range of features that can be incorporated into such exercises is shown in Figure 6. On the left is an assembly comprised of an axle block, rims, and wheel. This model lends itself well to use of the basic feature types such as Pads/Pockets and Shafts/Grooves. In addition both rectangular and circular patterning techniques can also be applied to create the studs and wheel thread respectively. More complicated features such as multi-section solid features and ribs/slots can also be found in more styled blocks. Figure 5 shows examples of custom designed blocks that use these feature types. One advantage of using blocks as material for exercises is that physical examples can be purchased or built so that students have something to handle that they can correlate with dimensioned drawings or step by step instructions they must follow.

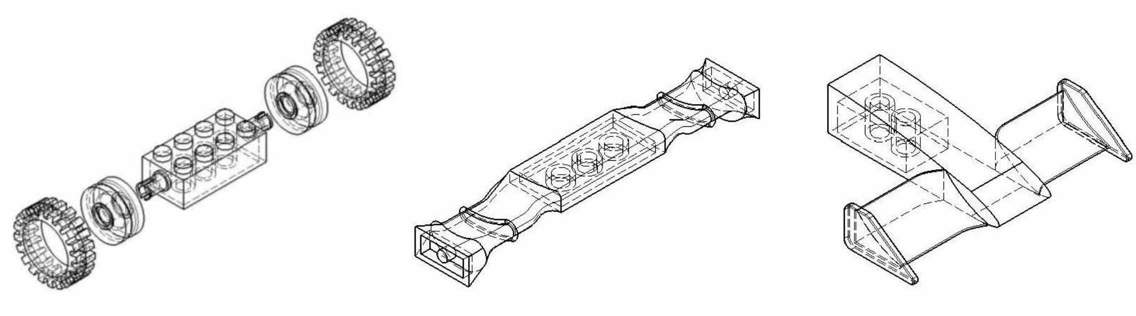

Figure 6. LEGO® Blocks Illustrating a Range of Feature Types that can be Used in Exercises

Conclusions

This paper presents the case for the use of LEGO® as a tool for teaching introductory CAD to Engineering Technologists. It provides several advantages over other project methods the most important of which is the ability to create a functional prototype that correlates well with the CAD model created. At the same time it is challenging enough to require meaningful consideration of *DFM* and *DFA* and the need to use a range of modeling techniques including advanced part design features. The ability to stimulate creativity within a project team while at the same time managing the effort to ensure equitable participation are also advantages. Results from such a project conducted within a freshman level introductory CAD class have been presented to support the case. Refinements to this project are currently underway to better manage consistency of effort across and within teams. In addition plans are underway to develop tutorial type exercises for instructional manuals that will use LEGO® blocks to teach modeling of basic to advanced features. Student feedback supports this effort and particularly values the ability to fabricate a prototype as part of the design process.

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