pre-college technology and engineering students learn bicycle design:

product realization process applied to bicycle frame production

By Andrew J. Hughes and Mike Stitzer

Designing, building, and riding a student's own bicycle is a compelling technology and engineering education project.

The intention of this article is to provide Technology and Engineering Educators (T&EEs) with a more thorough understanding of the product realization process (PRP) being implemented during machine design. Machines can be defined as the combination of simple machines and mechanisms for the purpose of doing work (Hughes & Merrill, 2021b). Machines are systems consisting of mechanical components and devices coordinated to meet human wants and needs. Machines involve moving parts that "transmit power and accomplish specific patterns of motion" (Mott, 2004, p. 3). Technology and engineering education commonly includes the design of machines like in the adaptive and assistive technology design of the REACH Challenge (ITEEA, 2021). Machine design is a part of the more general mechanical design field (Mott, 2004).

In this article, the PRP is being applied to a bicycle, but could be applied to successfully bringing any product or service to market (Hughes, 2022). The term product realization is used to describe a process that is focused on developing, manufacturing, delivering, and maintaining a product or service throughout its life cycle (Figure 1) (Hughes, 2022). Hughes (2022) detailed that the PRP includes the engineering design process, but also includes numerous other processes like quality management system (QMS) and design and development. Additionally, Hughes (2022) discusses the importance of the PRP for T&EEs including more thoroughly addressing the overall design process to promote student development related to knowledge, skills, and dispositions, and *Standards for Technological and Engineering Literacy* (STEL, 2020). This article should be used in conjunction with Hughes (2022) to help T&EEs more thoroughly address the *STEL* standards (2020) and the PRP. Additionally, an article including more information about the PRP applied to a bicycle will follow this article.

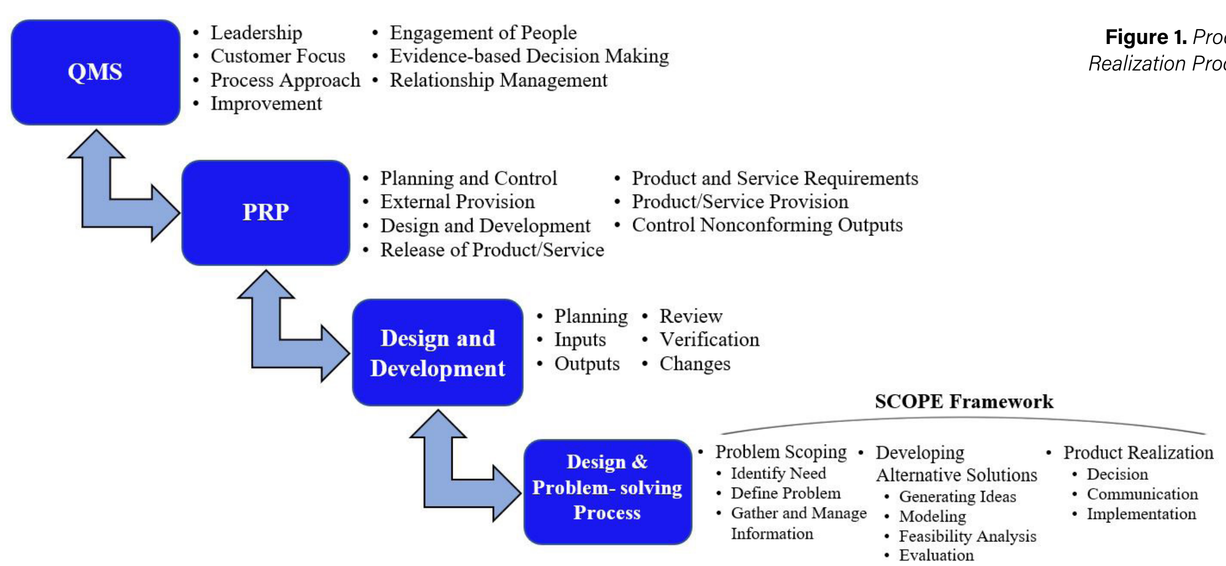


Figure 1. *Product Realization Process*

Important Role of Technology and Engineering Educators

Mott (2004) identifies five items considered knowledge and skill requirements for students beginning to learn about machine design including: 1. Sketching, technical drawing, and computer-aided design; 2. Properties of materials, material processing, and manufacturing processes; 3. Applications of chemistry such as corrosion protection, plating, and painting; 4. Statics, dynamics, strength of materials, kinematics, and mechanisms; and 5. Oral communication, listening, technical writing, and teamwork skills. *STEL* (2020) addresses students developing competency in all five of the items during experiences in the T&E education classroom (Figure 2). Mott (2004) suggests that students engaged in machine design utilizing the PRP will develop a high level of competence related to these requirements. The authors believe that this is especially true for students in T&E education. Bicycle design was a staple during the more utilitarian period of the technology and engineering education discipline. Hughes and Merrill (2021a) suggested that for the T&E education discipline to have staying power, educator preparation programs and educators should return to a "balance between high quality practical and theoretical learning through the implementation of scientific and mathematic practices and theories with robust connections to hands-on engineering and technological problem solving" (p. 15-16). This should be considered a good time to reflect on the teaching and learning that happens in your classroom related to these five items.

Mott (2004) Knowledge and Skill Requirements	Standards for Technological and Engineering Literacy		
	Standards	Practices	Contexts
Sketching, technical drawing, and computer-aided design	2: Core Concepts of Technology and Engineering 7: Design in Technology and Engineering Education	3: Making and Doing 4: Critical Thinking 5: Optimism	5: Information and Communication
Properties of materials, material processing, and manufacturing processes	2: Core Concepts of Technology and Engineering 4: Impacts of Technology 5: Influence of Society on Technological Development 6: History of Technology 7: Design in Technology and Engineering Education	3: Making and Doing	1: Computation, Automation, Artificial Intelligence, and Robotics 2: Material Conversion and Processing
Applications of chemistry such as corrosion protection, plating, and painting		3: Making and Doing	2: Material Conversion and Processing
Statics, dynamics, strength of materials, kinematics, and mechanisms	2: Core Concepts of Technology and Engineering 3: Integration of Knowledge, Technologies, and Practices 7: Design in Technology and Engineering Education	3: Making and Doing	4: Energy and Power 6: The Built Environment
Oral communication, listening, technical writing, and teamwork skills	7: Design in Technology and Engineering Education	6: Collaboration 7: Communication	5: Information and Communication

Figure 2. *Standards, Practices, and Context Alignment* (STEL, 2020)

When focusing on developing students' competencies related to these five items, there are standards-focused teacher-friendly resources available. For example, Hughes and Merrill (2020b, 2020c, & 2021a) introduced the engineering concepts and processes involved in solving force systems involving statics and strength of materials. Hughes and Merrill (2019 & 2020a) thoroughly addressed the concepts around strength of materials and manufacturing processes involved in designing, making, and testing the strength of a concrete beam. Additionally, Hughes and Merrill (2021b & 2021c) addressed mechanism design and analysis focusing on kinetics, kinematics, and mechanisms. These and other articles help form the foundation for students' ability to visualize force systems and motion of mechanisms, calculate force systems in equilibrium, and apply an understanding of strength of materials in the design process. Basic understanding of these articles aligns with the five knowledge and skill requirements presented by Mott (2004); and these requirements should be thoroughly addressed by T&EEs when teaching and learning about machine design.

Actualizing the Student as a Designer

The ultimate objective for T&EEs is to provide authentic design scenarios in which students can visualize themselves as designers responsible for product realization based on consumer wants and needs. T&EEs should spend more time properly sequencing design experiences using the PRP to help students have a more complete and genuine perspective of design (Hughes, 2022). The PRP is focused on "all functions that must happen to deliver a satisfactory product to the customer and to service the product throughout its life cycle" (Mott, 2004, p. 10). It emphasizes the importance of carefully identifying the wants and needs of consumers prior to starting the design process. Designing a machine also involves designing, verifying, and selecting appropriate components to meet design specifications. The process of identifying consumer and other individuals' expectations becomes a part of determining functions, requirements, and evaluation criteria also known as design specifications. These specifications are based on many factors including consumer expectations, safety, manufacturability, cost, and others. The remainder of the article is focused on providing a PRP example involving the design of a recumbent bicycle (Figure 3). This same process could be directly applied to any type of bicycle design.

Figure 3. *Student-designed Recumbent Bicycle*

Functions, Requirements, and Evaluation Criteria

Consider that you are the designer of a bicycle. To begin the design process, you must first identify the functions, requirements, and evaluation criteria. The identification of these specifications typically requires input from your own experience, other designers, marketing staff, engineers, service personnel, suppliers, customers, and potentially other individuals. Identifying specifications is an important first step that will help focus the design process. Hughes (2022) stated that "although a design may be technically sound, the design could be a waste of time and money if it does not meet all specifications" (p. 18). Thoroughly preparing clear specification statements will help focus the design process on the desired results. The following specifications are examples for the purpose of bicycle design in this article.

Functions:

1. Receive power and other control inputs from rider.
2. Transport a rider using only human power.

Requirements:

1. Hold a 170-pound rider
2. Fit a rider that is 6 feet tall
3. Rider is seated in recumbent position
4. Bicycle – only two wheels
5. Bicycle will have minimum turning radius of 25 feet
6. Bicycle must be stable
7. Bicycle must have braking on both wheels
8. Bicycle must be able to stop from 10 miles per hour within 20 feet
9. Bicycle must have multiple gear ratios

Evaluation Criteria:

1. Safety (i.e., strength, stability, maneuverability, and braking)
2. Performance (i.e., complete 1 mile in under 5 minutes)
3. Manufacturability
4. Serviceability
5. Operability
6. Desirable appearance, cost, and functionality (i.e., craftsmanship and comfort)

Bicycle Design

Designing the bicycle will require the student to consider designing, building, purchasing, and repurposing a frame, seat, grips, wheels, bearings, brakes, cables, drive train (i.e., derailleur, chain, cogset, pedal, crank, shifters), and other components. For the purposes of illustration, the article will focus on the strength of the frame. After determining the design specifications, students move to detailing other design considerations based on a donor bicycle (i.e., outside diameter of tires and wheels, crank length, fork characteristics, and others). Students then produce a scaled sketch of the potential frame design (Figure 4). This students' frame design is based on the design specifications and other considerations. Students will continue to test and refine their design sketches by focusing on how the bicycle fits and functions for the rider.

Rider Fit

Figure 4 details the fit of 6-foot-tall rider with 32-inch inseam. The large circle A has a scaled 32-inch radius corresponding to the rider's inseam. The small circle B has a scaled 170-millimeter radius corresponding to the length of the crank arm. A four-bar mechanism is drawn to determine rider movement while pedaling the bicycle. Hughes and Merrill (2021b & 2021c) described the design and analysis of four-bar mechanisms. In Figure 4, *Label 1* represents *member 1*. Member 1 represents both fixed points of rotation (i.e., the bicycle's frame). *Label 2* represents *member 2* (i.e., the rider's upper leg). *Label 3* represents *member 3* (i.e., the rider's lower leg). Finally, *Label 4* represents *member 4* (i.e., the bicycle's crank). Determining the rider's fit using four-bar mechanism analysis is also helpful in determining operability of handlebars and other controls of the bike, as well as determining bicycle performance and efficiency based on rider power input.

Load on Frame Members

After the students finalize the fit and layout of the bicycle, students then apply the methods of joints or sections to determine the force on each member of the bicycle frame. Students use resources like Hughes and Merrill (2020b & 2021a), which described the application of the method of joints and the method of sections, to help determine the forces in their bicycle frame design. External forces and forces in each member of the bicycle frame are determined based on the design requirements and each student's initial design (Figure 5). If a student decides to use a single frame member for the top tube, instead of a front triangle design, the student can apply bending force analysis as addressed in Figure 10 of Hughes and Merrill (2020a).

Strength of Frame

After determining the direct axial load on each member in the frame, students can then select appropriate materials for the frame based on stress analysis. For this article, the design will be based on 4130 chromoly round tubing for the front triangle and rectangular tubing for the rear triangle of the frame. Design properties

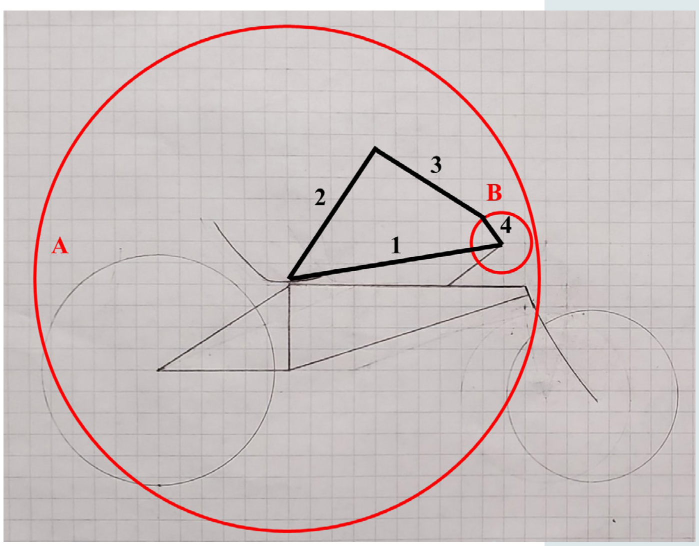
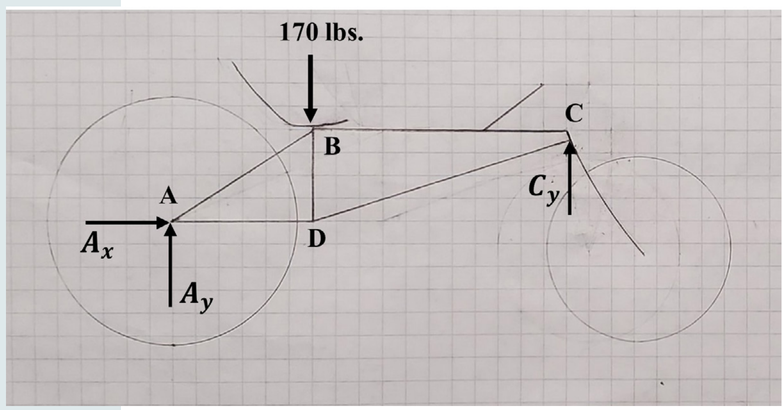


Figure 4. *Student Initial Frame Design with Detailed Rider Fit*



If a 170-pound external load is applied to the bike frame in Figure 4, the external forces and forces in each member equal:

A_x = 0 lbs.
A_y = 113.33 lbs.
C_y = 56.67 lbs.
AB = 208.08 lbs.* in compression
AD = 174.5 lbs.* in tension
CD = 183.48 lbs. in tension
BD = 56.698 lbs. in compression
BC = 174.5 lbs. in compression

*Note: Members AB and AD only represent one side of the rear triangle. Actual loads in each member of the rear triangle will be about half the calculated amount. Member AB would experience about 104 pounds in compression and member AD would experience about 87 pounds in tension.

Figure 5. *Student Initial Frame Design with External Loads and Axial Forces in Each Frame Member*

Direct tensile stress on member CD using 1.125 inch diameter 4130 chromoly tubing with a .035 inch wall thickness (cross sectional area of tubing = .12 in^2):

$$\sigma_{CD} = \frac{Force}{Area}$$

$$\sigma_{CD} = \frac{183.48\ lbs.}{.12\ in^2}$$

$$\sigma_{CD} = 1529\ psi$$

Figure 6. *Direct Stress Formula*

of materials used can be found online. The design properties for normalized 4130 chromoly tubing are an ultimate tensile strength ($\sigma_{ultimate}$) equal to 90 ksi, yield strength (σ_{yield}) equal to 57.8 ksi, and modulus of elasticity (E) equal to between 27500 and 30500 ksi. Note: ksi is kips per square inch, 1 kip equals 1000 pounds, 1 ksi = 1000 psi. The direct stress formula can be applied to determining stress in each member of the frame (Figure 6). Figure 6 shows that member CD with a 170-pound rider experiences a static stress of 1529 psi. Based on the design properties, we know that member CD could experience a stress of 57800 psi before yielding. Students may think that they could reduce the size of member CD by adjusting the *strength-to-weight* ratio. However, the dynamic stresses of the rider and bicycle in motion would need to be considered before reducing the size and ultimately strength of the material used. Although, the students may only be thinking about the bicycle being ridden on a paved level surface, they may want to consider how a consumer might actually use the bicycle. For example, riding off and over curbs that would induce additional load forces. Addition-

Rectangular Tubing:

Area

$$A = BH - bh$$

Moment of Inertia about the x-axis:

$$I_x = \frac{(BH^3 - bh^3)}{12}$$

Moment of Inertia about the y-axis:

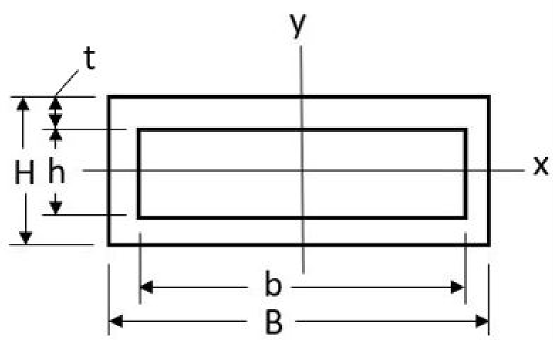
$$I_y = \frac{(HB^3 - hb^3)}{12}$$

Polar Moment of Inertia:

$$J = \frac{2t(H-t)^2(B-t)^2}{(H+B-2t)}$$

Radius of Gyration

$$r = \sqrt{\frac{I}{A}}$$



Round Tubing:

Area

$$A = \frac{\pi(D^2 - d^2)}{4}$$

Moment of Inertia

$$I = \frac{\pi(D^4 - d^4)}{64}$$

Polar Moment of Inertia

$$J = \frac{\pi(D^4 - d^4)}{32}$$

Radius of Gyration

$$r = \sqrt{\frac{I}{A}}$$

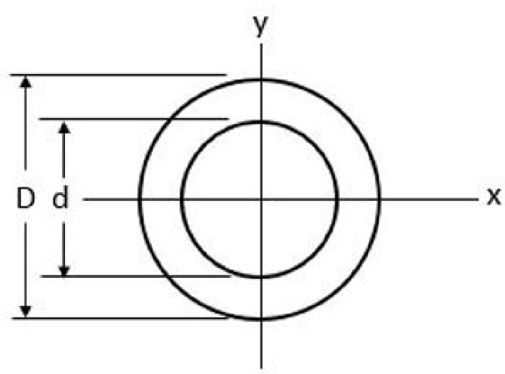


Figure 7.
Properties of Areas

	Formula	When to Apply Formula
Euler	$P_{critical} = \dfrac{\pi^2 EI}{(KL)^2}$	$Slenderness\ Ratio > Member\ Constant$ OR $\dfrac{KL}{r} > \sqrt{\dfrac{2\pi^2 E}{\sigma_{yield}}}$
J.B. Johnson	$P_{critical} = A\sigma_{yield}(1 - \dfrac{\sigma_{yield}\left(\dfrac{KL}{r}\right)^2}{4\pi^2 - E})$	$Slenderness\ Ratio < Member\ Constant$ OR $\dfrac{KL}{r} < \sqrt{\dfrac{2\pi^2 E}{\sigma_{yield}}}$

$P_{critical} = load\ causing\ buckling$

$L = length\ of\ frame\ member$

$K = effective\ length\ constant$

<u>Effective length constants (K) based on member end fixity</u>

If both member ends are pinned, K = 1

If both member ends are fixed, K = .65

If one end is fixed and the other free, K = 2.1

If one end is fixed and the other pinned, K = .8

Figure 8. *Selecting between Euler or J. B. Johnson Formulas*

$$P_{critical} = \frac{\pi^2 EI}{(KL)^2}$$

$$P_{critical} = \frac{\pi^2\ (27500000\ psi)(.0085\ in^4)}{(.65\ x\ 17.5\ in)^2}$$

$$P_{critical} = 17829.97\ lbs.$$

Figure 9. *Determining $P_{critical}$ for Member in Compression*

ally, materials with greater wall thickness are generally cheaper, but there would be a *cost-to-weight* ratio tradeoff that students would need to consider. At this point, there are many other tradeoffs and aspects related to the design specifications the students should consider like manufacturability.

For members in compression, designers are generally not as concerned with member failure in direct compression but member buckling due to compressive loading. The tendency for a compressive member to buckle is dependent on the cross-sectional area and moment of inertia (Hughes and Merrill, 2019). For members with a rectangular cross-section, both the x- and y-axis will have different moments of inertia. This means that a member with a rectangular cross-section is going to bend and ultimately buckle on the axis with the lower moment of inertia (Hughes and Merrill, 2019). In Figure 7, if you were to calculate the moment of inertia for I_x and I_y, you would see that I_x will have a lower value meaning that buckling would happen on the x-axis. Hughes and Merrill (2019) presented a moment of inertia lab to help students visualize how changing area, area orientation, and shape impacts moment of inertia.

For frame member AB, the student decided to use .75-inch square tubing with a .035-inch wall thickness. To calculate load causing failure due to buckling, we would apply either the Euler or J. B. Johnson formula based on the relationship between the slenderness ratio and member constant (Figure 8).

In this student's case, the slenderness ratio of member AB is greater than the member constant and Euler's formula is applied to calculating $P_{critical}$ for member AB (Figure 9). Figure 9 shows that member AB has a $P_{critical}$ of 17830 pounds before buckling. With a 170-pound rider AB experiences a static load of about 104 pounds (see Note in Figure 5). Again, the student designer will want to consider the safety factor, dynamic loading, and trade-offs before adjusting the selected frame material.

Brazing Frame Members

The process of brazing is what students will use to join frame members. Students will secure frame members in fixtures for brazing (Figure 10). The primary difference between soldering, brazing, and welding is temperature. The filler metal used is a copper alloy, typically brass or bronze, that consists of other materials including zinc or tin, respectively. Brass and bronze brazing materials typically have a working temperature between 1500 and 2000°F. The brazing material the authors are currently using with students is a flux-coated copper-nickel-zinc alloy also known as nickel-silver. Despite the name, there is no silver in this brazing material. Nickel-silver brazing rods offer a good balance between strength, ease of brazing, and ability to fill larger gaps between mitered frame members (typically within 1/16 of an inch). The design properties for the

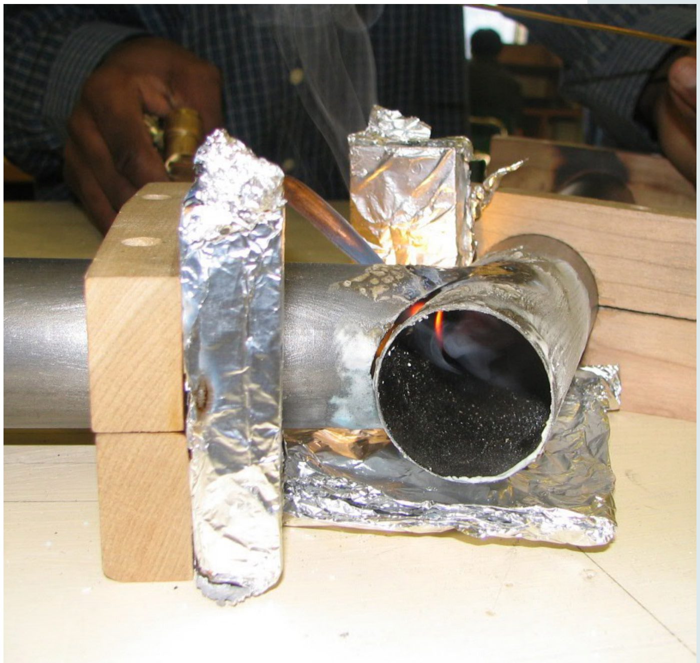


Figure 10. *Brazing Head Tube*

nickel-silver brazing rod are a yield strength (σ_{yield}) equal to 60 ksi. Using a factor of safety of 2, the allowable shear stress ($\sigma_{allowshear}$) would equal 30 ksi. The student's design indicated a 1/8-inch fillet braze. The student based the size of braze on the allowable load per inch equation. The allowable load per inch is equal to .928X, where X represents the number of 1/16ths in the fillet leg. In this case, there are 2/16ths so the allowable force per inch equals 1856 lbs/in. However, these design properties need to be seriously considered because the strength of the brazed joint can be impacted by many factors including initial gaps between members, temperatures, and joint quality (i.e., low voids, good penetration) (Figure 10).

Although the students will braze around the circumference or perimeter of a mitered butt joint, the strength of the braze will be determined based on viewing each brazed section as a straight line with no other dimensions. Viewing each brazed circumference or perimeter as a straight line allows the students to determine brazed joint strength in a simpler manner. Each joint is likely to experience four types of loading: (1) direct tension or compression, (2) direct vertical shear, (3) bending, and (4) twisting. There are different formulas used based on the loading to determine the force per inch of braze (Figure 11).

To analyze the tension of the brazed joint between members BD and CD, students will need to consider that the design specified the end of member CD is mitered to fit around BD, the 1/8-inch fillet braze around the miter, and the load at this joint is 183.48 pounds in tension. Using the formula from Figure 10 for direct tension, the current static force is 51.9 pounds per inch of braze. Considering the allowable force per inch is 1856 lbs./in. and the brazed circumference is about 4.4 inches, the allowable force on the member would be about 421.8 pounds. Students will again need to remember that 51.9 lbs./in. of braze is based on the static load of 170 pounds, and dynamic loading should be considered based on how the bike will be used by a customer. Circumference or perimeter of mitered members can sometimes be difficult to determine mathematically. Design software can be useful in determining these measurements. However, do not overlook other basic measurement strategies. For example, circumference can be determined using a string wrapped around the member, and then the string can be measured using a ruler.

Type of Loading	Formulas for Tubing	Round Tubing	Rectangular Tubing
Direct Tension or Compression and Direct Vertical Shear	$Force = \frac{Load}{A_w}$	$A_w = \pi D$	$A_w = 2b + 2h$
Bending	$Force = \frac{Moment}{S_w}$	$S_w = \pi \left(\frac{D^2}{4}\right)$	$S_w = bh + \frac{h^2}{3}$
Twisting	$Force = \frac{Torque}{J_w}$	$J_w = \pi \left(\frac{D^3}{4}\right)$	$J_w = \frac{(b+h)^3}{6}$

$$Moment = Force \ x \ Distance$$

$$Torque = Force \ x \ Distance \ (i.e. radius \ or \ width \ of \ frame \ member)$$

Figure 11. *Formula for Force per Unit of Braze*

Conclusion

Designing, building, and riding a student's own bicycle is a compelling technology and engineering education project. T&EE's utilization of projects like this lends credence to the science and mathematics students are already learning. Based on the authors' experience, projects like this help students self-answer their *why* questions. Thoroughly teaching problem solving or teaching to the problem and not just the tools is an important idea for T&EEs. This allows students to see the relevance of the tools such as math, science, handheld oxy-acetylene torch, and others. This article addressed utilizing the PRP applied to bicycle frame design based on stress and strength of material analysis. T&EEs applying this article will address *STEL* (2020) and help students develop knowledge, skills, and dispositions involved in thoroughly approaching the design process. Furthermore, the bicycle design activity fosters student development of shop skills, craftsmanship, technological literacy, and the tacit knowledge and skills developed through applying sound theories during practical hands-on learning. A future article will detail other bicycle design considerations including frame rigidity, chain drive, and bearings.

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