

Assessing and Justifying the Reasonableness of Answers to Open-Ended Problems

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Abstract— Engineering students have little practice solving the ill-defined problems they will encounter as professional engineers. Our research team has created an Open-ended Modeling Problem (OEMP) for students to begin practicing engineering judgment. This study investigates one aspect of engineering judgment, evaluating what is a good enough solution, or reasonableness. After solving an assigned OEMP, students were asked if their solutions were reasonable and to justify their answer. This paper examines the different justifications students provided and the assignment factors that may have led to those responses. This work has implications for designing future ill-structured problems and engaging students in engineering judgment.

Keywords—engineering science, open-ended problem, reasonableness

I. INTRODUCTION

Professional engineering work revolves around solving ill-defined, complex problems [1]; therefore, engineering students must learn to solve these kinds of problems. Research by Jonessen [1],[2], as well as others, have pointed to the gap between problems typically assigned to engineering students to complete for homework and the ill-defined, real world problems they will be expected to solve as professional engineers. Even engineering students recognize this difference, seeing closed-ended problems as classroom problems and open-ended problems situated in context as workplace problems [3].

Research on the “middle years” [4], the second and third years of an engineering degree, have shown students feel less engaged and have lower motivation in their courses. During these years, students are required to take discipline specific engineering science courses that are typically disconnected from each other. These courses generally focus on learning how to model natural phenomena (e.g. fluid mechanics, thermodynamics, mechanics of materials) under a set of simplifying assumptions that are inherently upheld in closed-ended homework problems. Research in both physics and engineering courses [5],[6] have shown students mostly

engage in calculations and procedural execution, or task production [7], [8], when solving these types of problems and don’t engage in the sense-making [9], [10] needed for deeper learning.

Our research team is inspired by these issues to create homework problems that:

- 1) are situated in a real-world context to provide better connection between students’ coursework and their experience in the world
- 2) better prepare students for the real world by being open-ended
- 3) still ask students to practice mathematical models they are learning in the particular engineering science course
- 4) give students an opportunity to practice engineering judgement [11]

We call such problems Open-ended Modeling Problems (OEMPs). The second author first assigned OEMPs in his sophomore aerospace mechanics of materials course in the Fall 2018 semester [12]. Initial survey data showed students enjoyed solving these problems and wanted more of them assigned in other courses [13]. Interviews with students describing their OEMP problem-solving process showed students practicing engineering judgement [11] by deciding when and how to use technology, determining representative elements, making assumptions, and determining if their calculated answer was reasonable [12]. Finding these initial results promising, our research team has begun expanding our research to include different types of courses and universities to better understand and scaffold the “productive beginnings” of engineering judgement.

In order to expand the use of OEMPs and understand the beginning of engineering judgement, the team has moved from measuring engineering judgement through retrospective interviews to examining student homework assignments. This allows us to examine engineering judgment in a greater number of students. Our first attempt at this [14] focused on understanding the assumptions students make when deciding

how to define their open-ended problem. This paper focuses on students' evaluation of the "reasonableness" of their final answer. Reasonableness, as we define it, is evaluating whether a solution is acceptable or not. We argue this is an essential skill to begin to develop in engineering students, as they will need the ability to evaluate their solutions to ill-defined problems similar to what they will encounter in professional practice [1], [15]. Assessing reasonableness is an understudied phenomenon in engineering education as it typically isn't taught as part of formal instruction [16],[17],[18]. Hanson & Brophy [17] reviewed ten commonly used structural analysis textbooks and found "little to no formal instruction is offered on how to evaluate the reasonableness of results" (p.2) and decided to investigate this phenomena through interviews with professional engineers. After asking students to evaluate the reasonableness to homework problems in their course, they saw an increase of 20% in students' ability to select a reasonable answer and justify the answer selection [16].

In a study of students solving ill-structured problems by Faber and colleagues [19], students reported assessing the reasonableness of their calculated answer as the most difficult part of the problem. Faber et al., Hanson et al., and Miskioglu & Martin all argue for the need to develop metacognitive practices in students through discussion and the explicit inclusion of these practices in courses [16]-[20]. Our research builds on their work in attempting to understand how undergraduate students determine the reasonableness of their results by examining their evaluation and justification of their calculated results to an ill-defined problem. Our research questions are:

- 1) How did students justify the reasonableness of their final answer?
- 2) What factors influenced student's assessment and justification of the reasonableness of their final answer?

II. FRAMEWORK

Engineers use many different types of models in their work--physical, computer, mathematical, theoretical/conceptual, and written models [21]. The focus of our work is how students in middle-years engineering science courses learn to use mathematical models of natural phenomena such as beam bending, air traveling over a wing, or the movements of a robotic arm. Using known mathematical models (e.g. Bernoulli's equation) requires making simplifying assumptions (eg. the fluid is incompressible, inviscid, and applied along a streamline). Typical "plug and chug" homework problems list or implicitly conform to these assumptions and provide a single exact numerical values for factors that actually have a range or an associated uncertainty in the real world, such as weight, speed, and size, so when the correct mathematical model is applied, the answer is found. When students are asked to solve an OEMP they must make

these determinations on their own, practicing the *engineering judgement* they will use when they are professional engineers.

Engineering judgement is a term used by Gainsburg [11] to encapsulate her observations of practicing structural engineers at two professional engineering firms employing "judgment to make a final call on the reasonableness of the analysis or design" [p. 287]. There are very few studies that have examined engineering judgment in practicing engineers or students. Our analysis of OEMPs is based off of the work of Gainsburg [11]. In Gainsburg's study [11], she found there were eight ways engineers used engineering judgement when constructing and using mathematical models in design. These eight include:

- EJ1. Determining what is a good or precise enough calculation or estimation
 - EJ2. Marking assumptions or simplifications to be the bases of mathematical models
 - EJ3. Overriding mathematically "proven" results
 - EJ4. Determining appropriate uses of technology tools
 - EJ5. Assigning qualitative factors (e.g. soil type) and applicable condition for selecting formulas
 - EJ6. Overriding official building codes
 - EJ7. Discretizing (grouping elements to reduce the number of types to be designed)
 - EJ8. Determining what elements or conditions were "typical" (representative) for the structure
- (p. 486-487, [11])

Our previous work [12] interviewed five students in the second author's course after they completed two assigned OEMPs about a hypothetical bridge between two on-campus buildings. Our analysis found students engaged in six of the eight categories of engineering judgment above (as EJ3 and EJ6 are typically not found in classroom practice or problems). During these interviews, we asked students to evaluate the "reasonableness" of their final answers for each of the problems—the diameter and material of a cable for OEMP1, and the shape, dimensions, and material for a beam in OEMP2. We found that students evaluated their answers in two different frames: the classroom and the real world. This question aligns with Gainsburg's EJ1 "Determining what is a good or precise enough calculation or estimation" [11].

This paper details our first attempt at analyzing students' assessment and justification of the reasonableness of their final answer at scale. Here, we analyze the written responses of students at two universities to two different OEMP problems (one problem per university). By analyzing two different problems at two different universities we increase the generalizability of our findings. Furthermore, we can compare students' answers to the two problems to identify which features of a problem lead to certain assessments and justifications of reasonableness.

III. STUDY CONTEXT

This study was conducted in mechanics of materials courses at two universities. Yellow University is a large public university located in the midwest. The mechanics of materials course was taught in an aerospace engineering department by the second author in the spring of 2019. Seventy-four students were enrolled in the course. Students were assigned two OEMP problems having to do with a hobby aircraft located in the lobby of the aerospace building, immediately outside the classroom where the course was taught. The first problem was due at the beginning of the 5th week of the course, and the second problem was due at the end of the 14th week. On the day that each problem was due, students were required to come to class to participate in a discussion in assigned groups of four students.



Fig.1 Picture of the hobby aircraft with notations from the second author that was featured in the assignment

The student solutions we analyze in this study are the responses to the first OEMP problem [Appendix I]. Students were asked to determine the safety factor, material, and diameter of the rear landing gear (the location of the red force vectors in Fig. 1). Students chose two of these parameters top-down, and then used their model to calculate the third parameter bottom-up. They were then asked to justify their answer and were asked “Is the size of the bar that you found physically reasonable? Is the size of the bar that you found the same as for the actual airplane? (It may not be.)”

Blue University is a small private university located in the northeast. The mechanics of materials course was taught in a mechanical engineering department by a teaching professor in the fall of 2019. Seventy-five total students were enrolled in two sections of the course. Students were assigned one OEMP problem for homework due in the 8th week of the course, and discussed a second problem on the last day of the course. The problem [Appendix 2] assigned for this course revolved around the iWalk 2.0 device [Fig. 2]. While solving the problem, students had access to a model of the device in the instructor’s office. For the assigned problem, students had to determine a material and diameter of bar AB [Fig. 3]. Students chose one of these parameters top-down, and then used their model to calculate the other parameter bottom-up. Students were asked “Justify your answer. Is the size of the bar you found physically reasonable? Why or why not?”



Fig. 2 iWalk 2.0 Handsfree Crutch from <https://iwalk-free.com/specifications/>

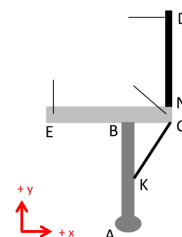


Fig.3 Simplified 2D model of iWalk 2.0

IV. METHODOLOGY

Students from both Yellow University and Blue University were asked to participate in our research study. All students submitted their assignments online for their course, and at the end of each semester the research team downloaded the student submissions for those who had consented to participate in the research.

Members of the research team (author three for Blue University, author four for Yellow University) identified the following three pieces of data from each student’s written work:

- The **parameter** that they calculated bottom-up (i.e. students’ “final answer”).
- Their **assessment** of whether the value of this parameter was reasonable or not.
- Their **justification** for why this value was reasonable or not.

The researchers listed each piece of data on a single spreadsheet to aid coding the data, the next step in the analysis.

The coding process began with author three openly thematically coding Blue University students’ justifications. At the end of this first open coding, four codes were identified: Mathematical, Comparison, Benefit, and Safety Factor. Authors one and three discussed the codes and determined the Mathematical code was too general of a term and needed to better identify the substance of students’ justifications. Author one openly and thematically re-coded the responses and replaced the Mathematical code with three separate codes: Size, Material, and Calculations. The final codes and definitions are found in Table 1.

TABLE 1 CODES AND DEFINITIONS

Code	Definition
Size	A student simply stated that the value of their calculated diameter was sufficient or insufficient
Material	A student's justification was based on the strength, or more specifically the tensile strength, of their calculated material
Comparison	A student compared their calculated diameter to the dimensions of the actual device being modeled, to other calculations within their work, or to other real-world devices
Benefit	A student described a benefit to the producer of the product or user of the product. The product, with respect to the student's calculations, was cheaper to manufacture or purchase, was easier for the user to operate, or the chosen material had a light density or was physically lighter to lift
Safety Factor	A student's justification was based on an appropriate safety factor for the application.
Calculations	A student postulated that something went wrong in their calculations or their model of the device contained unrealistic assumptions.

A particular chunk of text was only coded with one code, but because a student's justification could be multiple sentences long, their entire justification could be coded with more than

one code. A coding rule was established that none of the Yellow University data could be coded with safety factor, as these students were explicitly asked to determine a safety factor, and therefore were required to justify their selection of a particular safety factor.

In an effort to assess the clarity of the coding scheme, authors two and three independently coded 20% of the data from each university (11 students from Yellow University and 13 students from Blue University). During this initial pass, authors two and three reached 54% agreement. In discussing the results, the research team noted that the coded justification text from each student had addressed both the parameters that were selected top-down and the "final answer" parameter that was calculated bottom-up. Therefore, for a second check of the coding scheme clarity, each student's justification text was pared down to only address the parameter that was calculated bottom up. In this second check authors two and three then coded a second randomized 20% of the data and reached 70% agreement. They discussed each response where they did not match and came to a consensus. Finally, author three coded the entirety of the data set, identified text that was challenging to code, and discussed these with author two. Then all codes were reviewed by author two and then author one.

V. RESULTS

We present the results for each data set from each university in isolation. The following diagrams present data showing each pathway in which a student chose to solve the problem. Percentages reported in each of the diagrams are based on the total number of assignments analyzed for each university.

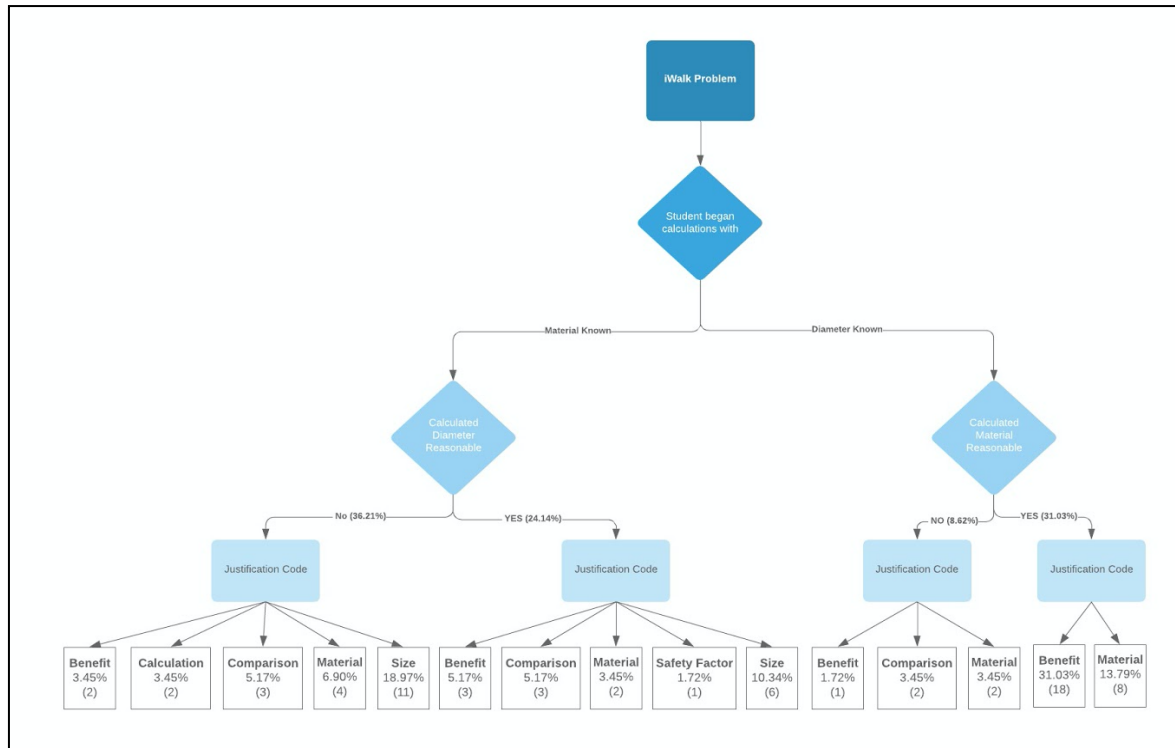


Fig. 4: Blue University (n=58)

Justification codes total to over 100% as many written justifications had multiple sentences, which allowed for the use of multiple codes throughout the entire.

Blue University had 62 students consent to participate in the study. Four assignments were not coded because two students provided no justifications and two written justifications were unintelligible. Of the remaining 58 responses, 60.3% of students first selected the material and then calculated the diameter of bar AB bottom-up, while 39.7% of students first selected the diameter of bar AB and then calculated the necessary material properties to help them select a material. Of students who calculated the diameter bottom-up, a greater percentage said their answer was not reasonable, citing the Size they calculated as the reason. Of students who chose the diameter top-down, a greater percentage said their answer was reasonable, citing a Benefit of the calculated material, such as being lightweight or low-cost, as their justification. All results can be found in Fig. 4.

Yellow University had 45 students consent to participate in the study. Seven assignments were not coded because four did not provide a justification and three were intelligible. Of the 38 responses remaining, 71.1% of students calculated the diameter of the landing gear bottom-up (i.e. after selecting a material and safety factor top-down), 21.0% of students calculated the material properties and selected a material bottom-up, and 7.9% calculated the safety factor bottom-up. Of the students who calculated the diameter, most of the students said their answer was not reasonable, citing a Comparison between their calculation and the real airplane as

the reason. Of the students who calculated material properties, most students thought their answer was reasonable, citing equally either a Benefit or the Material strength. Lastly, most of the small number of students who calculated the safety factor thought their answer was reasonable, citing a Comparison to a standard aerospace value the strength of their calculations. All results can be found in Fig. 5.

VI. DISCUSSION

This study analyzed the justifications students wrote when deciding if their answer to an OEMP was reasonable. The paper examined two OEMPs assigned in mechanics of materials courses at two different universities, Blue University and Yellow University.

Despite the fact that students at Blue University and Yellow University both had access to the physical device they were asked to model in their OEMP, students were more likely to Compare their results to the actual device when they were explicitly asked to do so. At Blue University, where the OEMP assignments did not ask students to make this comparison, they most frequently justified their answer by discussing the Size, intuitively feeling that the diameter was either too small or the correct size. At Yellow University, where the OEMP assignment asked students “Is the size of the bar that you found the same as for the actual airplane? (It may not be.)”, students most frequently justified the reasonableness of their calculation using this Comparison.

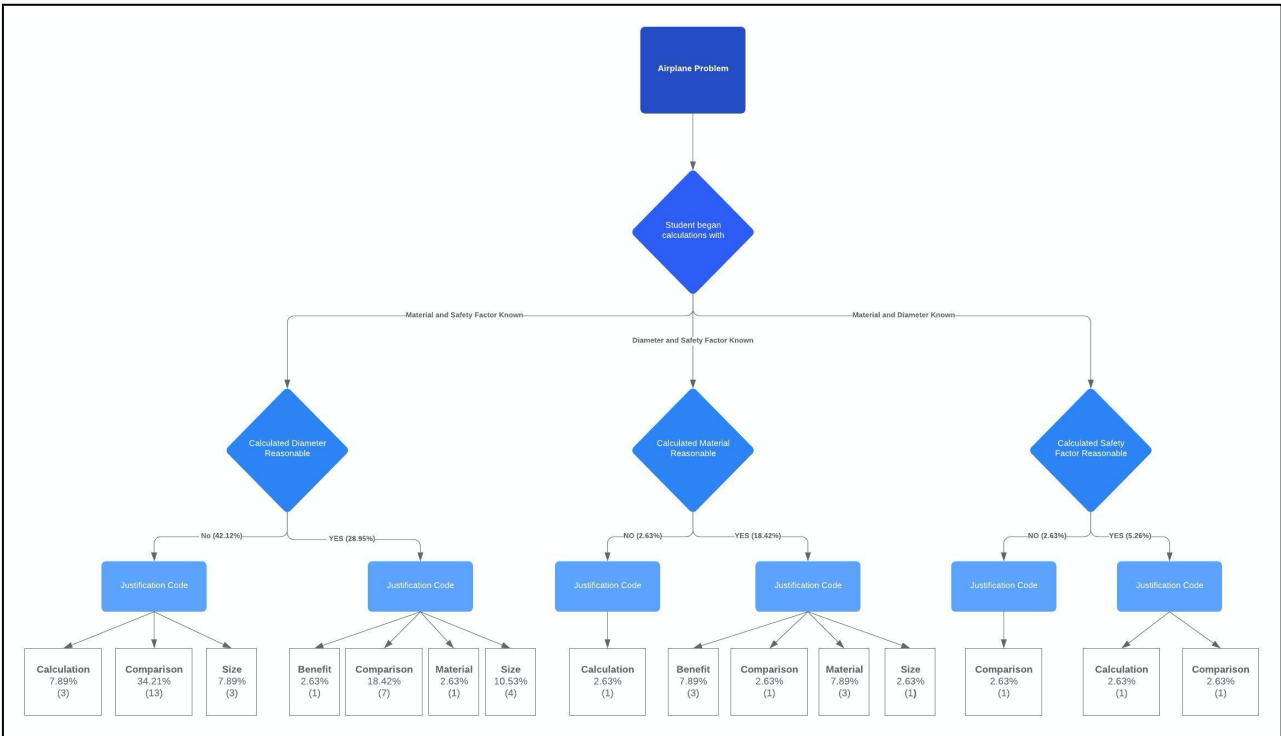


Fig. 5: Yellow University (n=38)

Even more interesting, in a survey of Blue University students ($n=61$) given on the last day of class 55.7% of respondents said they measured the iWalk device themselves, and 23% of students said they used the iWalk device. These results demonstrate in order for students to Compare their calculations with the actual device they need more scaffolding in their assignments. We see scaffolding this Comparison as an easy way to formally instruct students in assessing the reasonableness of their answer. The actual object provides an “objective” measure of what a reasonable bar diameter is, as it has obviously been designed to support the loads. So, students can be asked to compare their calculated answer to the actual device, and discuss possible reasons why they are similar or different.

The parameter that students chose to compute bottom-up (either diameter, material, or safety factor) affected the likelihood that they would determine their final answer to be reasonable. At both universities, students who calculated the material properties bottom-up (choosing a diameter first) were more likely to assess their material as reasonable, whereas students who calculated the diameter bottom-up (choosing a material first) were more likely to assess the diameter as unreasonable. Students who started by choosing a diameter obviously chose a reasonable one, either measuring the actual device, referencing a dimensioned diagram, or simply making a good estimate. More students who went on this solution path determined their material choice was reasonable, possibly because there are multiple materials that “work,” even if they chose a material that would be unrealistic for real-world use like magnesium, as one student did. Since there were multiple material choices that satisfied the necessary properties they calculated, students could select one that would have a Benefit to the user or designer of the device, such as being lightweight. Looking across responses, aluminum seems to have been a common choice for both of these reasons. This could also be because students have access to devices such as bikes that are made out of hollow aluminum tubes, so that choice probably seemed like a safe or right one.

If a student chose to calculate the diameter bottom-up, they often reached a small and unreasonable diameter because students generally underestimated the loads on the device in both assignments. When students selected a material top-down, their particular model of the device led to one “correct” answer for the diameter. Unlike when choosing from multiple materials that all fit the calculated criteria, students had no way to make their diameter reasonable except completely re-modeling the loads on the device. Furthermore, students could easily assess the reasonableness of a diameter as a calculation they have been performing for years and a measurement they taken of common object. It is also easy to make a direct comparison to an actual device, especially when they have access to the object being modeled, or have experiences with similar devices to have an intuitive sense of when a support bar is “too small.”

From analyzing students’ assignments, we do not see explicit reasons why they chose to select the material or diameter top-down at the beginning of the problem. It is likely that this was a mostly-random decision, and students did not put too much thought into it. However, this seemingly inconsequential decision had a significant impact on students’ experience with the project—particularly their opportunity to practice engineering judgement. If a student calculated the diameter bottom-up, they had to wrestle with the question of whether their calculation was good or precise enough (EJ1). Yet, if a student calculated the material bottom-up, they easily found multiple materials that worked and did not have the same opportunity to practice engineering judgment.

The multiple pathways in which the way students went about the problem also made it more difficult for us to analyze and code the data than we expected. In some cases, it was unclear what choices they made to solve the problem or their justification made no sense. Going forward, if we want to better understand students’ reasoning, thinking, and justification we need to ask better, more pointed questions. Alternatively, we could also look to the ways professional engineers communicate and explain their modeling and assess their work as if we were their boss.

VII. CONCLUSION

This paper examined students’ evaluation of the “reasonableness” of their final answer when solving an Open-ended Modeling Problem (OEMP) assigned to them in a mechanics of materials course. The overarching result of this paper is the impact that the writing of the OEMP assignment and students’ problem-solving paths have on their ability to practice engineering judgment during the OEMP. As our end goal is to have all students engage in the productive beginnings of engineering judgement, we need to better scaffold the assignment through pointed questions to elicit more student thinking about the process and decisions they are making as they are solving the problem. We found that students used six different justifications when assessing the reasonableness of the final answer they calculated bottom-up. Knowledge of these justifications is useful in developing this scaffolding, as we can explicitly ask students to assess the reasonableness of their answer through the lens of a particular justification (such as how the Yellow University OEMP asked students to Compare their answer to the actual advice).

Furthermore, our results highlight a tension between two stated goals of the OEMP: preparing students for the real world by being open-ended, and giving students an opportunity to practice engineering judgment. These two OEMPs were left open-ended in that students were just told to select a material and diameter (and, at Yellow University, a safety factor) for a support bar in the device. They were not told which of these parameters to select top-down and which to calculate bottom-up using the selected parameters. However, based on this decision, some students had a good

opportunity to practice engineering judgment and others did not. So, in order to give all students the opportunity to practice engineering judgment, it may be necessary to make the problem more closed-ended and ask them to choose a material top-down and then calculate the diameter bottom-up.

Going forward, our team plans to continue to revise OEMP assignments to better engage students in engineering judgment, as well as develop OEMPs for other engineering science courses. We agree with Hanson, Faber, Miskioglu & Martin, and colleagues [16]-[20] that more work needs to be done to understand how novice engineers assess the reasonableness of answers, and more faculty should include discussions or instruction on reasonableness as part of engineering courses. Lastly, our research team will continue to examine students' OEMPs and retrospective interviews to better understand and scaffold the productive beginnings of engineering judgement.

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AEROSP 215
Winter 2019

Open-Ended Problem 1

Written part due 2/1/19 at 8:30 am
Mandatory in-class discussion on 2/1/19

Possible points: 50

The *Lesher Nomad*, currently on display in the FXB atrium, is an experimental two-place aircraft designed and built by Edgar J. Lesher.

Lesher was born in 1914 in Detroit, Michigan. Although he completed his bachelor's degree and pursued graduate studies at Ohio State University, he completed a master's degree in Aeronautical Engineering at the University of Michigan in 1940. Lesher joined the department as a faculty member in 1942, retiring from the University of Michigan in 1985.

Lesher designed and built the *Lesher Nomad*, an all-aluminum, pusher propeller aircraft between 1958 and 1961. The first run was completed in 1962 at Willow Run Airport in Ypsilanti. The aircraft was flown regularly until Lesher's death in 1998.



We are going to be analyzing this aircraft throughout the course. In doing so, we will make many assumptions of varying validity. Pay attention to these assumptions and note how they could be improved.

There are two parts to this assignment:

- A written part (on the next page), which is due to Gradescope on Friday, Feb. 1 at 8:30 am. This part is worth 40 points, broken down as such:

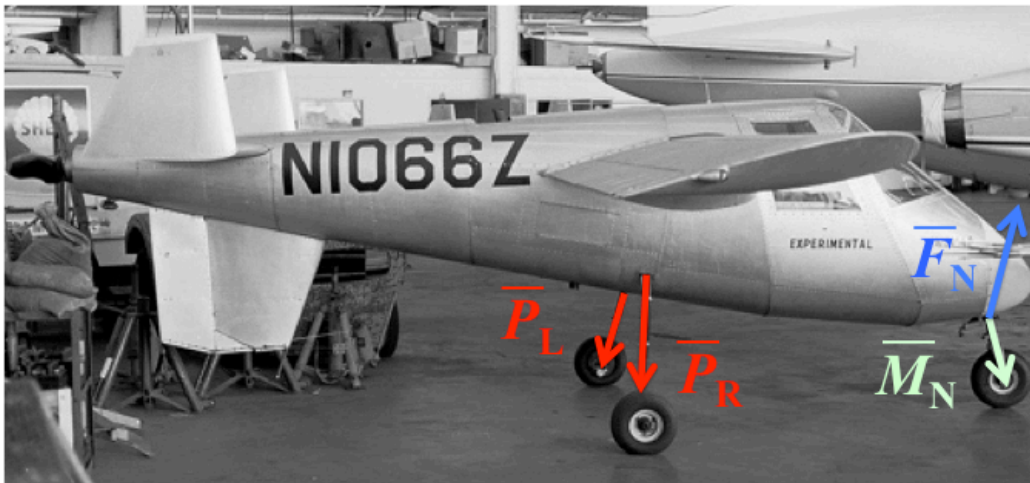
Part	1	2	3	4	5
Points	3	20	10	5	2

- Participating in a small-group discussion during class on Friday, Feb. 1. You should bring a copy of your written work to this discussion, as you'll be working with a small group of other students to compare your models of the *Nomad* and develop a group model that's better than any of your individual models. This part is worth 10 points.

Model 1: The Main Landing Gear as Statically-Determinate Rigid Two-Force Members

When the *Nomad* is touching the ground, its three landing gear support the *Nomad*'s weight and, potentially, the effect of other forces and moments. To make a first approximation of the forces within the landing gear, we will model the bars of the main (rear) landing gear as rigid two-force members with circular cross-sections. We will not model the bar of the nose landing gear as a two-force member because if we do, the math doesn't work out in many cases. Instead, we will model the joint where the nose landing gear connects to the fuselage as "universal joint" that can carry a reaction force vector with an unknown direction and a reaction moment vector with a known direction that is aligned with the nose landing gear.¹

The figure below shows the notation you should use for the reaction force vector at the nose landing gear (\vec{F}_N), the reaction moment vector at the nose landing gear (\vec{M}_N), and the axial force vectors for the main landing gear on the pilot's left (\vec{P}_L) and right (\vec{P}_R) sides. You will be solving for these four unknown vectors.



In this problem, you should imagine that you're Ed Lesher and are sizing the landing gear for actual operations. In other words, you should try to think about the operational scenario that puts the greatest load on the landing gear (e.g. *not* sitting unused in the FXB atrium, in flight, etc.).

Answer the following questions:

1. We've assumed that the bars of the main landing gear are modeled as two-force members. What does this imply about the way we're inherently modeling 1) the joint between these two landing gear bars and the fuselage, and 2) the joint between the landing gear bars and the wheels? Is this true-to-life?

¹ The joint where the nose landing gear connects to the fuselage is the same type of joint as the one at point *A* in problem 5 of homework 1.

2. Make a free-body diagram of the *Nomad* without its landing gear that includes:
 - The four unknown vectors:
 - The reaction force vector at the nose landing gear, \vec{F}_N
 - The reaction moment vector at the nose landing gear, \vec{M}_N
 - The internal force of both main landing gear bars, \vec{P}_L and \vec{P}_R
 - Approximate forces and moments, including any significant self-weight. **Explain all decisions you make.**
 - Dimensions (use the dimensions of the actual aircraft).

Cite (no particular format needed) all sources that you use for this part.

3. Find numerical answers for the components of the four unknown vectors.
4. Using the Material Properties Reference from Bedford & Liechti (on Canvas in the “References” folder), select a material and diameter for each of the main landing gear bars that you believe is sufficient given the yield stress of your chosen material and an aerospace-appropriate safety factor. **Justify your answers.** Is the size of the bar that you found physically reasonable? Is the size of the bar that you found the same as for the actual *Nomad*? (It may not be.)

Note that you are not sizing the nose landing gear, as it is not modeled as a two-force member.

5. What other factors beyond just strength might an engineer consider when selecting the material and diameter for the main landing gear bars? Name at least two.

Bonus (5 points)

As is mentioned above, we cannot model the bar of the nose landing gear as a two-force member because if we do, the math “doesn’t work out in many cases.” This brings up an important conceptual point that makes it hard to write good statics problems (as is evidenced by the changes I had to make to the problem) and is easy to miss (as I originally did).

So, for 5 bonus points on this assignment, write a little bit telling me what it means mathematically and physically that the math “doesn’t work out” when you model the nose landing gear as a two-force member. To answer mathematically, tell me how the mathematics break down and what errors arise. To answer physically, tell me what would happen to the *Nomad* if all of its landing gear were two-force members.

Hint: The problem lies with the stability of the system.

Appendix II

Open-Ended Modeling Problem (ME20)

The iWalker 2, a hands-free crutch, is an example of one of the many assistive devices used to help people with lower leg injuries live their life more comfortably.



The main advantage of this device is that it lets the person use both hands freely, which is not possible while using traditional crutches or knee scooters.



We are going to analyze this hands-free crutch throughout the class. Because this is your first mechanics course, we have to make certain assumptions and simplifications in order to have an analysis that you can complete. It is important to document all the assumptions and think about ways you can improve them.

There are two parts in this assignment:

- A written part which is due on October 28, at 12:00 am. You will be answering the questions at the end of this document. This part is worth 70 points.
- A small-group discussion part during class on October 28. You need to bring a copy of your written work to this discussion. You will be working with a small group of other students to compare your models of the hands-free crutch and develop a group model that's better than any individual model. This part is worth 30 points.

Model 1: The main bar supporting the weight of the person

When a person walks with a hands-free crutch, its base touches the ground and supports the weight of the person along with other forces that may develop during stance phase of the gait (Figure 1). Stance phase is a phase of during which the foot remains in contact with the ground. To simplify the calculation, we will experiment with a simplified 2D model of the device as shown in figure 2.

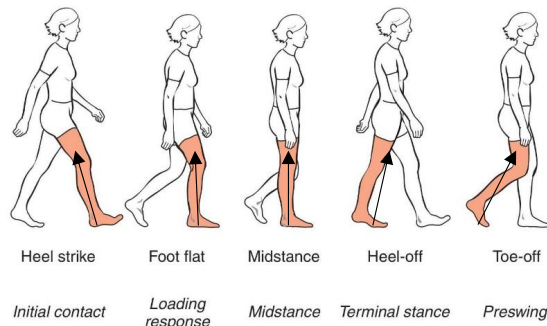


Figure 1. The stance phase of human gait, the arrows show the ground reaction force

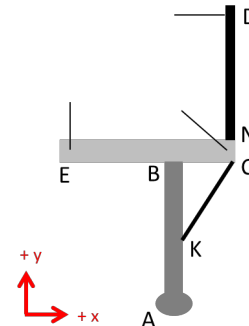


Figure 2. Simplified 2D model of the hands-free crutch

Assume that the origin of the system is at A, with $+x$ going to the right and $+y$ going up. Also assume that angles are measured from the $+x$ axis, with $+$ angles going counterclockwise. So, for example, a force that's in the $+y$ direction is at an angle of 90° , while a force that's in the $-y$ direction is at an angle of -90° .

Other assumptions you can make to simplify the problem:

- Straps at D, C, and E are looped cables with zero tension during stance phase.
- Member CK is connected to EC and AB through smooth pins.
- Member DN is welded to member EC.
- Member AB has circular cross-section and is massless.
- Human body segments can be considered rigid members.

You will also need to:

- Choose the type of connection that the device makes with the ground which best describes the real scenario.
- Choose the type of connection at point B. The connection of member AB to EC at point B can be either be through smooth pin or welded. Think about how your choice can impact the loading on member AB.

Your task:

Imagine that you are the designer and want to find the proper material and size for member AB that provides enough support while it is used for walking on flat surface only. To do so, you need to do force analysis and make further assumptions about the structure of the device. Remember to consider the instant during the stance phase that you think puts the highest load on member AB.

Answer the following questions if the hands-free crutch is being used by a person weighing 125 kg (weight capacity of the device) and having a height of 175 cm:

1. (15 points) Make a qualitative (i.e. no numbers) free-body diagram of the whole device (DN, EBC, CK, and AB together) **and** free-body diagrams of each member (DN, EBC, CK, and AB) separately. You need to draw all forces and moments that are acting on the system. You may want to consider forces such as:
 - The weight of each member
 - The load the user places on the crutch

However, this is certainly not an exhaustive list! For this part, you should clearly label each force/moment and each important dimension with a variable name, but you should not put any numbers on this free-body diagram.

2. (10 points) Calculate the value of each force, moment, and dimension in your free-body diagrams. Make a table clearly showing the variable name, its value (with units), its direction (remember, + angles are counterclockwise from the +x axis), and its x- and y-location from the origin. An example table is shown below:

Force / Moment	Variable	Value	Direction	x-Location	y-Location
Weight of member EBC	W_{EBD}	1,000,000 kg	-90°	2 m	4 m
...

3. (15 points) Specify any assumptions and simplifications you made in drawing the free-body diagram of the system and calculating the values of forces, moments, and dimensions. Also, if you used any references to determine values or assumptions, please cite these here.
4. (12 points) Compute the maximum **axial load** on member AB using the free-body diagrams and equations of equilibrium.
5. (10 points) Using the material properties table provided and the axial load on member AB that you just computed, select a material and diameter for the member AB that you believe is enough given the yield stress of the chosen material. Justify your answer. Is the size of the bar you found physically reasonable? Why or why not?
6. (3 points) In question 5 you computed the size of the member AB based on the axial loading. What other forces/moments do you think might influence our choice of size and material for member AB?
7. (5 points) We modeled the crutch for walking on a flat surface. What would change if you it is used for walking up and down a hill? Would that change the load and therefore your choice of size and material?
 - You don't necessarily have to do any computations, just explain how the answer would change. Try to use equations to prove that the change occurs in a certain direction, but you don't need to do numerical calculations.

Bonus question (5 points):

Calculate axial load on member CK. How would you expect this value to change if you chose a different type of connection at point B?