ŌTAUTAHI CHRISTCHURCH AOTEAROA NEW ZEALAND
35TH AUSTRALASIAN ASSOCIATION FOR ENGINEERING EDUCATION ANNUAL CONFERENCE
8-11 DEC 2024
THE ENGINEER AND THE WORLD

Developing Physical Models for Teaching Engineering Statics

Jeanne Chang, Jessie Joan Radda, Michael Crocco, Tony Vo
Monash University, Faculty of Engineering
Corresponding Author Email: tony.vo@monash.edu

ABSTRACT

CONTEXT

Understanding abstract engineering concepts can be a significant challenge for students. Various institutions utilise physical models to address these challenges as they are effective in aiding student comprehension (Ji *et al*., 2021; Welch & Klosky, 2006). First-year engineering statics units often introduce a range of concepts that present barriers to understanding for students who struggle with visualisation.

GOAL

This study aims to design and construct a physical model to enhance students' conceptual understanding of first-year engineering statics. This model is to be employed within large-scale units.

APPROACH

The challenges faced by students learning engineering statics in a large core first-year unit, as identified by the instructors, guide the design of a physical model. This process is coupled with a review of existing physical models used in statics and the key traits highlighted by Tang *et al*. (2022). These insights inform the development of a new physical model aimed at addressing common student misconceptions in engineering statics.

ACTUAL OR ANTICIPATED OUTCOMES

It is anticipated that the developed physical model will improve student engagement and learning of engineering statics through affordability, accessibility, functionality, and aesthetic appeal.

SUMMARY

This study will develop a physical model for large-scale units to address the common challenges experienced by students learning engineering statics. These learnings may provide insight into how physical models could be used for other engineering concepts.

KEYWORDS

Physical Models, First Year Engineering, Hands-on Learning, Statics

Introduction

Problem-solving is a critical skill for engineering professionals, necessitating deep conceptual knowledge to make sound engineering judgments. For instance, a structural engineer will often have to quickly assess how design changes affect the integrity of building frame members, requiring a robust understanding of core engineering principles (Chadha & Hellgardt, 2023; Streveler *et al*., 2008). Fundamental knowledge is first developed during formal education, but it is often observed that students can perform theoretical calculations without fully grasping the underlying principles. For example, students may misinterpret the deflected shape of a beam under various loading conditions or assume incorrect behaviour about idealised beam supports. Such misconceptions can persist despite students performing theoretical calculations correctly, which raises concerns about the graduate's ability to apply engineering concepts accurately in practice (Dwight & Carew, 2006).

Physical models (PMs) have a longstanding tradition in STEM education for illustrating complex phenomena (Horowitz & Schultz, 2014; Justo *et al*., 2022; Pan *et al*., 2015). Many engineering educators incorporate PMs into their instruction, and some develop custom-built models tailored to the specific needs of their units (e.g., Dart & Lim, 2023; Mejia *et al*., 2016; Sadowski & Jankowski, 2021). These custom models can address unique educational challenges and provide hands-on learning opportunities by transforming abstract engineering concepts into tangible experiences, facilitating learning through direct sensory engagement (Ji *et al*., 2021).

Despite their benefits, sophisticated, purpose-built laboratory equipment is expensive and often not feasible for all students due to its high cost and the limited availability of resources. Conversely, low-cost models that use everyday items such as rulers and pens are accessible but may lack the precision and complexity needed to effectively convey intricate concepts and address common misconceptions in engineering statics. Additionally, they are generally not visually appealing, which can diminish their effectiveness as educational tools and negatively impact student engagement and learning (Webster & Wolfe, 2013).

This study aims to design a PM that effectively addresses misconceptions in engineering statics within a large-scale first-year engineering unit. The proposed PM should be mass-producible, modular, and easily portable for wide distribution, and incorporate modern technology to ensure aesthetic appeal. The model is designed to be an effective teaching aid in various settings including classrooms and remote study environments, which provides a balance of affordability, accessibility, and functionality.

Background

Affordances of Physical Models

PMs offer several unique affordances that enhance learning in STEM education. According to Tang *et al*. (2022), the four key affordances of physical objects for making meaning in science classrooms include:

1. *Enacting Material Interaction* - PMs interact with the laws of nature, allowing students to observe phenomena directly. This interaction helps create or imitate the desired phenomena for observation. When students engage with these objects, they can verify and correct their conceptual understanding through dialogue and experimentation. For example, a PM of a beam under load can show how different materials and loads affect deformation, providing immediate feedback and reinforcing theoretical concepts.
2. *Providing Evidential Meaning* – PMs themselves do not inherently possess meaning, but instead, their meaning emerges through their use in specific, inquiry-based scenarios. Students can elucidate causal relationships and gain a clearer understanding of complex concepts through PMs. For example, a PM of a truss structure helps students see how forces are distributed, clarifying the theoretical principles behind structural analysis.

3. *Orienting 3D Spatial Meaning* - PMs allow individuals to interact from multiple perspectives, providing unique spatial information that is not easily conveyed through two-dimensional representations. This helps students build a more intuitive understanding of three-dimensional structures. For example, a PM of a building frame allows students to see how changes in design impact structural integrity and stability from various angles.
4. *Sensitising Experiential Meaning* – PMs can provide tactile sensation and haptic feedback to build understanding grounded in experience. The sense of touch engages students more deeply and creates a tangible connection to abstract concepts. For example, a PM with different geometries of beam samples, such as I-beams, rectangular beams, and circular cross-sections, would allow students to physically bend and test their responses to applied loads to better understand the second moment of area concept.

These affordances highlight why physical models are valuable educational tools. They not only make abstract concepts more concrete but also support active learning through sensory engagement and interaction. By leveraging these benefits, educators can help students build a deeper, more intuitive understanding of complex engineering principles.

Developing Engineering Judgement in Statics

Connecting theory to physical phenomena through PMs fosters intuition and improves students' capacity to form engineering judgements (Chadha & Hellgardt, 2023). Mejia *et al*. (2016) found that hands-on manipulation of PMs allowed students to correct their misconceptions and ultimately gain confidence in problem-solving. Their study involved scaled geometries of the theoretical truss structure problems assigned to students. This direct representation of theory in a three-dimensional form allowed students to verify their assumptions and receive visual confirmation of their theoretical analysis.

In a similar effort to illustrate textbook scenarios with physical objects, Dart and Lim (2023) developed 3D-printed PMs comprising thin flexible beams and different support types (fixed, roller and pin). Its modular design allowed for various beam support configurations to be constructed, imitating a range of loading scenarios. They found that the introduction of PMs early in the course helped students to grasp new and abstract ideas. With the onset of the COVID-19 pandemic, the PMs were also distributed as take-home kits for self-directed study. Responses to a questionnaire revealed that students attributed increased feelings of intuition to their experimentative, hands-on manipulation of the models as this allowed them to verify their predictions and receive instantaneous visuo-tactile feedback.

The affordances of in-person and physical interaction were absent in Sadowski and Jankowski's (2021) use of a large-scale truss model due to online learning. The PM was demonstrated via video and responses from a student survey showed that the model had minimal influence on student understanding of truss structures. A key feature of the PM is that compression and tension members appear as either blue or red LEDs respectively depending on the truss' arrangement and loading. Despite this functionality drawing a clear link between tangible and intangible concepts, the PM did not significantly increase an intuitive understanding of trusses. This suggests that only visual perception of an object provides minimal benefit, and that physical hands-on manipulation is important to amplify the benefits received from using PMs as learning tools.

The consideration of how a phenomenon should be simplified in a model is key to making it effective for its intended purpose. As there are many approaches that can be taken to perform this simplification, e.g., black-boxing, idealisation, exaggeration, and context elimination, Norström and Hällström (2023) propose a six-step framework to guide the model making process. Any phenomenon to be modelled should be intentionally *identified*, *isolated* and *simplified*. The created model should then undergo *validation*, *verification* using known or experimental data and be *presented* in a suitable form (e.g., PM, flow chart, diagram). By following this process, the accuracy of the model's representation of a phenomenon's characteristics and its limitations can be assessed.

Design Approach

Unit context and common misconceptions

At Monash University, all first-year engineering students are exposed to engineering statics concepts in ENG1011 – Engineering Methods. The unit has no formal prerequisites and typically enrols up to 800 students per semester. This unit involves fundamental mechanics and design skills involving CAD and 3D printing. This unit was used as a basis for the development of a PM. This research project has been approved by the Monash University Human Research Ethics Committee (Project ID 44669).

Reviewing past student performance in ENG1011 has identified idealised beam support reactions and deflections as commonly misunderstood concepts. Frequently observed misconceptions involve the incorrect attributions of support reactions and the deflected shape of a loaded beam, particularly around fixed supports. An example is shown in Figure 1, where a cantilever is loaded at the free end. The correct deflection is shown in the physical setup and two commonly incorrect deflection shapes are illustrated as dashed lines in the diagram.

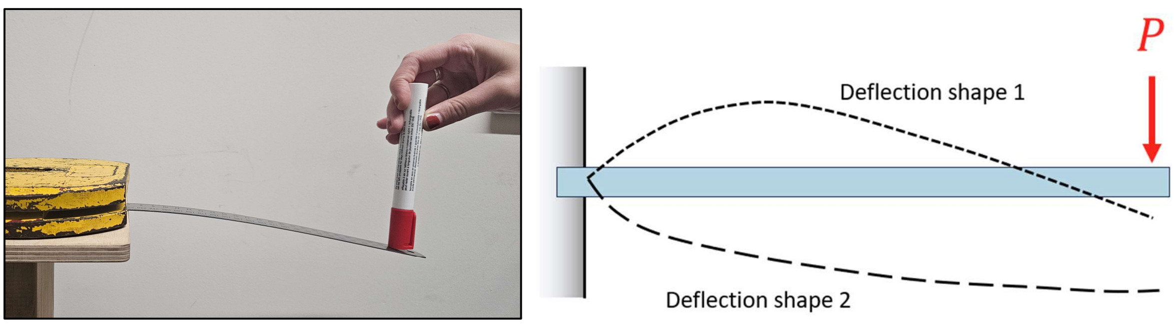

Figure 1: (Left) Deflection shape of a fixed cantilevered beam loaded at the free end. (Right) Illustration of common incorrect deflection shapes drawn by students for the same setup.

Another common misconception students convey is that the maximum deflection of a simply-supported beam subject to a single-point load will always occur directly under the load, which isn't the case. An exaggerated illustration of this difference is shown in Figure 2.

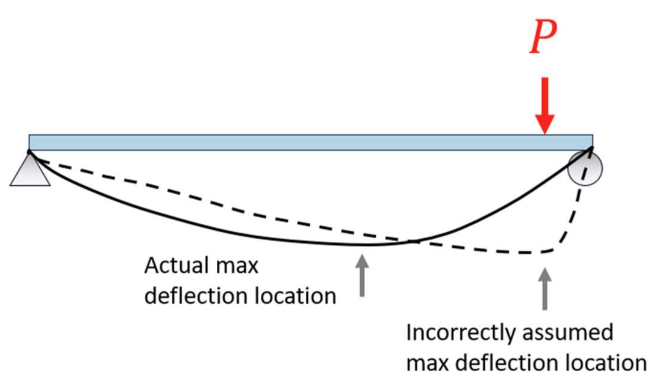

Figure 2: Illustration of the actual deflection shape (solid line) of a loaded beam vs. the student prediction (dashed line) that places the maximum deflection directly below the point load.

Currently, ENG1011 instructors use everyday items such as rulers, pens, nails, and wood blocks to demonstrate statics principles. For example, Figure 3 shows a simple model used to aid students' understanding of beam deflection and reactions when drawing free-body diagrams. It combines the drawing convention used for beam configurations and a physical 3D representation. Applied on top of these images are nails for pin and roller supports, and wood blocks with slots for fixed supports. A flexible ruler with tubing attached may be placed along different configurations and loaded in various ways, showing how the beam responds to external loading. A key feature of this design is the connection between the drawing convention used within the unit for beam simple analysis and a direct 3D representation of the resulting deflections. However, this PM is not easily adaptable and does not include an accurate representation of roller supports.

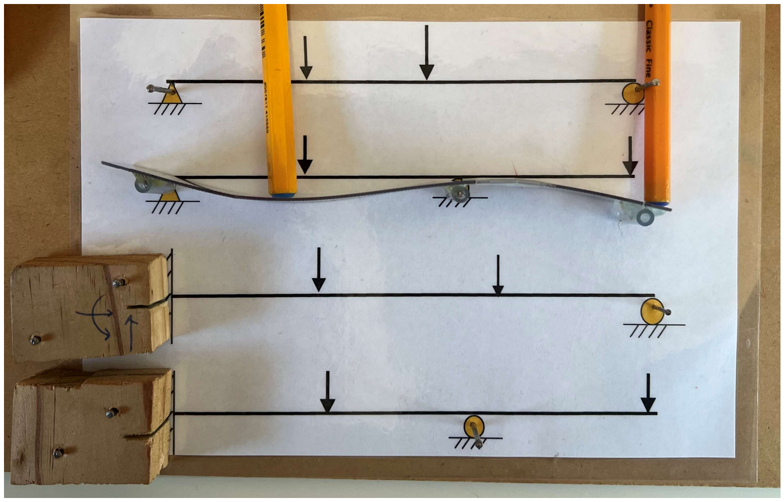

Figure 3: A simple model used in the unit to demonstrate the roles of various support types as well as the shapes of the deflections under various loadings.

While this model provides students with visual aids to complement their learning, the current instructors have indicated that students often do not engage with PMs unless they specifically relate to a specific problem or question. Moreover, the basic demonstrations may not fully engage students due to the limitations in precision and aesthetic appeal. Hence, there is a need for a new PM that leverages the affordances identified by Tang *et al*. (2022), visual appeal, and accessibility to better address these misconceptions and enhance student learning.

Evaluation of models used by other instructors

The physical model (PM) developed by Dart and Lim (2023) serves as a valuable starting point for the new design. Their model features modular 3D-printed components that can be assembled on an acrylic board to create various beam and support configurations. However, insights from private correspondence with Lim revealed several limitations in the model, particularly regarding durability in vulnerable areas, such as the stem of the support. Additionally, its small size posed challenges in achieving the correct tolerance between the beam and supports. Loose fittings often resulted in instability, while tight fittings risked damage during frequent use. The design also necessitated temporary supports during printing, which were difficult to remove, thereby extending the overall manufacturing time. Furthermore, the T-shaped geometries used to connect Dart and Lim's beam to its supports restricted their positioning.

This paper's model aims to address these limitations by optimising its design for 3D-printing processes. Specifically, it seeks to incorporate adjustable components that can be easily repositioned to better replicate a variety of textbook problems, enhancing flexibility and usability.

Problem definition

The design of the new PM must address the misconceptions identified in ENG1011, particularly concerning support types and beam deflection profiles. Table 1 summarises key design requirements for the model.

Table 1: Summary of design requirements

Requirements	Associated affordance or benefit
The model's design should be modular.	*Providing Evidential Meaning* – a modular design will allow the user to create multiple scenarios which can either confirm or challenge their hypotheses.
The model is intended for instructors, Teaching Associates and students.	Physical objects promote the use of mixed semiotic modes of communication, e.g., gestural and verbal. An instructor can point to physical locations along the model and rely less on verbal communication, which addresses language barrier issues.
It should take minimal effort and time for a user to learn how to assemble and use the model.	*Sensitising Experiential Meaning* – the hands-on experience of manipulating model parts and constructing the required assembly can assist in building intuition and should be straightforward.
It should be suitable for use in a variety of settings, e.g., compact, lightweight and portable.	This can allow for more frequent instances of individual, self-directed learning with the model and supplement off-campus learning. It will also relieve storage limitations if used in large classes.
The parts should be mass-producible through automated processes (e.g. 3D printing) or be easily obtained off-the-shelf.	*Enacting Material Interaction* – Variations in 3D printing parameters can alter a part's structural integrity and overall functionality, e.g. flexible versus rigid elements. This can be used to mimic or exaggerate the behaviour of physical structures analysed in engineering statics.
The model should be open source, to allow ease of use across institutions.	This benefits institutions without access to sophisticated physical models. Various efforts internationally have also been made to collate examples of useful teaching aids (Ji *et al*., 2021; Welch & Klosky, 2006).

Prototype

The prototyped model uses 3D-printed collars that slide along ridges on a thin printed beam (Figures 4 & 5), secured by nuts and bolts on a laser-cut acrylic sheet (Figures 6). Loosely fastened bolts allow horizontal and rotational movement, mimicking roller supports, while tightened bolts prevent sliding, simulating pin supports. Fixed supports are modelled with a keyed collar, and the collars are designed with representative icons to illustrate the type of support being used. e.g. triangle to denote a pin. The ridges keep supports in place but allow for them to be adjusted. Parallel cut-outs allow the attachment of imposed loads and angled members, and gridlines are etched on the acrylic board to show relative deformations (see Figures 7 & 8).

The purpose-designed modular components enable students to test different setups, observe beam deflections, and validate or challenge their own hypotheses. These experiences directly leverage evidential meaning, connecting their physical observations with theoretical concepts. This tactile interaction not only reinforces student understanding but also supports the sensitising experiential meaning affordance. Furthermore, the parts of the model are easily 3D printable, and the laser cutting process is straightforward, making it accessible for instructors and students. Additionally, the design of these components effectively addresses the durability, size, stability, assembly, and limited modularity issues identified in Dart and Lim's (2023) model.

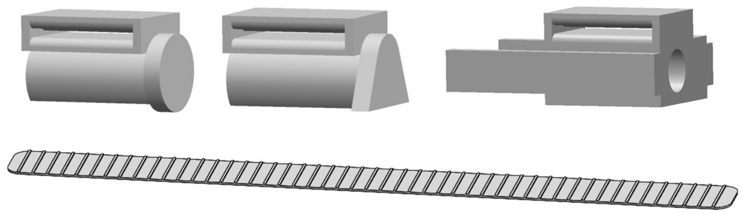

Figure 4: (Top, left to right) Collars to mimic roller, pin and fixed supports. (Bottom) Thin, flexible beam with ridges.

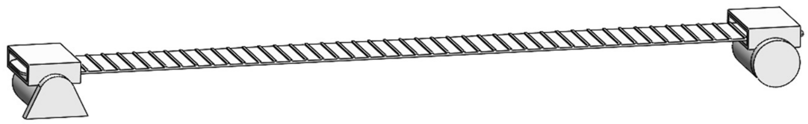

Figure 5: Beam inserted between a pin support (left) and roller support (right).

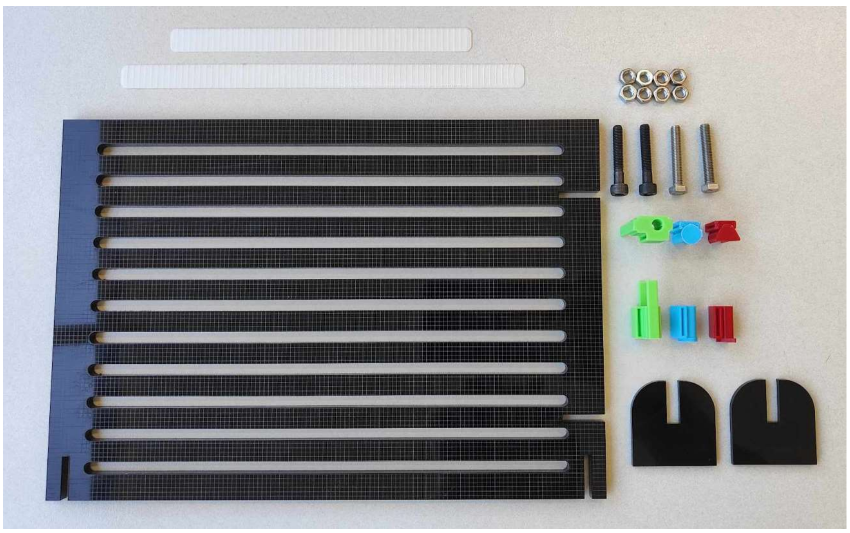

Figure 6: Model kit components

Instructor Interaction and Future Work

The prototype PM was presented to the ENG1011 instructors for hands-on interaction. The instructors were tasked with replicating the scenarios illustrated in Figures 1 and 2, allowing them to engage with the model and assess its functionality in real-time. The recreations are shown in Figures 7 and 8, which demonstrate the deflection of a fixed cantilever beam under a single point load and the maximum beam deflection for an applied point load along a beam, respectively.

Feedback from the instructors indicated that the model could be used in the unit to facilitate a deeper understanding of beam behavior and deflection principles. They appreciated the tactile experience provided by the prototype and the aesthetic appeal of the model. The model's modularity was particularly noted, as it enabled the creation of a variety of configurations to demonstrate different loading scenarios and support types. Instructors expressed enthusiasm about the potential for the prototype to be used by students or Teaching Associates to promote learning in the unit and address common misconceptions.

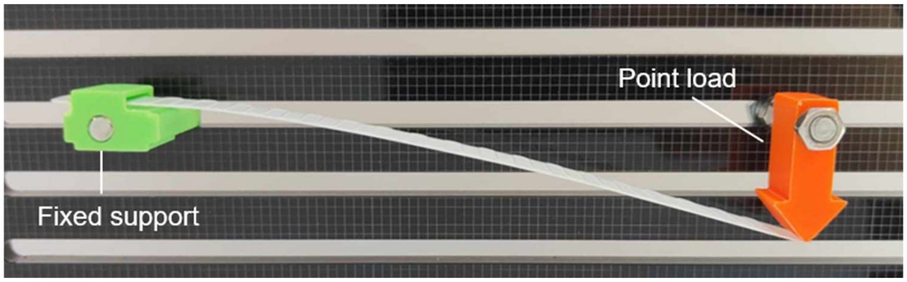

Figure 7: Deflection shape of a fixed cantilevered beam loaded at the free end using the PM.

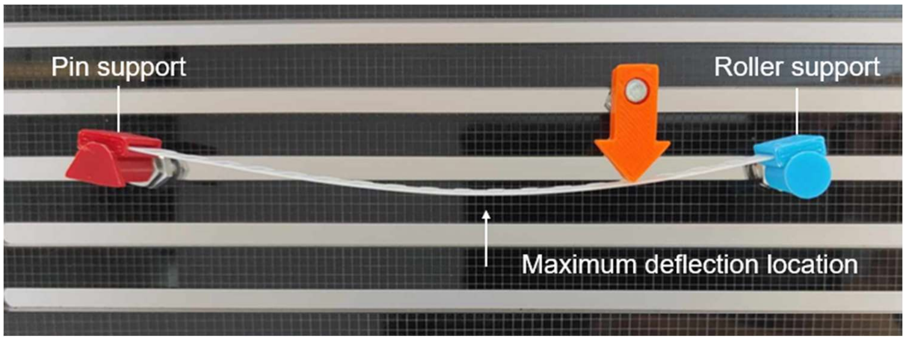

Figure 8: Simply supported beam under a single point load.

Ongoing work will focus on formally evaluating the physical model. Plans include conducting a comparative study to assess ENG1011 students' understanding through an initial survey, followed by retesting after they have interacted with the model. Additionally, interviews will be conducted with ENG1011 Teaching Associates to gather insights on the model's utility in the classroom and its efficacy in addressing common misconceptions. Their responses will be analysed using thematic analysis, aligning themes and codes with Tang's affordances. Moreover, there are intentions to develop additional models to enhance the learning of other topics within ENG1011.

Conclusion

This study outlines the initial development of a physical model designed to address common misconceptions in engineering statics. By leveraging insights from existing models and considering affordances highlighted by Tang *et al.* (2022), the prototype aims to enhance student understanding through tactile and visual representations of beam deflection and support reactions. While the current prototype demonstrates potential, future work will focus on assessing its effectiveness through targeted feedback and evaluation to enhance its role as an educational tool for engineering statics.

References

Chadha, D., & Hellgardt, K. (2023). A case of conceptualisation: Using a grounded theory approach to further explore how professionals define engineering judgement for use in engineering education. *European Journal of Engineering Education*, *49*(2), 1–22.

Dart, S., & Lim, J. B. P. (2023). Three-dimensional printed models for teaching and learning structural engineering concepts: Building intuition by physically connecting theory to real life. *Journal of Civil Engineering Education*, *149*(2).

Dwight, R.A. and Carew, A.L. (2006). Investigating the Causes of Poor Student Performance in Basic Mechanics. In: Proceedings of the 17th Annual Conference of the Australasian Association for Engineering Education: Creativity, Challenge, Change; Partnerships in Engineering Education. [online] Auckland, N.Z.: Australasian Association for Engineering Education, pp.180–190. Available at: https://search.informit.org/doi/10.3316/informit.495481692721085 [Accessed 10 Apr. 2024].

Horowitz, S. S., & Schultz, P. H. (2014). Printing space: Using 3D printing of digital terrain models in geosciences education and research. *Journal of Geoscience Education*, *62*(1), 138–145.
Ji, T., Bell, A., & Wu, Y. (2021). The philosophical basis of Seeing and Touching Structural Concepts. *European Journal of Engineering Education,* 46(6), 889–907.
Justo, E., Delgado, A., Llorente-Cejudo, C., Aguilar, R., & Cabero-Almenara, J. (2022). The effectiveness of physical and virtual manipulatives on learning and motivation in structural engineering. *Journal of Engineering Education*, *111*(4), 813–851.
Mejia, J. A., Goodridge, W. H., Call, B. J., & Wood, S. D. (2016/06/26/). *Manipulatives in Engineering Statics: Supplementing Analytical Techniques with Physical Models*. American Society for Engineering Education-ASEE.
Norström, P., Hallström, J. Models and modelling in secondary technology and engineering education. Int J Technol Des Educ 33, 1797–1817 (2023).
Pan, E., Chiu, J., K. Inkelas, Garner, G., Russell, S., & Berger, E. (2015). Affordances and constraints of physical and virtual manipulatives for learning dynamics. *The International Journal of Engineering Education*, *31*(6), 1629–1644.
Sadowski, K., & Jankowski, S. (2021). Learning statics by visualizing forces on the example of a physical model of a truss. *Buildings*, *11*(9), 395.
Streveler, R. A., Litzinger, T. A., Miller, R. L., & Steif, P. S. (2008). Learning conceptual knowledge in the engineering sciences: Overview and future research directions. *Journal of Engineering Education*, *97*(3), 279–294.
Tang, K.-S., Jeppsson, F., Danielsson, K., & Bergh Nestlog, E. (2022). Affordances of physical objects as a material mode of representation: a social semiotics perspective of hands-on meaning-making. *International Journal of Science Education*, *44*(2), 179–200.
Webster, R., & Wolfe, M. (2013). Incorporating the aesthetic dimension into pedagogy. *Australian Journal of Teacher Education* (Online), 38(10), 21-33.
Welch, R., & Klosky, J. L. (2006). An online database and user community for physical models in the engineering classroom. *Association for Engineering Education - Engineering Library Division Papers,* 11.207.1–11.207.17.

Acknowledgements

Generative AI was used to correct and improve the written expression of the author's ideas (Grammarly).

Copyright statement