The Complementary Nature of Computational Thinking and Critical Making in a Project-based Learning (PjBL) course on Design for Manufacture (DfM)

Francesco Ciriello*, Tabbi Wilberforce Awotwe, Jicheng Gong,
Samuel Piper, Charlotte Palmer, Ana Rubio Denniss
King's College London, United Kingdom, *francesco.ciriello@kcl.ac.uk

Abstract

In Engineering Project-based Learning (PjBL), learners often develop a physical prototype of a product, which provides an authentic context for the learning and experiential feedback on the design process. We often struggle as educators, however, to support learners in the analysis of the feasibility, viability and sustainability of the product when brought to production. This may be caused by the everchanging nature of supply chains and consumer demand, high capital costs associated to high production volumes, and the technical skills shortage within research-focused universities when considering how to scale commercial products for wide consumption.

In developing a new PjBL course at King's College London, we study how learners develop competencies for integrated problem solving associated to design for manufacture (DfM). Acknowledging the steep learning curve required to support open-ended projects, we have intentionally pushed the boundaries of how the design process is supported by computational thinking techniques, including automated quoting engines and embodied carbon estimators, generative design techniques, geometric design advice, AI-assisted digital product passport generation, manufacturing simulation and automated operation and toolpath planning. We study how these teaching innovations compound to shape the ability of a student to critically change the geometry of a component in response to multi-variate performance metrics. To this end, we compare the geometric features of more than 60 CAD models submitted by learners in the second week of the course, compared to the final product submitted after 12 weeks at the end of the course. We link this analysis to a thematic analysis of short reports that highlight key trade-offs for cost, sustainability and other performance metrics.

This methodology allows us to evaluate our cohort's decision-making process in selecting projects, computational techniques, and manufacturing strategies. The analysis reveals a strong yet nuanced relationship between the adoption and application of computational redesign tools and the quality and manufacturability of product designs. It also allows us to categorise various cognitive responses to the application of computational techniques in relation to DfM and relate these to outcomes.

Keywords: project-based learning, engineering design, manufacturing, computational thinking, critical making

Submission Category: Research Paper

Conference Community: IRSPBL

1. Introduction

In 2024, we introduced a new PjBL course at King's Engineering to develop our students' capability to manufacture physical projects and commercialise them into products. The course was framed around the principles of *computational design for manufacture* – the practice of redesigning an engineering component using computational techniques to improve its manufacturability and its commercial viability for high-production volumes.

DfM principles have been articulated in industry since the 1960s and further formulated into researched practices via seminal work that stemmed out of Amherst in the 1980s (Boothroyd 1996, Kuo & Zhang 1995). These principles became quickly embedded into design software, initially in the form of inspection and design advice tools. Many commercial software tools now connect DfM principles with computational design techniques, whereby a designer can define performance objectives for a component, *e.g.* to minimise mass for a prescribed structural load case, and the design tools can optimise its shape while considering the geometrical constraints of the manufacturing process, *e.g.* manufacturing-aware topology optimisation or generative design.

These tools enable the application of the four cornerstones of *computational thinking* (Seymour 1980): (i) the *abstraction* of the design into critical operation scenarios, (ii) the *decomposition* of its geometry into primitive features critical to assembly and function, (iii) the identification of geometric *patterns* that drive manufacturability and costs, and (iv) the *algorithmic* exploration of the design space in which a computer-aided design (CAD) model is setup for optimisation.

Critical making is an emerging topic that connects DfM to *critical thinking* pedagogical practices (Ratto 2009, Custer 2023). It involves reflective discourse that is contiguous with the experience of physical making. In our course, critical making was enacted via forming mixed study groups of academics, technician and students who regularly met to review each other's designs.

In this work, we evaluate the project journeys and outcomes of this course via these two lenses of computational thinking and critical making. We set out to study the cognitive reaction of learners during their epistemological development of critical making skills. The originality of this work lies in connecting this changing cognition to the evolution of the component geometry, and how this is shaped by computational and DfM principles.

In this practice paper, we present our learning design (§2), teaching setup, including innovations (§3), evaluation methodology (§4), analysis of results (§5) and conclude in §6.

2. Learning Design using Storytelling – the Character Arch of the Designer & the Tensions of Computational Design, Manufacturing & Commercialisation

Learners were tasked with redesigning a single-material component for manufacture over 12 weeks. They could select the component based on their interests and were required to use at least one form of computational design technique to redesign it for manufacture, for which they were trained on generative design (via a mandatory workshop), topology optimisation and field-driven computational latticing (via an optional workshop). They were also required to detail its manufacturing strategy for a high production volume (100,000 units per year) by designing the component, tooling and toolpath program required to make the part, while analysing the trade-offs between cost, performance and sustainability metrics. If they lacked agency to select the component, they could select a component for a bicycle (*e.g.* crank, pedal or fork), for which we provided a starting CAD model.

The course was intentionally designed with a plot, centred around the designer and his ability to overcome the project challenge. The designer would initially use computational techniques to improve the performance of an existing component. This would immediately create a tension between the geometry generated by optimisation algorithms and the manufacturability of the part. The remaining arch of the course would involve the continuous redesign of the component and its manufacturing strategy as the learner would develop skills related to DfM and receive physical feedback from making activities.

Learning was scaffolded with a series of experiential CAD and CAM workshops and manufacturing sessions on plastic and mould design, multi-axis milling and turning, additive manufacture, design for sustainability and sheet metal design. The projects were reviewed at four stages, with reviews targeting the component (week 3), tooling (week 5), toolpath program (week 7) and final product (week 9), respectively. We collected CAD models for evaluation in week 2 and for the final submission in week 12.

3. Teaching Innovations in Support of Rapid Design Space Exploration

A key instructional challenge laid in the open-endedness of projects relative to the technical skills requirements imposed by completely detailing a manufacturing strategy. We worked hard to weave computational thinking and critical making techniques to accelerate design iterations and link them to multi-criteria performance, including automated quoting engines and embodied carbon estimators, generative design techniques, geometric design advice, AI-assisted digital product passport generation, manufacturing simulation and automated operation and toolpath planning. While investigating the role of each innovation is out of scope of this treatment, we were keen to understand how these innovations compounded to change the cognition of learners relative to the manufacturability and viability of their projects.

4. Methodology

To this end, we structured an evaluation framework alongside the course design to address the following **research questions:**

- **RQ1.** how did learners leverage computational thinking to redesign their components?
- **RQ2.** how did learners enact critical making reviews to redesign their components and what impact does this have on the geometry of the CAD model?
- **RQ3.** how did learners inform their redesigns from investigating additional trade-offs, such as sustainability, cost, and feasibility for commercial production scale?

Evaluation was conducted in two ways, via: (i) the ethnographic participation of the teaching team in design reviews 4x2hr, (ii) a 2hr focus group with the teaching team, in which the team reviewed CAD models from weeks 2 and 12 and deduced tags for the thematic analysis (see §5) and (iii) asynchronous review of portfolio submissions to enhance the data set for RQ3. The teaching team was composed of subject-matter experts in design and manufacturing (namely the authors), including three members of academic staff and three manufacturing technicians. Sixty-four learners were enrolled in the course from the third-year cohorts of the General (67%) & Electronic (30%) Engineering Programs and from the Robotics MSc (3%), who each submitted an individual design portfolio and participated in the design reviews.

5. Thematic Analysis of CAD Models & Reports via Subject-Matter Expert Review

Herein, we analyse student project submissions, composed of CAD models and portfolios, to study how learners engaged with computational tools and critical making practices in redesigning components for manufacturability.

5.1 Component Selection and Rescoping

Learners exhibited diverse preferences in component selection, with 31% (20/64) opting for a bicycle component—the default choice provided by the teaching team—while 27% (17/64) selected consumer products such as golf clubs, carabiners, and pill bottles. A further 31% (20/64) chose mechanical components embedded within larger assemblies, such as wheel rims, piston rods, or robotic brackets.

Notably, 33% (21/64) of students altered their component selection between weeks 2 and 12. While it is difficult to directly correlate these changes to intended learning outcomes, this shift suggests that some students reassessed the suitability of computational techniques for their initial selections. However, students who persevered with their original component choice achieved higher average portfolio marks (71.7%) compared to those who changed their selection (59.7%), indicating that continuity in project focus may have contributed to stronger design outcomes.

5.2 Adoption and Cognitive Reactions to Computational Tools

The thematic analysis revealed varied cognitive responses to computational methods as students developed critical making skills:

- some students rejected computational techniques outright and opted to change their project scope;
- others dismissed computationally generated design outcomes and manually redesigned their components;
- a subset of learners used computational outcomes as a guide for manual redesign;
- and some fully integrated computational methods into their redesign process.

Computational tool adoption increased over the duration of the course. While 53% (34/64) of students initially applied some form of computational design technique—predominantly generative design—this figure rose to 66% (42/64) by the end of the module, with a broader range of computational strategies employed.

5.3 Impact of Computational Approaches on Redesign Quality

To evaluate the relationship between redesign approaches and project outcomes, students' portfolio submissions were categorised into four performance bands: poor (<40), average (40–60), good (60–75), and great (>75).

- **Great redesigns (22%, 14/64):** Among the highest-performing projects, 93% (13/14) incorporated computational techniques. Nine students primarily utilised generative design with minimal manual modifications, while three traced computational outcomes to simplify designs while retaining structural performance. One outlier rejected computational methods entirely, achieving high performance through fully manual redesign.

- **Good redesigns (47%, 30/64):** Computational tool adoption declined slightly, with 63% (19/30) employing these techniques. Fewer students modified computationally generated geometries manually.
- **Average and Poor redesigns (31%, 20/64):** Computational tool adoption dropped further, with only 40% (8/20) applying any computational methods, and none attempting to refine generated geometries.

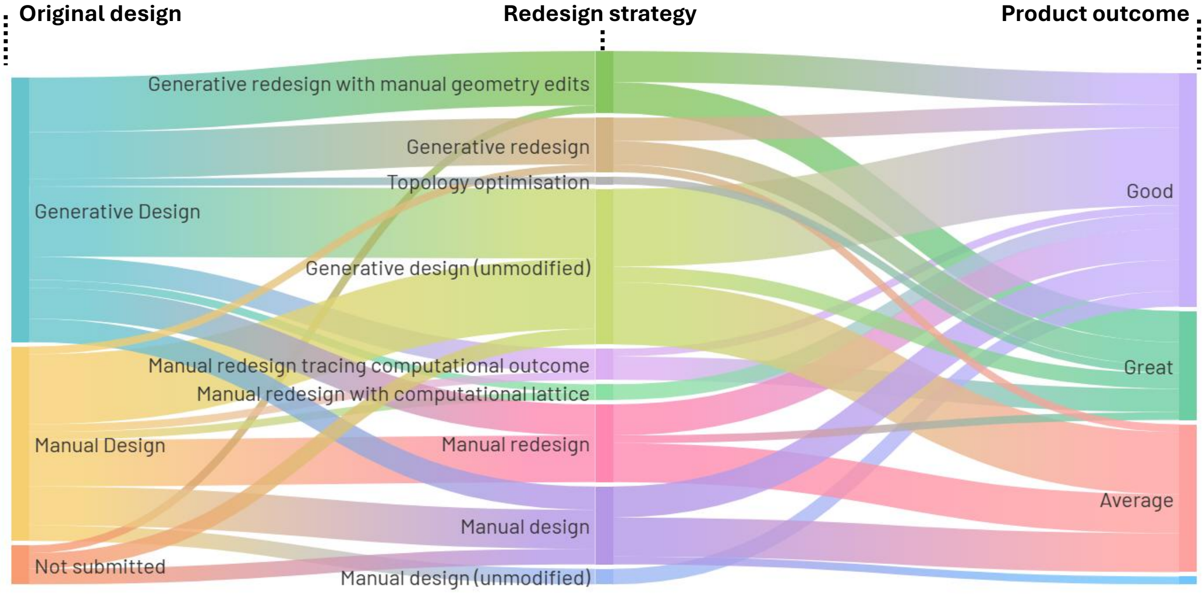

Figure 1: *shows a Sankey Diagram resulting from tags from the thematic analysis. It tracks how learners redesigned their original component, which had been generatively or manually designed, and how these were related to the quality of the final portfolio.*

5.4 Evolution of Manufacturing Strategies

The diversity of manufacturing strategies considered by students increased throughout the course. Initially, nine distinct strategies were explored, expanding to fourteen by the final submission (Figure 2a). A small subset (6%, 4/64) demonstrated self-directed learning by selecting manufacturing techniques not covered in formal instruction, indicating a level of independent inquiry.

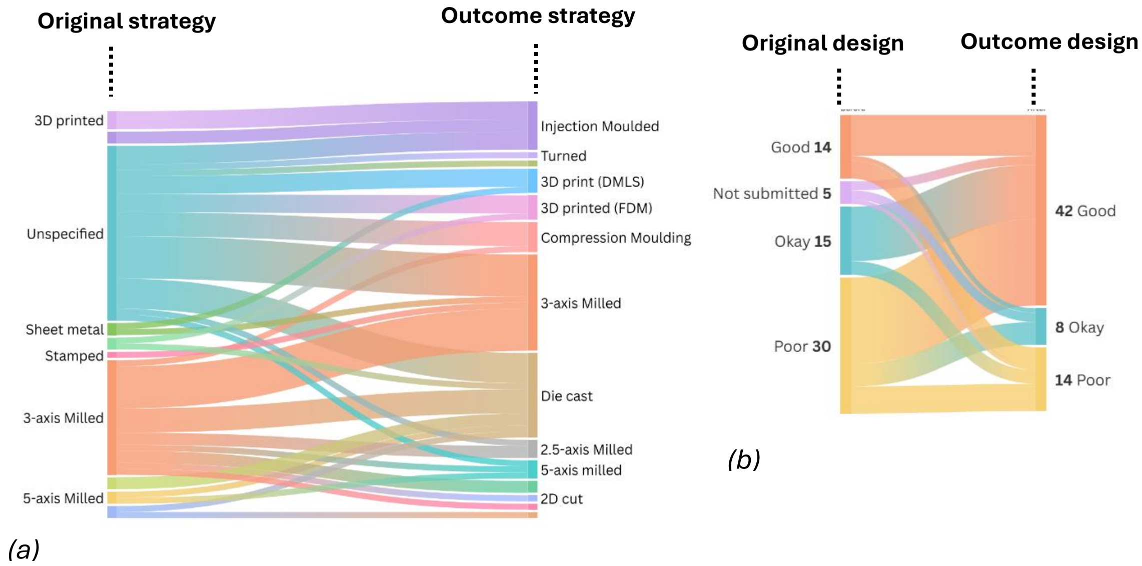

Figure 2: *shows Alluvial Diagrams that tracks how learners (a) re-selected their manufacturing strategy for the project, and (b) increased the manufacturability of their design.*

5.5 Design for Manufacturability and Sustainability

A substantial proportion (43/64, 67%) of students improved the manufacturability of their components, with many simplifying geometric complexities to enhance production feasibility (Figure 2b). However, a significant portion (8/64, 12.5%) worsened manufacturability, mostly due to a change in manufacturing strategy without adapting the geometry to suit.

While most learners engaged with design advice tools to align material selection and manufacturing strategies with embodied carbon considerations, there was no clear correlation between the use of computational redesign techniques and the ability to apply design for sustainability principles. This suggests that while computational tools facilitated manufacturability improvements, their integration into broader sustainability-driven decision-making remains an area for further pedagogical exploration.

6. Discussion

The integration of computational thinking and critical making in this course reveals a profound shift in how engineering students approach complex design challenges. Computational tools, such as generative design and topology optimisation, acted not merely as aids but as **enabling frameworks**, supporting students in exploring design spaces with unprecedented speed and depth while retaining the essential human elements of creativity and judgment. This duality is crucial: computational thinking, as Papert (1980) envisioned, amplifies cognitive capabilities but does not replace the need for deep domain expertise and intuitive problem-solving. The most successful student redesigns were those that combined algorithmic exploration with manual refinement, reflecting a sophisticated understanding of how to leverage computational outputs within the constraints of manufacturability. This hybrid approach is not just a practical strategy but a central **pedagogical intervention**, as it mirrors industry practices where engineers must balance the creative potential of automation with the realities of production (Boothroyd, 1996).

Critical making, operationalised through collaborative reviews involving academics, technicians, and peers, emerged as a powerful mechanism for fostering adaptive problem-solving and epistemological flexibility. Students who engaged deeply with these reviews demonstrated resilience and a willingness to rescope their projects in response to new insights, even when initial choices proved unfeasible. This adaptive behaviour, while sometimes associated with lower marks, signals an important developmental stage in engineering education: the ability to reassess and pivot in light of new information. The variability in how students engaged with feedback highlights an opportunity to further structure reflective practices, particularly for those less confident in interpreting computational suggestions or articulating design rationales. This aligns with Ratto's (2009) argument that critical making bridges abstract problem-solving with tangible outcomes, grounding computational exploration in real-world constraints.

The evolution of manufacturing strategies over the 12-week period illustrates a growing awareness among students of the trade-offs inherent in production-scale design. However, the weak correlation between computational redesign and sustainability decisions points to a significant gap in current engineering education. While 67% of students improved manufacturability, sustainability considerations often took a backseat to immediate performance goals, such as structural integrity or cost reduction. This disconnect suggests that sustainability must be explicitly embedded into the design process, potentially through targeted prompts or tools that visualise environmental impacts alongside technical metrics. Similarly, the commercialization requirement, namely designing for 100,000 units annually, was frequently overshadowed by prototyping concerns, indicating a need for stronger connections to industry realities, such as supplier constraints or scalability simulations.

This study is not without limitations. The single-institution context may limit the generalisability of the findings, and the reliance on expert-led thematic analysis introduces potential bias. Future work could incorporate student self-reports to provide additional perspectives on the learning experience. While the narrative framework of the "designer's journey" offered a compelling structure for the course, its impact on learning outcomes was not quantitatively assessed. Exploring student perceptions of this storytelling approach could yield further insights into its efficacy as a pedagogical device.

Ultimately, this study demonstrates that the synergy between computational thinking and critical making can foster adaptive, industry-ready problem-solving skills. By refining how these elements are integrated, particularly in addressing sustainability and commercial viability, educators can better prepare students to navigate the multifaceted challenges of modern engineering design.

7. Conclusion

This study highlights the interplay between computational thinking and critical making in a project-based learning (PjBL) course on Design for Manufacture (DfM). Our analysis reveals that students who effectively leveraged computational tools achieved higher-quality redesigns, though manual refinement remained a key strategy for optimisation. While computational methods improved manufacturability and design outcomes, their adoption varied, with some learners rejecting or selectively integrating them. The increasing diversity of manufacturing strategies suggests a growing understanding of production trade-offs, yet the link between computational redesign and sustainability decision-making remains inconclusive. These findings underscore the importance of integrating computational tools with reflective design practices to enhance problem-solving skills in engineering education. Future work will explore targeted interventions to strengthen sustainability considerations and refine the balance between automation and designer agency in engineering design curricula.

8. References

Boothroyd, G. (1996). Design for manufacture and assembly: The Boothroyd-Dewhurst experience. In *Design for X: Concurrent engineering imperatives* (pp. 19-40). Dordrecht: Springer Netherlands.

Kuo, T. C., & Zhang, H. C. (1995, October). Design for manufacturability and design for" X": concepts, applications, and perspectives. In Seventeenth IEEE/CPMT International Electronics Manufacturing Technology Symposium. 'Manufacturing Technologies-Present and Future' (pp. 446-459). IEEE.

Papert, S. (1980). *Mindstorms: Children, computers, and powerful ideas.* Basic Books.

Ratto, M. (2009, September). *Critical making: Conceptual and material studies in technology and social life.* Paper presented at the Hybrid Design Practice workshop, Ubicomp 2009, Orlando, FL.

Custer, D. An odyssey of a maker seminar, Thoughts on teaching making for project-enhanced learning in first-year physics. Transforming Engineering Education 2023, 237.