27TH INTERNATIONAL CONFERENCE ON ENGINEERING AND PRODUCT DESIGN EDUCATION
11-12 SEPTEMBER 2025, UNIVERSITY OF MALTA, MALTA

THE ROLE OF PHYSICAL SKETCH MODELLING IN THE DIGITAL DESIGN ERA

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ABSTRACT
The focus for this paper is on physical sketch modelling, and in particular 3D mock-ups, as tangible and experiential representations of product form and function. Although physical sketch modelling is not a new practice, there is a danger that it may become marginalised as digital modelling tools become ever more ubiquitous and favoured in student design processes. The paper puts forward a timely reappraisal of the relevance and value of physical sketch modelling in the digital design era. Definitions of product form and function are provided and then linked to general principles of modelling and sketching in design. Cognitive modelling and externalised modelling in media are introduced as a theoretical grounding for physical sketch modelmaking, followed by a review of the materials and resources typically required. Tensions between digital and physical form creation approaches are discussed. The main study comprises a design studio project, where undergraduate industrial design students (n=85) worked in teams to design sustainable take-away food packing and serving solutions. Students were required to develop and communicate product form and function ideas via 3D mock-ups. An analysis of the outcomes established five key areas where 3D mock-ups have generative and evaluative advantages over computer aided design (CAD): human factors, form definition and styling, usage scenarios, materialisation, and design communication. The paper highlights the importance of retaining physical sketch modelling as a complementary approach in design education, emphasising its benefits in developing product forms, improving spatial reasoning, and enhancing early-stage design development.

Keywords: Physical sketch modelling, 3D mock-up, workshop practice, digital design

1 INTRODUCTION
Today's computer-aided design (CAD) software equips product design students with comprehensive tools for modelling and visualising product forms. However, for exploring and assessing three-dimensional qualities of a developing product design, especially at the 'fuzzy front end', CAD software has limitations. The authors' lasting impression after 30 years of teaching and learning on studio projects is that students' design proposals suffer significant shortcomings if physical sketch modelling (creating low-fidelity 3D mock-ups or product form studies) has been skipped or poorly implemented.

This is not a novel argument of course, but in the current digital era it requires reiteration and revisiting, firstly because students are seemingly inseparable from their digital devices, and secondly because without proper briefing higher education management may see workshop spaces required for physical sketch modelling as a resource-intensive luxury, suitable for removal. Within this frame, the paper presents a manifesto for keeping (and raising) physical sketch modelling within product design curricula. It draws upon some early, fundamental studies in form creation and product design, carried out when digital design tools were relatively primitive. These early studies are valuable because they are especially lucid about what there is to gain and lose when shifting away from physical sketch modelling. Complementing the literature is a case study on 3D mock-up creation within the authors' design studio. An analysis of student outcomes, from design process and proposal perspectives, reveals the multifaceted benefits of product form and feature exploration outside of CAD.

2 PRODUCT FORM & FUNCTION
Form is the 3D external definition of a product, considered either holistically or via the assembly of various separate product components. It defines the morphological arrangement, volumetric extents, and external appearance of a product [1]. At a closer scale, 'form features' refer to additions and subtractions on a product surface that may provide, for example, user interface elements, additional styling, or joining

and assembly details. Designers spend considerable effort on form studies, striving to generate forms, or assemblies of forms in more complex products, that are functionally appropriate, attractive, and meaningful. They ideate and iterate many different forms until a favoured proposal is reached.

2.1 Modelling and Sketching in Design

The activity of generating models of design ideas, simply known as 'modelling', has been suggested as the "language" of designing [2], [3]. Design is rarely performed just in the mind, with capability in 'cognitive modelling' (seeing in the mind's eye) known to be effective in design ideation [4]. Very often is it helpful to externalise design ideas using various media, such as hand-drawn sketches, CAD models, and mock-ups. These not only help the designer evaluate and iterate their designs but also facilitate discussions with colleagues or other stakeholders, who need to grasp the qualities of a design through clearly communicated media [5]. Models created in digital and non-digital media are essentially carriers of externalised cognitive modelling; their presence can spark new or refined mental imaging, thereby initiating a dialogue oscillating between implicit and explicit design representations (Figure 1).

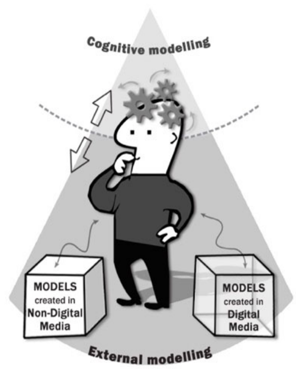

Figure 1. Interplay between cognitive modelling (imaging) and externalised modelling (explicit representations). Image based on [6], p194

2.2 Physical Sketch Models

Physical sketch models, which may fall into two basic types (tangible form studies, and 3D mock-ups), are low-fidelity and low-durability physical representations of design intent. Used at the front-end of a design process, they help designers 'test out' an idea before deciding whether to invest time and effort on development [6], [7], [8], [9].

Tangible form studies generally take a sculptural additive/subtractive approach using malleable or low-resistant materials such as polystyrene foam, plaster, and ceramics. In contrast, to simultaneously demonstrate form and function, 3D mock-ups utilise a wider range of low-cost materials, including paper, card, fabrics, insulating foam, plaster, wax, sheet plastics, metal wire, MDF, and chipboard. All these materials can be relatively easily shaped and fabricated using hand tools (e.g., pens, knives, files, drills, abrasive paper) or simple workshop machinery (e.g., laser cutters, thermoforming machines, band saws, lathes, sanding machines). Sometimes 3D mock-ups include parts made via more elaborate processes, to achieve intricacy (e.g., 3D printing) or complex curvatures (e.g., vacuum forming). Physical sketch modelling is rarely carried out using intended end materials: they are generally too expensive, or it is too difficult to create one-offs or low volume quantities.

With physical sketch modelling, the aim is not to create surfaces that reproduce sensorial qualities of durable end-product materials (e.g., the visual and tactual qualities of finished plastics, metals, ceramics, composites, wood, etc.). Indeed, material surfaces are often left in a natural 'bare' state or else lightly colourised. The low-fidelity, work-in-progress, open-for-interpretation qualities make tangible form studies and 3D mock-ups open for critique and discussion about what can be improved and why. Furthermore, low-resistance materials make physical sketch models suited to quick editing. All these qualities set physical sketch models apart: a tangible form study is not the same as an appearance model, made in final materials or simulated final materials; a 3D mock-up is not the same as a working prototype, made with durable materials and construction and to an advanced design [10].

3 TENSIONS BETWEEN DIGITAL AND PHYSICAL FORM CREATION

We have observed in the last ten years that product design students have increased their usage of surface, solid and mesh-based modelling software (e.g., Fusion 3D, Rhino, Blender etc.) as a primary medium for design ideation and iteration, even at the early stages of a design project. Students often forgo hand sketching or physical sketch modelling for quick initial renderings generated digitally. Certainly, there is an irresistibility of CAD to those who are competent: it is convenient, highly functional, adaptable, correctable, and apart from access to a high-powered computer, requires no special facilities. Recent developments in generative AI extend this situation, relieving students of some of the responsibility of ideation by providing impressions of 3D products based on prompt-and-suggestion dialogue, bypassing the pedagogical objectives of 3D modelling. Hand sketch-to-mesh CAD model tools powered by AI are also developing quickly. In our experience, once students have committed their ideas to CAD, they rarely step out to explore other design development media (unless incentivised, for example by grades). Furthermore, there is a general tendency towards even more digital modelling as projects progress, for example to obtain photorealistic renderings, run simulations, or generate 3D printed prototypes. However, CAD modelling is essentially modelling by proxy, lacking the '"movements, space, and rhythm" [11] associated with physical sketch modelling in real materials. Within all this digitality, without a concerted effort, the benefits of physical modelling can become lost, as mentioned below [2]:

> *"…digital modelling has now become the norm in most industries even when other models are also used. In almost every field it has become the essential link between the designer and the production process. The designer may well continue to use drawings, models or storyboards as part of the personal creative process and there is now a move to revalue the potential of such media. It is becoming clear that they have a unique position in their ability to energise and externalise the dynamic between interior or mental models and externalised or physical models." (p72)*

4 STUDIO PROJECT: SUSTAINABLE FOOD PACKAGING AND SERVING

To construct a general view of the benefits of physical sketch modelling, we set a brief for third-year undergraduate industrial design studio students to design sustainable take-away food packing and serving solutions [12]. Students were directed to use a 'buy-a-container' or 'borrow-a-container' business model to remedy the problem of throwaway single use packaging. Built into the project was the objective to make a full cohort of students (n=85), working in teams, become self-aware of the benefits of physical sketch modelling. The brief included a compulsory requirement to develop product form and function ideas via 3D mock-ups (Figure 2), for which necessary workshop space and resources were provided. Students had experienced 3D mock-up making in their prior semesters, so they were technically competent. We did not direct students to use their 3D mock-ups in any specific ways; rather, they were free to explore the media and decide for themselves. In response, we made special effort during critiques and juries to observe students' usage of 3D mock-ups. Furthermore, we analysed product process portfolios submitted at the end of the project, which contained documentation of 3D mock-up creation and evaluation. We also recalled presentations and critiques where students used 3D mock-ups to explain design ideation and rationale.

Figure 2. Sample 3D mock-ups for sustainable take-away food packaging and serving solutions

5 OUTCOMES AND EXPERIENCES

We observed that students created 3D mock-ups mostly as physical embodiments of pre-conceived design ideas (i.e., designing-then-making), and much less as a physical artefact to support design ideation and iteration, through a cyclic designing-and-making activity. Most likely this was because we asked for 3D mock-ups to be created, with their emphasis on functional exploration, rather than tangible form studies focused more on styling and semantics. The latter type of physical sketch model, realised for example in foam, has greater potential for integration as a design-and-make medium providing a playground for design experimentation [13]. Figure 3 provides the results of our analysis, outlining general shortfalls of taking a digital design approach and observations on 3D mock-ups from the design studio project.

Shortfall of Digital Design Approach	Observations on 3D Mock-Ups from Design Studio
Human Factors Underdeveloped physical ergonomics considerations, concerning anthropometric fit and UI (user interface) design.	3D mock-ups support physical ergonomics and UI evaluations and adjustments through tangible interactions (handing, touching, grasping, etc.). Tactile feedback and comfort evaluations are limited because 3D mock-ups do not usually replicate intended material properties. Supports task analysis to reveal users' actions and cognitive processes during interaction.
Form Definition and Styling Unrefined spatial comprehension and decisions regarding size, scale, morphology, proportions, balance, surfacing, and styling.	Creating 3D mock-ups at 1:1 scale forces all volumetric-spatial evaluations and adjustments to be realistic. 3D mock-ups can be placed in an intended environment or compared with existing benchmarks to support aesthetic, semantic, and other appraisals. Sculptural forms (organic, complexly curved) can be generated more intuitively.
Usage Scenarios Poorly explored usage scenarios where the product is not clearly placed in a storyline of use.	By using 3D mock-ups as props for role playing, real-world usage scenarios can be acted out according to a timeframe and evaluated. Product design changes can be identified accordingly and implemented.
Materialization Impractical material and manufacturing routes, compounded by uncertainties about individual component assembly and disassembly.	3D mock-ups help make connections between product form and feasible materialization routes (material selection, shaping, joining, assembly), since the concern for physicality is pervasive within a 3D mock-up.
Design Communication The skill to imagine something physical from an abstract representation (such as 2D or 3D CAD model viewpoints) cannot be taken for granted amongst non-designers (users, colleagues, test subjects), opening the possibility of misunderstandings over product design.	3D mock-ups overcome communication barriers by offering a tangible representation of a product design that is easy to comprehend and critique by everyone, not just internally by designers. This opens-up the use of 3D mock-ups as ideal media for participatory design and evaluation sessions.

Figure 3. Digital design approaches versus 3D mock-ups

6 DISCUSSIONS

The uses and benefits of physical sketch modelling can be supported by three discussion points, each signalling essential qualities of the medium. The first point (sketchiness, abstraction, and potential) relates most strongly to tangible form studies, whilst the second and third points (modifiable; craftsmanship and access to facilities) cover both tangible form studies and 3D mock-ups.

6.1 Sketchiness, Abstraction, and Potential

The capability to 'see' how, in the mind's eye, something can be construed as more than what is obvious to the naked eye, is generally held with high regard and importance for how design modelling and ideation feed off one another [14]. It is clear from Table 1 that physical sketch models are a powerful medium for 'seeing' the potentials of a design idea and deciding ways in which it may be iterated and improved. But this is only possible if the sketch model is indeed 'sketchy' or to some degree ambiguous about its features and functioning (Figure 4a): if it is too refined, too hi-fidelity, too obvious, or too much giving the impression of a finished design then there is a risk of fixation on that offered design, to the detriment of seeing or experiencing other possibilities [15], [16]. This echoes early work in children's learning, where during the process of constructing something from building blocks, a young child develops a feeling that what is being created will, or perhaps will not, meet expectations, as Harrison (1978) points out [17]:

"He stands back from it to see how it looks, to see if it is going right, what it is turning into, how it is failing to develop one way or another, how it may be emerging as something of which he can be proud or persist in disappointing him by falling down just as it is about to be [metaphorically or literally] something." (p192)

Pedagogically, one's capability to 'see' or 'image' more than there is to the naked eye seems to be a foundational skill for design students to learn and practice, as confirmed by recent research [18]. This skill is obviously in demand during physical sketch modelling.

6.2 Modifiable

Hand sketching in the context of product design has been characterised as a "visual dialogue" or "argument" between opposing points of view, changing in its details by small increments until a satisfactory outcome is reached [19]. A starting sketch prompts a follow-up idea, which prompts critique and a refined idea, and so forth. These principles transfer to physical sketch modelling and the development of product form. For a 3D mock-up, the design develops as the designer holds a conversation with the individual modelled parts: how they come together now, and how they may be modified or come together differently. With an open and searching mind, the designer engages in a kind of improvisation and experimentation, usually guided, but always receptive to serendipitous discovery. Such dimensions are a clear example of Dewey's 'learning-by-doing' and journey of discovery approach to knowledge generation, as well as Schön's 'reflection-in-action' or 'reflective conversation' [14], [20]. Low cost, low-resistance materials promote easy 3D mock-up modifications, such as changing the design of a handle, swapping a lid design for an alternative (Figure 4b), or modifying the stacking geometry of multiple containers.

6.3 Craftsmanship and Access to Facilities

Physical sketch modelling crucially does not demand the high level of practical making skills and craftsmanship associated with professional modelmaking. Indeed, the need for sketchiness and abstraction favour rather more primitive making strategies and techniques (Figure 4c). Furthermore, the use of low resistance materials brings the practices of physical sketch modelling closer to DIY activities and hobbyist crafts-making. Educationally this is advantageous, since it precludes investment in metalworking and possibly even negates the need for comprehensive dust extraction facilities. Relatively basic workshop facilities are sufficient for effective physical sketch modelling. However, these spaces must tolerate mess and debris, students must be trained in health and safety for hand/machine tools, familiarity with MSDS (material safety data sheets) is important, and good technician support should be provided.

Figure 4. (a) Cake and drinks container with sketch qualities, (b) modifiable open-close detail for hot food container; (c) sufficiently crafted drinks bottles and holder

7 CONCLUSIONS

The migration towards fully digital design processes threatens to marginalise physical sketch modelling, whilst also acting as a catalyst to reduce or close workshop spaces. This paper has highlighted the importance of maintaining physical sketch modelling within product design education, to complement and counterbalance digital tools and workflows. Students have much to gain if they are educated, convinced, and practised in the benefits of physical sketch modelling, whether as tangible form studies or 3D mock-ups. We argue that product design education should preciously hold on to practices and facilities for physical sketch modelling, or even invest and expand in them, because digital alternatives even in the current era still fall short of delivering equivalent benefits or experiences for students. This point should be borne in mind whenever management raise discussions on the need (or not) to have 'making' as a part of industrial design or product design education.

Perhaps the most striking and enduring benefit of 3D mock-ups, which essentially borrows methods and techniques from stage acting, is their use as props within storylines. Students can test out usage scenarios (within a macro timeframe) or user-product interaction steps (within a micro timeframe), becoming physically and critically engaged in their design proposals, in contrast to viewing hand sketched ideas more in the role of an audience member than a participant. Such tests also cannot currently be achieved meaningfully using CAD software or immersive AR/VR environments. Although VR holds potential, the persistent technological constraint of unconvincing tactual feedback and proprioceptive/haptic sensations within VR systems makes imminent breakthroughs unlikely. Furthermore, the time and effort to construct and program an interaction-ready VR model is likely to be far greater than preparing a low-fidelity physical sketch model. The transfer of methods and techniques of stage acting into design scenario exploration with 3D mock-ups seems a fruitful area of future research.

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