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HOW SHOULD WE PROTOTYPE? ESTABLISHING THE AFFORDANCES OF PROTOTYPING MEDIA AND APPROACHES

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ABSTRACT

The breadth of media and approaches used when prototyping are vast, with each holding inherent properties that vary their suitability for a given prototyping activity.

While several have established classifications of types and purposes of prototypes, there is little by way of guidance for designers on how select and strategise prototyping given their activity needs, or how the prototype chosen may influence their process, success or efficiency.

This paper presents nine affordances of prototypes derived from literature, together characterising the properties of prototyping media or approaches that affect their suitability across prototyping activities.

The affordances are illustrated through application to physical and digital classes of prototypes and four real prototype cases, showing descriptive capability, inherent differences between the media, and enabling direct and consistent comparison.

By mapping affordances across many media and approaches, this work enables better method selection to align with activity needs, better description and comparison of media and approaches, and the ability the broadly interrogate and direct future development of prototyping technologies.

Keywords: Prototyping, Design process, Design methods, Early design phases

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1 INTRODUCTION

Prototyping is a ubiquitous and critical part of the new product development process, appearing formally in many process models and with considerable interest focus from the academic community. It is used to support decision-making, development, and evaluation throughout design (Ulrich and Eppinger, 2016), with prototypes used for learning, communication, stage-gating, exploration, and refinement (Camburn et al., 2017; Houde and Hill, 1997; Menold et al., 2017). While precise definitions of what constitutes a prototype vary, they are typically considered to be '*an approximation of the product along one or more dimensions of interest'* (Ulrich and Eppinger, 2016), as such comprising a vast array of physical, digital, and descriptive media (Camburn et al., 2017; Ulrich and Eppinger, 2016) at varying levels of detail and sophistication (Pei et al., 2011). Further, media may be applied in different ways through different 'types' of prototype (here termed *approach*), (see Houde and Hill, 1997; Camburn *et al.*, 2017; Menold, Jablokow and Simpson, 2017). While the ultimate aim of prototyping remains consistent – to support designers in producing better products – the manner in which prototyping may be performed is exceptionally broad (Kent et al., 2021a; Real et al., 2021).

The particular media (i.e. material used to prototype) or approach (type of prototype / process by which it is applied) selected to perform a prototyping activity (the act of using the media, according to the approach, to generate learning) are critical, and must directly align with the needs of the specific task (Isa and Liem, 2014). Each holds an inherent degree of cost (time and monetary), complexity, skill, accessibility, breadth of learning and more, and so it is vital that those approaches and media employed are suited to the specific needs of the prototyping scenario (Isa and Liem, 2014; Menold et al., 2017). However, while much research has focused on classification of prototypes by purpose (Petrakis et al., 2019) or the characteristics of individual types (Camburn et al., 2017; Pei et al., 2011; Ulrich and Eppinger, 2016), there is a lack of extant research on supporting the appropriate selection of prototyping approaches (Christie et al., 2012; Liker and Pereira, 2018; Menold et al., 2017; Verlinden and Horváth, 2009). It is perhaps for this reason that industry prototyping approach is often variable or even ad-hoc (Christie et al., 2012; Goudswaard et al., 2021) with selection preference then tending to the expertise of the designer. Given that a majority of budget is dedicated during research and development stages this creates risk – should prototyping approach not be optimal, time and money may be lost while simultaneously producing non-optimal products. This dearth of knowledge underlines the need that this paper begins to address; better support for prototype selection to align with the needs of a specific design activity, and hence to deliver effective and efficient prototyping processes for new product development.

This paper achieves this through a framing by which the affordances of prototyping media and approaches can be described, evaluated, and compared. The framing allows detailed characterisation of how a given prototype may be used or support different aspects of the prototyping activity dependent on its media, which may then be compared to the needs of a specific scenario to ensure appropriate selection is made. For example, some media support higher fidelity prototyping (Hallgrimsson, 2012), more capable analysis (Ulrich and Eppinger, 2016), or higher accessibility and wider stakeholder participation (Verlinden and Horváth, 2009) and so may better suit scenarios when such properties are beneficial. Through characterisation and evaluation of media and approaches against this framing, it is then viable to identify those preferred for a given task, to identify gaps in capability across prototyping, and to set direction for the future development of new prototyping tools.

This work then provides contribution in three ways: [1] a consistent means to compare prototyping approaches and media; [2] a means to evaluate identify gaps in capability across approaches and media; [3] a means to audit and support industry media and approach selection, and to direct future technology development. This paper proceeds to derive the framing from academic literature, before applying it to two illustrative classes of prototype (physical and digital) and four specific examples of prototyping media. Following, the ability of the framework to support comparison and evaluation is demonstrated, as well as to support process selection. Finally, implications for academia and future work are discussed.

2 PROTOTYPING MEDIA, PURPOSE, AND AFFORDANCE

Many taxonomies of prototyping are extant in literature, categorizing based on purpose (Petrakis et al., 2019), media (Pei et al., 2011; Stowe, 2008), activity, role, and strategy, amongst many others. These often highlight the interplay between the prototype and the activity in which it is applied (i.e. the act of using the prototype), such as the PfX framework (Prototyping for Viability, Feasibility, or Desirability) (Menold et al., 2017), the activity categories of Camburn (2017) (i.e. active learning, exploration, refinement, and milestones), or the use of prototypes to evaluate product role, implementation, or look/feel (Houde and Hill, 1997).

Amongst these works it is regularly noted that different prototyping media (i.e. material) and approaches (type of prototype / way in which it is used) are better suited to different purposes, roles, activities, etc., due to their inherent properties. For example, (Bähr and Möller, 2016; Exner et al., 2016; Liker and Pereira, 2018) all discuss the benefits of virtual or mixed prototyping (combined physical/virtual) over purely physical, including increased flexibility, higher fidelity, and increased potential for automated or advanced analysis. Similarly, Pei (2011) discusses utility across four levels of Visual Design Representation (sketch, drawing, prototype, model making), Stowe (2008) across levels of system scope (amongst several delineations), and Camburn (2017) across many forms of prototyping media in an excellent review of prototyping state of the art. Still others have claimed alignment between media and forms of learning (Real et al., 2021), levels of stakeholder accessibility (Isa and Liem, 2014; Verlinden and Horváth, 2009), support of collaboration (Bähr and Möller, 2016; Exner et al., 2016; Verlinden and Horváth, 2009), and model management (Tseng et al., 1997; Zorriassatine et al., 2003).

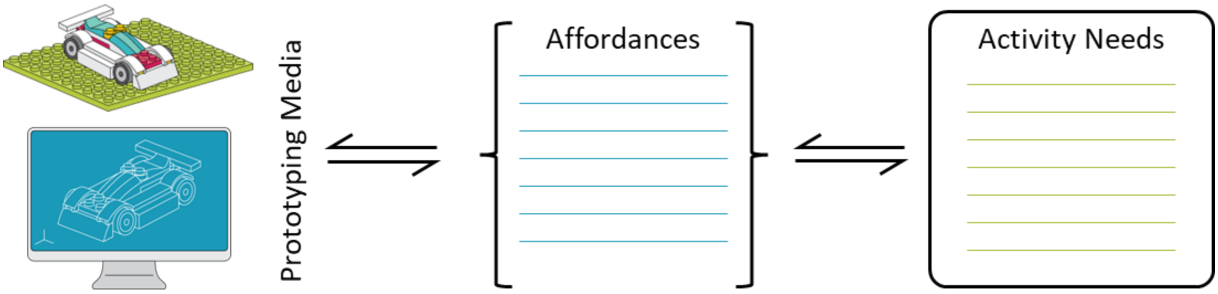

Figure 1. Relationship between media, affordance, and activity needs.

However, while such directionality between the inherent properties of prototyping media and their utility for different design activities is widely accepted, there is to date no clear framing or overview of such properties as a set that would then enable fair comparison between media and approaches. For selection then, there is no clear and holistic overview of the affordances that media and approaches provide, and hence little guidance on what benefits or costs a chosen approach may impose on the designer. As illustrated in Figure 1, this work proposes that between the prototype media and its intended use sit a set of specific properties (termed ***affordances***) that influence the media's suitability for that task. By mapping the affordances of media to the needs of a given activity, it is then possible to support improved selection of media for that task, or to select media that will encourage certain activity goals such as reduced cost, increased speed, or broader accessibility.

3 A FRAMEWORK OF PROTOTYPE MEDIA AFFORDANCES

The inherent properties of prototyping media or approaches that influence their suitability in a given activity are here termed their *affordances*. Through mapping these affordances across media and approaches, this work contends that better understanding of prototyping, better ability to compare and contrast media, and better ability to support prototype media selection may be gained.

Nine affordances have been extracted from academic literature (see Table 1, sources in Table 2) focusing on prototyping best practice, prototype classification, and specific media and their implementation. In each case, affordances were extracted when works proposed a reason as to the varying suitability of a specific or class of prototyping approach for a certain activity or situation. This set of nine affordances was condensed from an initial set of twelve highlighted in literature, following three combinations due to higher interaction under orthogonality analysis. Those removed as categories in their own right were *collaboration* (combined with Stakeholder Accessibility), *System Integration* (combined with Scope), and *Breadth of Learning* (combined with Flexibility). The remaining nine affordances are as follows.

Flexibility: With major goals of prototyping being exploration and active learning from and about design options (Camburn et al., 2017), the ability to reconfigure, change, and iterate prototypes at pace

Table 1. Categories of affordance extracted from literature

Affordance	Description
Flexibility	The degree to which the prototype allows change, supporting exploration or application across purposes.
Fidelity	The degree to which the prototype is a realistic representation of the intended final product or idea, or constituent parts of it.
Scope	The completeness of the prototype with respect to all properties of the intended final product or idea.
Analytic Capacity	The degree to which the prototype enables a range of active testing and analysis, and/or the form of analysis that may be applied.
Technical accessibility	The degree of operational and technical overhead associated with creating or using the prototype, including cost, speed, time, and skill.
Stakeholder accessibility	The degree to which the prototype enables engagement and communication across stakeholders, including for collaboration.
Breadth of Learning	The degree to which the prototype enables broad learning against a range of knowledge goals required for the design.
Interactivity	The degree to which the prototype allows a range of interactions with the designer or other stakeholder, and/or the forms of interaction that may be performed.
Feedback Immediacy	The rate at which the prototype generates learning via feedback to the designer or user during its use.

Table 2. Occurrence of affordances in extant literature. References listed in footnote[1].

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Flex.	●		●	●	●	●		●				●	●	●	●		●	●	●		
Fid.	●	●	●		●	●	●	●	●	●	●	●	●		●	●	●	●	●	●	●
Scope						●	●	●	●	●	●									●	●
Ana.			●					●	●				●	●	●		●	●	●	●	●
Tech. Acce.	●	●	●		●			●	●	●				●	●	●	●		●	●	●
Sta. Acce.	●		●			●	●	●	●		●	●	●	●		●	●		●		●
Brea. Lea.				●	●	●		●					●	●	●	●	●	●			
Inte.						●			●	●	●	●	●	●	●	●	●	●			
Fed. Imm.		●				●		●					●			●					

and with minimal associated cost is highly valuable. This regularly occurs for media employed in earlier design stages, where it is important that designers are able to manipulate forms and behaviours to probe and refine their ideas (Isa and Liem, 2014; Ulrich and Eppinger, 2016), while pre-production prototypes are often single use and isolated in their evaluation. In particular, the ability for virtual models to rapidly iterate parameters and evaluate the change that this incurs creates high flexibility that can be leveraged to accelerate design (Kent et al., 2021a; Zorriassatine et al., 2003).

Fidelity: To provide actionable insight, it is important that the prototypes created realistically embody the design solution along some set of dimensions (McCurdy et al., 2006). Beyond simply low-fidelity and high-fidelity, this set of dimensions is broad, encompassing realism across geometric, functional, structural, interactivity, and aesthetics (McCurdy et al., 2006), with potential for realism across all typically increasing as design moves towards production (Pei et al., 2011). The ability of different media to achieve high fidelity across such broad dimensions is variable but trends can be observed. For example, geometric CAD modelling may achieve high geometric fidelity (Hallgrimsson, 2012), card, paper and junk mockups give low functional fidelity but high aesthetic (Camburn et al., 2017), and physical media provide higher fidelity but at a higher cost (Liker and Pereira, 2018).

Scope: At different stages, designers may wish to prototype either isolated functions, systems, or behaviours, or to create integrated prototypes encompassing many aspects of the design (Houde and Hill, 1997). This is captured by Ulrich *et al.* (2016) in their delineation between focused and comprehensive prototyping media and approaches, with earlier stage prototypes typically provide low system coverage, increasing as materials and behaviours increase in fidelity towards production.

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[1] (1) (Isa and Liem, 2014); (2) (Kent et al., 2021b); (3) (Kent et al., 2021a); (4) (Real et al., 2021); (5) (Yang, 2008); (6) (Pei et al., 2011); (7) (Houde and Hill, 1997); (8) (Ulrich and Eppinger, 2016); (9) (Stowe, 2008); (10) (McCurdy et al., 2006); (11) (Lim et al., 2008); (12) (Exner et al., 2016); (13) (Bähr and Möller, 2016); (14) (Ahmed and Demirel, 2020); (15) (Zorriassatine et al., 2003); (16) (Verlinden and Horváth, 2009); (17) (Tseng et al., 1997); (18) (Bordegoni et al., 2009); (19) (Liker and Pereira, 2018); (20) (Christie et al., 2012); (21) (Camburn et al., 2017)

Analytic Capacity: As the purpose of prototyping is to learn, the ability to perform broader or more sophisticated evaluation on a prototype creates higher potential value. In many cases prototypes are built for only a single set of tests and are limited in their capacity (i.e., softer materials, rapid manufacture (Isa and Liem, 2014; Liker and Pereira, 2018), but some allow a wide range of analysis to be performed quickly and effectively (i.e., virtual and mixed reality (Christie et al., 2012; Kent et al., 2021a) while others offer limited testing but high confidence in results (Pei et al., 2011).

Technical Accessibility: Resource drain is a major driver for prototyping strategy selection (Christie et al., 2012), with different media holding vastly different costs, lead times, and skill requirements during fabrication (Kent et al., 2021b; Ulrich and Eppinger, 2016). Typically early-stage media are often low-cost and useful for ideation but also low fidelity and isolated in scope, while costs increase as the prototype becomes more complex and moves towards production (Pei et al., 2011; Ulrich and Eppinger, 2016) at the benefit of high fidelity (Isa and Liem, 2014). Here a balance must be struck between needs of the process, and the resource cost of its fabrication.

Stakeholder Accessibility: With varying backgrounds and degrees of technical experience, including none at all, the ability of a diverse range of stakeholders to usefully understand and input into design through prototypes is critical (Camburn et al., 2017). Physical prototypes tend to provide a tangible and accessible experience when targeted appropriately (Kent et al., 2021a; Pei et al., 2011), while the flexibility of virtual prototypes provides broad opportunities for interaction, leading to better learning. Mixed reality methods blend these benefits creating supporting high diversity of communication (Bähr and Möller, 2016; Verlinden and Horváth, 2009). Physical methods also provide deeper capacity for scrutinizing that which is not possible with CAD (Hallgrimsson, 2012).

Breadth of Learning: The purpose of prototyping is largely to catalyse learning, with each often targeted towards specific knowledge goals, as captured in many prototype taxonomies (see Menold, Jablokow and Simpson, 2017; Petrakis, Hird and Wodehouse, 2019). The media employed equally will support these knowledge goals to varying degrees, for example with physical media providing broad learning (Real et al., 2021) and realistic performance testing (Isa and Liem, 2014), while sketching is often more limited to functional, behavioural, and geometric information (Real et al., 2021).

Interactivity: Different media provide the potential for different modes of interaction, which in turn enable different forms of learning for the designer (Bähr and Möller, 2016) and across different stakeholder groups (Ahmed and Demirel, 2020). Enabling high fidelity interactions at earlier stages of design through (e.g., mixed reality prototypes) brings forward important design decisions (Exner et al., 2016; Kent et al., 2021a), while the tangibility and realism of physical prototypes gives interactive freedom, but often a more limited range of possible interaction types than virtual (Isa and Liem, 2014).

Feedback Immediacy: As a learning tool within a design episode, the ability of the prototyping method to provide quick feedback to the designer or user supports quick iterative cycles that align with cognitive processes (Bähr and Möller, 2016; Zhang et al., 2019). Sketches, drawings, and other early-stage media often allow such quick cycles (Pei et al., 2011; Ulrich and Eppinger, 2016), while precise and high fidelity approaches increase lead time and lead to lower responsiveness (i.e. CAD (Bähr and Möller, 2016)) necessitated by the higher sophistication that these prototypes embody.

3.1 Summary

Depending on the intended purpose and learning for a given prototyping activity, the designer will have different needs and will ask different requirements of the prototype itself. For example, when at early stages with an intention for rapid design exploration across a range of stakeholders, the prototype must be flexible and allow wide stakeholder accessibility, most likely at a cost of fidelity and analytic capacity. Similarly, when the purpose is to test a single sophisticated behaviour the fidelity must be high, while flexibility, breadth of learning, and interactivity may be low. These dimensions of affordance then provide a language and framing by which the suitability of a given media may be evaluated for a given purpose or required output.

4 APPLICATION OF THE FRAMING TO PROTOTYPING MEDIA

This paper continues by demonstrating the framework through two sets of illustrative cases; classification of physical and virtual prototyping as distinct prototype classes drawn from literature, and classification of 4 real prototyping cases. Each are mapped against the affordances, allowing visualization of their individual footprints of capability as corridor plots, see Figure 2. It is notable that each affordance is presented as a spectrum, implying a relative scale against which different media could be assessed or ranked. While this is intuitively valuable, many affordances are more subtle than such a scale allows. For example fidelity spans several sub-dimensions, with general acceptance that a low-to-high fidelity spectrum is insufficient (McCurdy et al., 2006). While this work uses exactly that framing for brevity, each affordance should be carefully expanded to unpack any dimensions within it that allow its definition as higher or lower in that affordance than any other method. Characterisation should hence be considered illustrative at this point – while effort has been made to create relative precision between media, the position on each spectrum does not imply quantitative accuracy.

4.1 Physical and virtual prototyping

A distinction is often drawn between physical and digital prototyping, with each holding distinct and typically counterpoint strengths and weaknesses (Kent et al., 2021a; Lim et al., 2008). To demonstrate application of the framing to describe affordances of media, Table 3 draws from literature to establish typical locations of physical and digital classes of prototyping media against each affordance, then visualized in Figure 2.

Table 3. Generalised affordances of physical and digital prototypes

Affordance	Physical	Digital
Flexibility	Flexible in some forms seen in early design (i.e. card, clay), but often isolated and inflexible due to costs of fabrication.	Often quickly reconfigurable through parameter variation.
Fidelity	Feasible to be very high fidelity, but typically at a high cost.	High fidelity within bounds of programming. Increased fidelity introduces complexity + cost.
Scope	Potential to range from highly focused to fully comprehensive pre-production prototypes.	Limited to the scope of their programming. May be comprehensive, but at a cost.
Analytic Capacity	Often limited to isolated tests based on their specific intended purpose, and the complexity of fabrication for broad testing.	While technical challenges exist, can often be subjected to a battery of simulations and analytic test at high pace.
Technical accessibility	While some are very low cost, fabrication time and skill to create are often high.	Often require specific skills to create, but may be iterated at a high pace with minimal cost.
Stakeholder accessibility	High tangibility often aids understanding across a diverse range of technical and non-technical personnel.	Unless specifically designed for communication, can be cognitively challenging to interpret without expertise. Excellent for distributed collaboration.
Breadth of Learning	Very broad, depending on the form used. Ranges from comprehensive tests of entire designs to focused prototypes investigating sole elements.	Learning is limited to the scope of programming. Broadly capable, but focused towards specific outputs with less room for interpretation.
Interactivity	Allows organic and user directed interaction, but is limited to the constraints of the specific physical form.	Flexibly allows a wide range of interactions when programmed to do so, but typically must be specifically created.
Feedback Immediacy	When designed to do so, may instantly react to designer. However, a need for refabrication is also common and time consuming.	Learnings within bounds of programming can be immediate, with rapid iteration and analysis. More complex analysis or sophisticated interactions re

Shaded areas within Figure 2 indicate 'zones' in which prototypes of physical and digital states typically lie according to extant literature. Notable within this classification is the counterpoint benefits of physical (realism, scope, stakeholder accessibility, interactivity) and digital (flexibility, analytic capacity) as noted by several researchers, and varying spread against certain affordances (i.e. scope, breadth of learning for physical), where the actual position achieved will be determined by the application case, with the media defining the breadth of the range.

4.2 Application to specific prototyping cases

Table 4 and Figure 2 apply the framework to four specific prototyping activities, themselves shown in Figure 3, to investigate specific affordances achieved in practice. These prototyping activities occurred during the IDEA challenge (Goudswaard et al., 2022), with prototypes and activity rationale captured using the Pro2booth system (Giunta et al., 2022). Classification of each prototype against the affordance framework occurred through discussion with the organizer of the IDEA event.

5 DISCUSSION OF THE AFFORDANCE FRAMEWORK

5.1 Discussion of illustrative cases

Classification of both physical and digital classes and the four specific prototyping cases (see Figure 3illustrate feasibility of classification of both specific prototyping cases and larger classes of prototype by the affordance framework. At a base level, they imply that the posited benefits of different forms of prototype may be seen in real examples of prototyping. Key here is that these applications suggest different affordance 'footprints' for different media and approaches, with each then providing different capabilities and learning for the designer or stakeholder. As such, they underline that some care should be taken to ensure that chosen approaches align with activity requirements; i.e. should a designer require exploration to identify potential solutions quickly, a flexible method with high accessibility.

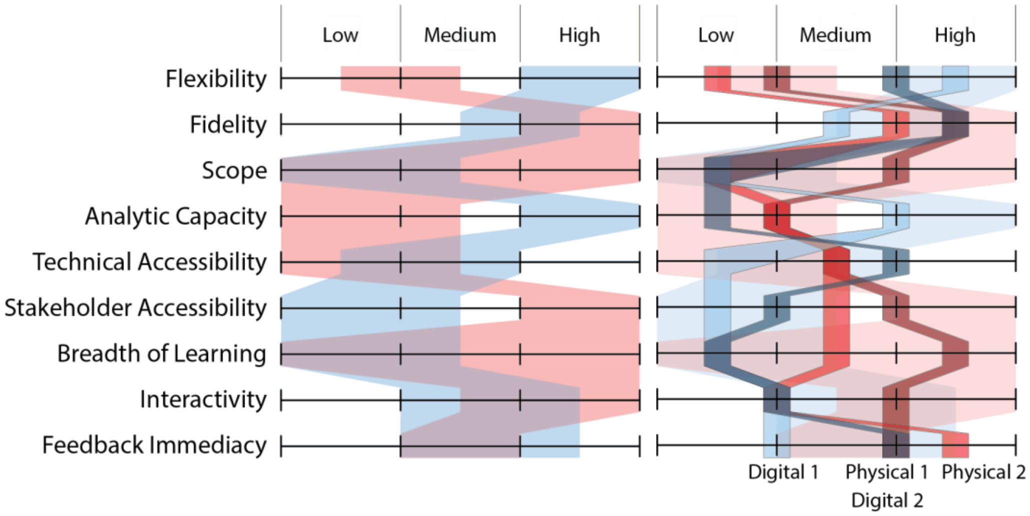
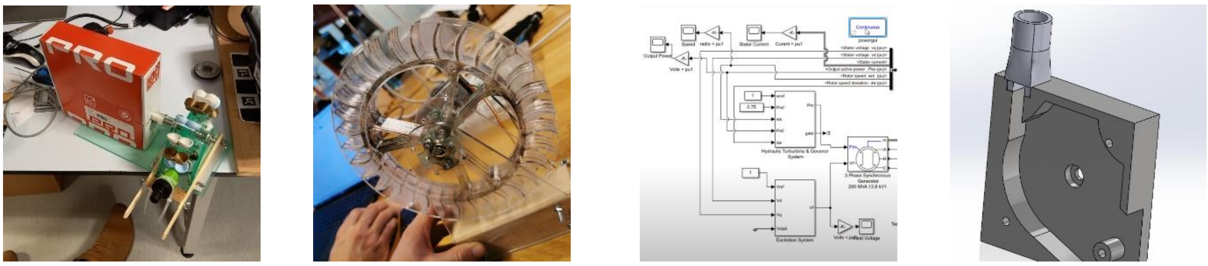


Figure 2. Corridor plots for (left) digital (blue) and physical (red) prototype classes; (right) Individual prototype cases. Light blue: D1; Dark blue: D2; Dark red: P1; Light red: P2.



Physical 1: Full system integration test

Physical 2: Assembly test for water wheel

Digital 1: Simulink model to test power generation

Digital 2: CAD geometry to develop component interface

Figure 3. Physical and digital prototypes classified against the framework

Looking specifically at the classified prototypes, there is a general alignment between each and the corridor plot that describes its class (i.e. the digital prototypes lie within the digital class boundary), to a degree verifying the posited benefits of each class found in literature. There is however some deviation, in that D2 demonstrated a very low analytic capability, and that P2 demonstrated a very low interactivity, both against the general capability of their respective classes. This indicates simply that while each media may favour certain affordances, the specific case in which they are ultimately applied will drive their utility. Understanding predisposition for specific media to provide certain affordances is useful to support selection, but should not be considered final or hard limits.

5.2 Discussion of the framework

The needs identified for this paper included the ability to compare and contrast prototyping approaches, to support efficient prototyping approach selection for industry, and to create direction for development of future prototyping tools and technologies.

General Discussion of the Framework: The categories of affordance identified here are entirely extracted from a wide body of extant literature. It is widely acknowledged that different prototyping approaches are appropriate for differing scenarios, but to date little attempt has been made to establish the generalised characteristics that make them so across all media and approaches. By extracting these categories, some direction may be set to better understand how the benefits designers receive from prototyping may vary, and hence be improved. While the categories are each widely discussed in literature, as presented here they are high level and overlook the subtly of each area. For example, the fidelity category should rightly comprise several forms of fidelity (McCurdy et al., 2006) each orthogonal to the others and forming its own sub-spectra. Refinement of categories is necessary to establish detailed and fully useful classifications. Similarly, the scales by which media are classified on each spectra should be investigated. Here, a low-medium-high spectrum was considered; for many this could be both more descriptive and more granular to create higher precision in classification. As-is, this framework demonstrates potential for utility, but requires further detailing before broader uptake.

Table 4. Affordance classification for prototyping activities

Affordance	Physical 1	Digital 1	Physical 2	Digital 2
Flexibility	**Low/med:** Specific purpose only, would require refabrication to change.	**High:** Allows quick change of components, variables, parameters.	**Low:** Specific purpose only.	**Med/High:** Minimal breadth, but scope for quick iteration.
Fidelity	**High:** Functionally and behaviourally realistic.	**Med:** Functional realism. Isolated to performance simulation.	**Med / High:** Functional, behavioural realism.	**High:** Geometrically accurate + as-final.
Scope	**Med/high:** Near-production, testing majority of systems.	**Low:** Isolated to specific sub-system.	**Low:** Isolated to single sub-system	**Low:** Isolated to single sub-assembly.
Analytic Capacity	**Low/med:** Allows function + behaviour testing, some organic evaluation.	**Med/high:** Detailed analysis, but subset of programmed behaviour.	**Low/med:** Testing of fit, + for performance	**Low:** Isolated to testing fit.
Technical accessibility	**Med:** Cheap components / materials. Some expertise for 3D printed parts.	**Low:** Expertise to create / operate; may be time-consuming or costly.	**Med:** Cheap, some expertise for laser cutting.	**Mid/High:** Some CAD expertise, but v. cheap + quick.
Stakeholder accessibility	**Med/High:** Diverse range can observe, but requires expertise to interpret.	**Low:** Requires expertise to interpret.	**Med:** Clearly interpretable, but technical in context.	**Low/Mid:** Simple to understand, but expertise to iterate.
Breadth of Learning	**Med/high:** Potentially broad across performance testing + assembly.	**Low:** Highly focused on specific behaviour + functional testing.	**Med:** Focused on fit, with organic learning from performance.	**Low:** Highly isolated on individual element.
Interactivity	**Med/High:** Specific behaviours, but organic interaction + abstraction.	**Low/Med:** Single point of interaction as part of standard operation.	**Low/Med:** Organic assembly interaction; limited when testing.	**Low/Med:** Visual/CAD interface only.
Feedback Immediacy	**Med/High:** Immediate performance feedback, but delay in time to creation.	**Low/Mid:** Once created, quick feedback. Slow to create (1-3hrs).	**High:** Evaluated immediately as assembled.	**Mid/High:** Some lag via construction, but minimal from testing.

Utility to understand, compare, and contrast prototyping media: By classifying inherent properties of media and prototyping approaches that cause them to tend towards certain values in each affordance, this framing then gives means to compare and contrast the capabilities of different media. Once detailed and robust assessment against each affordance is established, media may be weighed against one another for their specific capabilities, grouped into types suited for certain forms of activity, and prioritized according to the preferences of the designer. For example, with cost as the major driver for strategy selection (see Christie *et al.*, 2012), this framework could enable prioritization of media by this driver (under technical accessibility) while also weighing the cost/benefit of capability in each other affordance. Further, by auditing those approaches used in industry against the needs of the activity, detailed understanding may be built of how designers achieve their goals, and how their selection of approach helps (or hinders) their success.

Utility to support prototyping strategy and media selection: This naturally leads to support for better approach selection. Following population of a database of approaches against the affordances, designers may search, identify, and investigate potential approaches given the needs of their specific scenario, including weighing cost and benefit. For example, should they require high flexibility and high analytic capability, they may use these affordances to audit options and select those that are most suited to their needs. Given at present industry often claims there is no particular strategy to their selection (Goudswaard et al., 2021), this approach would allow them to confirm their expert intuition, or to identify alternative approaches to their typical ones that may bring enhanced or additional value, with close alignment to their specific needs.

Utility to support future media and tool development: Finally, with a broad body of knowledge of affordances across media, this framework may support development of future approaches. By identifying areas that few or no approaches enter, or opportunities for new approaches to bring benefits of multiple previous ones together, the framework provides a means to create direction for future tool development, find 'blind spots', find common weaknesses, and interrogate groups. A recent example of this lies in the emergence of mixed reality prototyping tools (Kent et al., 2021a; Snider et al., 2022), which combine several benefits of both physical and digital prototyping approaches into a single workflow, while also minimising weaknesses.

Future Work: This work has highlighted several areas for further development. While affordance categories are widely present in literature, they should be sub-divided and detailed with special attention paid to their assessment scales. Following this, a broad body of prototyping approaches should be classified using the framework firstly to verify broad applicability, and second to create a database by which the utilities discussed above may be operationalised. While classification is anticipated to be a research activity, it would ideally occur jointly with industry to ensure validity of interpretation.

6 CONCLUSIONS

While it is widely accepted that different prototyping approaches are better suited to different scenarios, the characteristics of the approaches that make them so are not well understood. This creates challenges when evaluating prototyping, when selecting appropriate strategies for a given case, and when developing future prototyping tools and technologies, as there is little clarity on how specific prototyping goals may be achieved or hindered by the prototyping approach chosen.

This paper fills this gap by synthesising nine categories of affordance present across all prototyping approaches, which allow detailed interrogation and classification of how their inherent properties influence the prototyping activity. It then illustrates utility by applying the framing to physical and digital classes of prototype and four individual prototypes, highlighting their affordances. This application indicates utility of the framework itself to interrogate approaches, and also highlights that approaches do indeed provide different benefits and limitations to the designer and the prototyping activity. As such, the framework developed in this paper is demonstrated to provide the means to deepen understanding of prototyping tools and technologies, support improved prototyping strategy selection, and to create direction for the development of future tools that further enhance prototyping activity.

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