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Accelerating product prototyping through hybrid methods: Coupling 3D printing and LEGO

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This paper introduces Hybrid Prototyping as a way to couple different prototyping methods; combining their complementary affordances and mitigating their limitations. To characterise and investigate this approach, a simulation-based study was conducted into the coupling of low-cost 3D printing and LEGO®. Key benefits hypothesised are reduced fabrication time and increased reconfigurability. Six primitive 3D shapes are simulated using a continuum of hypothetical brick sizes. Results show a reduction in fabrication time of 45% and a reconfigurability of 57% at the optimum. A case study highlights the compounded improvements over 3D printing for an iterative prototyping process. These findings mean that increases in prototyping iterations can be made due to reduced time and material costs, accelerating the product development process.

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Keywords: product development, design process, simulation, technology, prototyping

Prototyping is an essential part of the product development process and it is widely accepted that increased prototyping – both physical and virtual – leads to improved products (Camburn et al., 2017; Menold, Jablokow, & Simpson, 2017). Further benefits of prototyping include exploration of the design space (Dow, Glassco, & Kass, 2011; Hess & Summers, 2013) and learning about the design problem (Jensen, Elverum, & Steinert, 2017; Yang, 2005), supplementation of designers’ mental models (Gerber, 2009; Oxman & Planning, 2004; Viswanathan & Linsey, 2011), discovery of unexpected phenomena (Kiriyama & Yamamoto, 1998; Otto & Wood, 2001; Ward, Liker, Cristiano, & Sobek, 1995), and as boundary objects for communication (Boujut & Blanco, 2003; Buchenau & Suri, 2000; Carlile, 2002).

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Correspondingly, a multitude of prototyping tools and methods have been developed specifically to support form-based prototyping in the early stages
of the design process. Examples include 3D printing enabling designers to physically interact with their designs (Das, 2004; Neeley, Lim, Zhu, & Yang, 2013), the use of cardboard prototypes (James Dyson Foundation, 2010; Kim, 2009), and using construction kits to engage with non-technical stakeholders and foster co-design (Boa, Mathias, & Hicks, 2017; Garde & van der Voort, 2016).

For designers, there is a trade-off between quality and time when choosing between tools and methods (Sass & Oxman, 2006). Furthermore, it has been shown that these tools and methods possess varying strengths and weaknesses making them more suited to different stages of the product development process and particular design tasks (Mathias, Hicks, Snider, & Ranscombe, 2018). More generally, the tools and methods can be considered to lie on a spectrum from high fidelity/slow fabrication/low flexibility, to low fidelity/rapid fabrication/high flexibility (See Figure 1).

Examples of tools and methods at opposite ends of the spectrum include additive and subtractive manufacturing methods versus cardboard modelling and Meccano® construction kits. These are described in detail in Section 1.1. While previous work has investigated individual prototyping methods this paper considers the coupling of different methods with the aim of combining the complementary affordances of each. To investigate the potential of coupling, two prototyping methods are considered that occupy different ends of the spectrum. These are low cost 3D printing and LEGO® construction kits. These methods also possess some common properties which makes

![Figure 1 A diagram showing common physical prototyping techniques occupying a spectrum of fidelity, reconfigurability and skill level. Clay Modelling image from https://commons.wikimedia.org/wiki/File:Renault_clay_model_-_front.JPG](https://commons.wikimedia.org/wiki/File:Renault_clay_model_-_front.JPG)
their coupling more straightforward. These include the construction materials and the level of tolerance required/achievable. It follows that the focus of this paper is on the investigation of affordances of coupling prototyping methods, rather than methods of connection or integration and, as a result, other combinations of prototyping materials are equally valid for in-depth study.

Previous work by Mathias et al. (2018) has shown that LEGO® offers flexibility and ease of use without getting fixated on producing a high fidelity prototype, while low cost 3D printing methods have been developed with the specific aim of producing high fidelity form-based prototypes (Conner, Manogharan, & Meyers, 2015).

Given the findings of the extant studies, it can be asserted that the coupling of low cost 3D printing with LEGO® could yield benefits. Two key benefits are identified:

1. Reduced fabrication time for iterations of prototypes through modular construction and reduced 3D printing volume. 3D printing is slow and so by reducing the amount that is printed provides opportunities for decreasing the fabrication times.
2. Reconfigurability of prototyping through the reuse of existing parts and fabrication of alternative parts that can be used interchangeably to modify form or features in successive prototype iterations.

In each case, scope exists to reduce time commitment of the prototyping design-build-test cycle, where rapid cycles are known to be key in effective prototyping usage (Camburn et al., 2015; Gerber & Carroll, 2012; Neeley et al., 2013; Thomke, 1998). Further, the re-use of prototyping materials allows potential reduction in prototyping cost and the development of reconfigurable, modular prototypes, again increasing the benefits that may be gained from the prototyping process.

A potential third benefit is the affordance given to designers engaging physically with their designs and the design process and allowing them to ‘design by-hand’. This benefit builds on Sass and Oxman’s (2006) proposed methodological framework for integrating physical rapid prototyping into the design process and helps bridge the gap between conceptual design and physical fabrication. However, investigation into this potential benefit is out of scope for this paper but is considered in future work.

To investigate if, and characterise how, coupling can accelerate the product development process we formulate the problem as a simulation such that we can explore overall fabrication time, potential levels of reuse, and the impact of different scales of LEGO® on these.
The paper begins with an overview of prototyping and the relative affordances and limitations of different methods. The rationale for selecting FDM and LEGO® is stated, and the expected benefits are summarised. The methodology, including the framing of the problem as a simulation, and the variables investigated are then described in which a range of primitive and complex forms are studied. Following presentation of the results of the simulations, the paper concludes with the key findings, a characterisation and challenges of the affordances of hybrid methods and a reflection on the opportunities of coupling other prototyping methods.

1 Background
This section provides an overview of prototyping in the product development process, before focussing on physical prototyping and the opportunities for improvement. The affordances and limitations of common prototyping methods are described. From this the rationale for coupling FDM printing and LEGO® and the expected benefits are developed.

1.1 Prototyping in product development
Prototyping is a critical activity in the product development process (Wall, Ulrich, & Flowers, 1992) and can be described as the “activity of engaging with the product-to-be, instantiating the design process” (Camere & Bordegoni, 2016). Prototyping encourages learning in the design process and provides decision variables – helping designers answer specific design questions while also giving rise to new ones (Jensen et al., 2017; Menold et al., 2017; Yang, 2005). Prototyping has four distinct purposes – Learning, Communication, Integration, and Milestones - within the product development process (Ulrich & Eppinger, 2016). Similarly, Ullman (2003) defines four uses of prototypes based on their role; Proof-of-Concept, Proof-of-Product, Proof-of-Process, and Proof-of-Production. All of these different purposes require different types of prototypes and approaches to prototyping. The properties and characteristics of a Milestone or Proof-of-Production prototype area far closer embodiment of the final product (in every dimension) than those of a Learning or Proof-of-Concept prototype. Several taxonomies have been developed to classify these different properties and characteristics. These classifications include:

- Investigation of the form versus function of the prototype (Buchena & Suri, 2000; Hallgrimsson, 2012; Pei, Campbell, & Evans, 2011).
- The tools and methods used to embody the prototype (Blomkvist & Holmlid, 2011; Deininger et al., 2017; Mathias et al., 2018; Ulrich & Eppinger, 2016).
- The level of fidelity that the prototype achieves (Jensen, Nissen, Bilde, & Özkil, 2018; Lim, Stolterman, & Tenenberg, 2008).
Although prototyping can be used to design services (and software), this study will be focussing on discrete, physical products that have to be designed and manufactured. Ulrich and Eppinger (2016) state that products lie between two ends of a continuum: technology-driven products at one end; and user-driven products at the other. These are defined as follows:

- **Technology-driven** products - the core tenet of these products is based on technology, or ability to achieve a particular technical task. These products are predominantly bought for their technical performance, rather than aesthetic or ergonomic requirements.
- **User-driven** products - the benefit of these products is generated from functionality of interfaces and aesthetic appeal. There is usually a high degree of user interaction with these products, and the external appearance is used to differentiate between competitors. User-driven products can be technically sophisticated; however, this is not usually a differentiator.

Examples of technology-driven products include desktop computers and bicycle tires, while user-driven include video game controllers and reusable coffee cups.

In the design of user-driven products, the user interaction and form of the design is a critical component for their success. Correspondingly, eliciting stakeholder and customer feedback over multiple iterations allows designers to enact and develop their input into subsequent iterations.

McCurdy, Connors, Pyrzak, Kanefsky, and Vera (2006) state that the “the current range of prototyping methodologies are generally described within a spectrum of fidelity.” Typically, low fidelity prototypes (such as sketches or junk models) are low-cost and created quickly to help inform and learn about the design, while high fidelity prototypes (such as highly finished, detailed foam models, or coloured 3D prints) require significant effort to produce and are used to demonstrate and communicate designs. Generally, the higher the fidelity of the representation, the more skill and time is required to create it. Higher fidelity prototypes may force the designer to make additional decisions about design details in order to achieve the desired level of fidelity.

Sauer and Sonderegger (2009) and Jensen et al. (2018) found that prototype quality and fidelity played an important role in how stakeholders perceived the design. This is not limited to physical prototypes, for example, Macomber and Yang (2011) investigated how sketch quality influenced stakeholder feedback and found that realistic and clean sketches were ranked higher than rough sketches. Furthermore, Camburn et al. (2017) state that higher fidelity representations lead to accurate interpretation of the design.
Consequentially, in the design of user-driven products, high fidelity prototypes are required to elicit useful stakeholder and user feedback on the design. However (Jensen et al., 2018), state that low fidelity prototypes are still valuable as they provide a high design insight to cost/time ratio. As a result, low fidelity prototyping can support a greater number of design iterations within the same budget constraints. For these reasons, low fidelity prototyping is still widely used in the early stages of the design process — largely because there are few, if any, approaches that offer higher fidelity at similar cost or time.

According to Hallgrimsson (2012), prototyping methods are chosen based on three aspects:

- **Purpose** — *looks-like* versus *works-like* prototypes, what is sufficient to answer the design questions?
- **Effectiveness** — Level of fidelity/precision required? How easy it is to build/change?
- **Appropriateness** — Is the prototype suitable for the audience?

In addition, Hallgrimsson states that designers should consider the available tools and materials, as well as their own experience in using the different methods.

In the design of user-driven products, frequently the form and shape of the design are the focus of the prototyping efforts (*looks-like* prototypes), with the stakeholders and users as the target audience. The purpose of these prototypes is to evaluate and elicit feedback on the overall form, ergonomics and usability.

However, part of the decision in choosing prototyping methods is the level of required fidelity. Where construction kits and cardboard can be used to quickly create a primitive design representation, while foam modelling or 3D printing take time to produce higher fidelity prototypes.

### 1.2 Physical prototyping

Many forms of prototypes are used in the design of physical products (Ulrich & Eppinger, 2016); from sketches and CAD models, through to cardboard mock ups and fully-functional prototypes. While sketching and virtual techniques are ubiquitous in the design process, the importance and benefit of physical prototyping cannot be understated — with more tangible prototypes facilitating creativity, interaction and communication for both users and designers (Donati & Vignoli, 2015).

In *user-driven* products, having a tangible, physical prototype that users and designers can interact with, not only allows the overall form to be evaluated,
but also the ergonomics and interactions in an intuitive way. Correspondingly, this study will be considering physical techniques that are used to prototype the form of user-driven products.

Common physical prototyping techniques for early stage design include: Construction Kits, Foam and Cardboard Modelling, Clay Modelling, and Low-Cost 3D Printing. These methods occupy a spectrum of fidelity, reconfigurability, and skill level, shown in Figure 1.

At one end of the spectrum are construction kits, such as LEGO®. These are good for exploring design concepts and engaging stakeholders (Garde & van der Voort, 2016; The LEGO Group, 2013).Due to the modular and reconfigurable nature of construction kits, the skill threshold is very low and modifications to designs are quick and easy to make. However, the resulting prototypes are blocky and low fidelity with very limited scope for the creation of even simple, curved surfaces, with the exception of bespoke LEGO® components. As a consequence, cardboard and foam are frequently used to represent the form of a design (Hallgrimsson, 2012; James Dyson Foundation, 2010) as they are also low cost, workable and easily finished. While organic shapes are more easily achieved with foam modelling, it is hard to be precise and achieve the desired form without the sufficient experience and extensive use of templates and jigs (Hallgrimsson, 2012).

In addition to cardboard and foam, clay modelling is another prototyping technique, used particularly in the automotive industry (Singh, 2006), where its affordances for creating smooth, complex, curved surfaces see it employed in the design of the form of the car. With a skilled designer, clay prototypes can be high fidelity but are very time-consuming to produce and change. In the context of automotive design, these prototypes are used to gain stakeholder feedback on aesthetics and to perform preliminary testing.

At the other end of the spectrum is low cost 3D printing, such as desktop material extrusion printing. This technique affords the fabrication of high fidelity designs with complex geometry and features with the trade-off of slow print times (Cassaignau, Core-Baillais, de Wargny, & Lonjon, 2016). While cheaper than traditional manufacturing techniques (e.g. CNC machining), the cost of materials is high compared to the other prototyping techniques such as cardboard (Redwood, Schoffer, & Garret, 2017). The use of low cost 3D printing does require a high level of competency with CAD software or access to an existing library of designs (Goudswaard, Hicks, Gopsill, & Nassehi, 2017). Furthermore, once printed, the design is fixed and cannot be easily modified without changing the digital model and reprinting.
As this spectrum shows, there is no single technique that affords high fidelity prototypes, and that can be rapidly fabricated with some flexibility (i.e. edit-able and reconfigurable).

1.3 Coupling low cost 3D printing and LEGO®
Most attempts at improving prototyping have focussed around heuristic prototyping frameworks that help direct the prototyping strategies and efforts (Camburn et al., 2017; Menold et al., 2017) — i.e. what methods to employ, when to apply them and how best to use them. For example, designers can be more innovative by strategically implementing fast and cheap prototyping methods (Viswanathan & Linsey, 2010). However, the two biggest factors hindering the use of physical prototypes in the design process is the cost and the time required to produce them (Camburn et al., 2015; Otto & Wood, 2001).

Proposed methods to overcome the issues of prototyping around fabrication time, cost, fidelity, and flexibility include: editable physical models (Lennings, Broek, Horváth, Sleijffers, & de Smit, 2000); the use and reuse of existing products or components (Camburn et al., 2017); speed up 3D printing through wire printing and laser cutting by sacrificing fidelity (Beyer, Gurevich, Mueller, Chen, & Baudisch, 2015; Mueller, Im, et al., 2014). Furthermore, methods for adapting LEGO® to be more suited to higher fidelity prototyping have been presented (Boa et al., 2017).

Another approach to improving prototyping could be to couple different techniques to merge their complementary affordances while mitigating their limitations. There are several combinations that could be investigated including foam modelling and laser cut sheets, or cardboard and CNC machining. In addition to occupying opposite ends of the spectrum (see Figure 1), LEGO® and low cost 3D printing were chosen as these methods possess some common properties which makes their coupling more straightforward. These include the construction materials and the level of tolerance required/achievable. Furthermore, they do not require health and safety precautions to work with (i.e. management of dust/swarf from CNC machining and foam modelling, or fumes from laser cutters) and do not require tools (i.e. knives/abrasives/glue for modelling foam or cardboard) or expensive machines. Finally, LEGO® is reusable and reconfigurable therefore minimising waste of materials.

Coupling low cost 3D printing and LEGO® introduces a level of fidelity un-achievable by LEGO® alone while maintaining the flexibility and reconfigurability of a construction kit. It affords rapid ideation and modification with a physical prototype to avoid breaking user studies or creative episodes. The approach characterised in this paper takes one of several potential avenues for coupling low cost 3D printing and LEGO®. The chosen avenue is a
volumetric one that uses LEGO® to occupy the internal volume of a prototype, with 3D printing providing high-fidelity surfaces to attach onto the LEGO®. There are parallels with CNC machining where the LEGO® is a ‘rough cut’—forming the quick, approximate shape, and the 3D printing is a ‘finishing pass’—creating high fidelity detail more slowly.

Previous work on coupling low cost 3D printing and LEGO® (Mueller, Mohr, Guenther, Frohnhofen, & Baudisch, 2014) only considered the fabrication time in two case studies in a demonstration of the technology. The novelty in the paper we present is that it is the first to quantify and characterise the benefits of coupling prototyping methods. It investigates the fabrication time in more detail, as well as the effect of brick-to-object scale, and how the reusability and reconfigurability can affect the cost of successive prototyping iterations.

2 Methodology
A computer simulation approach was used to investigate coupling of low cost 3D printing and LEGO® as it is a deterministic problem with a large number of variations to consider. As a result, no variance in simulation results can occur from repetition, and each simulation need only be run once (i.e. there is no need to investigate variance which is present with user studies). Furthermore, the cognitive aspects and physical affordances of user focussed prototyping is beyond the scope this paper making simulations a suitable experimental method.

Following a preliminary investigation, the results were implemented in a looks-like prototype for a video game controller (see Section 4.3). The iterative case study helps to illustrate the potential benefits of coupling building blocks and low-cost 3D printing across multiple iterations of the design.

2.1 Metrics
The correlation between the number of prototypes and performance is widely acknowledged. Neeley et al. (2013) showed that participants that created more prototype iterations “performed better, and showed significantly greater improvement between iterations”. Dow (2011) describes how iterating in parallel - creating multiple alternatives — helps reduce fixation, discourages emotional investment, and encourages candid discussions between design team members. Furthermore, Camburn et al. (2017) provide evidence that it is critical to prototype multiple iterations in the early phases of the design process.

Therefore, making prototyping iterations quicker and/or cheaper allows more iterations to be developed and explored within the time and cost constraints of the design process.
Consequentially, the two key metrics that we are investigating in this study are the total fabrication time and the reconfigurability of a prototype. Table 1 explains the importance and benefits of studying these two metrics.

2.1.1 Calculation of metrics

When creating looks-like prototypes of user-driven products, they will usually be built as a solid form (Hallgrimsson, 2012). As this paper is focusing on this class of prototypes, it is valid to assume that the low-cost 3D printed prototypes will be solid models.

Optimising FDM printing for speed of printing is out of scope of this paper – there are many variables to consider, including layer-height, sparse infill percentage and head movement speeds, all of which can have significant impact on the print time (and output quality). As looks-like prototypes only need to be strong enough to be handled, the recommended infill percentage is between 10 and 20%. Alteration within this range will not drastically alter the print time (Álvarez, Lagos, & Aizpun, 2016).

For the study described in the paper, Cura (Ultimaker, 2018), a 3D printing slicing tool was used. The default print settings were used throughout. These settings were as follows: 0.15 mm layer height, 18% infill, and 60 mm/s print speed.

To calculate the total fabrication time, the rates of 3D printing and LEGO® assembly need to be estimated. The print time per unit volume was estimated by calculating the print time for a range of different objects. Figure 2 shows the relationship between the volume of different shapes and their respective print times. For a general estimate of Print Rate for calculating the fabrication times a linear function was fitted. The Print Rate \( R_P \), as time per unit volume, was found to be \( 8.328 \times 10^{-2} \text{s/mm}^3 \).

<table>
<thead>
<tr>
<th>Metric</th>
<th>Definition</th>
<th>Importance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fabrication Time</td>
<td>The length of time it takes to fabricate a prototype.</td>
<td>A shorter fabrication time leads to more prototyping through faster, compressed, design iterations influencing learning and the quality of the final product. It also reduces product development costs.</td>
</tr>
<tr>
<td>Reconfigurability</td>
<td>The ability to reuse or edit parts of a prototype.</td>
<td>A reconfigurable prototype reduces material wastage, improves resource utilisation and speeds up fabrication, and supports thinking-speed exploration of design alternatives. High reconfigurability enables rapid modification and lower resource use.</td>
</tr>
</tbody>
</table>

Table 1 Metrics studied in the simulations

Accelerating product prototyping through hybrid methods
Although the fit of the line is good ($R^2 = 0.99$), it is worth noting that there appears to be some non-linearity. This is likely due to the relationship between surface area and volume of printed parts as the perimeters of each layer are slower than the infill to print. So, in smaller parts that have a larger surface area to volume ratio, the perimeter printing becomes more significant.

The Print Rate was used in Equation (1) when calculating the print times for the objects:

$$ \frac{T_p}{V_o} = \frac{V_o}{C_0 V_B} R_p^\frac{1}{3} $$

where $T_p$ is the object print time, $V_o$ is the volume of the object, $V_B$ is the volume of all the bricks used and $R_p$ is the print rate.

The total fabrication time for a prototype is the sum of print times (for the printed parts) and the assembly times (for the LEGO® parts). However, there was no existing literature or sources on average LEGO® assembly times. The assembly time per brick was, therefore, estimated experimentally. 14 participants were asked to build a model rover out of 17 LEGO® bricks.

Table 2 shows the results from this experiment and shows that the Assembly Rate ($R_a$), as time per brick, is 18.33 s/brick. One assumption that has been made is that the assembly rate is independent of the size of brick. This value was used when calculating how long it would take to assemble the LEGO® portions of the prototypes:
where \( T_B \) is the brick assembly time, \( N_B \) is the number of bricks, and \( R_a \) is the assembly rate. Therefore, the total fabrication time is given by:

\[
T_f = T_B + T_p
\]

where \( T_f \) is the total fabrication time of the prototype, and \( T_B \) and \( T_p \) are defined in Equations (1) and (2).

The metric of reconfigurability considers how much of a prototype instance can be reused or reconfigured into another prototype instance. The assumption here is that only building blocks can be reconfigured into a new prototype iteration while none of the 3D printed parts can be reused. However, in practice it is possible that some of the 3D printed parts could be reconfigured and reused between iterations.

The measure of reconfigurability is based on the volume of the design. The mass of the prototype is difficult to estimate as the building blocks and 3D printed parts will have different densities (and be dependent on the print settings used). As a result, it is difficult to calculate the reconfigurability based on mass. Correspondingly, a volume-based approach is adopted for comparisons between prototype iterations.

This was measured as the proportion of the object that was constructed from construction kit bricks, expressed as a percentage.

\[
P = \frac{V_B}{V_o} \times 100
\]

where \( P \) is the brick proportion percentage, \( V_o \) is the volume of the object, and \( V_B \) is the volume of all the bricks used.

2.1.2 Data collected
In order to calculate Equations (1)–(4), three values were recorded for each simulation:

- \( V_o \) – Volume of the object.
- \( V_B \) – Volume of bricks used.
- \( N_B \) - Brick count – including the overall count and brick type counts.
The volume of the object was calculated using in built software functions. The volume of the LEGO® bricks was the simple summation of the cuboid volumes of each of the bricks used. To get the overall brick count, the numbers of each brick type were summed together.

2.2 Variables

There are several different variables that could be considered when investigating hybrid prototyping methods. At a high level these include; prototype design purpose, level of prototype functionality, and complexity of objects. However, these are challenging to measure and difficult to simulate in a robust and repeatable manner. Consequentially, to investigate the affordances, three key independent variables were identified: the object shapes, size of the objects, and the sizes of bricks. A corollary variable that related the size of objects to the size of the bricks was also used.

Table 3 shows the four variables that were chosen to be changed between the simulations. The following sections describe these variables.

2.2.1 Object shapes

The first independent variable altered over the course of the simulations was object shape. The 3D shapes chosen for the simulation runs were taken from Constructive Solid Geometry (CSG) Modelling (Requicha & Voelcker, 1977). The primary axiom of CSG Modelling is that any shape can be generated through the combination of simple primitives, and thus these primitives are justified as the base objects for the construction of any form-based prototype. These primitives consisted of: Cube, Cylinder, Cone, Sphere, Tetrahedron and Triangular Prism. Figure 3 shows the six different primitives.

The use of primitive shapes covered most types of geometry that are found in more complex designs: planar surfaces (Cube, Tetrahedron, Triangular Prism), orthogonal geometry (Cube, Cylinder, Triangular Prism), non-orthogonal (Tetrahedron, Triangular Prism), single curvature surfaces (Cylinder, Cone) and double curvature surfaces (Sphere). As we are investigating coupling 3D printing and construction kits more generally and these

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Object Shapes</td>
<td>The 3D geometric shape of the object</td>
<td>Cube, Cylinder, Cone, Sphere, Tetrahedron and Triangular Prism</td>
</tr>
<tr>
<td>Object Size</td>
<td>The volume of the object</td>
<td>1 \times 10^3 - 8 \times 10^3 \text{ mm}^3</td>
</tr>
<tr>
<td>Construction Kits</td>
<td>The different scales of construction kit used</td>
<td>NANO Blocks, LEGO®, DUPLO®</td>
</tr>
<tr>
<td>Brick-to-Object Ratio</td>
<td>Normalised ratio of brick to object volume</td>
<td>0 &lt; r \leq 1, where 1 would be using brick the same volume as the object</td>
</tr>
</tbody>
</table>
geometries are frequently combined into more complex shapes, the results presented do not consider the primitives individually. Rather the medians of the results of simulations for all six primitives are taken.

2.2.2 Object sizes
The second variable was the size of the objects. The reason for exploring different object sizes is that we expect different levels of benefit of hybrid method prototyping depending on the ratio of prototype size to the brick size. Such that there will be a trade-off between LEGO® proportion percentage and the total fabrication time for ratios of prototype to brick sizes.

The ratio of object to brick size was initially described by keeping the construction kit size fixed and varying the object size. The volume of the objects was varied over a range of $1 \times 10^3 - 8 \times 10^3 \text{mm}^3$. These volumes were used as they are within the bounds of feasibility for most commercially available desktop low cost 3D printers—such as the Ultimaker 3 ($9.42 \times 10^3 \text{mm}^3$ (Ultimaker, 2018)) and Makerbot Replicator + ($9.45 \times 10^3 \text{mm}^3$ (MakerBot Industries, 2018)). The simulations were stepped 50 times over this volume range. This was then repeated for each of the object shapes, and each of the sizes of brick.

2.2.3 Sizes of construction kit bricks
The third variable was the different sizes of bricks that were used. By changing the relative size of the bricks with the object, the effect of scale on fabrication times and flexibility could be explored. The initial brick size was LEGO® with dimensions of $8 \times 8 \times 3.2 \text{mm}$. For these simulations, a pool of standard bricks could be used to reduce the overall brick count (see Section 3.3.2). Smaller and larger bricks were considered either side of LEGO®, these include NANO ($4 \times 4 \times 3.2 \text{mm}$) and DUPLO® ($16 \times 16 \times 19.2 \text{mm}$). The use of different sizes of brick affords different levels of fidelity, with the expectation that the smaller bricks will allow a better approximation of more complex geometry. For the purposes of this paper a continuum of brick sizes is considered, and the three instances of NANO, LEGO® and DUPLO® are used as reference points.
The comparisons of brick sizes can be seen in Figure 4. The interface between different construction kits forms a design consideration that is out of scope of this paper.

2.2.4 Normalised brick-to-object ratios
There are issues associated with fixing object dimensions to the limited number of dimensions of available brick sizes — this can be addressed by generating a brick-to-object size ratio. It affords more robust comparisons between the primitive shapes and a better insight into how the ratio between brick volume and object volume affects the level of reconfigurability and fabrication time. In the simulations using these ratios, the object size is fixed, and a hypothetical brick size is created using the brick-to-object ratio. The brick-to-object ratios ranged from $1 \times 10^{-4} : 1$ to $1 \times 10^{-2} : 1$.

3 Implementation
3.1 Overall process
The overall process for the simulations is shown in Figure 5. The simulations are repeated for each of the six primitives (see Figure 3) and over the range of sizes and ratios (see Section 2.2.2).

Each of the six primitive shapes in the overall process undergoes simulations for a range of brick sizes. For the selected brick size, the intersection calculations are performed to generate the locations of the bricks inside the shape. The brick packing is then performed to fit the standard library of bricks (see Figure 6). The data from the simulation is outputted before selecting the next size. This process is repeated for all the primitives and all the sizes.

3.2 Software platform
The free and open source 3D computer graphics software, Blender 2.79 (Blender Foundation, 2018), was chosen as the software platform. Other 3D modeller such as Rhino 6 (McNeel Europe, 2018) or Autodesk 3DS Max (Autodesk Inc., 2019) could have been used, however Blender was used for two main reasons:

Figure 4 Comparison of the three sizes of construction kit brick
It has an extensive and well-documented Python-based API that allows Blender’s powerful functions (such as ray intersection, 3D volume calculations, Boolean operations on 3D objects) to be leveraged programmatically.

Figure 5 A flow diagram of the overall simulation process

Figure 6 The library of standard LEGO® bricks

Accelerating product prototyping through hybrid methods
It is well suited to handling mesh data, such as STL files, and manipulating them.

The scripts were written as Blender Add-ons in Python 3, making use of the Blender API to create a Graphical User Interface (GUI) to interact with and set up the simulations.

3.3 Simulation calculations
The two main calculations that are performed in the simulations are outlined in the following sections and include intersections and packing.

3.3.1 Intersection calculation
In order to generate the locations of bricks inside the object, the bricks’ intersections need to be calculated. The calculation algorithm employed is a variant of the discrete voxel approach described by Nooruddin and Turk (2003) — using parity count ray casts to determine whether a point is inside an object or not. However, to improve the reliability the rays were cast along each of the edges of a brick (ignoring the stud) and from the centre of the brick. This provides a more robust result that could also be used for thresholding the level of brick intersection.

A 3D array, of size $N \times M \times O$, was generated using the brick and object bounding box dimensions where each element represented a brick in 3D space. The intersection calculation was performed on each element (brick) in the array to return it as Boolean, showing whether each brick was inside the object or not.

3.3.2 Brick packing algorithm
Brick packing was applied in the simulations to reduce the overall brick count. This could be achieved as there are standard libraries of bricks (shown in Figure 6) that are discrete combinations of the base brick. The brick packing optimisation was applied to combine the bricks in the 3D array (from the intersection calculations) into bricks from the standard library.

Using this set of bricks, a first-fit decreasing bin-packing algorithm was used that tried to fit the largest brick (i.e. a $2 \times 6$ LEGO brick in Figure 6) down to the smallest (i.e. a $2 \times 1$ LEGO plate in Figure 6). Before decreasing the brick size, the brick was rotated $90^\circ$ to test if it fitted in an orthogonal direction. This bin-packing process was repeated until no more bricks could be fitted. DUPLO® and NANO have similar standard libraries of bricks and so their implementation was identical to that of LEGO®.

No optimisations of brick packing arrangement are performed in the simulations. While optimising for layout, strength and ease of printing are important
from a practical perspective, for the theoretical studies conducted idealised results reflect limits, and hence bounds on potential benefits. Furthermore, performing these optimisations is computationally expensive due to the large number of possible brick arrangements (Gopsill, 2018).

### 3.4 Simulation output

This section shows an example output from the simulation to illustrate what the results mean in context of the physical objects. Figure 7 shows the simulation run on three identical cones using NANO, LEGO® and DUPLO®. The coloured bricks are the reconfigurable proportion of the cone, while the remaining grey volume is 3D printed to interface with the bricks and provide a high-fidelity surface. Table 4 shows the numerical results from the simulation of the three instances.

### 4 Results

This section presents the results of the simulations with respect to fabrication time and reconfigurability. This is supplemented by an illustrative example of coupling low cost 3D printing and LEGO® highlighting improvements over

<table>
<thead>
<tr>
<th>Cone Volume/ mm³</th>
<th>Brick Proportion</th>
<th>Brick Count</th>
<th>Fab Time (build + print)/s</th>
<th>Cone Print Time/s</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>DUPLO® 2.6×10⁻⁵</td>
<td>15.0%</td>
<td>2</td>
<td>18540 (60 + 18 480)</td>
<td>21780</td>
<td>−15%</td>
</tr>
<tr>
<td>LEGO®</td>
<td>67.9%</td>
<td>152</td>
<td>9780 (2760 + 7020)</td>
<td>55%</td>
<td></td>
</tr>
<tr>
<td>NANO</td>
<td>80.1%</td>
<td>4097</td>
<td>79 380 (75120 + 4320)</td>
<td>264%</td>
<td></td>
</tr>
</tbody>
</table>
purely 3D printing over iterative prototyping process of a video game controller.

4.1 Fabrication time

The total fabrication time is given by the LEGO® assembly time and the print time of the outside surface (see Equation (3)). The simulations were run over the 50 object sizes for each of the six primitives — using the three sizes of brick (see Figure 4). Figure 8 shows the simulation results of total fabrication time (brick assembly time + shell print time) against object volume. A reference line for 3D printing the entire object is also plotted. As can be seen, there is a significant difference between the total fabrication time for the three sizes of bricks. The use of NANO bricks resulted in a slower fabrication time than just printing the object. While coupling with LEGO® bricks saw the greatest improvement in fabrication time. However, it is apparent that there is a trade off between brick size and object volume — with the larger DUPLO® bricks performing worse than the LEGO®.

This trade off was investigated further by adjusting the simulations to run varying brick sizes against fixed sized objects giving a continuous brick-to-object ratio between $1 \times 10^{-4} : 1$ to $1 \times 10^{-2} : 1$. The resulting fabrication time was normalised against the time it would take to 3D print the entire object. These simulations were run on the same six primitives over a range of 200 brick-to-object ratios. Furthermore, successive simulations of each primitive in different orientations were performed to avoid any potential issues where the orientation could affect the results.

![Figure 8 A plot showing the total fabrication time against the object volume for the three brick sizes, a reference line for solely printing the object is included](image)
Figure 9 shows the median and interquartile range of the fabrication time difference for the range of brick-to-object ratios simulated. For the size and dimensions of the primitives used, reference points of NANO and LEGO® bricks are shown to contextualise the findings (DUPLO® bricks are beyond the data range plotted). It shows that as the brick-to-object ratio gets smaller (i.e. smaller bricks for the same object) the fabrication time becomes shorter, until the ratio is too small (i.e. very small bricks) when the fabrication time rapidly rises above that of 3D printing the entire object due to the increased assembly time. The step changes in time difference arise from packing bricks of one discrete size into a fixed 3D form followed by bricks of a slightly larger size. In some cases, the bricks fit well, occupying most of the space (larger reduction in fabrication time due to less printing), then a small change in brick size means that they cannot pack as many in (smaller reduction in fabrication time due to a larger proportion being printed).

Based on the median line, the optimum brick-to-object ratio is \((4 \times 10^{-4})/1\) for the objects investigated in this study — achieving a 45% reduction in fabrication time. Thus, when using hybrid prototyping brick-to-object ratios of this order should be selected to minimise fabrication time. To contextualise this with a typical 3Dprint (100 \times 100 \times 100 mm dimensions, \(1 \times 10^6 \text{ mm}^3\) volume), the optimum ratio gives an optimum brick size of 10 \times 10 \times 4 mm which is smaller than a DUPLO® brick (16 \times 16 \times 19.2 mm) but only slightly larger than a LEGO® brick (8 \times 8 \times 3.2 mm).

4.2 Reusability
The reusability of a prototype is the amount that can be reused in another prototyping instance. Figure 10 shows the reusability (measured as brick
proportion percentage — see Equation (4)) against the object volume for the three brick sizes. As expected, when the object size increases the approximation of the geometry improved across all the brick sizes used. NANO Bricks performed the best, and DUPLO® the worst. This implied that using smaller bricks (compared to object size) would result in a greater proportion of the prototype constructed from bricks and so have a greater level of reusability.

After the initial simulation using discrete brick sizes and varying the object size, the object-to-brick ratio was varied while keeping the objects at a fixed size. As in Figure 9, the six primitives were used over the 200 ratios. Figure 11 shows boxplots of the brick proportion percentage for each of these ratios. For the size and dimensions of the primitives used, reference points of NANO and LEGO® bricks are shown to contextualise the findings (DUPLO® bricks are beyond the data range plotted).

This confirmed the findings from the initial simulations in Figure 10 — that as the brick-to-object ratio decreases (object gets bigger, or bricks get smaller) then the brick proportion tends to 100%. This, therefore, means that the level of reusability is higher, and less material is required to print the remainder of the object (See Figure 7). To create a more reusable prototype the brick-to-object ratio must be as small as possible.

To maximise prototype reusability and minimise fabrication speed, the brick-to-object ratios need to be selected at the ideal ratio — which becomes dependent on fabrication speed as the reusability tends to 100% with smaller bricks.
Using the optimum fabrication time ratio found in Section 4.1, the reusability is 55%.

### 4.3 Iterative case study
To illustrate how coupling 3D printing and LEGO® construction kits could be used when prototyping a design, four iterations of the design for a video game controller were simulated. Figure 12 shows the four design iterations with increasing details and geometric complexity as the design progresses.

LEGO® bricks were used as the brick size in the simulations for each of the iterations. Figure 13 shows the results comparing using hybrid methods and solely 3D printing for each iteration. The print settings were kept at 0.15 mm layer height, 18% infill, and 60 mm/s print speed (see Section 2.1). It shows that there is a clear time saving in using a hybrid approach over 3D printing each iteration.

To better highlight how this time and material saving accumulates over successive iterations, a comparison of cumulative 3D filament material usage and time cost were plotted. These are shown in Figure 14.
Table 5 shows the total material usage and time cost for the four iterations combined. Hybrid prototyping shows significant time and material savings of 56.4% and 68.2% respectively. This demonstrates that by using a hybrid approach to form-based prototyping the design process can be more efficient.

5 Discussion
This section discusses the key findings and validity of results of coupling low cost 3D printing and LEGO® construction kits, the affordances of hybrid...
prototyping, and the opportunities of coupling other prototyping methods before presenting the key findings of the study.

5.1 Coupling low cost 3D printing and construction kits

In this study we have shown the viability of step-change benefits in both time (45% time reduction over 3D printing) and resource cost (57% prototype reusability) in prototyping via coupling opposing prototyping methods. This accelerates product development by reducing the cost (time and material) of prototyping iterations allowing design-build-test cycles to be run more frequently.

The key findings from the investigation into coupling low cost 3D printing and LEGO® construction kits are summarised in Table 6.

Finding 1 states that the median optimum reduction in fabrication time is 45%. This near halving of time cost means that design iterations can be performed faster resulting in better product development outcomes (Camburn et al., 2015; Gerber & Carroll, 2012; Neeley et al., 2013; Thomke, 1998).

Finding 2 shows that reconfigurability improves with smaller bricks (tending to 100%), however it needs to be balanced with fabrication time. At the optimum ratio found from the minimum fabrication time, the reconfigurability was 57%. Improved reconfigurability means that the cost of each prototype is reduced allowing more physical prototyping to be performed throughout the product development process.

Finding 3 is that the optimum brick-to-object ratio is \(4 \times 10^{-4}:1\). As this is normalised against object size, it affords the prototyping of designs at any

<table>
<thead>
<tr>
<th>Finding</th>
<th>Implication</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Median prototype fabrication time is reduced by 45%.</td>
<td>Leads to faster iterations in the product development process.</td>
</tr>
<tr>
<td>2. Reconfigurability tends to 100% with smaller bricks (57% at optimum brick-to-object ratio).</td>
<td>Less material wastage between prototypes, reducing the prototyping costs.</td>
</tr>
<tr>
<td>3. The size of construction kit used must be matched to the scale of the prototype using the following ratio: (4 \times 10^{-4}:1).</td>
<td>Ensures the optimum balance between minimising fabrication time and maximising reconfigurability.</td>
</tr>
</tbody>
</table>

Table 6 Summary of the key findings from the study
scale provided the bricks can be fabricated (or bought commercially, in the case of LEGO®). This ratio finds the balance between minimising fabrication time and maximising reconfigurability.

5.1.1 Affordances

The primary affordance of coupling 3D printing and LEGO® is that it accelerates the product development process through faster and cheaper iterations by reducing the proportion of the design that is fabricated with slow 3D printing processes. The reuse of existing parts and fabrication of compatible alternate parts (that can be used interchangeably in successive prototypes) ensures the flexibility of this approach. Furthermore, due to the modular nature of the resultant prototype kits, this hybrid approach could afford easier design and modification of the prototype by both designers and users through providing opportunities to physically edit and manipulate their designs. For example, by adding new building blocks or swapping out 3D printed parts. These tangible design modifications would lower the barrier to stakeholder and user input. This could help develop the designers’ understanding of the design problem through the manual construction, as well as encourage participation and engagement from non-technical stakeholders (Gerber & Carroll, 2012). It also affords hands-on design that encourages physical exploration that can supplement CAD modelling (Shih, Sher, & Taylor, 2017) or even allow designers to move away from the limitations of CAD (Ranscombe & Bissett-Johnson, 2017) by digitising their designs with the aid of a vision-based object tracking/scanning system. Ultimately, this approach to prototyping looks to bring divergent, exploratory design into the physical world by bridging the gap between conceptual design and physical fabrication.

5.1.2 Validity of results

The fabrication times reported in the results rely on the validity of the print and assembly rates (described in Section 2.1). The use of these values is considered to be valid as they were kept constant between simulations and allowed direct comparisons of fabrication time to be made between different shapes and their sizes. The print rate model could be improved by determining the actual print times of the resultant parts rather than relying on their volume. However, as Figure 2 shows, the overall relationship between volume and print time is a strong linear fit, and accounting for the deviations from the line of fit would not significantly alter the results presented. The brick assembly rate does not consider the brick size and the associated dexterity required to manipulate them. By using participants creating models with a small design task, a conservative estimate for the assembly rates was calculated as it included searching for bricks, considering their placement and assembling. Figure 15 shows the sensitivity of the fabrication time to changes in the estimated assembly rates. It shows that there is little sensitivity to the assembly rate and that the fabrication time is dominated by the 3D print time.
The assembly rate estimate could be further reduced with sorted bricks and detailed instructions, or even by performing the assembly with an automated pick-and-place machine. Consequently, an improved estimate would likely reveal an increase in the potential benefit of using construction kits with 3D printing.

A set of six primitives was used in this study as they are the fundamentals of constructive solid geometry modelling where complex shapes are constructed from these primitives. They also provide baseline objects for future studies. Normalising the size of objects and bricks through a brick-to-object ratio, and normalising the fabrication times with respect to the 3D print times, means that the results became agnostic and independent to the scale of the object. While it might mean that the optimum sized bricks are not commercially available, it does allow this approach to hybrid prototyping to be applied to designs of any scale.

6 Conclusions
In this study we considered coupling additive manufacture and construction kits as they occupied opposite ends of the spectrums of fidelity and reconfigurability - giving rise to prototypes that could be fabricated faster and cheaper than just using low cost 3D printing. More generally, we can characterise hybrid prototyping methods as approaches to combine the affordances, and mitigate the limitations, of complementary prototyping methods to provide some benefit over using a single method. This benefit can be tangibly measured as time or material usage reductions, or can be seen as improving designerly behaviour or lowering skill barriers to stakeholder participation.
Overall, the main insight from this work is introducing a novel approach to creating looks-like prototypes that allows individual prototyping iterations to be fabricated faster and at lower resource cost. There is further potential for these benefits to compound over multiple iterations where parts can be reused across successive iterations.

This approach to creating looks-like prototypes of user-driven products is form dependent. Consequently, there could be better approaches using different prototyping methods to reduce the fabrication time and costs for particular designs. Examples of couple other prototyping methods could include:

- Cardboard and Clay modelling — the majority of the form can be created out of a cardboard substructure with detailed geometry and complex surfaces embodied in clay. The clay affords some flexibility in prototyping as small changes can be implemented easily and cheaply. The cardboard allows the rough form to be constructed quickly without having to shape large amounts of clay. This process has many similarities with that already used in the automotive industry (Singh, 2006).
- CNC machining and Meccano Construction Kit — the standard library of Meccano construction parts can be supplemented with bespoke prototype specific CNC machined parts. This could afford similar benefits of reusability and fabrication speed to using 3D printing and LEGO® construction kits.

6.1 Limitations and further work

The main limitation with the hybrid prototyping approach reported here is that it does not allow the creation of mechanically functional parts due to the limitations of 3D printing and the basic LEGO® construction kits. This arises for two reasons: the parts (both LEGO® and 3D printed) must interconnect; and the parts do not have dynamic capability or mechanical functionality. This results in limiting the use of the current embodiment of these prototypes to form-based design in the early stages of the design process. From this start point, there is scope for this research to be extended to use LEGO® Technic (gears, axles and mechanisms) to create mechanically functional prototypes with high fidelity 3D printed form. This could more effectively leverage the inherent properties of the combined prototyping techniques.

Further work is required to realise the physical practicalities of producing prototypes using this hybrid approach, including optimising brick layout for part strength and ease of construction, and to generate 3D printable surface pieces that attach to the LEGO® bricks. As the resultant prototype is modular it would need to be constructed in such a way that it could be strong enough
to withstand designer/user interaction without falling apart yet be easy enough to dismantle or reconfigure.

It will also be worth investigating other approaches for coupling 3D printing and construction kits, such as variable fidelity across a prototyping instance or modular feature isolation for quick edits to particular prototype features.

Investigation into the benefits of physical design that Hybrid Prototyping affords and how that affects designers understanding and engagement with the design process should also be considered. It would be interesting to characterise how the effect of being able to physically alter designs changes the designer behaviour, activities, and outcome.

**Declaration of interests**
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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