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Play well, print well: using LEGO bricks as an intuitive benchmarking tool for 3D printers

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Abstract

In 3D printing, calibration is crucial for accurate prints, particularly those with complex or intricate features. This paper focuses on developing, manufacturing, and testing a benchmarking model to assess the dimensional accuracy of 3D printers. The aim is to evaluate the 3D printed model against a universally recognized real-world equivalent – a LEGO® brick – using its interlock function as a test with an engaging element. An interlock benchmarking framework aids further analysis of the model's performance, and a checklist for the model is provided for additional visual analysis.

Keywords: 3D printing, calibration test, dimensional accuracy, process modelling

1. Introduction

3D printing (3PD) is gaining widespread usage, with falling costs and operational simplicity making the technology more accessible in the consumer market (Campbell et al., 2011). The most popular consumer 3DP devices are Fused Deposition Modelling (FDM). This technology (more generically called FFF for fused filament fabrication) refers to a process of additively building up material by selectively dispensing through a nozzle. However, these devices can be limited when building more intricate features or complex parts due to their lower resolution and accuracy (Kamran and Saxena, 2016).
In 3DP, calibration is critical. Lack of correct printer calibration will result in prints with unsatisfactory geometry and dimensions. Because of this, various 3DP benchmark model designs have appeared in recent years to help users test the quality of their printer and flag any issues that require device re-calibration (Boca et al., 2020; Grunewald, 2018). This project aimed to provide an engaging benchmarking model for testing the dimensional accuracy of 3D printers, with applications as an object that can be effectively integrated into a pre-existing product (PEP) assembly.

1.1. Benchmark models in 3D printing

Benchmark models assess a 3D printer's parameters such as dimensional accuracy, resolution, and alignment. A well-calibrated printer yields more robust results with fewer issues. Key test features (Boca et al, 2020; Hsiang Loh et al, 2020; Kortelainen et al, 2021) include:

- Dimensional Accuracy (DA) - Precision in relation to the CAD model (or PEP).
- Overhangs - Material that is only partially supported by the layer below.
- Bridging - Printed flat sections that span between two supports or anchor points.
- XY Ringing - Vibrations that cause oscillations on the surface of the prints.
- Z-axis Alignment - Tests the alignment and accuracy of the vertical features.

Our primary focus was on creating a dimensional accuracy (DA) benchmark model to test against a non-3D printed PEP. In existing interactive testing models, two forms are notable: (1) Using 3D prints, exemplified by Devin Montes' Test Puzzle, this method risks false feedback due to potential poor calibration (Grunewald, 2018). The interlocking of 3D printed jigsaw puzzle pieces serves as a test for DA. (2) Assessing features against standardized parts, as seen in CtrlV's Octagon, where a hole's external size matches an M4 nut (Hullette et al., 2024). This approach faces challenges in tightness measurement due to a lack of clear labelling on standardized parts. The deficiency in measurement precision can lead to delayed and inaccurate feedback. A model offering prompt and reliable feedback would significantly enhance the evaluation of 3D printer DA.

1.1.1. Dimensional accuracy troubleshooting

A calibrated printer ensures that every print turns out the same every time. It can also be used to optimise the printers' abilities. But what is the impact and cause of a printer that needs to be recalibrated? Typically, it means the dimensions of the print are wrong, and the X or Y-axis calibration is out depending on the orientation used to print a benchmarking model (Bell, 2014). If only one axis is out of calibration, the top/base of cylindrical objects will appear oval rather than round. The X and Y-axis calibration is out if these features are round (Kortelainen et al., 2021; Hsiang Loh et al., 2020).

1.2. The 2x4 LEGO® brick

Developing a benchmark model focusing on DA means a model that requires accurate, easily measurable dimensions and cylindrical features for diagnosing which axis, if not both, requires recalibrating. The 2x4 LEGO® brick is an ideal candidate due to its universal availability, function, and unique design. Small internal tubes provide a secure grip when stacked, so the brick enhances structural strength while remaining easy to disassemble. (Boulter et al., 2022). Since 1958, all 2x4 bricks have adhered to the same measurements outlined in their 1961 patent (The LEGO Group, 2017). In 2012 alone, 45.7 billion bricks were produced at 5.2 million per hour (Tucker, 2013).

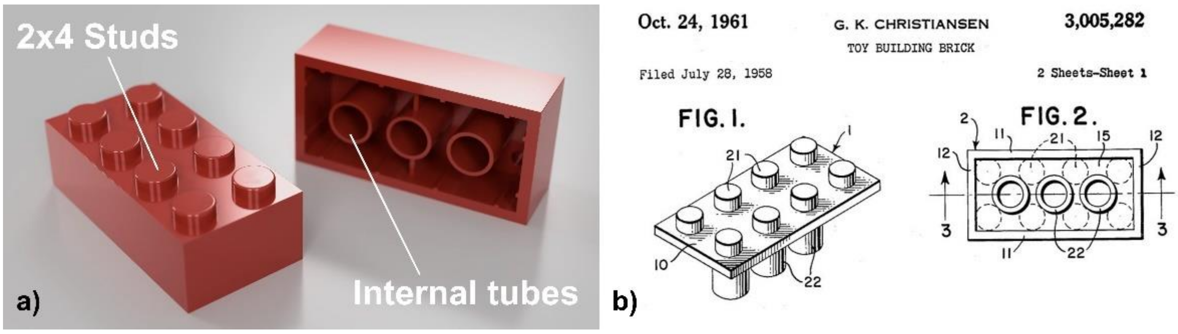

Figure 1. (a) Interlocking studs & tubes (b) Section of 1958 Patent (Christiansen, 1961)

LEGO® bricks are plastic injection moulded with Acrylonitrile Butadiene Styrene (ABS) material (Lauwaert, 2008). Although there is no publicly available official data on the tolerances of LEGO® bricks, the precision of the production moulds, accurate to within 0.005mm, ensures that only 18 in every 1 million bricks deviate from the high-quality standard (The LEGO Group, 2017; Boulter et al., 2022). The 2x4's precision, consistency, functionality, and global availability make it easily accessible and suitable as a universal product to benchmark a 3D printed duplicate.

1.2.1. Haptic memory and tactile experiences

The tactile experience of assembling LEGO® can serve as immediate feedback for a benchmarking model. Even though we may not be fully conscious of it, research indicates our impressive ability to store and recall memories linked to the sense of touch (Gallace and Spence, 2009). Designers and engineers have an intuitiveness with how LEGO® pieces interlock, driven by an understanding stored in haptic memory. This underscores our efficiency in processing and remembering tactile experiences. (Lawson et al., 2015), and the potential for using it as quick pass-and-fail criteria, reducing time, equipment, and costs in early product development. A detailed analysis would, however, remain crucial in later stages.

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2. Methodology

The 2x4 LEGO® brick served as the reference for evaluating the Benchmark Brick (BMB) in assessing 3D printer accuracy and build qualities. Leveraging haptic memory from LEGO® assembly, the authors could promptly assess 3DP quality and accuracy by interlocking a BMB with its real-world counterpart.

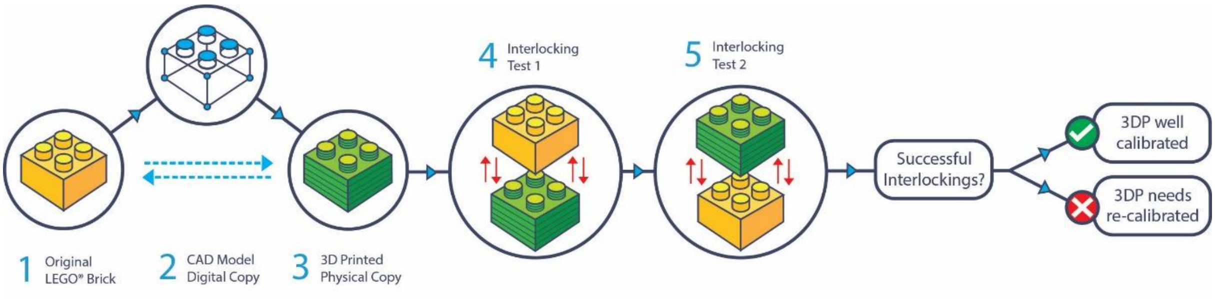

Figure 2. An illustrated process for using a LEGO® brick as a benchmarking tool

For experimentation and BMB development, a MakerBot produced 49 iterations, initially starting with default printer settings. Each BMB underwent detailed validation, analysing the interlocking mechanism with a LEGO® brick for DA and utilising haptic memory for immediate feedback. Subsequent visual inspections examined bridging, overhangs, Z-axis alignment, XY ringing, and stringing. Analysis of the BMB's performance informed iterative modifications to both the BMB design and printer settings, refining the benchmarking model and optimizing 3DP output. While a successful interlock test doesn't cover all 3D printing aspects, this process and the BMB address immediate points for optimizing print performance and 3D printer DA. A developed checklist systematically troubleshoots issues and identifies areas for improvement through predominantly visual inspection of the BMB.

2.1. Software and equipment

The benchmarking model's initial development used a MakerBot Replicator 2X with a layer resolution of up to 100µm, a deposition speed of 175mm/s, and a heated print bed. User-adjustable features include filament width, alternating speeds/temperatures for different build sections (MakerBot Industries, 2013). ABS, similar to official LEGO® bricks (The LEGO Group, 2017), was used as the workpiece material, but not in the same granule form. The recommended software for this device is MakerBot Desktop (Ultimaker, 2022). A highly accurate input (STL) file was crucial for effective interlock test, validated by precise measurements of the LEGO® brick using a Coordinate Measure Machine with 1.7µm accuracy (Mitutoyo, 2019). For that purpose, a workpiece was placed on the machine table, and a probe was used to identify the workpiece geometry by measuring different points of the PEP and mapping the XYZ coordinates. An accurate CAD model of the BMB was then generated accordingly (Fig. 3).

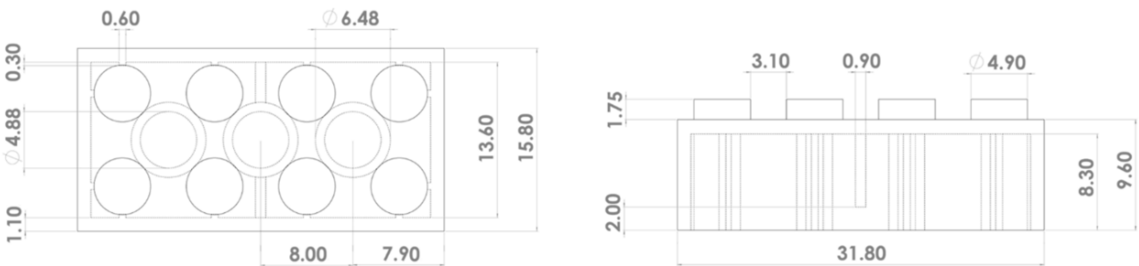

Figure 3. Original BMB dimensions, measured from PEP using a Coordinate Measure Machine

The CAD models were first converted to STL files and then imported into MakerBot Desktop, where they were manipulated into a coordinated toolpath specific to the Replicator 2X. These instructions were formatted in a standardised g-code file used by machine tools worldwide (Brown and de Beer, 2013). The general tolerance was set at 0.01mm, the same as a LEGO® brick (Boulter et al., 2022).

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2.2. Key factors of a benchmarking test print

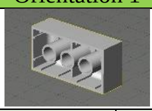
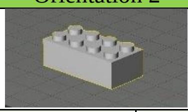
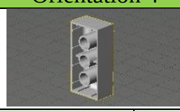
Various parameters can affect prints; thus, the scope of this work requires limitations. The key factors and optimal print orientation concluded as having the most significant effect on the dimensional accuracy and overall quality of prints are based on previous studies (Simplify 3D, 2019; Bhavnagarwala, 2018; Jennings, 2019) and the authors' knowledge of the given 3D printer. Table 1 details the factors significantly impacting DA and the overall print. 49 initial experiments were completed, systematically testing each key factor, with Trial 049 (STL, Appendix A) providing an optimised print.

Table 1. Key factors with a significant effect on DA and overall print quality

Key Factor	Trial Sequence	Explanation	Default	Min/Max	Optimum	Unit
Layer Height	001-009	Danger of dimension conflict with 3DP	0.2	0.05-0.34	0.2	mm
Print Speed:						
First Layer	001-023	Fast prints may not adhere to the print bed	30	0-175	5	mm/s
Infills	041-046	Fast prints may not adhere to previous layer	90	0-175	90	mm/s
Bridges	041-049	Fast prints may not adhere to previous layer	40	0-175	5	mm/s
Insets	048-049	Fast prints may not adhere to previous layer	90	0-175	40	mm/s
Number of Shells	009-042	Will impacts strength of vertical walls	2	1-20	2	/
Infill Density	009, 024-045	Stronger, solid walls + aid interlock function	10	0-100	10	%
Wall Thickness	010-037	Danger of dimension conflict with 3DP	/	0.05-16	0.8	mm
Cooling Fans:						
First Layer	022-049	Prevent uneven shrinkage - Shrinks 1.5%, cools quicker	0.5	0-1	0.5	/
Insets/Outline	028-048	Prevent uneven shrinkage - Shrinks 1.5%, cools quicker	0.5	0-1	0	/
Bridging	041-049	Prevent uneven shrinkage - Shrinks 1.5%, cools quicker	0.5	0-1	0.5	/
XY Travel Speed	024-027, 045	Rate of acceleration (jerk), too much = ringing	150	0-175	100	Mm/s
Print temp. Extruder	024-026	Temp. of the extruder doing print	230	0-255	230	°C
Print temp. Platform	024-034,037-049	Prevent uneven shrinkage + eliminate rafts	110	0-130	120	°C

Due to the anisotropic nature of FDM processes, it is crucial to position the CAD model at the proper orientation to achieve the most optimal mechanical performance and DA (Chacón et al., 2017), with considerations for support material and cleaning. Orientation was evaluated based on the averages of print time, material usage, and support. Orientation 2 was selected due to its non-requirement for support, which reduced print time, material usage and cleaning.

Table 2. Different Orientations of BMB prints and impacts

Orientation 1		Orientation 2		Orientation 3		Orientation 4	
							
Avg. print time:	16 mins	Avg. print time:	14 mins	Avg. print time:	15 mins	Avg. print time:	16 mins
Avg. material use:	2.56 g	Avg. material use:	2.89 g	Avg. material use:	3.27 g	Avg. material use:	3.11 g
Support required:	Yes	Support required:	No	Support required:	Yes	Support required:	Yes
Trial sequence:	Ori 1-4	Trial sequence:	Ori 5-8	Trial sequence:	Ori 9-12	Trial sequence:	Ori 13-16

3. Experiment & results

All benchmarking 3D prints were recorded on a spreadsheet, collecting data on each print's settings and results to identify the optimal settings and design for the BMB. All default printer settings were applied in the first print, followed by later corrections, to allow for the design of the BMB and adaptations. DA was the primary focus of this experiment, but further test features were also identified to be examined.

While literature detailing friction forces in the interlocking process would be valuable, no official public data on the required forces to interlock and separate two 2x4 LEGO® bricks currently exists. Nevertheless, an estimated value of approximately 3N is considered adequate for the interlocking and separation of two 2x4 LEGO® bricks, each weighing 2.5g. This estimate aligns with findings by Kollsker and Malaguti (2021), who stated that the force required to separate two 2x4 LEGO® bricks is 2.5N. Moreover, the authors theorize that haptic memory can serve as a means of delivering instantaneous feedback to users, offering an effective method of evaluation.

After generating a successful CAD model, the subsequent phase involved testing the BMB across various 3D printers. Different printer types and materials were employed to validate the BMB's efficacy as a benchmarking model for 3D printer DA.

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3.1. Primary test feature results and redesign

The key assessment criterion for the BMB primarily focused on dimensional accuracy, evaluated through the interlock functionality. Subsequently, the benchmark model underwent a comprehensive checklist to scrutinize additional features. This checklist encompassed an examination of Z-axis alignment, identification of XY Ringing traces, assessment of bridging capabilities, scrutiny of overhang performance, monitoring of machine temperature and cooling efficiency, and print speed evaluation.

3.1.1. Dimensional Accuracy

Initially, any attempt to print the BMB without a raft proved difficult due to warping. Insufficient temperatures were concluded to cause the ABS to rapidly cool and lack proper adherence to the build platform. This realisation increased the building platform temperature from 110°C to 120°C. Additionally, the First Layer Print Speed was reduced from 30mm/s to 5mm/s, and the Filament Cooling Fan Speed was also disabled to maintain the heated temperature for this early stage of the build (Kortelainen et al., 2021; Simplify 3D, 2019; Bhavnagarwala, 2018). These adjustments proved successful (Fig. 4) and crucially allowed the BMB to be printed independently of any rafts.

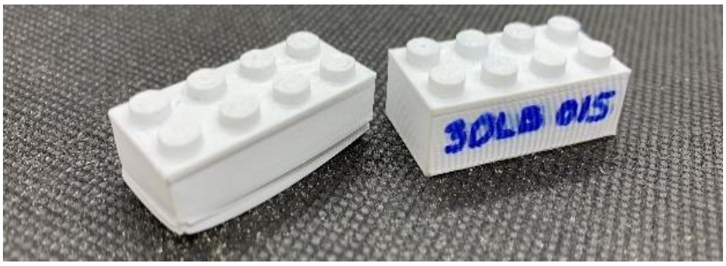

Figure 4. Warped BMB (left) compared to BMB with the warping issue resolved (right)

The initial design intended the vertical walls to be 1.10mm wide and solid, but was printed hollow (Fig. 5a), affecting the BMBs interlock test function, due to an incompatibility with the FDM printer's nozzle. To resolve this, the CAD model underwent adjustments aligning wall widths with multiples of the 0.4mm standard nozzle diameter (Simplify 3D, 2019). Opting for a 0.8mm wall thickness preserved structural integrity, facilitating successful interlocking (Fig. 5b, c), as a 1.2mm thickness risked compromising DA of the inner ribs (Fig. 5a). Additionally, shrinkage-induced concave geometry was addressed by disabling Inset and Outset Cooling Fans (Jennings, 2019). The resulting prints entailed stronger, solid walls with all crucial dimensions facilitating the interlocking function (Fig.5b, c).

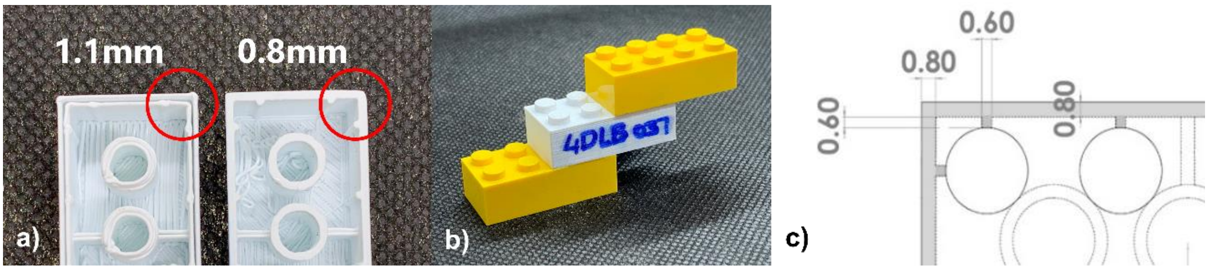

Figure 5. (a) 1.1mm vs 0.8mm walls (b) PEP/BMB interlocking (c) new wall/rib dimensions

3.1.2. Bridging

The BMB design's roof was initially deemed suitable for basic bridging tests on an FDM 3D Printer. However, issues arose as the 0.8mm wide walls didn't provide sufficient area for secure bridging (Fig. 6a). To address this, the CAD file was edited to add a 2mm fillet in the walls and roof joint area, boosting the surface area for bridges to anchor by 335%. Immediate improvements were evident in the first print, with no visible bridging errors (Fig. 6).

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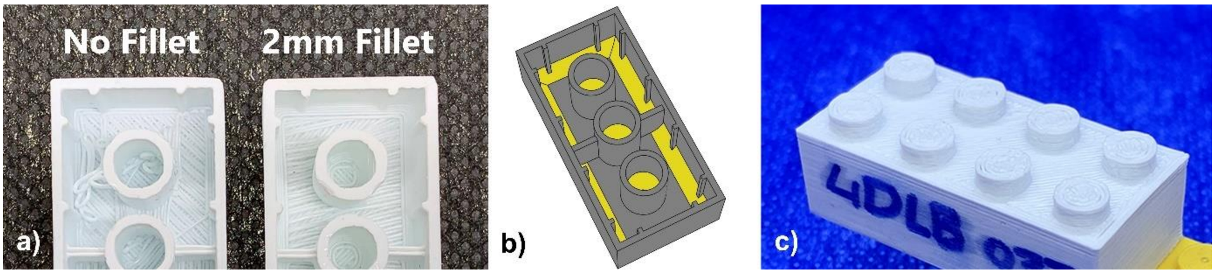

Figure 6. Before/after fillets (a) Filleted areas highlighted (b) resulting topside bridging (c)

3.1.3. Overhangs

The initial BMB design lacked an overhang feature test. To enhance its utility, a fillet was added between vertical walls and the roof, initially set at 1mm. Test prints revealed improvements but some inefficiencies in bridging. The fillet was increased to 2mm, providing extra surface area for bridges to anchor. This adjustment significantly improved the bridging feature, enabling the benchmark tool to test basic overhangs, as depicted in Figure 6.

3.1.4. Other primary test feature results

The BMB design includes a detailed *z-axis alignment* test, examining external walls, underside tubing, and topside studs. Any lack of x-axis wall levelness can cause print variations, necessitating recalibration (Jennings, 2019; Simplify 3D, 2019). The BMB prompted recalibration twice during testing. Initial prints with XY Ringing, due to the extruder moving too quickly (Jennings, 2019; Simplify 3D, 2019), were resolved by reducing the printer's XY Travel Speed from 150mm/s to 100mm/s.

3.2. Benchmark checklist and default settings

Considering the test feature results and corresponding adaptations to the benchmark model dimensions and design, several default settings have been established for the Checklist. A further requirement of the BMB was that it was quick to print (around 15 minutes) and used minimal material. The default slicer settings are seen in Table 3 and primarily focus on FDM printers, but Material Jetting is also considered:

Table 3. Setting types and defaults used in case studies

Setting Type	Default	Unit	3D Printer Type
Scale (unmodified in size)	1:1	/	All
Orientation	2 (studs up)	/	All
Supports	No	/	FDM/FFF
Supports	Yes	/	Material Jetting
Layer Height	0.2	mm	FDM/FFF
Layer Height	0.016 – 0.032	mm	Material Jetting
Wall Thickness	0.8	mm	All
Infill	90	%	FDM/FFF
First Layer Speed	5	mm/s	FDM/FFF
Print Speed (extrusion)	Up to 50	mm/s	FDM/FFF
Print Speed (travel)	Up to 100	mm/s	FDM/FFF
Print Nozzle Diameter	0.4	mm	FDM/FFF

Users are encouraged to test and try different settings to see what difference they make. While projects may modify these recommended settings for BMB prints, they serve as a suitable baseline. This project doesn't intend to create an all-encompassing test or calibration tool for every aspect of 3D printing. Nevertheless, it does focus on various key factors to optimize print performance.

3.2.1. Interlock tests and checklist

A framework was developed to explain the process of building the BMB print and utilising the two interlock tests (Fig.7). Three inputs are required before the benchmarking process can begin.

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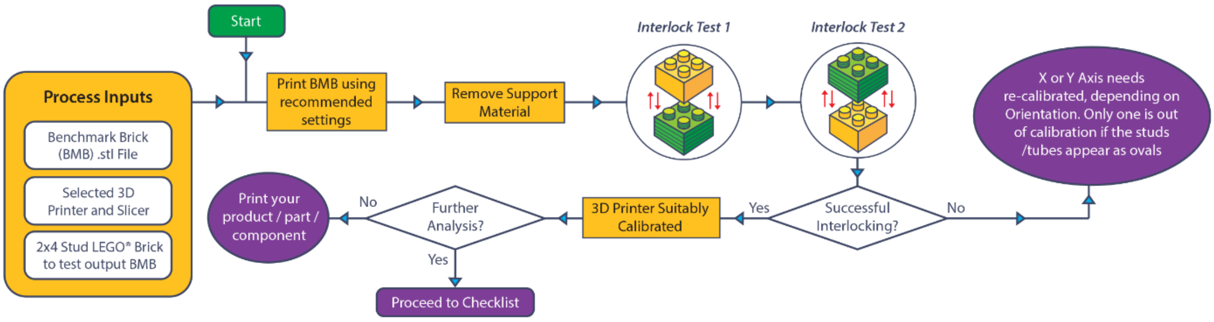

Figure 7. A Framework for Interlock Tests 1 and 2

The interlock tests serve as a means to assess DA. If either test fails, printer recalibrating is likely necessary. Successful tests allow users to proceed with a broader systematic check. Based on earlier experiments with printing and developing the BMB as a benchmark model, the authors have formulated the points below for systematic issue identification of a 3D printed BMB (Table 4).

Table 4. BMB Checklist and possible defect reasons

BMB Feature Checks		Defective?		Possible Defect Reason(s)
		Yes	No	
T1	Interlock test 1			X or Y-axis needs recalibrating
T2	Interlock test 2			X or Y-axis needs recalibrating
1	**Detail Check**			
1.1	Internal fillet/Overhang drooping			Ineffective part cooling/printing too fast + hot
1.2	Bridging under studs is drooping			Ineffective part cooling/printing too fast + hot
1.3	Studs are not round			X or Y-axis needs recalibrating
1.4	Studs are vertically uneven			Inadequate part cooling *or* printing too fast
1.5	Uneven or shifted layers (z-axis)			Loose belt *or* cooling fans to close to the build
2	**Overall Print Quality**			
2.1	Stringing (threads of excess filament)			Nozzle temperature *or* retraction issues
2.2	Excessive blobs / extra filament			Over-extrusion
2.3	Prominent thinning of layer lines			Under-extrusion
2.4	XY Ringing (repeated patterns)			Vibrations – print too fast/loose belt/print bed
3	**Underside Examination**			
3.1	Extrusion lines are clearly visible			Nozzle too far from bed / print temp. too low / insufficient (first layer) width.
3.2	Elephant's foot (lip at print base)			Nozzle temp. or bed too high
4	**Measure Dimensions**			
4.3	External top (W) 31.80 x (D) 15.80 mm			X or Y-axis needs recalibrating
4.2	External height (H) 31.80 mm			First layer issue
4.1	Internal base (W) 30.20 x (D) 15.20 mm			X or Y-axis needs recalibrating

Users can investigate solutions for any identified issues based on possible defect reasons. It is assumed that most users are familiar with the terminologies and probable solutions. Future work aims to integrate solutions into a broader framework, such as the Interlock Test framework illustrated in Figure 7.

3.3. Case studies of 3d printers and materials

Since the initial experiments undertaken in Section 3.1, the latest version of the BMB (LB049) and Checklist were used to evaluate and troubleshoot various other 3D printers. The printers were all at different levels of perceived quality and provided a combination of Material Jetter and FDM machines.

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In addition to the original tests (001-049) on a MakerBot Replicator 2X, this test was used on five further machines using various materials. The printers in Table 5 below used BMB design 049, Orientation 2 (Table 2), and the recommended settings (Section 3.2). The machines listed above were used to test the usability of the BMB on different models, types, and levels of 3D printers.

Table 5. 3D Printers, materials and setup used in case studies

Model	3DP Type	BMB	Material(s)	Support	Settings	Success?
MakerBot Replicator 2X	FDM/FFF	001-049	ABS	None	Table 3	BMB Test
MakerBot Replicator +	FDM/FFF	049	ABS	None	Table 3	✓
Objet Eden350	Material Jetting	049	VeroBlack Plus	Soluble	Table 3	✓
Stratasys J850	Material Jetting	049	Digital ABS Plus/Agilus30	Soluble	Table 3	✓
Stratasys F900	FDM/FFF	049	ABS-M30	Soluble	Table 3	✓
Stratasys F170	FDM/FFF	049	ABS-M30	Soluble	Table 3	✓

Successful output results from these 3DPs (via the interlock tests) would validate the usefulness of the BMB as a benchmarking tool for 3D printers. Rigid materials with properties like ABS were used for all printers in the validation process. Variations of material were inevitable. However, they were also necessary to prove validity as a benchmark tool for all types of printing.

3.3.1. 3D Printer case studies

The authors consistently employed a BMB to assess the accuracy of various 3D printers before building in any other parts or components in other projects. Printer errors can lead to costly and time-consuming failures, making calibration crucial. The BMB, interlocked with a real-world counterpart, served as a calibration test with instant feedback. In addition to the original tests on a MakerBot Replicator 2X, this practice extended to four further machines with different materials, revealing varying successes:

- Material Jetter 1 – Objet Eden350: Successful print with good interlock (additional support removal was required, no obvious issues after using checklist).
- Material Jetter 2 – Stratasys J850: Successful print & interlock (high-quality output, support easy to remove. No obvious issues after using checklist)
- FDM 1 – Stratasys F900: Successful print with interlock (high resolution but layers visible)
- FDM 2 – Stratasys F160: Successful print with interlock (lower resolution with rougher surface finish, but successful)
- FDM 3 – MakerBot Replicator+: Successful print with interlock (warping occurred due to no heated bed)

The Checklist and troubleshooting are more consistent with FDM printers and provide a successful and systematic evaluation method. 3D prints on the material jetting machines typically show less apparent issues and have greater success rates due to higher quality builds. Therefore, it is more suitable for these printers to utilise the Interlock Tests and not the subsequent Checklist, which is ideal for FDM prints.

3.3.2. Material impact and applications

Another aspect to consider in this research is material impact. LEGO® bricks are crafted from ABS, a widely used thermoplastic polymer produced through injection moulding (Lauwaert, 2008). ABS is known for its impact resistance, toughness, and rigidity. The BMB Checklist is designed with ABS and materials possessing similar properties in mind. Exploring the potential use of LEGO® bricks for assessing materials with diverse properties was crucial. Would an elastomer BMB be effective in gauging a 3D printer's dimensional accuracy, or is evaluating printers using ABS and similar plastics more appropriate?

A new BMB print utilising elastomer material was created using the Stratasys J850 for its high resolution, which is particularly suitable for elastomer prints (Stratasys, 2020). Agilus 30 White, a durable rubber-like photopolymer with a Shore A value of 30, was chosen, capable of high resilience to repeated flexing (Stratasys, 2021). The elastomer BMB print successfully interlocked with the LEGO® brick in testing. However, it was decided to restrict the ideal materials for these prints to rigid ones matching the LEGO® brick's properties due to concerns about the potential stretching of elastomers during tests, leading to false or inaccurate results.

4. Conclusions

This project aimed to create a novel yet entertaining benchmarking model for testing 3D printer dimensional accuracy (DA) and print quality through interaction using a universally accessible product (PEP) – the 2x4 LEGO® brick. The study identified key design features, focusing on the interlocking assembly test for DA. The successful interlocking of a LEGO® brick and a 3D printed duplicate signifies adequate DA, providing a quick and user-friendly evaluation utilising users' nostalgic and haptic memory to provide instant feedback. The design evolved to incorporate additional benchmarking features like bridging, overhangs, Z-axis alignment, and XY ringing. A checklist was developed for a more comprehensive analysis, offering troubleshooting insights. While not a perfect all-around benchmarking model, further design enhancements may be explored in the future. Currently, it uniquely tests DA through an entertaining, simple, and intuitive approach. After all, LEGO® assemblies are a nostalgic, general form of additive manufacturing.

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Appendix A

STL file download of Benchmark Brick LB049. https://dx.doi.org/10.15129/53615a26-0174-41dc-a5e3-cd8afe7ca4ff