Design Science

A generative-based design methodology to enable the democratisation of 3D printing

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Abstract

3D printing technologies, such as material extrusion (MEX), hold the potential to revolutionise manufacturing by providing individuals without traditional manufacturing capabilities with powerful and affordable resources. However, widespread adoption is impeded by the lack of user-friendly design tools due to the necessity of domain-specific expertise in computer-aided design (CAD) software and the overwhelming level of design freedom afforded by the MEX process. To overcome these barriers and facilitate the democratisation of design (DoD), this article introduces an innovative, generative-based design (GBD) methodology aimed at enabling non-technical users to create functional components independently. The novelty of this methodology lies in its capacity to simplify complex design tasks, making them more accessible to non-designers. The proposed methodology was tested in the design of a load-bearing part, yielding a functional component within two design iterations. A comparative analysis with the conventional CAD-based process revealed that the GBD methodology enables the DoD, reflected in a 68% reduction in design activities and a decrease in design difficulty of 62% in requisite know-how and a 55% in understanding. Through the creation and implementation of this methodology, the article demonstrates a pioneering integration of state-of-the-art techniques of generative design with design repositories enabling effective co-design with non-designers.

Keywords: Democratisation of design, Generative design, 3D printing, Material extrusion, Design repositories

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1. Introduction

Co-design is a specific instance of co-creation referring to "the creativity of designers and people not trained in design, working together in the design development process" (Sanders & Stappers 2008). Many parallels can be seen between this and the democratisation of design (DoD), which is defined as enabling "more 'non-designers' to become involved in idea generation, development and production of products, services or processes" (Fleischmann 2015). In essence, both movements recognise that "all men are designers" (Papanek 1971) and seek to enable the creative power of the world to be harnessed.

With respect to the creation of products, increased access to manufacturing technologies has been observed from 2000 to 2020, in part, due to the emergence and rapid ascendance of additive manufacturing (AM) technologies such as material extrusion (MEX) (Goudswaard *et al.* 2021*a*). This is significant as it has the potential to provide businesses and consumers, who traditionally would not be able to make things for themselves, with highly capable and affordable manufacturing resources that are operable in homes, workplaces and communities (Wittbrodt *et al.* 2013; Rundle 2014). Application of this capability has the potential to enable grassroots innovation, and empower communities to develop products that can meet their local needs (Birtchnell & Hoyle 2014). This blurs the traditional boundaries between consumers and producers with the emergence of 'prosumers' (Benkler 2006; Kohtala 2015).

Whilst increased provision and accessibility of manufacturing capability is a potential enabler of greater innovation, it is thwarted by a lack of similarly accessible design tools (Birtchnell & Hoyle 2014; McCutcheon *et al.* 2014; Sculpteo 2019). This is due in a general sense to the domain-specific expertise required to use computer-aided design (CAD) software (Ibrahim & Rahimian 2010; Shih, Sher & Taylor 2017; Ranscombe *et al.* 2019). Presently, the only alternate means to access designs for AM are through the use of design repositories which, although widely used, are only able to offer a limited number of pre-determined, fixed designs. Additional complications are added when designing for AM due to the large design freedoms afforded by the manufacturing technology with the possibility of customising parts' internal structures (Popescu *et al.* 2018; Goudswaard, Hicks & Nassehi 2021*b*) resulting in a multi-dimensional design space for both internal and external geometries and materials. In other words, whilst manufacturing has, to some extent, been democratised, design has not followed suit. To enable greater innovation and manufacturing independence, the democratisation of design and the underpinning design tools is necessary.

We propose that generative design is a potential enabler of design democratisation for AM. Generative design is about not only the design of an object but the process to generate objects (Hansmeyer 2012). It consists of a range of design approaches that 'use algorithms to generate designs' (Caetano, Santos & Leitão 2020). This algorithmic approach permits the rapid exploration of large and multi-dimensional design spaces such as that which is present when designing for AM. As such, the contribution of this article lies in the creation, instantiation and evaluation of a generative-based design (GBD) methodology that can enable the DoD for MEX through augmentation of the existing capabilities of design repositories. The distinction between these contributions is presented in Figure 1.

The remainder of the article is structured as follows. First, the literature review (Section 2) presents extant tools and technologies that are currently used in design for 3D printing and that offer the potential to democratise design. The research approach in Section 3 draws together the contents of this review by defining the tool chain that will be operationalised in a design methodology that can enable the

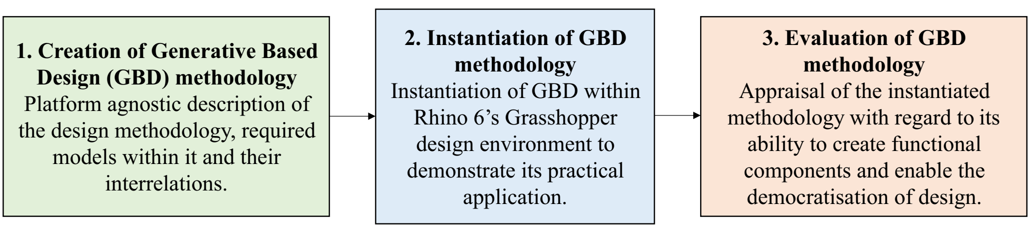

Figure 1. Contributions of this article.

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DoD. An overview of the design methodology is then presented in Section 4, paying particular attention to the impact that it will have on the activities that the user must perform and how this will enable the DoD. An illustrative application (Section 5) is used to instantiate the methodology in the design and manufacture of a functional-load-bearing component. Within this, the steps of this design study are characterised and contrasted with those used in a traditional CAD-based process. Section 6 considers the generalisability of the methodology, its limitations and the next steps towards its wider implementation.

2. Background

To contextualise the work in this article, this section will provide the following: (i) a synopsis of key trends in designing and making that precipitate the emergence of DoD; (ii) definitions of the DoD, its current state and related movements; (iii) an exploration of the MEX manufacturing process – a widely used additive manufacturing technology that could benefit from the DoD; and, (iv) design tools and technologies for AM to present what is currently available both commercially and in academia. The findings from each of the following sections are drawn together in Section 2.5 to shape the research approach taken in this article.

2.1. Trends in designing and making

This section will explore trends that define the future of designing and making. Some enablers and inhibitors of these will be explored in Sections 2.3 and 2.4. Principle means of manufacturing and consumption are characterised by Global Production Networks (GPNs). Within these, the processes of design, manufacture and distribution of products span the globe in order to achieve low-cost production. These are characterised by complex supply chains and regime-driven factories, and encourage damaging environmental practices (George 1986; Slade 2006; Sumner & Mallett 2013; Birtchnell & Hoyle 2014).

Drawbacks of GPNs came to the fore during the 2020 coronavirus pandemic, when supply chains were severed and the existing manufacturing infrastructure was unable to adapt to new demands (Gopsill *et al.* 2021). This has added to the existing re-shoring movement that seeks to bring manufacturing 'home' so as not to be dependent upon global supply chains (Bailey & Propris 2014; Moradlou, Backhouse & Ranganathan 2017).

Distributed manufacturing is an alternative paradigm enabled by digital manufacturing technologies that can remedy issues associated with GPNs (including AM that will be explained in Section 2.3). It is characterised by a shift from large centralised manufacturing centres to diversified and distributed manufacturing resources (Wu *et al.* 2015) where flexibility and scalability of manufacturing units enable a move away from the centralisation tendencies of GPNs (Srai *et al.* 2016).

Movements towards distributed manufacturing indicate a paradigm shift in the way things are made. The advancements in Digital Manufacturing that underpin this shift are also a pre-requisite for the paradigm of design for mass personalisation (Ozdemir, Verlinden & Cascini 2022) – where products are designed to specific customer needs in a near continuous design space (Wang *et al.* 2017) – in other words; designing for a market of one. In this design paradigm customers

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are given an active and direct role in the design process to ensure products are designed to meet their individual needs (Sikhwal & Childs 2021).

Design for mass personalisation enables leveraging the benefits of digital manufacturing technologies; however, consumers of these products remain customers of a business – that is, there is no real blurring of the consumer/producer boundary. An alternative design paradigm that leverages digital manufacturing techniques is the DoD where these barriers are fundamentally removed. This will be explored in the following section.

2.2. The DoD

Communities can be empowered to innovate for themselves due to the availability of capable and affordable manufacturing technologies such as 3D printing. If the process of designing can be made openly accessible too, this is taken a step further as communities are able to design and make products in response to local needs.

In other words, the DoD – the enabling of more non-designers to become involved in design (Fleischmann 2015) – needs to be enabled. The DoD can be broken down into three main facets: (i) increased engagement of the general public; (ii) reduction of pre-requisite technical skill and, (iii) enabling of the input of many into one goal (Goudswaard *et al.* 2019*a*).

In the context of this article, the first two facets are the most relevant. We can therefore define DoD as *the reduction in skill level required to realise functional parts via 3D printing such that non-technical users, who typically would not be able to create parts, are able to innovate for themselves.*

Parallels with the DoD can be drawn with open design (Harhoff, Henkel & Von Hippel 2003; Koch & Tumer 2009), which has expanded from its software origins and provides a framework for sharing design information stemming from hardware as well as physical objects (Vallance, Kiani & Nayfeh 2001). Open design is defined as 'the state of a design project where both the process and the sources of its output are accessible and (re)usable, by anyone and for any purpose' (Boisseau, Omhover & Bouchard 2018). It is considered to be an ideal representing a direction of openness rather than something actually achievable. It allows anyone with an appropriate set of skills to innovate for themselves. It is on this point that the DoD differs as its underpinning is about reducing the requisite skills to design as a barrier to entry as opposed to in open design where a certain skillset is required in order to be able to design.

In a similar way to open design representing a direction of openness, the DoD is considered as a direction or vector towards a wider goal which may be in practice unattainable. Achieving the DoD is therefore about moving along this vector such that design practice may be more accessible to a particular audience. This shares similarities with inclusive design which seeks to reduce 'the level of ability required to use each product, in order to improve the user experience for a broad range of customers, in a variety of situations' (University of Cambridge Engineering Design Centre 2023).

If the aim of democratising design is to reduce the skill level required to create functional components via 3D printing, the associated difficulty in doing this is related to the manufacturing technology and available design tools for 3D printing. These will be explored in the following sections.

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2.3. Material extrusion

3D printing technologies afford a wide range of advantages over traditional subtractive processes. These include permitting design freedoms not possible through other manufacturing methods (Attaran 2017), enabling manufacturing cost reduction (Berman 2012) and improved sustainability outcomes (Holmström, Liotta & Chaudhuri 2018). They also permit design optimisation to reduce waste, the design and manufacture of lightweight products and the manufacture of products with bespoke properties (Foresight 2015). Because of these benefits, AM technologies have been part of the home fabrication movement enabling local production of appliances, tools and replacement parts (Holzmann, Schwarz & Audretsch 2018).

The most widely used 3D printing technology is MEX[1] (Sculpteo 2021). Its applications include weather stations (Freitag 2015), rural farming production (Obydenkova, Anzalone & Pearce 2018), disaster response (Dotz 2018), microscopes (Sharkey *et al.* 2016) and PPE during the coronavirus pandemic (Rendeki *et al.* 2020). Because of the technology's versatility, it is widely used by hobbyists and end manufacturers alike with machines available at price points from $100 right up to industrial machines for $10000 s (Pick-3D-Printer 2022).

MEX, like other AM techniques, builds parts additively layer by layer, and it is via means of a plethora of manufacturing parameters that can be controlled in this process that many of the aforementioned design freedoms and benefits are enabled. Example parameters are shown in Figure 2, including build orientation, layer height, infill percentage and number of solid shells. The design and manufacturing freedom afforded by MEX, therefore, comes at the expense of a large multi-dimensional design space.

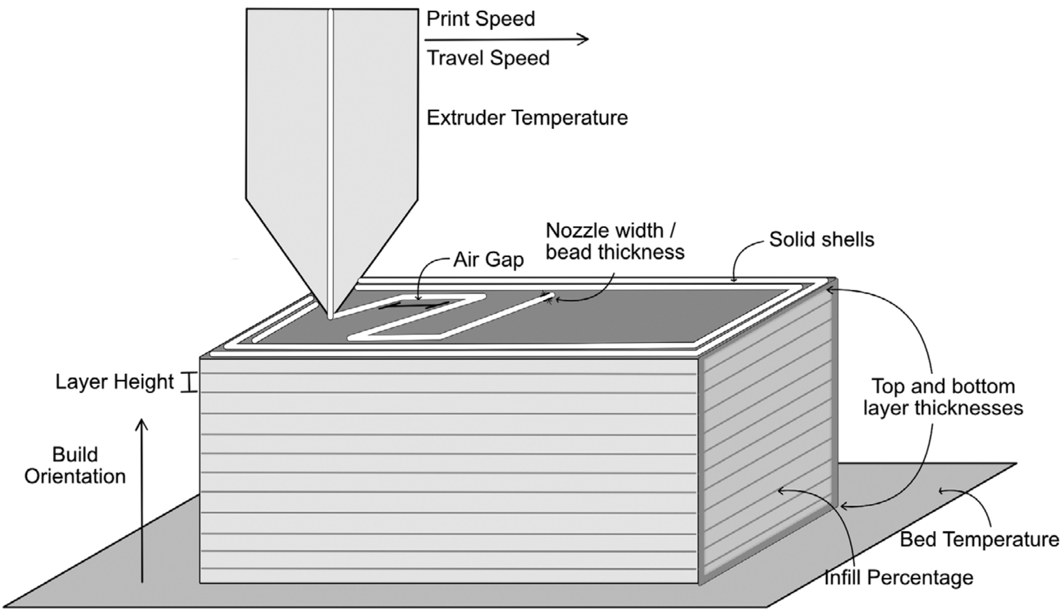

Figure 2. MEX manufacturing parameters.

[1]Also referred to as filament deposition modelling (FDM) or fused filament fabrication (FFF).

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Early applications of MEX were largely aesthetic or for prototyping, with a focus on high-quality prints to generate consistent, geometrically accurate parts with good surface finishes but with little consideration of their functional performance. As such, these parts needed to 'look right' rather than 'perform right', and because of this methods of geometric benchmarking (Rebaioli & Fassi 2017) including an ISO standard (ISO 2019) as well as design rules (Umaras & Tsuzuki 2017) for MEX printing have been designated, enabling great increases in part quality with respect to geometric accuracy.

The focus is now moving towards manufacturing parts with consistent functional performance. This is due to the technology having developed further and MEX parts finding more end-use applications (Sculpteo 2021). Subsequent studies have therefore sought to characterise the mechanical performance of parts, and how this varies with respect to different manufacturing parameters. The impact that a selection of parameters has on mechanical properties is presented in Table 1. The wide-ranging impact of these parameters means that MEX and other additive manufacturing methods are heterogeneous manufacturing techniques with different printers and manufacturing parameters yielding parts with varying and anisotropic geometric and mechanical properties.

Whilst these demonstrate a range of empirical relationships, it is noted that these have taken place with a wide range of printers, polymers and conditions, meaning that generalising trends from extant data is difficult (Popescu *et al.* 2018). In addition to these, previous work by the authors shows that the mechanical

Table 1. Impact of manufacturing parameters on mechanical properties of MEX parts

Parameter	Impact on mechanical properties
Layer height	Smaller layer heights are generally shown to increase part strength (Sood, Ohdar & Mahapatra 2012; Onwubolu & Rayegani 2014; Tymrak, Kreiger & Pearce 2014; Zhao, Chen & Zhou 2019; Garzon-Hernandez *et al.* 2020), though some studies have shown the contrary (Alafaghani *et al.*2017) or both depending on build orientation (Chacón *et al.* 2017)
Build orientation	Parts manufactured by MEX are anisotropic and are weakest in the direction of build (Z-direction) (Sood, Ohdar & Mahapatra 2010; Croccolo, Agostinis & Olmi 2013; Onwubolu & Rayegani 2014; Tymrak *et al.* 2014; Lanzotti *et al.* 2015; Alafaghani *et al.* 2017; Chacón *et al.* 2017)
Raster angle	Parts are strongest when raster angle is in the direction of applied load, a wider raster increases strength as does a negative air gap between rasters (Sood *et al.* 2010; Croccolo *et al.* 2013; Onwubolu & Rayegani 2014; Lanzotti *et al.* 2015; Casavola *et al.* 2016)
Infill percentage	Increased infill percentage increases part strength (Alafaghani *et al.* 2017)
Number of solid shells	Increased solid shells increase part strength (Croccolo *et al.* 2013; Lanzotti *et al.* 2015)
Extrusion temperature	Significantly impacts mechanical properties with each material having a distinct optimum extrusion temperature (Wittbrodt & Pearce 2015; Alafaghani *et al.* 2017; Zhang *et al.* 2017)
Material	Mechanical properties vary with different materials types (Onwubolu & Rayegani 2014; Tymrak *et al.* 2014) and colours (Wittbrodt & Pearce 2015)

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properties of parts do not scale with part size and also vary according to cross-sectional shape (Goudswaard, Hicks & Nassehi 2020).

Studies into applications of these techniques in home settings have revealed that the vast majority of parts (96%) that people would wish to make with additive manufacturing technologies would be to either replicate, improve or repair existing items (Shewbridge, Hurst & Kane 2014). In the context of Pahl and Beitz (Pahl *et al.* 2007) this corresponds to variant or adaptive design, which by their measures, combined account for 75% of design tasks. For the purpose of this article, these use cases (replicate, improve, repair, variant, and adaptive) will be collectively referred to as *variant* design. Variant design undertaken in the context of additive manufacturing is in itself complex as designs need to be tailored to individual printers as well as user requirements. Solution generation in these cases, therefore, requires the exploration of a multi-dimensional design space.

MEX has been shown to be a widely accessible and affordable manufacturing method that enables a wide range of design freedoms not exhibited by other manufacturing methods. This freedom is enabled by a large multi-dimensional design space underpinned by manufacturing parameters that can be individually controlled. Whilst empirical directives of these have been deduced, the impact these parameters have on mechanical performance cannot be generalised. In a general sense, it is hard to ensure the manufacture of parts with reliable mechanical performance. In the context of enabling the DoD, this is harder still as there are no design methods that can assist a non-expert designer in selecting appropriate manufacturing parameters given the functional requirements of their parts.

2.4. Design tools and techniques for additive manufacturing

This section will explore existing design tools and techniques that are currently available for additive manufacture.

The realisation of a functional part via an AM technique such as MEX commonly has five main stages:

1. Identify part requirements;
2. Design for AM – determine a part's form (external geometry);
3. Process planning for AM (definition of internal geometry through assignment of manufacturing parameters and tool path generation);
4. Part build; and,
5. Part validation.

These steps, along with their associated outputs, are shown for a traditional CAD process in Figure 3. Of these, the first two (Design for AM and Process Planning for AM) are of most interest as here design freedom can be found representing all phases of the engineering design process. Through the combination of the design of a part's form, and Process Planning for AM, a manufactured part's behaviour is fundamentally defined.

Design for AM outputs models first in a CAD tractable format which is often specific to the CAD software used. For slicing, this must be converted to a Computer-Aided Manufacturing (CAM) tractable format of which the most common is the Stereolithography (STL) file type.

An alternative to CAD is to use a design repository. By using these a user can download one of many freely available designs already in an STL format.

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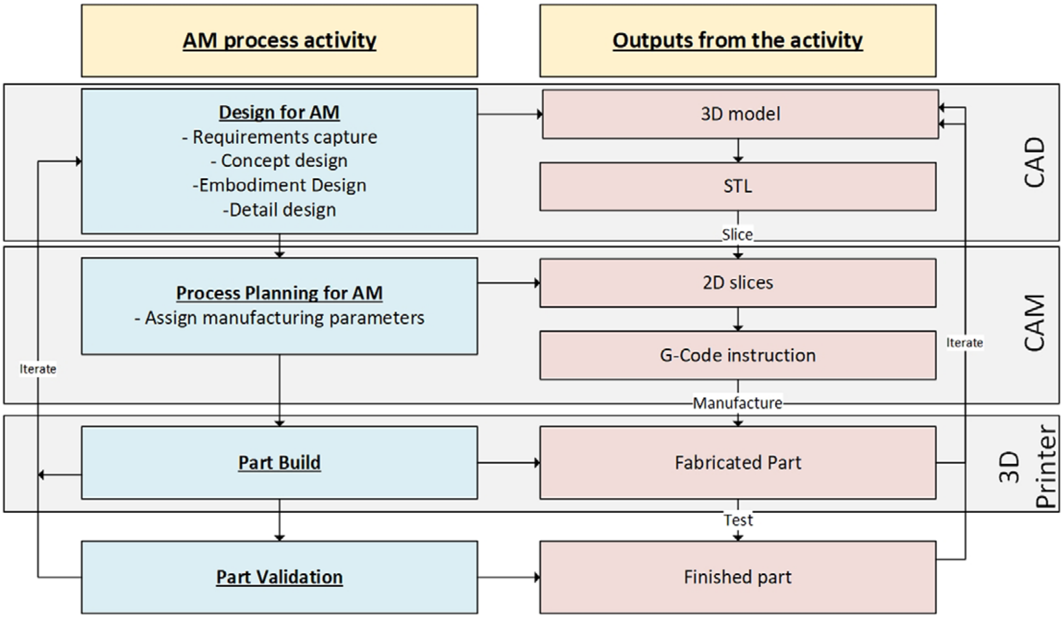

Figure 3. Traditional CAD AM design process stages and respective outputs. Adapted from Qin *et al.* (2019).

This results in greatly reduced steps in the design process, but also limits design flexibility. These design approaches will be explored in the following sections.

2.4.1. Computer-aided design

A large number of CAD packages are available to design parts for MEX which can be commercial or free to use. Commercial CAD packages (such as Autodesk Inventor, Fusion 360, Solidworks and Siemens NX) range in price from a few hundred dollars per year to tens of thousands of dollars, with the average price being around $3,000 per year (Carolo 2021).[2] Whilst these are powerful modelling tools, they come with hefty price tags and their un-inuituive, complex interfaces yield steep learning curves for a user to become proficient in their use.

Whilst CAD systems do afford excellent design freedoms, they possess a number of drawbacks in that

1. they are not intuitive (Ibrahim & Rahimian 2010) and require time and skill to become proficient with;
2. they are difficult to obtain and use and their input/output devices can interrupt creativity (Shih *et al.* 2017) and
3. making design changes with CAD is difficult (Ranscombe *et al.* 2019).

As such, difficulties are identified as key CAD challenges in terms of how designers are able to turn an idea into a design (Piegl 2005) and are more recently identified as a necessary barrier to overcome in achieving mass uptake of AM technologies (Birtchnell & Hoyle 2014).

[2]Prices of packages are negotiable and therefore can vary, however, indicative figures are provided to demonstrate that cost is a barrier to entry.

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The part creation process for traditional CAD is shown in Figure 3. When contextualised with respect to the Pahl and Beitz engineering design framework (Pahl *et al.* 2007), traditional CAD approaches are tools that can correspond to concept definition and detail design phases of the design process. Production definition is incorporated as part of the CAM process. This versatility across the design process represents a significant strength of CAD as tools can be used in concept generation, embodiment and detail phases. In essence, they enable design freedoms but only for those with an appropriate skillset and/or suitable software licence.

2.4.2. Design platforms

In place of users designing parts themselves, existing models can be retrieved from, or designed in collaboration with, design platforms (Rayna, Striukova & Darlington 2015). Services offered by design platforms include Design hosting with static models in repositories (such as Thingverse; MakerBot 2022), aesthetic design customisation (such as Thingiverse's Customiser; Makerbot 2022), co-design in collaboration with an expert (such as Shapeways; Shapeways 2019) and 3D print services (such as Hubs; Hubs 2022).

Design retrieval from design repositories is a means of accessing designs for AM that is widely used with over a million designs uploaded and more than 200 million downloads (Watkin 2015). While a straightforward means to access designs, a user is limited to extant designs on the platform which may not suit their requirements or manufacturing capability. The steps of the engineering design process in this instance are more limited, with a user only able to determine their requirements and select an appropriate model from the repository. In other words, design repositories provide free-to-use designs for all, but are limited with respect to designs that are available and the capacity to amend these designs to an individual's needs and/or manufacturing capability.

In previous work, the principle types of design challenges overcome by 3D printed parts in design repositories were found to be size (how components interact with others on a macro-scale), fit (topological interactions with other components) and load (the manner in which a component responds to load) (Goudswaard *et al.* 2017). These design challenges combined accounted for over 75% of functional components considered in the study.

2.4.3. CAM tools

For part generation by both traditional CAD or design repositories, Computer-Aided Manufacturing is required. CAM is the process of using software and computer-controlled machinery to automate a manufacturing process. In the context of AM, this involves the conversion of a CAD model to a G-code manufacturing instruction. This represents the tool path the 3D printer will follow in order to realise the requisite part. This is known as slicing (dividing a continuous model into discrete layers) and is carried out by slicing software. The input CAD model is combined with a set of manufacturing parameters (selected by the user) to create this.

A plethora of capable slicing software is available (Locker 2019). These include commercial offerings such as Autodesk's Netfabb and a wide range of free slicing

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packages that can be bespoke to 3D printer brands (such as Ultimaker's Cura) or open to be used with a variety of 3D printers.

The slicing process for 3D printing requires a user to select their manufacturing parameters which significantly impact the properties of a manufactured part. As shown in Section 2.3, this yields a large multi-dimensional design space. Given the aim of democratising design, this will need to be navigated on behalf of the user.

The separation of CAD and CAM processes is significant as it requires two stages to determine important parameters that come together in combination to define a part's behaviour. These are typically areas considered separately as Design and Manufacture, respectively. To reap the benefits afforded by AM design freedoms, these areas need to be considered together. This is also identified by Thompson *et al.* (2016), who identify this also as an opportunity for MEX, stating that 3D printing will re-define the role of design and manufacture by bringing them together.

2.4.4. Generative design

Generative design is about designing not only the object but a process to generate objects (Hansmeyer 2012) or put another way, they constitute 'design approaches that use algorithms to create designs' (Caetano *et al.* 2020). Via a computational exploration of design spaces, generative design techniques are able to rapidly explore a wide range of designs and have a wide range of commercial and academic applications. These existing tools can be used to fully map design spaces – requiring a user to select a candidate design, or automatically produce a candidate design based on an objective function.

Available commercial generative design packages include Fusion 360, Cogni-CAD, Solid Edge, Creo 7.0, MSC Apex, CATIA V6 and NX. These are capable packages for generating designs; however, they are unable to account for anisotropic material properties (as present in AM) (Junk & Burkart 2021). They also have a high skill barrier to entry as highly technical steps are required to, for example, define areas of material preservation, deduce load cases and highlight manufacturing constraints when setting up a generative design scenario (Buonamici *et al.* 2020). In addition to this, accessibility of the software is reduced due to the high costs of licences – for example, Fusion 360 costs $1,200 per year plus $33 per run (Develop3D 2021).

Further applications of generative design within the context of AM can be found in the literature. These include the following:

1. Methods for topological optimisation of additively manufactured parts (Silva *et al.* 2018).
2. The creation of an interactive tool that generates 3D-printed legs for walking robots based on a desired motion profile (Megaro, Thomaszewski & Gross 2015).
3. The amendment of internal and external properties of printed parts to re-distribute mass in order to allow them to balance (Prévost *et al.* 2013).
4. Managing manufacturing parameters to optimise the moment of inertia of a structure to increase the spinning time of a spinning top (Bächer *et al.* 2014).
5. The generation of 3D printed model joints that can provide friction during operation in order to make a functioning prototype (Calì *et al.* 2012).
6. The generation of custom 3DP infill based on required load and specific load profiles (Gopsill & Hicks 2016).

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7. A sketch-based method of interacting with topological optimisers for AM to simplify the interaction process (Chen *et al.* 2018).
8. A generative method based on parameterisation for the generation of variant designs in the design process (Krish 2011).
9. A bio-inspired generative design method to create bio-mimetic support structures (Zhang *et al.* 2020).
10. A generative approach for creating auxetic structures via MEX (Gromat *et al.* 2022).

These methods are contrasted in Table 2 according to whether the methodologies presented are appropriate for non-technical users, manage internal part structures, are validated with physical parts and are applied to MEX – potential prerequisites for enabling the DoD. None of the methods covers all of these areas.

Table 2. Generative design studies in the context of AM

	Potential requisites for enabling the democratisation of design			
Paper	Is the methodology appropriate for non-technical users?	Does the method manage internal geometry?	Method validated with physical parts?	Is the method applied to MEX?
Chen *et al.* (2018)	Yes	No	Yes, but not physically tested to confirm simulated behaviour	Yes, but without validation
Silva *et al.* (2018)	No	No	No	No
Megaro *et al.* (2015)	Yes	No	Yes, but results not incorporated into the design process	Yes, but without consideration of anisotropy
Prévost *et al.* (2013)	Yes	Yes[a]	Yes	No
Bächer *et al.* (2014)	Yes	Yes[a]	Yes, but results not incorporated into the design process	No
Calì *et al.* (2012)	Yes	No	Yes	No
Gopsill & Hicks (2016)	No	Yes[a]	Yes	Yes, but only one build orientation
Krish (2011)	Yes	No	No	No
Ozdemir *et al.* (2022)	Yes	No	No	No
Zhang *et al.* (2020)	No	No	Yes	No
Gromat *et al.* (2022)	No	Yes[a]	Yes	Yes

[a]Re-casting of internal structure rather than assignment of manufacturing parameters.

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Generative design approaches are therefore shown to have a wide range of applications in the context of AM and more generally for searching large design spaces but fall short of enabling the DoD for MEX. Commercial options cannot manage parts with anisotropic properties such as those manufactured via MEX. They also have high cost and skill barriers to entry much like traditional CAD packages.

Whilst they have the capability to manage large multi-dimensional design spaces, at present they have not been used in a manner that would permit a non-technical user to create functional components for MEX.

2.5. Concluding remarks and research gap

The findings of the preceding sections can be consolidated as follows. The field of Design and Manufacture is evolving towards new paradigms, moving away from the traditional approach of localised mass production to a more distributed model that focuses on creating personalised products. Whilst 3D printing technologies are widely available, design tools need to be democratised to empower people to design and manufacture themselves. In addition to this, 3D printing technologies such as MEX present challenges in terms of a large design space and mechanical properties that are hard to predict.

Traditional design tools separate the creation of form and assignment of manufacturing parameters and therefore do not explore the AM design space adequately. They are also either difficult to use (traditional CAD) or do not offer design freedoms (Design repositories). Generative design approaches are used for AM but not for MEX as they typically either do not account for the manufacturing process, do not incorporate physical testing results to validate part performance or remain difficult to use. Setting up a generative design problem from first principles is very difficult and could be considered more specialised than CAD. As a result, design repositories that host generative templates or seed designs could be a significant advantage to non-expert designers and enable the DoD.

Given the above, a research gap emerges in the application of generative design to augment the existing capabilities of design repositories. Design repositories already have a substantial user base and the incorporation of generative design could permit parts to be customised to an individual's requirements and manufacturing resource capability whilst exploring the AM design space and leveraging the affordances of the manufacturing technology. Moreover, design repositories would also be an appropriate platform to host seed designs. These would constitute a single setup of a generative design problem that could then be run by many according to their individual requirements and constraints.

The remainder of this article will detail such a design methodology and then demonstrate and evaluate its performance.

3. Research approach

In the preceding sections, the need and opportunity to increase use of MEX through the DoD has been established along with the potential to achieve this through the augmentation of design repositories with generative design approaches.

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The Design Research Methodology (DRM) of Blessing and Chakrabarti (2009) was selected to explore this proposition requiring the following: (i) research clarification; (ii) a descriptive phase one to identify the requirements of DoD; (iii) a prescriptive phase to propose and implement a design methodology to enable the DoD and (iv) a descriptive phase two to ascertain if and how the DoD is achieved. DRM was selected in favour of alternatives such as Action Research (Stringer 2013) as it can have issues with generalisabilty of results (Gopsill 2014) and a Design Research Approach (Duffy & O'Donnell 1999) which is less widely used than DRM.

Following these key DRM phases, the research approach in this article consists of the following steps:

1. identifying the requirements of the DoD;
2. presenting the required underpinning tools and technologies to achieve the DoD;
3. proposing a method of assessing whether DoD has been achieved;
4. presenting a design methodology that can enable the DoD;
5. providing an illustrative example of the design methodology applied in the design of a functional component; and,
6. evaluating if and how the proposed methodology is able to achieve the DoD.

DRM descriptive phase one constitutes steps 1–3, the prescriptive phase constitutes steps 4 and 5 and the final descriptive phase 2 constitutes step 6. The research clarification phase has presented already in Sections 1 and 2.

Steps 1–3 are dealt with in the remainder of this section with steps 4–6 addressed in Sections 4 and 5, respectively.

3.1. The requirements and pillars of the DoD

The requirements of a methodology that can enable the DoD for MEX were deduced via assessment of current MEX applications, characterisations of the design for MEX process and the MEX manufacturing process itself. These are defined as follows:

1. *To permit a user to undertake variant design tasks*: The majority of items produced via MEX are the replication, repair or improvement of existing items rather than the creation of new designs (Shewbridge *et al.* 2014). If contextualised with respect to the Pahl and Beitz framework, a democratising design strategy would therefore need to cover the embodiment and detail stages (Pahl *et al.* 2007).
2. *To make reasoned design decisions on behalf of the user*: The greatest difficulty experienced when designing for MEX is the decision-making process. This is in part due to the large and complex MEX design space (Goudswaard, Nassehi & Hicks 2019*b*) and in-depth engineering knowledge required to create functional parts. It is these decision processes that need to be automated (Section 3.3).
3. *To account for variability in process and lack of process knowledge*: There are significant gaps in the knowledge of the MEX manufacturing process (Huang *et al.* 2015). This was identified through empirical deduction of the variability of MEX components (Goudswaard *et al.* 2020). Given this, the only means to address this is through the incorporation of feedback from physical testing in order to validate the behaviour of parts.

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Table 3. Pillars of design democratisation and validation

Pillar	Justification
Build upon existing design repository capability	Design repositories are currently widely used, providing static CAD models which can be manufactured by users (as identified in literature review). To enhance their capability, the design methodology will incorporate customisable seed models which can be specified to an individual user's requirements and available manufacturing capability
Take reasoned design decisions	The seed models will consist of a functional model which permits a simulation of a part's predicted behaviour. This coupled with a capability profile will allow the generation of geometries and manufacturing parameters that enable the automated creation of a satisfactory part
Incorporate physical testing	Despite the use of functional models and capability profiles to simulate a part's behaviour, due to inherent variability in the manufacturing process itself, it is necessary to physically validate a part's behaviour. The methodology will therefore incorporate a physical testing element, the results of which can either confirm a satisfactory part or adjust target values for the next round of part simulation
Permit multiple design iterations	Because a given design may be unsatisfactory, multiple design iterations must be possible in order to arrive at a satisfactory solution through the incorporation of physical testing results

4. *To permit iterative design*: Results from physical evaluation need to be incorporated and used within the design process. To allow this the design process must cater for multiple iterations.

To meet these requirements, four pillars of design democratisation are defined that can enable non-technical users to design and manufacture functional components for themselves. The pillars and how they meet the requirements above are defined in Table 3. Physical testing can be more broadly considered as functional testing of a component through its envisaged use case.

3.2. Capability profiling

Capability profiles relate to the impact that machining or manufacturing parameters have on a part's properties. They represent the capabilities that a specific machine tool will be able to provide at a specific time on a specific product (Newman & Nassehi 2009). This, combined with information about the geometry and stock material, enables a part's characteristics to be described. This can take place at a range of levels, from the geometry of a part to chemical integration at atomic scales (Klocke, Brinksmeier & Weinert 2005).

In the context of MEX, given extant progress towards geometrically accurate parts (as described in Section 2.3), a capability profile is required to relate a part's manufacturing parameters to its mechanical properties. It is incorporated within the design methodology to enable mapping of the large solution space enabled by

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MEX and therefore contributes towards meeting requirement two of the DoD – making reasoned decisions on behalf of the user.

The manner in which a capability profile could be incorporated in the design for additive manufacture process is explored in depth in previous work (Goudswaard *et al.* 2020).

The capability profile used in the design methodology incorporates five manufacturing parameters (layer height, solid shells, top/bottom layers, infill percentage and build orientation). A tensile testing program was undertaken to enable empirical deduction of the impact that each parameter had on mechanical properties. An artificial neural network was trained on the experimental data to form a capability profile able to predict a part's ultimate tensile strength and tensile modulus based on input manufacturing parameters and geometries. The summation of design parameters multiplied by each synapse weight and hyperbolic tangent activation function enables the calculation of mechanical properties. An in-depth exploration of how this capability profile was formed and validated can be seen in Goudswaard, Hicks and Nassehi 2021 along with the definition of synapse weights. Appendix A steps through how geometric and manufacturing parameters are converted into mechanical properties via the use of the capability profile.

3.3. DoD assessment methodology

The DoD seeks to increase the accessibility and involvement of non-technical users in the design process. In the context of creating functional MEX parts, this is achieved through the reduction and where possible elimination of domain-specific highly skilled decisions and operations. Given this, the assessment methodology employed is comparative, that is, characterising and contrasting the 'as-is' with the 'as-democratised' processes. Consideration of the process necessarily requires a range of design activities to be appraised including those that

1. are directly CAD based;
2. are related to the design cognition[3] of the designer during the process;
3. involve interaction with the artefact or its intended use environment; and
4. interact with a manufacturing resource.

This section will explore existing methods of comparing design processes with respect to the above design activities before defining the approach used in this article.

3.3.1. Existing approaches

In order to make a comparison between two design approaches, it is necessary to compare three dimensions of design cognition Hay, Cash & McKilligan (2020):

1. Higher-order cognition – for example, decision-making;
2. Design process – incorporating methods, tools, technologies, human–computer interaction; and,
3. General design work including basic actions in design.

[3]"Design cognition aims at measuring design reasoning, processes and patterns; divergent and convergent thinking; design fixation; design creativity; visual reasoning in design; design space co-evolution and design collaboration with design cognition tools, among others" (Gero & Milovanovic 2020).

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For completeness, each will need to be incorporated into a design evaluation approach.

As the design process is performed digitally, usability inspection methods (Nielsen 1994) that permit the evaluation of user interfaces are applicable. The most relevant of these to this research are the methods of cognitive walk-through (to simulate a user's problem-solving process) and heuristic estimation (to quantitatively evaluate usability between two interfaces). Nielsen notes that it is appropriate for cognitive walk-through and heuristic estimation to be undertaken by a single evaluator. These can be combined with design cognition elements to more fully understand the design process.

In addition to considering UI, specific attention must be given to the CAD activities of the design process as the importance of interfaces in enabling effective software use has long been recognised (Nielsen (1993) provide numerous examples). Existing approaches for direct CAD characterisation have been carried out by Gopsill *et al.* (2016) and Rosso *et al.* (2021) with the aim of sequencing and identifying variance in these processes. In these studies, CAD approaches are characterised with respect to the type and order of steps a user undertakes.

Lastly, Hay *et al.* (2017) suggest that protocol analysis – the interpretation of a subjective verbal report of a designer's cognitive processing (Ericsson & Simon 1982) – is well suited to exploratory investigations in underdeveloped research areas. Of the existing applications of protocol studies, 17% use sample sizes of one or two (Hay *et al.* 2017).

As previously noted and given the need to appraise the overall process and CAD-based tasks, the methodology used in this research combines elements of all the aforementioned methods including the following:

- Cognitive walk-through and step-wise design characterisation – to understand the design steps undertaken when realising a functional component via MEX and how these contribute difficulty to the process;
- Heuristic estimation – to permit quantitative comparison of two approaches and identification of where the difficulty is reduced by DoD; and,
- Protocol analysis – to assess the underlying cognitive processes of the designer that are less related to practical steps but understanding and application of more general designerly skills.

3.3.2. DoD assessment process

This first stage involves logging a description of each step of the design process undertaken by a designer when generating, manufacturing and validating a component. This corresponds to element one from the literature – cognitive walk-through and step-wise design characterisation. Design steps are categorised into one of the following five bands:

1. *Software Interaction* – for example, opening a program or exporting a file.
2. *Hardware Interaction* – for example, operating a 3D printer.
3. *Decision* – for example, choosing a course of action and deciding how to use the software to achieve a goal.
4. *Observation/Measurement* – for example, evaluating a part's performance, identifying or measuring design features, for example, the size of an interfacing component.
5. *Geometry alteration* – generating or changing 2D or 3D geometry.

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Table 4. Assigned difficulties and examples

Difficulty	Description	Know-how	Understanding
0	Not relevant to design step	–	–
1	Requires everyday knowledge	Open Autodesk Inventor	Identify what a required part needs to interface with
2	Requires awareness of technical terms, high-level functions of environment	Open a sketch	Identify the overall necessary form of a part
3	Requires technical knowledge that could be learned through hands-on experience	Apply a fillet to a corner in CAD	Identify interfacing measurements for a design
4	Requires technical knowledge of downstream functions and engineering properties	Use more advanced CAD features such as Autodesk Inventor's offset function	Decide a shape profile to minimise stress concentrations
5	Requires knowledge that was taught in an engineering degree	Edit a thread profile to better suit interface requirements	Decide strategy to reduce a part's deflection under load

Design steps are then assigned difficulties. These are defined in Table 4 along with examples of the types of steps that could correspond to each difficulty level. Difficulty levels higher than 3 are considered as 'specialist', requiring knowledge acquired through, for example, an engineering degree. Values are assigned for two types of difficulty. The first regards *know-how* – the methods or techniques of doing something, especially something technical or practical (Collins n.d.). These relate most to step-wise design characterisation.

The second regards *understanding* – grasping 'how a constellation of facts relevant to that subject are related to one another (causally, inferentially, explanatorily, etc.) in such a way as to be able to make new connections or draw new inferences with novel information' (Huxster *et al.* 2018). This is more related to design cognition measured via protocol analysis.

Heuristic estimation is carried out for both *know-how* and *understanding* permitting a separate comparison of each. This allows the distinction of process difficulty that is (i) directly associated with the use of a specific design tool or method (e.g. undertaking a design step) and (ii) agnostic of tools and more generally related to the design problem at hand (e.g. elucidating a course of action).

DoD assessment will be undertaken by a single designer as it is identified to be appropriate for exploratory studies in the context of protocol analysis (Hay *et al.* 2017), cognitive walk-through and heuristic estimation (Nielsen 1994).

Aligned with the definition of DoD presented in Section 2.2, determining whether DoD is achieved relates to the comparison of the 'as-is' with the 'as-democratised' process considering the differences between the average difficulty of process steps as well as the most difficult steps within each process. The DoD can be considered to be achieved if average and maximum step difficulties are reduced.

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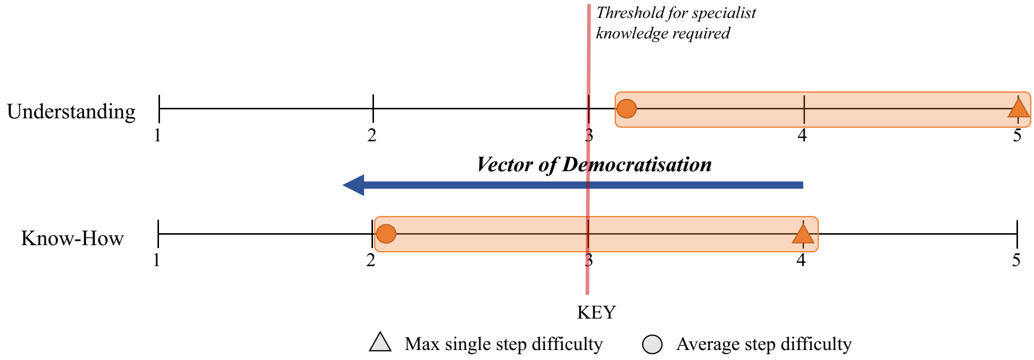

Figure 4. Spectrum of democratisation for Understanding and Know-how with overall figures for CAD-based process and vector of democratisation.

In addition to this, this article considers a threshold difficulty of 3 as a target as this indicates a requirement of specialist knowledge to undertake the process.

The spectrum of democratisation along with a preliminary characterisation of a CAD-based design process applying the methodology outlined above is presented in Figure 4. Further details of the characterisation are reported in the literature (Goudswaard *et al.* 2017) and key quantitative results for DoD comparison will be considered further in Section 5. The outcome of this previous study framed requirement 2 of DoD in Section 3.1 – to make reasoned design decisions on behalf of the user.

4. GBD methodology overview

The GBD methodology will be defined by (i) defining the models within it and their interrelations; (ii) providing an overview of the high-level steps within the design methodology; and (iii) providing an IDEF0 activity diagram demonstrating the process in greater detail.

A detailed walk-through of the user experience will not be provided here as a detailed analysis of the GBD compared to a traditional CAD-based design process will be covered in Section 5.3.

4.1. Models within the GBD

Three model types are included within the GBD methodology and are as follows:

1. *Capability profile* – to relate and convert print parameters to mechanical properties;
2. *Part functional model* – to convert mechanical properties and geometry into part function; and,
3. *Structural parametric model* – to convert geometric parameters into a CAM tractable STL which can then be used in slicing software.

In addition to these models, user requirements and a physical part are necessary. The process is driven by the user requirements as these are needed to direct the creation of a design instance. A physical part is necessary to validate its functional performance and direct a subsequent design iteration if it is required.

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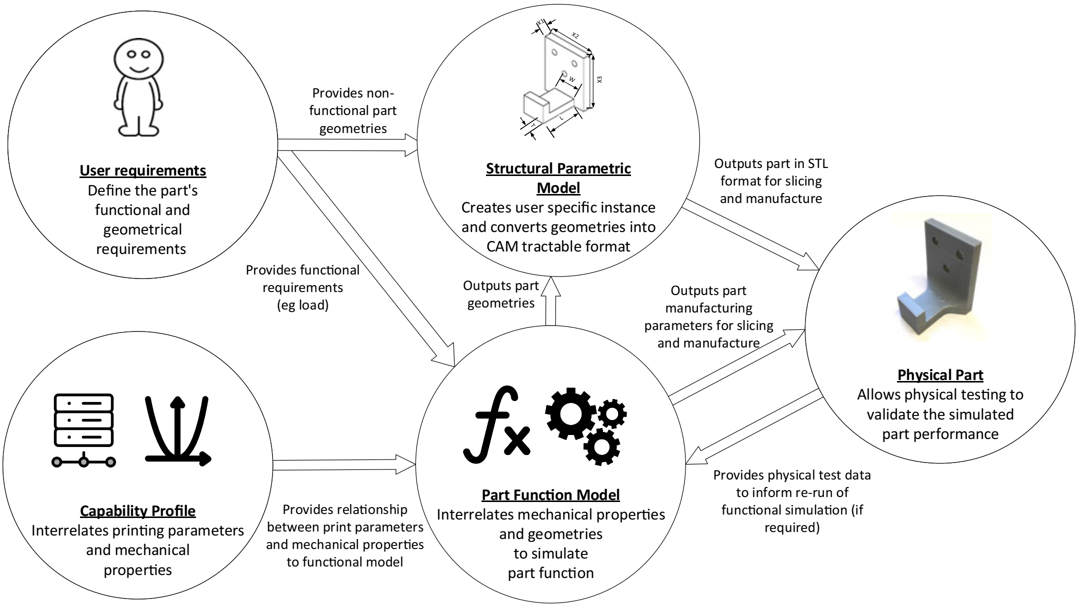

Figure 5. Models and objects in the GBD methodology, their functions and interrelations.

Figure 5 demonstrates the models and objects within the GBD methodology and their interrelations.

The capability profile (presented in Section 3.2) is specific to a manufacturing resource. The Part Functional and Structural Parametric models can be considered as *seed models* which can be considered as 'the starting point for all subsequent transformations and is specifically created to allow some form of personalisation by the intended end-user/customer' (Bingham 2019). In this way, the seed models represent a design space in which a design solution unique to a user's functional requirements and manufacturing constraints can be found. The construction and navigation of this design space will be explained in the following section.

4.2. GBD methodology activities

The GBD methodology incorporates design activities from physical and digital domains and continues iteratively until a satisfactory part is manufactured. An overview of the GBD methodology is shown in Figure 6. Step 1 of the methodology involves the user inputting their functional requirements. Through simulation in the digital domain via Particle Swarm Optimisation (PSO)[4] and a Part Functional Model (steps 2, 3 and 4), the design of a part is predicted to meet the requirements. This part is then manufactured (step 5) and physically tested to validate its actual behaviour (step 6). This actual part behaviour is contrasted with its predicted behaviour. If the part is unsatisfactory, the physical testing results are incorporated

[4]PSO was selected as the metaheuristic within the methodology as it was shown in previous work to outperform evolutionary algorithms and simulated annealing with respect to quality and consistency of results in the context of manufacturing parameter selection for MEX (Goudswaard *et al.* 2019*b*).

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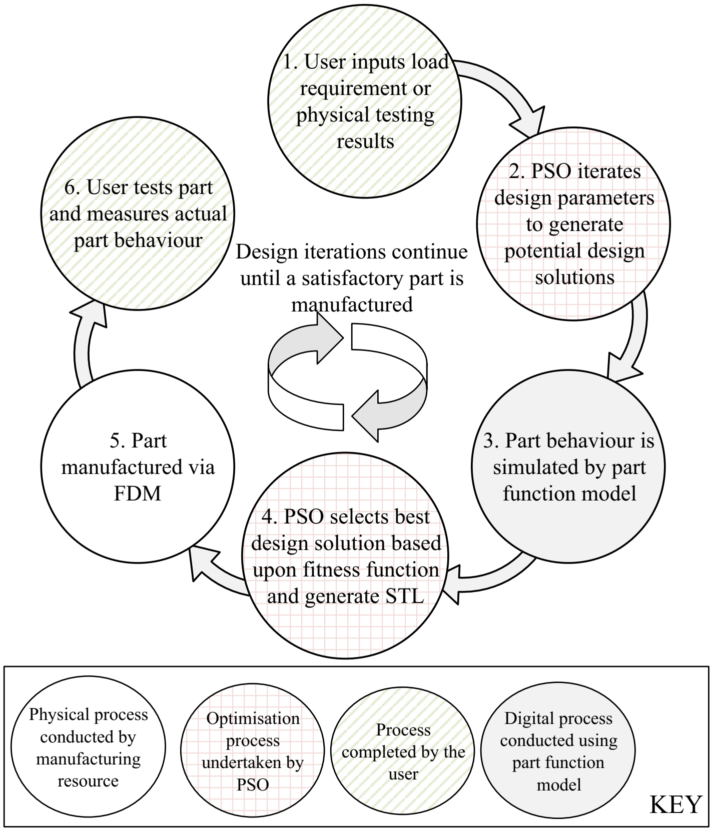

Figure 6. Overview of the generative-based design methodology (adapted from Goudswaard *et al.* 2021*b*).

into the next design iteration and the process is repeated until a satisfactory part is generated and validated.

Figure 7 shows an IDEF0 (Ross *et al.* 1981) representation of a single iteration of the GBD methodology, demonstrating its activities and the inputs, outputs, controls and mechanisms of each.

In the *Generate instances, simulate behaviour and select instance activity* (A1) User needs are translated into geometric parameters, manufacturing parameters and predicted behaviour by the mechanisms of PSO and Part function model and controls of the capability profile and part requirements. The *Generate Geometric Instance* (A2) activity takes geometric parameters as a control translating them to a design instance in STL format via means of the structural parametric model. In the *Slice Geometry* (A3) activity, the STL input is sliced in accordance with manufacturing parameters (control) by slicing software (mechanism) to generate a manufacturing instruction (output). The *Manufacture Part* (A4) activity part is then manufactured from raw material (input) by an MEX printer (mechanism) following a manufacturing instruction (control). In the *Test Part* (A5) activity, the user (mechanism) takes the manufactured part (input) and evaluates it according to testing criteria (control). The final activity, *Compare part's*

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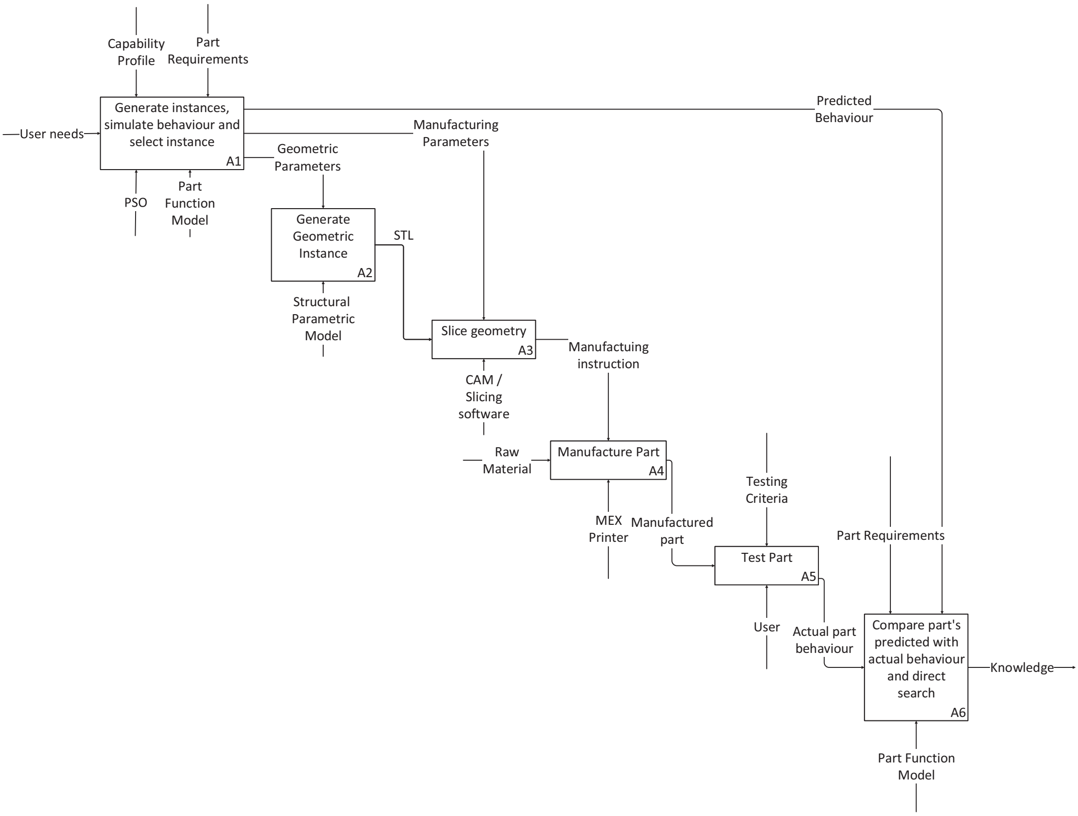

Figure 7. IDEF0 activity diagram for single iteration of the GBD methodology.

predicted with actual behaviour and direct search (A6), takes the actual part behaviour (input) and contrasts it with the part requirements and predicted behaviour (both controls) and generates knowledge (output) which would be used to refine subsequent design iterations.

Figure 7 shows only a single design iteration but a multi-iteration design process would take the knowledge output from A6 and use it as a control for the next iteration's *Generate Geometric Instance* activity.

5. Illustrative application

The GBD methodology was implemented in Rhino 6's Grasshopper parametric design environment. The implementation is shown in Appendix B. Further details on the technique and illustrative application can be found in the author's PhD thesis (Goudswaard 2020).

As a use case, an S-hook was chosen as an appropriate load-bearing component and is shown in Figure 8a. This was based on an extant design for holding IV fluid that is implemented and used by Field Ready as shown in their parts catalogue (Field Ready 2018). Field Ready specialise in the local manufacture of parts via techniques such as MEX that otherwise could not be purchased or made. The aim

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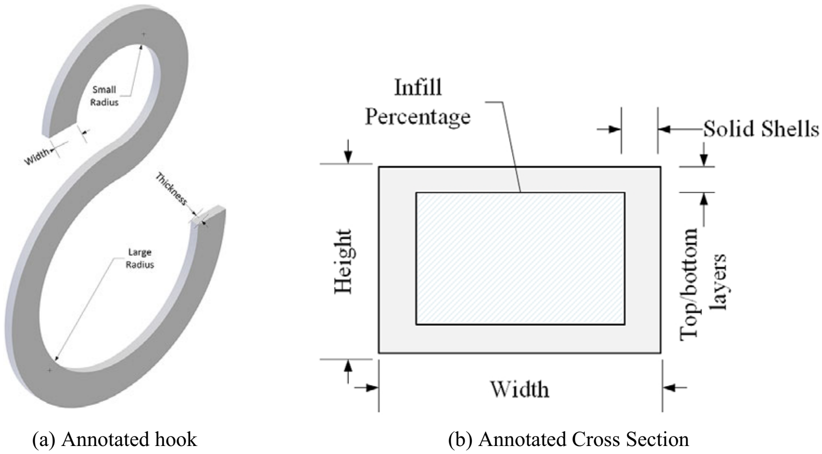

Figure 8. Parametrised S-hook and cross-section.

of this use case was to generate an S-hook that can accommodate a load of 150 N – the recommended loading of 10 times the weight of an IV bag.

The general steps that expert and non-expert designers need to take in this use case are as follows. A non-expert designer requires an S-hook that can meet their unique geometric and load requirements and can be manufactured on their specific 3D printer. The non-expert lacks the required knowledge of static mechanics or AM to define the internal and external geometries of their part. An expert designer would generate the seed model (comprising of a structural parametric model and part function model as defined in the following sections) that can generate a satisfactory component for the individual requirements of the user. The non-expert designer is required to locate the appropriate seed model (i.e. the S-hook), input their load and geometric requirements, print the part and test it once it has been made.

5.1. Defining the solution space

The solution space is defined by the seed designs. These constitute the structural parametric model, part function model and objective function. These will be defined in this section.

5.1.1. Structural parametric model

The structural parametric model for the S-hook use case is shown in Figure 8a which demonstrates the input variable dimensions. Large and small radii are selected by the user; width and height are generated by the GBD methodology. In addition to these external dimensions, manufacturing parameters of infill percentage, solid shells, top/bottom layers and layer height are also generated by the GBD methodology (shown in Figure 8b). These six parameters define the solution space in which a design solution can be generated. The limits on each of these parameters are defined by penalty multipliers shown in Table B1 which can be found in Appendix B.

5.1.2. *Part function model*

The part function model uses mechanical properties defined by the capability profile and a static mechanics analysis of where the part is envisaged to fail.

This approach could be considered an extension to that presented by Umetani and Schmidt (2013), which can identify weak points in designs and use this to recommend print orientations for parts. The static mechanics approach used in the following use case goes further. Through combination with a capability profile, it is able to recommend a full suite of manufacturing parameters.

The functional model, in this case, is based upon the Euler–Bernoulli beam theory as shown in equation (1). Describing the part of a curved beam in this way is valid as the radius of curvature is large compared to the cross-section.

$$\sigma = \frac{My}{I}, \tag{1}$$

where σ is equal to the UTS, M is the applied moment, y is the distance to the neutral axis and I is the second moment of area calculated about the neutral axis (as shown in equation (3)). σ is calculated by the artificial neural network of the capability profile as explained in Section 3.2.

Shape analysis calculates areas of both shell and infill. In this bending use case, it permits calculation of solid material at the cross-section (A_{mat}) as per equation (2).

$$A_{\mathrm{mat}} = A_{\mathrm{shell}} + \alpha A_{\mathrm{infill}}, \tag{2}$$

where A_x corresponds to shell and infill areas, respectively, and α is the percentage infill.

$$I_{\mathrm{tot}} = I_{\mathrm{shell}} + \alpha I_{\mathrm{infill}}, \tag{3}$$

where I_{tot} is the second moment of area of the entire cross-section, I_{shell} for the shell and I_{infill} for infill.

5.1.3. *Objective function*

The objective function for this use case seeks to produce a part that can fulfil its required function by withstanding a given load with minimal material usage. Each design iteration also requires it to incorporate results from physical testing. The equation of the fitness function is shown in equation (4)

$$\phi = \frac{\psi L}{A_{\mathrm{mat}}}, \tag{4}$$

where ϕ is the fitness value to be maximised, ψ is the product of penalty multipliers and L is the required load and is equal to $\mathrm{Min}\left(F_{\mathrm{target}}, F_{\mathrm{required}}\right)$. F_{target} is the load the part needs to be able to take. F_{required} is calculated according to equation (5)

$$F_{\mathrm{required}} = \tau F_{\mathrm{target}}, \tag{5}$$

where τ is the Load Ratio and is calculated as $\frac{F_{\mathrm{target}}}{F_{\mathrm{actual}}}$. F_{actual} is a result from physical testing. F_{target} is the load that the part is required to take.

Penalty multipliers are implemented in order to do the following:

1. Ensure solutions generated are within the bounds of what the capability profile can generate;

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2. Ensure the dimensions generated are possible (e.g. internal geometries are not larger than external geometries);
3. Ensure the print is reliable; and
4. Direct the algorithm more quickly to a solution.

Eight penalty multipliers were incorporated with values of either 0.1 or 0.01, these are shown in Table B1 in Appendix B.

5.2. Design outputs

Results from the iterations are shown in Table 5. The first generated component failed at a load of 130 N. This test result was fed back into the GBD to increase the target load, which then permitted the generation of a satisfactory part for the second iteration. Through the use of the methodology, a part able to meet requirements was designed in just two generations without any technical input on the part of the user. Moreover, this is achieved via rapid exploration of a seven-dimension solution space facilitating the generation of a functional part with minimal material usage.

The generation of a successful component validates the functional aspect of the design methodology. As the focus of this article is on design democratisation, the next section will explore if and how design democratisation is achieved.

5.3. Evaluating the DoD

The evaluation approach defined in Section 3.3.2 was used to evaluate the difficulty of the GBD methodology contrasted with a traditional CAD-based approach.

The assigned difficulty scores and categorisation of design steps permit the appraisal of design democratisation at two levels. The first level is the overall process with attention paid to the total number of design steps, their types and the difficulty they contribute. The second level considers categorised design steps, to

Table 5. Outputs from each iteration of S-hook generation

	Iteration	
Parameters	1	2
Build orientation	X	X
Height (mm)	4	4
Width (mm)	15	15
Infill (%)	79	81
Solid shells	2	4
TB layers	6	6
Layer height (mm)	0.3	0.3
Predicted load (N)	150	173.9
Actual load (N)	130	150
Ratio of actual/predicted	0.867	0.863

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Table 6. Overall step totals and average difficulties

	Trad CAD			GBD		
	# Steps	Avg. difficulty (1–5)		# Steps	Avg. difficulty (1–5)	
Step type		U	K-H		U	K-H
Software interaction	30	3	1.7	24	1.3	1.2
Hardware interaction	6	0	2	2	0	1
Decision	40	3.3	3	6	2.2	0
Observation or measurement	8	2.9	1.7	3	1.7	1.7
Geometry alteration	27	3	2.3	0	0	0
Total	111	3.2	2.1	35	1.8	1.3

provide insights on where in the process difficulty has been removed. These two levels permit elucidation of the extent to which the DoD has been achieved and, if it has, the types of steps that are removed or reduced to enable this.

To facilitate the aforementioned appraisals, Table 6 presents categorised total steps for each design methodology, and average difficulty scores for both *know-how* (K-H) and *understanding* (U) in the creation of a load-bearing component. Figure 10 presents the total steps for this process at each difficulty level for both K-H and U. Figure 9 presents a breakdown of step types by category and difficulty for both K-H and U. This permits the comparison of a traditional CAD approach with the GBD methodology.

To provide insight into the overall process, it can be seen from Table 6 that total steps required to create a functional part are reduced from 111 to 35 with average difficulties for U and K-H reduced from 3.2 to 1.8 and 2.1 to 1.3, respectively. With respect to the reduction and/or removal of steps, geometry alteration steps are fully removed in the GBD methodology (shown in Table 6). As such, the average difficulty for geometry alteration is reduced from 3 to 0 (U) and 2.3 to 0 (K-H). Decision-making steps are reduced from 40 to 6 (shown in Table 6). Because of this, the average level of difficulty in decision-making is reduced from 3.3 to 2.2 for *understanding* and 3 to 0 for *know-how*. This demonstrates that the GBD methodology takes some design decisions on behalf of the user. Substantial reductions are also observed for other types of steps with the exception of software interaction which shows only a relatively lower decrease (30 to 24 steps).

Figure 10 shows a sum of the total steps at each difficulty level for both *know-how* (K-H) and *understanding* (U). All steps with difficulties of 4 and 5 for both K-H and U are removed for the GBD; at a difficulty level of 3, total K-H occurrences are reduced to 0, and U occurrences are reduced from 26 to 2. This can be seen by the shift down and to the left in Figure 10 when moving from trad CAD on the left to GBD on the right.

These reductions in total design steps and average difficulties indicate that design democratisation, to some extent, has been achieved through the use of the GBD methodology. At an overall process level, this is largely due to the removal of geometry alteration steps, and a large reduction in decision-making steps.

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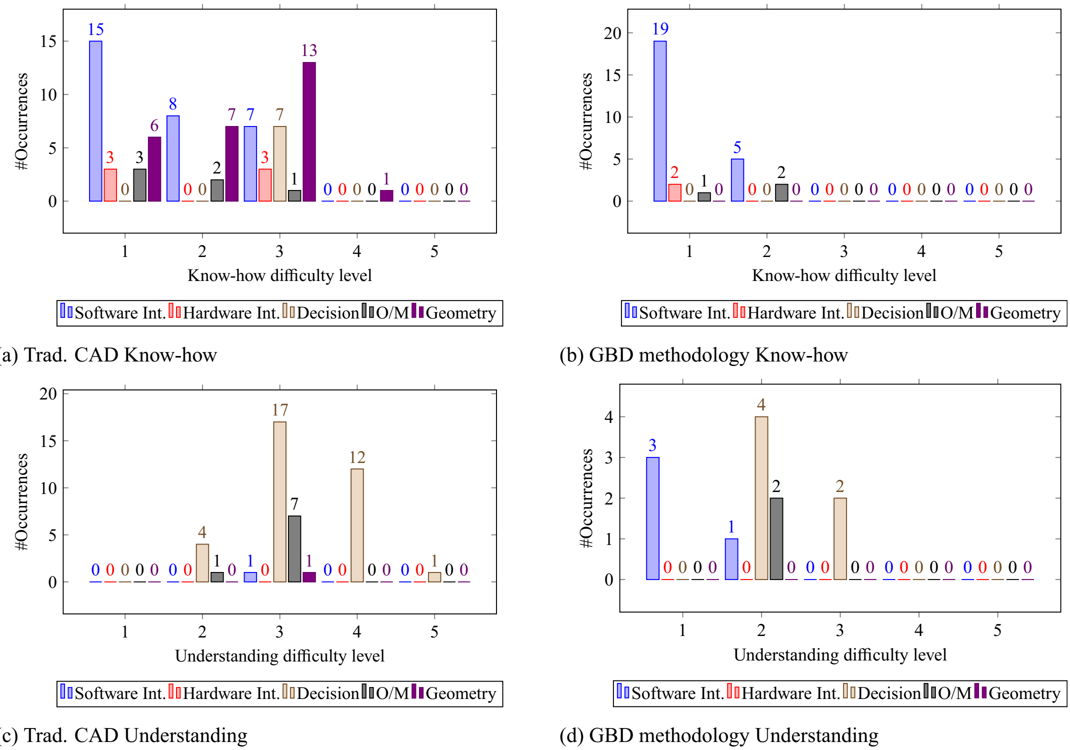

Figure 9. Generative-based democratised (GBD) methodology versus traditional CAD-based approach compared for know-how and understanding.

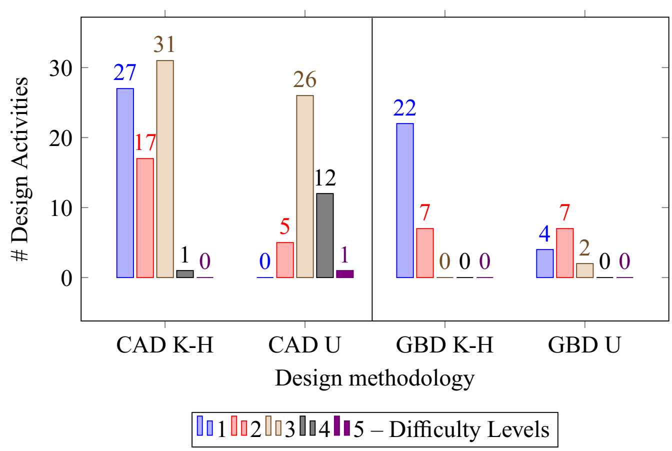

Figure 10. Difficulty comparison for Understanding (U) and Know-how (K-H) for traditional CAD-based design versus GBD methodology.

Additional mechanisms for design democratisation can be elucidated by exploring the difficulty levels of step categories in greater detail.

Comparing difficulty changes in *know-how* (shown in Figure 9a compared with Figure 9b) it can be seen that (i) maximum difficulty for software interaction is

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reduced from 3 to 2; (ii) maximum hardware interaction difficulty is reduced from 3 to 1 and (iii) maximum observation and measurement difficulty is reduced from 2 to 1.

Comparing difficulty changes in *understanding* (shown in Figure 9c compared with Figure 9d) it can be seen that (i) maximum decision difficulty is reduced from 5 to 3; (ii) maximum software interaction difficulty is reduced from 2 to 1.

These maximum difficulties can be considered threshold difficulty values. Their implications, along with those of the aggregate reductions in difficulty, will be considered in Section 6.

6. Discussion and further work

This section will consider the implications of the GBD methodology on the DoD and the generalisability of the paper's findings, and outline steps for further work.

6.1. The implications of the GBD methodology on the DoD

The quantitative evaluation provided in Section 5.3 can be further explored via the difficulty levels defined in Section 3.3.2 to identify the implications of design democratisation enabled by the GBD methodology. Design steps are considered 'specialist' for values higher than 3 as these require knowledge that could, for example, be learned in an engineering degree. When contrasting the GBD methodology with a traditional CAD-based design approach (as shown in Section 5.3), total steps are reduced from 111 to 35 with the average difficulty of design steps shown to reduce from 3.2 to 1.8 (U) and 2.1 to 1.3 for (K-H). When using the GBD methodology, the overall process to create a functional component is shown to be shorter and less difficult than when using a traditional CAD approach. Additionally, threshold or maximum step difficulty was seen to be reduced from 5 to 3 (U) and 4 to 2 (K-H), demonstrating that all design steps in the GBD have difficulties of 3 or lower indicating that design steps considered to be specialist have been removed. Reductions in both average and threshold measures demonstrate that the DoD has been achieved. This is depicted in Figure 11 which presents the change in maximum and average difficulty values for steps in both the GBD and

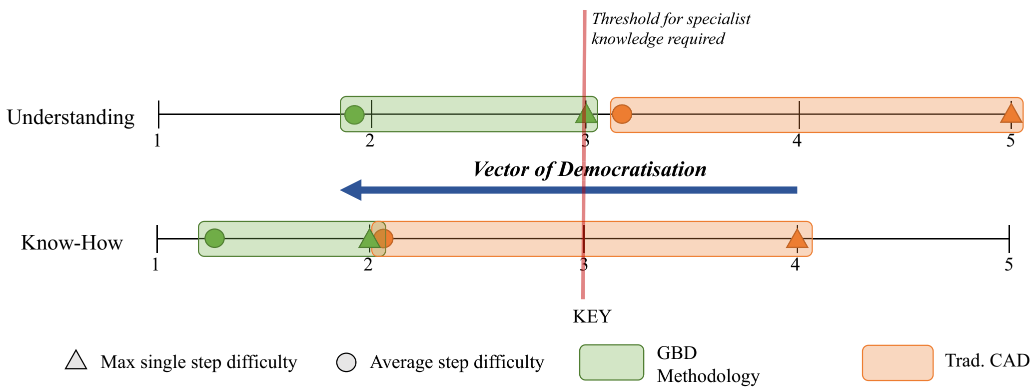

Figure 11. Difficulty comparison on the spectrum of understanding for Understanding (U) and Know-how (K-H) for traditional CAD-based design versus GBD methodology.

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traditional CAD-based process. For both know-how and understanding, leftward shifts can be observed indicating that the DoD has been achieved.

The DoD is about enabling non-technical users to develop parts for themselves and, in the case of the GBD methodology, a principle mechanism for enabling this is found to be the reduction of decision-making steps and removal of geometry alteration, which are undertaken on behalf of the user. However, as with any form of design democratisation, an 'expert' is required somewhere in the process (Goudswaard *et al.* 2019*a*). In the case of the GBD methodology, an expert designer is required to develop the seed models that would be hosted in the design repository. This is not indifferent to the present situation with design repositories, where users upload their designs so others may freely re-use them. In this way, the GBD methodology facilitates design with non-designers via a one-to-many relationship; an expert designer creates a seed model and (traditionally) non-designers are able to use them to create variant and bespoke parts to fulfil their needs. Steps to enable this will be considered in Section 6.3.

It is also noteworthy to consider whether cumulative (i.e. average) or threshold (i.e. maximum) difficulty is more important when enabling the DoD. The average difficulty of design steps in the process to generate a functional part could correlate to the time taken to design, where a difficulty threshold is about the requisite skill and knowledge of the designer.

6.2. Generalisability

The work undertaken in this article demonstrates the successful DoD for a load-bearing part, for which the determination of whether a part is satisfactory or not is binary and, therefore, straightforward. This represents a limitation of the illustrative application demonstrated in this article as other categories of design tasks such as fit-type problems involving interfacing components are more challenging. In these cases, it would be unclear what would need to change in order to arrive at a satisfactory design. In lieu of requiring a user to manually measure a part, automating this process would require a means of scanning the physical part to understand how it fails to meet its requirements. The GBD methodology can therefore be said to be generalisable for functional load-bearing design tasks but, for other functions such as fit, requires further work.

Related to the types of design tasks used to instantiate the design methodology is the extent to which the methodology (and implementations thereof) may reasonably be expected to capture all that is required to achieve high-performant design outputs. This can largely be considered to be dependent upon the creation of a robust framework to enable the generation of the seed models that underpin the methodology. As such, this is outside of the scope of the research presented in this article, but will be commented upon in Section 6.3.

The design process comprises a number of different areas that contribute to the difficulty. The GBD methodology enables a non-technical user, without experience in CAD, static mechanics or assignment of manufacturing parameters to generate a functional load-bearing part. In this way, it can be considered that 'functional' design democratisation is enabled by the GBD methodology and has been demonstrated in its instantiation by moving cognitive load from the user to the design tool. This does not, however, constitute the whole picture when it comes to the DoD. The interface which permits a user to interact with a system is also essential as

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even with difficulty from the aforementioned areas removed, a poorly designed interface will prevent a user from interacting with the design tool effectively. Whilst this is crucial in deploying a fully usable design tool, it was not central to the paper's aim and would need to be developed *in situ* within a design repository. As such, it can be considered that the outputs and results of the article remain perfectly valid. This, along with testing with un-skilled participants, will be considered in greater detail in Section 6.3.

6.3. Further work

Difficulty reduction and subsequent design democratisation are both quantified through the undertaking of design tasks by a single user. Due to the small sample size, further user testing is necessary to confirm that the DoD is more widely achieved. As such, an avenue for further work is identified as undertaking further user testing.

In order for the method to function, expert designers are required to generate the seed designs that non-technical users require. This article has not considered the manner in which these would be generated but this is essential for enabling a practical implementation of the methodology. Further work will therefore consider the generation of a framework that expert designers would be able to follow in creating seed designs.

This article has presented a GBD methodology that could be used to augment the existing capabilities of design libraries. Following validation that the method is able to democratise design, embedding the approach into an existing design library is a logical next step. This article constitutes a proof of concept which demonstrates that the GBD methodology can achieve design democratisation. Incorporating the methodology in a design library would also enable field testing, permitting elucidation of whether the design methodology is useful and practical in its envisaged environment.

7. Conclusion

This article has presented a GBD methodology to enable the DoD for 3D printing applied in the context of the MEX manufacturing process.

To direct the generation of the methodology, the requirements of the DoD for MEX were presented. These state that to democratise design a design methodology needs to (i) permit a user to undertake variant design tasks; (ii) make reasoned design decisions on behalf of the user; (iii) account for variability in the MEX process and (iv) permit iterative design.

To meet these requirements, a first-of-a-kind GBD methodology is presented that is underpinned by an ANN-based capability profile linking mechanical properties of parts with manufacturing parameters and seed models consisting of a part function model and a structural parametric model. These, when coupled with a user's part requirements, facilitate the generation of a variant or bespoke part via PSO. The methodology is iterative; the behaviour of the manufactured part is used to validate the generated part, and if it is hitherto unsatisfactory, the part's actual behaviour can be used to direct a subsequent design iteration.

The methodology is implemented in Rhino 6's Grasshopper parametric design environment. As an illustrative example, the creation of a load-bearing part is considered and a satisfactory part is generated via means of the GBD in two design iterations.

To determine if the DoD has been achieved, the GBD methodology is contrasted with a traditional CAD-based design approach. To create a functional load-bearing part, it is shown to enable a 68% reduction in number of design activities and, in terms of the average design process difficulty, the GBD methodology shows a 62% reduction in requisite know-how and 55% reduction in understanding. In addition, threshold design difficulty is shown to be reduced such that any specialist design steps are removed enabling a non-technical user to create a functional component. The principle mechanism for DoD is observed to be through the removal of decision-making and geometry alteration steps.

Whilst the DoD is demonstrated for the use case presented, further work will involve applying the methodology for more use cases and users. Wider implementation of the methodology requires a framework to guide expert designers to create seed models, which would in turn enable the implementation of the GBD methodology within its intended environment of a design repository.

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A. Appendix A

The following steps are required to convert geometric and manufacturing parameters into mechanical properties via the use of the ANN, the structure of which is shown in Section 7. The synapse weights from the capability profile are represented by matrices B and O shown in equation (A1). Where B represents synapse weights from the input to the hidden layer; O represents the weights from the hidden to the output layer.

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$$B = \begin{pmatrix} H1:1_1, & H1:2_1, & \dots & H1:7_1 \\ \vdots & \vdots & & \vdots \\ H1:1_7, & H1:2_7, & \dots & H1:7_7 \end{pmatrix} O = \begin{pmatrix} UTS_1, & EM_2 \\ \vdots & \vdots \\ UTS_8 & EM_8 \end{pmatrix}. \tag{A1}$$

The capability profile receives manufacturing parameters as inputs. Continuous inputs first need to be normalised according to equation (A2)

$$x_{\mathrm{norm}} = \frac{x - \overline{x}}{\sigma}, \tag{A2}$$

where x_{norm} is the normalised value of parameter x, $\overline{x}$ is mean x value and σ is the standard deviation. Build orientation is treated as a categoric variable and has three separate binary inputs (x,y,z) into the capability profile.

Once the input values are normalised they are formed into an input array A shown in equation (A3)

$$A = (b,\ x,\ y,\ z,\ \upsilon,\ \alpha,\ \beta,\ \omega), \tag{A3}$$

where b is bias and equal to a value of 1, x,y,z are binary inputs corresponding to build orientation, υ is layer height, α is infill percentage, β is top and bottom layer thickness and ω is the number of solid shells.

The first stage of the calculation process involves the hyperbolic tanh function being applied to the summed inputs and respective synapse weights to create C as shown in equation (A4).

$$C = \tanh(A \cdot B). \tag{A4}$$

C is then prepended with a bias value of 1, forming D for the next phase of calculation.

Finally, UTS (σ) and E can subsequently be calculated by equation (A5). These are provided as outputs from the capability profile.

$$(\sigma,\ \ E) = D \cdot O, \tag{A5}$$

where O corresponds to the values from the output layer of the neural network as defined in equation (A1). These can then be used as inputs for the functional models.

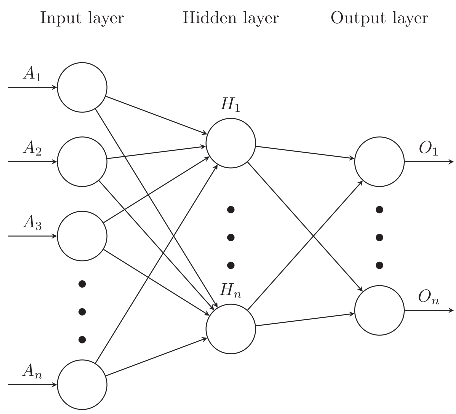

Figure A1. Capability profile ANN layers.

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B. Appendix B

This section contains supplementary figures to support the illustrative application shown in Section 5. Penalty multipliers for the objective function are shown in Table B1. The Grasshopper canvas is shown in Figure 10. The first and second iteration hooks are shown in Figure B2a,b, respectively.

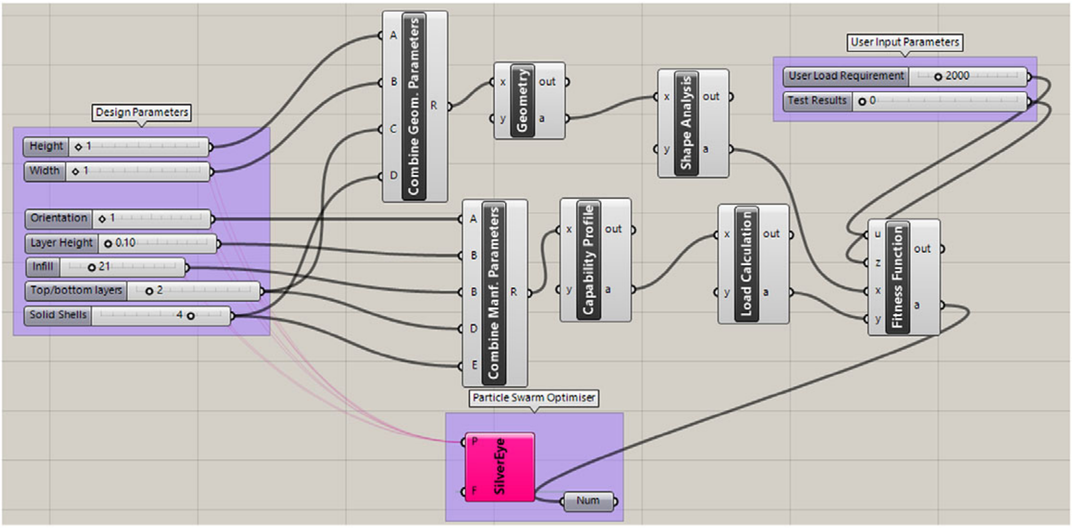

Figure B1. Grasshopper canvas for S-hook implementation.

(a) First created hook holding a load of 10kg

(b) Second hook holding a load of 15kg

Figure B2. S-Hooks made via use of the GBD methodology.

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Table B1. Penalty multipliers incorporated in fitness function

Multiplier	Value	Decision	Explanation – applied if:
1	0.1	UTS > 60 MPa	Part has UTS outside of predictive capability of CP
2	0.1	TB > 2 mm	Top and bottom layer thickness is below bounds of what the CP can predict
3	0.1	SS > 2 mm	Solid shell thickness is below bounds of what the CP can predict
4	0.1	TB < 0.5 mm	Top and bottom layer thickness is below bounds of what the CP can predict
5	0.1	2 × SS > Height	Total solid shell thickness exceed part width
6	0.1	2 × TB > Thickness	Top and bottom layer thickness exceed total part thickness
7	0.01	Load < Required load	Predicted load is less than required load of the user
8	0.1	Infill < 20%	To avoid low infill that would yield an un-reliable print