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Digital Manufacturing for Earth Construction: A Critical Review

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Abstract

Recent years have witnessed a rapid adoption of digital manufacturing techniques in the architecture and construction industry, with a strong focus on additive manufacturing and 3D concrete printing. The increasing awareness of the undesirable environmental implications of cement-based products has led to reapproaching earth materials within a digitally based construction process. The attempts to digitise earth construction started in 2011; however, the past three years have seen a surge in the number of research projects that explore the potentials of digital earth construction. This paper collected, reviewed and analysed the state-of-the-art research on digital earth construction since 2011, then focused on highlighting the potential of, as well as the challenges associated with the process of adopting this new construction method on an industrial scale. The insights from this study will bridge the gaps in knowledge among disparate research threads and collectively provide critical information for an enhanced utilisation of digital techniques in earth construction in the future.

1. Introduction

The recent years have witnessed an eager quest by the constrcution industry for faster production process with ever-increasing complexity of forms. Architects and engineers have been migrating steadily to the digitally driven manufacturing process as it offers solutions to achieve desired efficiency and complexity of forms (Soto et al., 2018). The term digital manufacturing/fabrication has been introduced to the constrcution industry since the 1980s (Kolarevic, 2001). However, the adoption rate of digital fabrication technologies in the construction industry has witnessed a dramatic increase only in the recent decade. Digital manufacturing techniques in the constrcution field commonly represent the use of four main methods: subtractive, additive, formative and assembly. Additive manufacturing (AM) methods, 3D printing (3DP) specifically, have been receiving most of the attention in modern industry due to its wide applications, in addition to its technical and environmental benefits to several industries (Paolini et al., 2019; Stavropoulos and Foteinopoulos, 2018).

Several studies have demonstrated that a well-developed digital/automated process can provide substantial benefits to the construction industry, such as higher design freedom and enhanced productivity (Zareiyan and Khoshnevis, 2017). In the pursuit to harness these qualities, the construction industry has been investigating and developing digital manufacturing methods for large scale structures and building components (Feng et al., 2015; Gomaa, et al., 2021). Nowadays, the race to develop a fully automated construction process is well under way. Several institutions around the world have been exhibiting a wide range of digitally manufactured prototypes of structural components, furniture and full-scale buildings. Several universities and firms have also been rapidly upscaling the 3D printing (3DP) process to produce full-scale constructions. Firms such as Apis Cor©, CyBe©, WASP©, COBUD© and PERI© introduced 3D printed constructions around the world (Endres et al., 2021; Geneidy et al., 2019). Both Apis-Cor and CyBe produced two of the largest 3D printed concrete buildings in the world in 2019 in UAE and KSA respectively, while they are also contracted for several other large projects around the world (Apis-cor, 2019; CyBe, 2019; Geneidy et al., 2019). All these projects are intensively dependent on cement-based materials (Alhumayani et al., 2020) and most ongoing investigations and published work focus on digitally fabricated cement-based products, with 3D concrete printing (3DCP) being the most prevalent (Shakor et al., 2019; Siddika et al., 2019).

This pursuit of cement-based products is causing rising concerns over the possible environmental implications. The construction sector is already responsible for almost 40% of the energy consumption and greenhouse gas emissions globally (Agustí-Juan and Habert, 2017). Moreover, 50% of the world's processed raw materials are used for construction (Weißenberger et al., 2014), while 5–8% of global CO_2 emissions are generated from cement production (Kajaste and Hurme, 2016). This has led to an urgent need to improve the environmental footprint of modern construction which in turn motivated researchers to investigate other more sustainable construction materials. This move has resulted in the search for, and use of, earth materials as an alternative to the cement-based constructions, which are associated with high CO_2 emissions, high embodied energy and depletion of natural resources due to the use of concrete (Alhumayani et al., 2020; Chandel et al., 2016). Unlike concrete, earth materials are traditionally made of variable mixtures of soil and water, with occasional additions of fibres (e.g., straw). Normally used for external walls of 450 mm or thicker, earth materials provide high thermal mass, leading to an excellent passive thermal design (Ben-Alon et al., 2019; Hamard et al., 2016). Earth construction is also significantly cheaper compared to other conventional building materials such as concrete and masonry (Quagliarini et al., 2010). Nevertheless, using earth materials has become rare in modern constructions, as concrete offers higher strength and faster construction processes, while it is also less labour-intensive.

While construction methods using concrete, timber and masonry are experiencing a revolution thanks to the introduction of digital fabrication processes such as 3DCP and robotic fabrication, earth construction remains one of the least studied methods of construction (Gomaa, Jabi, et al., 2021; Perrot et al., 2018). The question then arises: Can digital fabrication be the key to promote the re-use of earth construction in a contemporary context? Veliz Reyes et al., (2019) have demonstrated the importance of developing more flexible modern construction systems that are able to harness the qualities of vernacular architecture. In addition, substantial sustainability benefits can be gained through the integration of digital fabrication techniques into earth-based materials in construction. The number of feasibility investigations of digitally fabricated earth materials has been steadily increasing globablly over the past decade (Gomaa et al., 2021a). The first recorded approach to digitise earth materials goes back to 2011, when Kayser (2011) experimented with on-site additive manufacuring of sand in Egypt and Morocco on a small scale using solar energy to melt sand and power the printing system. The following years between 2012 and 2017 witnessed a slow but steady rate of research output on Digital Manufactring for Earth Construction (DMEC). The year 2016 was a key milestone, when WASP 3D printed the first actual full-size earth structure in Italy (WASP, 2016). Since then the rate of work has increased noticeably. There has been a significant increase in the number of recorded works on DMEC since 2019. Indeed, there were 10 projects and publications on this topic in 2021.

Despite an increase in the number of studies on DMEC, the current experiments and applications are still in their early stages and remain fragmented (Endres et al., 2021; Gomaa, 2021; Alejandro Veliz Reyes et al., 2019). Most of the research projects focus on the design possibilities of DMEC but fail to provide scientific information on the constructability aspects (e.g., fabrication machines, construction workflow and processes, material standards) and the performance aspects (e.g., structural, thermal and environmental performance). This lack of information or evidence has prevented the construction industry from adopting the new techniques and the regulating authorities from approving their use. This reluctance has made the aim of industrialising DMEC harder to achieve (Gomaa et al., 2021b).

This paper aims to critically review and analyse the existing state-of-the-art research on digital manufacturing for earth constructions, to highlight the potential and establish a better understanding of the challenges that hinder the process of adopting this new construction method on an industrial scale. The paper starts by establishing a basic understanding of the meaning of both traditional and modern earth construction. It then describes the adopted methodology for the systematic data collection and inclusion criteria. Finally, the paper provides an analysis of the recorded work in the literature, followed by an extensive discussion and closing remarks. The insights from this study will bridge the gaps in knowledge among the disparate research work and collectively provide critical information for a successful utilisation of digital techniques in future earth constructions. It is expected that this will motivate stakeholders to make more informed decisions and pursue further investigations and implementations of DMEC as a substitute to other digital techniques such as 3DCP in modern construction.

2. Traditional earth construction

Earth architecture, as a branch of vernacular architecture, is an architectural style based on local materials, local needs, and local builders' skills, where buildings are made from mixtures of soil and water, with occasional addition of fibres. Earth materials have been used in construction for centuries. Nearly 30% of the present world's construction is made from earth, spanning almost every country in the world (Houben and Guillaud, 1994; Keefe, 2005) (Figure 1). The perception of earth architecture has been evolving to reflect different environmental, technological and cultural contexts (Niroumand, Barceló Álvarez, and Saaly 2016).

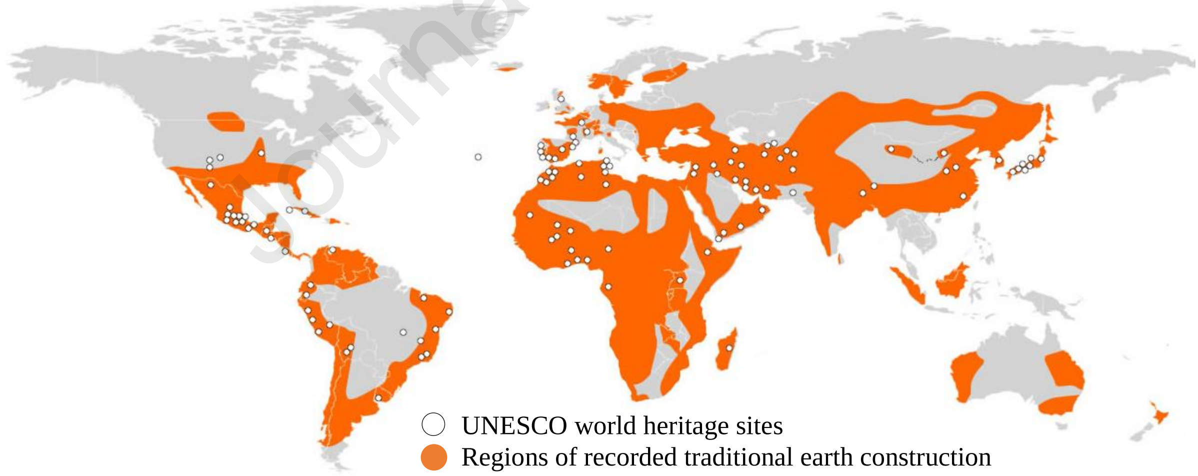

Figure 1. Map of the traditional earth-construction regions around the world, with the locations of the UNESCO world heritage sites (CRAterre, 2021).

Figure 2. Examples of traditional earth-construction. Adobe houses of the Kasbah at Ait Benhadou in Marrakesh, Morocco (left)(Ahmed and Ibrahim, 2018), and Keppel Gate cob house in Devon, UK (right) (McCabe, 2020).

The term "earth construction" combines different techniques under its wide umbrella. These techniques basically differ according to the mixtures of materials and the building process characteristics (Keefe, 2005). Several studies provide different classification of earth construction methods (Keefe, 2005; Kouakou and Morel, 2009). However, according to findings by Hamard et al. (2016), the most appropriate classification is based on the distinction between the wet and dry compaction methods of producing the mixtures and shaping the geometries (Figure 3). The wet method describes the use of earth mixtures at a plastic state with a relatively high moisture content, where the mechanical strength of the structure is gained through hardening and densification during the drying and shrinkage process until the optimum moisture content is reached. The wet method includes, but not limited to, techniques like cob, adobe, wattle and daub, and earth plaster. However, only cob and adobe are load-bearing. On the other hand, the dry method includes techniques such as compressed earth block and rammed earth, which are both load-bearing (Hamard et al., 2016; Keefe, 2005) (Figure 2).

The basic ingredients for forming an earth mixture are subsoil and water. Subsoil refers to the excavated soil at a depth of more than 1.0 meter below the ground surface. This is important to avoid any organic substances in the topsoil (e.g., plants). Rammed earth is the mixture of subsoil and water, with occasional use of lime and/or minor addition of cement to stabilise the mix. Cob and adobe bricks, on the other hand, consist of subsoil, water and fibres (e.g., straw). Some adobe mixtures use other natural substitutes to fibres to improve its tensile strength and reduce shrinkage. Clay is a sub ingredient of soil, which could be used as found in nature or manufactured. Adding water to the raw clay produces a clay mixture, which is also a wet method (Keefe, 2005). Sand is another sub ingredient of soil; however, it requires special processing (e.g., adding binders) to create a constructible sand mixture, which is usually formed as blocks. The processing method is what qualifies sand as an earth-based construction or not (Kulik et al., 2012). Earth walls perform both load-bearing and non-loadbearing roles in earth construction. The wall thickness varies according to the constrcution type (e.g., adobe, cob), wall function (e.g., load-bearing) and the expected loads, with an average of 60 cm (Quagliarini et al., 2010; Weismann and Bryce, 2006). The wall thickness increases proportionally with the number of stories or the height of the building and may also taper to be larger at the bottom and smaller at the top. In general, the mechanical properties of earth mixtures depend on several factors: subsoil properties, water content, the use of fibre, and the quality of craftsmanship.

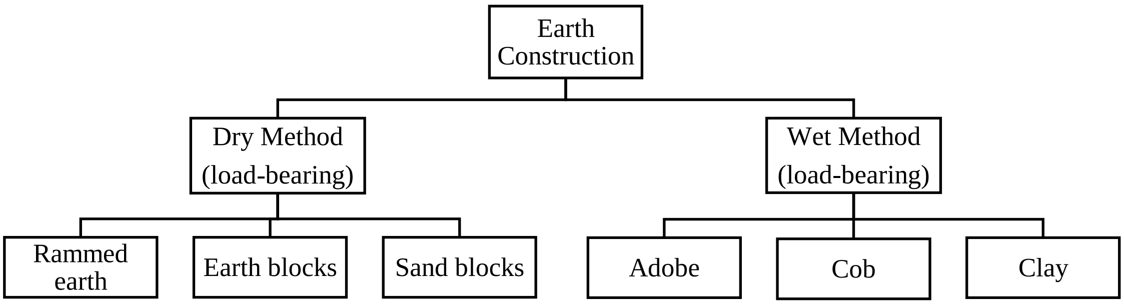

Figure 3. Suggested classification of earth construction, adapted from Hamard et al., (2016) and Keefe, (2005).

Raw-earth materials are highly sustainable due to the very limited embodied energy involved in the material production and construction process (Martín et al., 2010). Several studies have highlighted that most earth constructions have very low embodied energy as compared to other conventional materials in construction such as concrete and masonry (Chandel et al., 2016; Hamard et al., 2016; Liu et al., 2010). Morton et al. (2005) also demonstrated in their study that earth bricks had much lower level of embodied energy compared to other masonry materials. To put this in numbers, a house made of earth walls with an area of 92 m^2 can achieve an impressive reduction of 14 tons of CO_2 emissions as compared to aerated concrete blocks. Moreover, according to Pacheco-Torgal and Jalali (2012), an estimated reduction of 100 thousand tons of CO_2 emissions every year could be achieved just by replacing 5% of concrete block masonries by earth masonry (the case of the UK). Another energy efficiency aspect of earth construction is its indoor thermal comfort. Earth walls have a historic reputation of being thermally efficient due to their large thermal mass, leading to a slow cycling of temperature from the outdoor environment to the indoor (Goodhew and Griffiths 2005; Reardon et al. 2013). However, improving the thermal performance of earth walls usually requires larger thicknesses of walls, which then increases the embodied energy as it involves consuming more raw material. It is important to highlight that the embodied energy, and the environmental performance in general, of earth construction is also location-dependent, where transportation of raw material has a critical influence on the overall embodied energy of the construction process (Alhumayani et al., 2020; Arrigoni et al., 2017).

3. Modern earth construction

According to Hall et al., (2012), the definition of a "modern" construction depends on several factors. First, the construction process must benefit from the state-of-the art technological advancement in tools and materials during the 20th and 21st centuries. Second, a modern construction must reflect a high level of quality in detailing, accuracy, finishing and reproducibility. Third, the construction must comply with modern building regulations for structural, thermal and environmental performance. Fourth, and most importantly, the building must meet the contemporary expectations and needs of occupants, in terms of design, comfort and well-being.

In this context, modern earth buildings can be classified into two categories based on their technology of construction. The first category is where the construction process utilises modern mechanical machines, powered by fuel or electricity, for material transportations, mixing, pumping, casting, compacting and formworks fabrication. The process is similar to modern concrete construction. This method usually has an organised balance between human power (i.e., labour) and machines, where workers have constant control over operating, directing and observing the machines. Machines in that context are not programmed to be functioning in fully automated modes. There are recent examples around the world for earth buildings that match the modern standard as described, where the construction process leverages modern machinery, while the building presents high quality, enhanced performance and contemporary aesthetics. Nowadays, several organisations and firms worldwide provide earth construction with modern standard, while they also renovate existing buildings, such as Rammed Earth Enterprise© in Australia (Figure 4), Sirewall© in USA (Figure 5), Rammed Earth Artisan Ltd© in Canada (Figure 6) and Earth Structures Europe Ltd in the UK.

Figure 4. Kalkee Road Children's & Community Hub by Rammed Earth Enterprises© (2019).

Figure 5. NK'Mip Desert Cultural Centre by Sirewall© (2021).

Figure 6. Rammed earth house in Canada by Rammed Earth Artisan (REA, 2021).

The second category of modern earth construction, which will be reviewed in detail in section 5, is the digitally manufactured earth construction. This method utilises one or more techniques of digital manufacturing. The use of digital manufacturing techniques in construction has been rising in the past 20 years as a result of the increasing quest for more complex forms, less labour intense and faster process of construction (Soto et al., 2018). In general, digital fabrication/manufacturing can be classified into 2D and 3D techniques, where the 2D basically includes cutting technologies such as laser and water-jet nozzles, where the mechanical motion of the cutting head/nozzle involves two axes of movement. The 3D techniques include four categories of manufacturing: additive, subtractive, formative and assembly (Figure 7) (Kolarevic, 2001). These techniques involve machines that can move in three or more axes to conduct the manufacturing process (e.g., industrial robotic arms). Automated manufacturing, and AM in specific, has been receiving most of the attention in the field of construction and architecture in the recent years, which consequently led to a substantial development to large-scale 3DP technologies in construction (Geneidy et al., 2019). Most of the current research and application of digital earth construction are concentrated on 3D printing technology, which is similar to the well-developed technology in digital cement-based construction (Gomaa et al., 2021a).

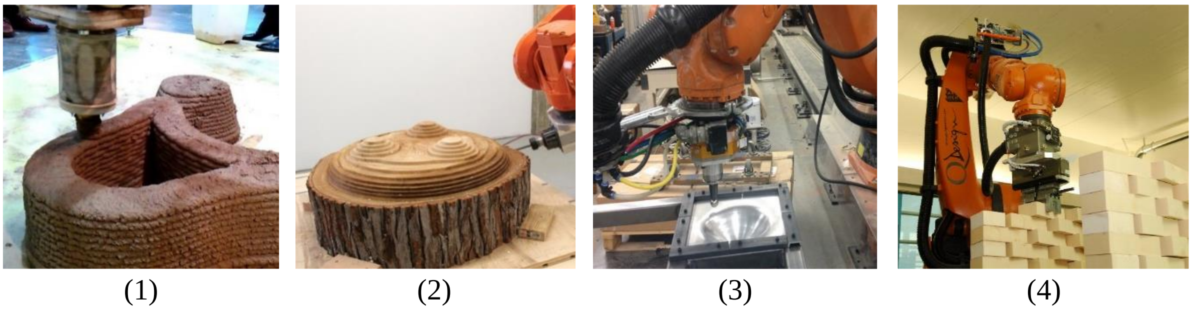

Figure 7. Different types of 3D digital fabrication techniques: (1) Additive (WASP, 2014); (2) Subtractive; (3) Formative (Kalo, 2020); (4) Assembly (Kohler, 2006).

According to Agustí-Juan and Habert (2017) and Ford and Despeisse (2016), adopting digital manufacturing techniques in modern constrcution, AM methods in specific, provides three significant sustainability benefits. First, it increases material/resources efficiency during the production phase, with an estimated 25-60% in material reduction and 30% time saving as compared to traditional manufacturing techniques. Second, it extends the estimated product life (from technical perspective) as it facilitates the repair and refurbishing processes. Third, it improves the value chains by providing simpler, shorter, more localised production and supply chain (Soto et al., 2018). However, leveraging these benefits is heavily dependent on the size and complexity level of the constrcution project, where conventional constrcution methods can outperform the digital methods in terms of cost, and even environmental efficiency, when building small and/or simple projects. The current digital construction market is eagerly heading towards cement -based methods, supported by large cement manufacturers who have patented confidential 3DCP recipes (Geneidy et al., 2019; Siddika et al., 2019). While digital technologies generally promise less environment implications of construction, the use of cement/concrete is inevitably harming the environment, thus the sustainability of future construction. Incorporating digital manufacturing methods with earth materials provides a sustainable and cleaner production of an alternative that is hoped to compete/ substitute some of the digital construction market share that is currently dominated by cement-based products (A. Veliz Reyes et al., 2019).

4. Review Methodology

The study classifies the DMEC works found in the literature according to completion date, location, and fabrication techniques. This study also discusses the potential, challenges, technical problems, and limitations associated with DMEC methods. The findings presented in this study are based on reviewing the literature found through the following online scholarly databases: Web of Science, ScienceDirect and Google Scholar. The inclusion criteria for work/data extracted from the literature are as follows:

- The review focuses only on digitally manufactured earth constructions, which is referred to in this study as DMEC.
- The reviewed work must address actual building components/prototypes, either on a small scale (e.g., modular components, bricks/blocks) or on large scale (e.g., full-size walls). Cladding, artistic, furnisher and non-functional pieces are disregarded.
- Only soil/earth-based materials are considered (timber, bamboo, salt block and so on are disregarded).
- Focus has been placed on work that involved actual experiments rather than purely theoretical work. Theoretical approaches or review papers will be mentioned, but not discussed or analysed at significant length.

The search terminologies included combinations between digital fabrication and earth construction. Search terms such as “digital earth construction” “additive manufacturing of earth” “3DP of earth materials” were used. The full list of terms is presented in Table 1. The search using the inclusion criteria resulted in 38 recorded works associated with digital fabrication of earth-based materials. The recorded works also included 17 published papers (13 journal articles and 4 conference papers) and one book. The rest of the works are available online as showcases, commercial prototypes and student projects, which are all presented using online platforms such as institutional websites, online magazines, online videos, and social media (LinkedIn, Instagram and Twitter). Table 2 presents the list of recorded works, in addition to the key information about each project, such as the manufacturing method (e.g., 3DP), the explored aspects (e.g., workability, mechanical properties), the source of information (e.g., journal article) and the location of the project.

Table 1. The selected searching terminologies for the literature review.

Category	Specific terminology

Digital fabrication / manufacturing	Digital fabrication of + (cob, clay, adobe, mud, rammed earth, earth-based materials)
Robotic fabrication /manufacturing	Robotic fabrication + (cob, clay, adobe, mud, rammed earth, earth-based materials)
Additive manufacturing	Additive manufacturing + (cob, clay, adobe, mud, rammed earth, earth-based materials)
3D printing/3DP	3D printing + (cob, clay, adobe, mud, rammed earth, earth-based materials)
Modern	Modern + (cob, clay, adobe, rammed earth, earth-based materials) + construction.

Table 2. Recorded literature on the digital manufacturing of earth-based materials categorised by construction method/material, and arranged in chronological order.

Material	Referenced Project	Manufacturing method	Explored aspects*	Source**	Location
Sand	Kayser, 2011	AM (3DP)	1	a	Egypt
	Kulik et al., 2012	AM (3DP)	1,2	a	Spain
Clay	WASP, 2014	AM (3DP)	1	a	Morocco
	Doerfler et al., 2014	Hybrid	1	c	Switzerland
	Giannakopoulos, 2015	AM (3DP)	1	a	Spain
	Izard et al., 2017	AM (3DP)	1	b	Spain
	Dubor et al. 2018	Hybrid	1, 3, 4	b	Spain
	Chang et al., 2018	Hybrid	1,2,3	a	Spain
	Dubor et al., 2019		1	c	
	Kontovourkis and Tryfonos, 2020	AM (3DP)	1,2	b	Cyprus
	Gramazio Kohler, 2021	Hybrid	1,2	a	Switzerland
Adobe/Cob	WASP, 2016	AM (3DP)	--	a	Italy
	Chatzivasileiadi et al., 2017	AM (3DP)	1,3	d	UK
	WASP and RiceHouse, 2018	AM (3DP)	1,2,3	a	Italy
	Veliz Reyes et al., 2018	AM (3DP)	1, 2	c	UK
	Perrot et al. 2018	AM (3DP)	1, 2	b	France
	Chiusoli, 2019	AM (3DP)	1, 2	a	Spain
	Emergent Objects, 2019	AM (3DP)	1, 2, 3	a	USA
	Veliz Reyes et al., 2019	AM (3DP)	1	b	UK
	Gomaa et al., 2019	AM (3DP)	1, 3	b	UK
	Emergent Objects, 2020	AM (3DP)	1	a	USA
	Alhumayani et al., 2020	AM (3DP)	4	b	UK
	Gomaa et al., 2021a	AM (3DP)	1	b	UK
	Gomaa et al., 2021b	AM (3DP)	2	b	UK
	WASP and MCA, 2021	AM (3DP)	1	a	Italy
	WASP and Tinybe, 2021	AM (3DP)	--	a	Germany
	Rael, 2021 Mud Frontiers IV	AM (3DP)	--	d	USA
	Ganem Coutinho et al. 2021	AM (3DP)	1, 2	a	Spain
Rammed Earth	Sauer and Kapfinger, 2016	AM	1,2	f	Austria
	Öztürk et al., 2017	Hybrid	1	a	Turkey
	Kloft et al., 2019	AM	1,2	b	Germany
	Kim et al., 2020	Hybrid	2	b	S-Korea
Multiple materials***	Craveiro et al., 2019	AM (3DP)	--	b	EU & USA
	Jagoda, 2020	AM (3DP)	--	e	USA
	Fratello and Rael, 2020	AM (3DP)	--	b	USA
	Endres et al., 2021	AM (3DP)	--	c	Germany
	Schuldt et al., 2021	AM (3DP)	--	c	USA

Schweiker et al., 2021	Multiple	--	b	Germany

Notes:

[*] *Tested aspect key*: (1) Workability & design; (2) Mechanical/Structural properties; (3) Thermal performance; (4) Environmental performance/ Life cycle assessment (LCA).
[**] *Source type key:* (a) Online article; (b) Journal article; (c) Conference paper; (d) Online media; (e) Thesis; (f) Book
[***] The publications in this category reviews multiple materials in addition to earth (e.g., cement).

5. Digital manufacturing of earth-based material

The concept of utilising local natural material in a digital construction process goes back to 2004. In his famous study, Khoshnevis (2004) demonstrated the contour crafting approach, which was the foundation of what is known now as 3D construction printing (3DCP). Khoshnevis envisaged several designs for houses that could be remotely and automatically constructed with 3DP technologies using locally available materials on the construction-site. The 3DP process can produce the structural components, as well as the finishing. This innovative approach was deemed suitable for construction on Earth, and also in the outer space such as the moon or Mars. Interestingly, the idea of utilising 3DP technologies for space exploration was upscaled later in 2010. A study by Ceccanti et al., (2010) explored the potential of 3D printing of lunar regolith to build future habitat on the Moon. To mimic the characteristic of lunar regolith on earth, a simulant was made from the ashes of the Bolsena volcano in Italy. This study established critical guidelines for several other studies on space colonies since 2010 (Cesaretti et al., 2014; Kading and Straub, 2015; Savage, 2017).

The resonance of these aforementioned applications, combined by the need for more environmentally friendly construction materials, has inspired other researcher to conduct focused explorations on digital manufacturing of local natural material. As stated earlier in section 4, the review of literature between 2011 and 2021 resulted in 37 recorded work on digital manufacturing of earth-based materials. The reported types of earth-based materials vary according to the manufacturing method and material mixtures formula. Generally, there are four main types found in the literature: sand, clay, adobe/cob, and rammed earth.

5.1. Sand

Sand was the very first earth material to undergo an on-site digital fabrication processing. The Solar Sinter project, conducted by Markus Kayser (Kayser, 2011) in Egypt and Morocco, presented a novel approach to additive manufacturing of sand using sunlight sintering (Figure 8). The process was completely sustainable, where the material was sourced on-site, while the 3D printing system was powered by the harvested solar energy from portable photovoltaics panels. A group of Fresnel lenses were used to produce focused sunbeam for sintering. This project raised the early questions about the potential of utilising sustainable materials and energy resources for the future of architecture manufacturing. Later in 2012, a team of students from the Institute for Advanced Architecture of Catalonia (IAAC) developed a portable on-site robotic 3D printing system of sand and soil. The project, named as Stone Spray Robot, aimed to find eco-friendly and efficient means of 3D printing of architectural structures using raw material (Kulik et al., 2012). The 3DP system generates geometry through combining raw sand/soil with liquid binders, then spray them from a special nozzle directly onto the construction platform. The sprayed mixture solidifies rapidly as it accumulates on the printing surface, which then creates successive layers forming the desired design (Figure 9). No further examples on digital production of sand for construction scale were found in the literature.

Figure 8. Solar sintering of sand by Markus Kayser (Kayser, 2011).

Figure 9. Stone Spray Robot (Kulik et al., 2012).

5.2. Clay

Clay has received most of the attention in 3D printing applications for many years compared to other earth-based mixtures, mainly due to the rheological qualities of the wet clay mixture which enhance the controllability of the 3D printing process. Clay is also easy to source locally, easy to mix and does not require sophisticated 3DP system. It can be used for both small and large scale 3DP application, with nozzle sizes that can go as low as 4 mm. While some of the early trials of clay printing were not made for construction applications, the first recorded project of 3D clay printing for construction purposes is by WASP© (WASP, 2014), which used red clay collected on-site in the village of Ait Ben Haddou in Morocco to produce prototypes of building components. This project also marked the launch of the first commercial prototype of 3D clay printing system by WASP. The 3D printer adopted a Delta mechanism with 3 axes of freedom.

In 2015, IAAC developed a new 3D printing system for clay that combined a robotic arm with a stand-alone clay extruder, forming one of the earliest transitions from standard 3 axes printing to robotic 6 axes printing of clay. This transition enabled IAAC in the following years to upscale the clay 3DP process to a construction level. Pylos was the first exhibited project by a team of postgraduate researchers in IAAC (Figure 10). The project objective was to explore the mechanical potentials of 3DP clay formation for large scale construction, with the aim of providing a more environmental and economic substitute to cement-based construction. Several 3DP clay formations of columns were created during the testing, reaching a maximum height of 2 meters and a cross-section of 50 cm × 50 cm. The project also conducted various tests to optimise material usage and fabrication time, leading to enhanced results in the later projects in IAAC.

TerraPerforma came out in 2017 as another project by researchers in IAAC, who were the first to construct a full-size 3DP clay wall (Figure 11). The project design adopted a modular approach to construction, where the wall was segmented into small modular blocks of 3DP clay. The blocks were parametrically designed and optimised to provide good thermal performance and structural integrity upon assembly (IAAC, 2017). In 2018, the findings of both Pylos and TerraPerforma projects were leveraged in the Digital Adobe project by a team of students in IAAC, who upscaled the 3DP wall size to 5 meters high and 2 meters wide using interlocking modular blocks (Figure 12). This project presented a higher level of practicality by introducing an integrated wooden structure, forming a stairway to an upper floor slab. Generally, all of IAAC 3DP clay prototypes combined intricate design that enabled improved thermal efficiency, self-shading and reduction in material consumption. These promising environmental qualities, combined with the proven higher adaptability to the digital manufacturing process, have led to further sophisticated exploration to clay 3DP in construction. In 2020, Kontovourkis & Tryfonos, (2020) developed an enhanced process for robotic 3D clay printing that utilises parametric toolpath planning with high adjustability to open-source clay 3D printer and multiple nozzle sizes. The new system claims to provide higher efficiency in terms of printing time and achieved design complexity level as compared to conventional methods of construction.

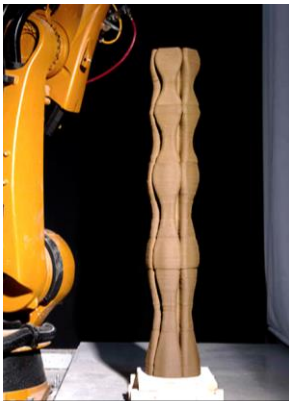

Figure 10. Pylos 3DP clay (Giannakopoulos, 2015).

Figure 11. TerraPerforma (IAAC, 2017).

Figure 12. Digital adobe (Chang et al., 2018).

Where all the previous work on clay manufacturing focused on additive/3DP methods, Gramazio Kohler research group in ETH exhibited two unique approaches to digital clay construction. The first project, known as Remote Material Deposition (RMD), creates building structures on-site by robotically throwing brick-sized clay elements in pre-calculated trajectories to their targeted assembly points (Figure 13-left) (Doerfler et al., 2014). This approach intended to provide a less-constrained process of digital assembly; however, it faces major challenges in terms of controllability over environmental changes on-site. The second project is the Clay rotunda (Figure 13-right), which features a cylindrical structure with a diameter of 11 meters and height of 5 meters. The structure consists of 30,000 soft clay bricks, each brick being 15 cm in height and 9 cm in diameter. An on-site mobile robotic system was used to collect the bricks, one by one, from a picking station, then press it into the designated position precisely to form sequential layers. This innovative hybrid technique of fabrication, combining both formative and assembly methods, led to an enhanced structural rigidity of the clay wall with less material compared to conventional clay walls (Gramazio Kohler, 2021).

Figure 13. Remote material deposition project (left) (Doerfler et al., 2014), and the clay rotunda project (centre, right) (Gramazio Kohler 2021).

5.3. Adobe and Cob

All of adobe, cob and clay fall under the wet techniques of earth construction. However, adobe and cob differ from clay in the added fibre content to earth mixture. Adding organic fibre such as rice or wheat straw to the earth mixture improves the mechanical properties of earth walls, leading to an enhanced thermal and structural performance. Traditionally, adobe and cob mixtures consist of similar ingredients (subsoil, straw and water). The main difference between adobe and cob is the construction method, where adobe refers to building earth walls using sun-dried earth bricks, while cob refers to building monolithic earth walls using malleable wet earth blocks (Hamard et al., 2016; Keefe, 2005). Nonetheless, the review of the literature on digital manufacturing of earth-based material shows that the terms adobe and cob are used interchangeably to represent the same construction process in the context of 3D printing process.

WASP© has been working actively on developing 3DP systems of earth-based materials for several years. They conducted the first attempt of 3DP of adobe mixture in 2016, where they presented an early concept of a 3DP earth house (WASP, 2016). WASP aimed mainly to put their new on-site 3DP machine (Big Delta©) with its extrusion system under examination to verify its capacity to conduct large-scale tasks for earth-based materials. The project used 40 tons of material to build circular walls aggregating on 5 meters diameter. While the structure was not completed as intended due to technical issues, the project was considered a milestone and a successful proof of concept for large-scale earth construction. In 2018, WASP joined forces with Rice House and presented the first complete 3DP earth house in the world using their newly upgraded 3DP system, Crane WASP© (Figure 14). The house, named as Gaia, was printed entirely on-site from a mixture of subsoil, water, rice straw, rice husk, and lime. Rice straw was also used to fill the inner voids in the walls for added insulation. The printing process of the walls took 10 days and covered 30 square meters. However, the 3DP earth walls were not intended to be load-bearing as that stage; hence, the house used timber frames to support the roof loads. The house also included glazed openings and a timber roof.

Figure 14. Earth house prototype by WASP in Italy (left), and the 3D printing system of earth (right) (WASP and RiceHouse, 2018).

In 2019, IAAC, in collaboration with WASP, further examined the load-bearing capabilities of 3DP adobe by constructing a wall prototype with an embedded staircase. The wall prototype, engineered and designed by IAAC, has an intricate cross section design to provide support for interlocking timber elements acting as stairs and floor structure (WASP, 2019)(Figure 15). Crane WASP was used to perform the 3D printing using the previously developed adobe mixture by WASP and Rice House in the Gaia project. One of the critical upgrades to Crane WASP system at this stage was the adoption of a stationary material feeding system, where the adobe mixture was pumped through a hose to the extrusion nozzle, unlike the precedent method which required a worker to feed material directly to the extrusion nozzle. This extrusion technique was developed simultaneously by 3D Potter, which is a US-based company specialises in developing 3DP systems for cement and clay-based materials (3D Potter, 2021).

Scara H.D. © is a portable 3D printer by 3D Potter that can deliver 3DP earth structures with a standard height of 2.75 meters and a diameter of 3.65 meters, at a speed of up to 100 mm/sec. The dimensions of the building envelope can be modified according the project requirements. Several prototypes of 3DP earth construction were built in the US by 3D Potter and Emerging Objects© using Scara H.D.(Emerging Objects, 2019; Fratello and Rael, 2020) (Figure 16). The first prototypes, known as the Mud Frontiers, were developed and constructed in 2019 in Orlando using local adobe mixture, with the objective of investigating different design geometries, structure functionality, texture and reinforcing. These preliminary designs combined a single space house. The Mud Frontiers project continued in the years 2020 and 2021 to present a dramatic upscale in the size of the houses. Casa Covida was the second generation of earth construction by Emerging Objects, which comprised three enclosed spaces: living area, sleeping room and a bath. The overall height of the structure reached 4 meters (Emergent Objects, 2020). At the time of this study, Emergent Objects are working on the fourth phase of their ongoing project "Mud Frontiers". The released information so far reflects an upscaled building area and improved design, with more living space and geometrical refinement (Rael, 2021).

Figure 15. 3DP adobe wall with embedded staircase (Chiusoli, 2019; WASP, 2019)

Figure 16. 3DP adobe prototypes by Emergent Objects: SCARA H.D. printer by 3D Potter (left) (3D Potter, 2021), Mud Frontiers part I prototype (centre) (Fratello and Rael, 2020), CasaCovida prototype (right) (Emergent Objects, 2020).

All the previous projects presented by WASP, 3D Potter and Emergent Technologies on adobe 3D printing used standard gantry style 3D printing, which have limited freedom of movement to 3 axes. The use of robotic 3D printing of cob was presented in 2018 by both Veliz Reyes et al., (2018) and Perrot et al. (2018a) to overcome the limitations in the gantry printing system (Figure 17Figure 18). The study by Veliz Reyes et al., (2018) presented an early testing of the design and workability aspects of robotic 3DP of cob. The early findings demonstrated the promising potential of robotic 3DP cob, and also highlighted some of the processing limitations in extrusion system. On the other hand, Perrot et al. (2018a) conducted a study that was considered the first published work to explore the mechanical properties and structural performance of 3DP earth-based material. The material composite was made from a mix of earth material and alginate seaweed biopolymer (as a substitute for straw). The study demonstrated the ability of 3DP cob to act as load-bearing construction member.

Figure 17. Robotic 3DP of cob (with alginate) by Perrot et al., (2018)

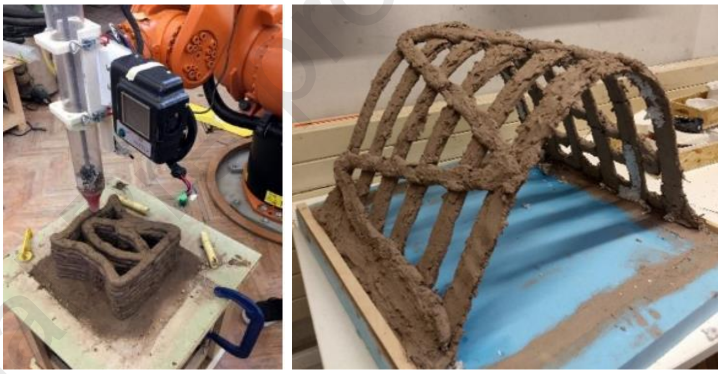

Figure 18. Robotic 3DP cob (with wheat straw) by Veliz Reyes et al., (2018)

The feasibility of robotic 3D printing of cob was extensively investigated by a team from Cardiff University, and the University of Plymouth in the UK and the University of Adelaide in Australia. This feasibility study explored aspects of 3DP cob workability, design, material processing, structural performance, thermal performance and life cycle analysis (LCA) (Gomaa, 2021). According to Veliz Reyes et al., (2019), the key challenge that faced 3DP cob in its early stage of research was the material extrusion system and the mechanism of integrating it properly with the robotic arm. As cob is conventionally constructed in a nearly dry state, a revised cob mixture with an increased moisture content of up to 25% (instead of the 18-20% in traditional cob) was introduced to facilitate the 3D printing process (Veliz Reyes et al., 2018). However, the early stage of 3DP cob faced several issues related to the extrusion system such as the slow extrusion rate, inconsistency and short refilling cycle (Gomaa et al., 2019). Gomaa, Jabi, et al., (2021) illustrated an extensive and systematic exploration of various pneumatic and mechanical cob extrusion systems. The exploration eventually led to the development of a unique bespoke extrusion system capable of improving the speed of printing and the quality of finishing, while being fully compatible with the industrial robotic arms (Figure 19). This study also provided comprehensive details on the design and workability aspects of 3DP cob, which could serve as a guideline for the replication process, bringing 3DP cob closer to industrial applications.

The studies on the performance aspects of 3DP cob and adobe also witnessed a surge in the last two years. Gomaa et al., (2019) conducted thermal conductivity tests on four different types of 3DP cob walls at 1:4 scale that mimicked the possible variations of 3DP wall-sections. The study demonstrated that the thermal conductivity of 3DP cob walls could reach 0.32 W/mK, which is lower than most of conventional concrete and masonry brick walls. This improved thermal performance was a result of the incorporated inner voids in the wall-section design. Later, Alhumayani et al., (2020) conducted an LCA study to examine the environmental implications of 3DP cob walls as compared to 3DP concrete. The study showed that 3DP has superior environmental benefits compared to other modern construction techniques, while it indicated that using renewable energy resources can greatly increase the potential of 3DP earth-based materials for sustainability. Another study on the structural performance of 3DP cob, also conducted by Gomaa et al., (2021b), proved the feasibility of 3DP cob to act as load-bearing walls in multi-storey houses. This study also provided a comprehensive description of the interrelation between 3DP cob wall section design and the overall design of the building.

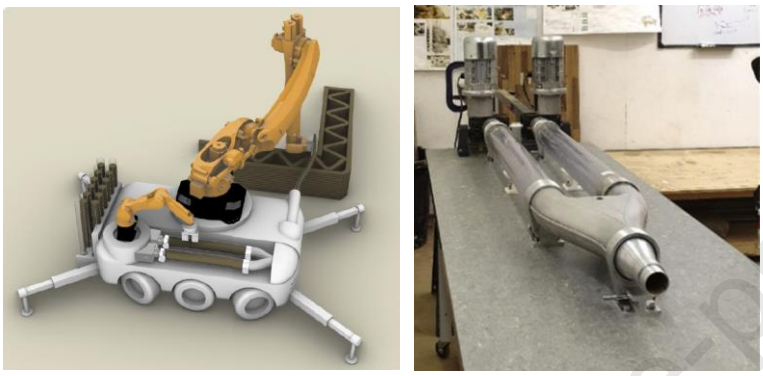

Figure 19. Bespoke 3DP system for cob (Gomaa et al., 2021a)

Figure 20. Testing compressions strength of 3DP cob (Gomaa et al., 2021b)

In 2021, a further attempt to realise the actual structural capacity of 3DP earth construction was carried out by a team from IAAC in the project “152 Travessera de Gracia” in Spain (Figure 21). The design adopted a modular system which combined 3DP earth components with interlocking timber elements to provide structural support for staircase and floor system (Ganem Coutinho et al., 2021). On the other hand, WASP presented their largest 3DP earth construction, TECLA, in collaboration with Mario Cucinella Architects (WASP and MCA, 2021) (Figure 22). The project vision and design aimed to propose a new housing concept that embraces sustainability in every aspect. The preliminary design combined two interlinked cells; both were 3D printed simultaneously using two synchronised Crane WASP printers. The house design adopted a dome-shaped structure, which eliminated the use of excessive roof structure. The construction process consumed 60 cubic meters of raw materials over 200 hours of 3D printing, while the energy consumption was impressively below 6 kW. Recently in 2021, WASP also revealed a small prototype of 3DP earth structure in Germany that represented an evolving artwork by Alison Knowles, firstly visioned back in 1968. The project, named “The House of Dust” and located in front of the Museum Wiesbaden in Germany, is opened to visitors, which is beneficial to increase the community awareness and adaptability of the emerging Digital earth construction (Figure 23).

Figure 21. 152 Travessera de Gracia (Ganem Coutinho et al., 2021)

Figure 22. TECLA project (WASP and MCA, 2021)

Figure 23. The House of Dust (WASP 2021)

5.4. Rammed earth

The examples of automating rammed earth construction are very low compared to clay, adobe and cob. There are only three attempts found in the literature to produce rammed earth wall using digital fabrication techniques. Despite the stronger structural performance that rammed earth offers compared to other earth-based methods (Keefe, 2005), the dry nature of the construction process combined with the need for formwork make the automation trials more challenging. The first recorded approach to mechanise the production process of rammed earth was introduced by Lehm Ton Erde LLC, an Austria-based firm in 2015 (Sauer and Kapfinger, 2016). Their method used automated machines for earth distribution and compaction within formwork to create prefabricated rammed earth walls. The attempt to adopt a robotically-assisted production of rammed earth components was later introduced by a team from Istanbul Bilgi University in 2017 (Öztürk et al., 2017). The project adopted a unique hybrid fabrication process combining both additive and formative techniques. The wall model consisted of modular rammed earth blocks that were designed with pockets to accommodate plants. Each block was created by manually ramming earth mixture over a digitally fabricated Styrofoam geometry inside a metal skeleton (Figure 24). The authors stated that manual ramming of earth was chosen to reduce the project's carbon footprint.

Another technique to fully-automate rammed earth walls using robots was investigated by Kloft et al., (2019), who developed a robotic manufacturing process for rammed earth components. The basic concept of construction is like traditional rammed earth in nature, where a formwork and tampers are used to compact the earth mixture into successive layers (Figure 25). The digital transition in the process is manifested in replacing manual tampering with a robotically assisted hydraulic tamper, while the formwork is actively moving along the path of compaction. Both the tamper and formwork create a semi-enclosed cell that is controlled by the robotic arm. A collaborative feeding system adds a layer of earth mixture along the wall path, then the robotic tampering cell follows the same path to apply the compaction. This automated approach aims to deliver higher precision, better quality and economic advantages compared to the traditional rammed earth process.

Figure 24. Digital fabrication of rammed earth, Common action wall project by Öztürk et al. (2017)

Figure 25. Robotic rammed earth components (Kloft et al., 2019)

6. Discussion and remarks

It has become clear that the research on automating earth construction has undergone a significant development in the past 10 years. The preceding prototypes and projects demonstrate great potential of earth construction as a modern and renewed construction method and provide many benefits to the environment and economy (Schweiker et al., 2021). Yet, earth construction in its conventional mode lacks some of the workability advantages and structural performance qualities when compared to the well-established cement-based counterparts. Nevertheless, with the noticeable increase in the adoption rate of DMEC in the recent years (Figure 26), it is expected that future efforts will evolve to reveal improved solutions to the current challenges. The analysis of the reported projects/research on DMEC in this study revealed 3 domains that urge further improvements. Remarking the potential and the challenges that hinder the progress in each domain is the key to establishing strong framework for future development of DMEC. These domains are:

1) Manufacturing technologies.
2) Performance aspects.
3) Research reliability, validity and visibility.

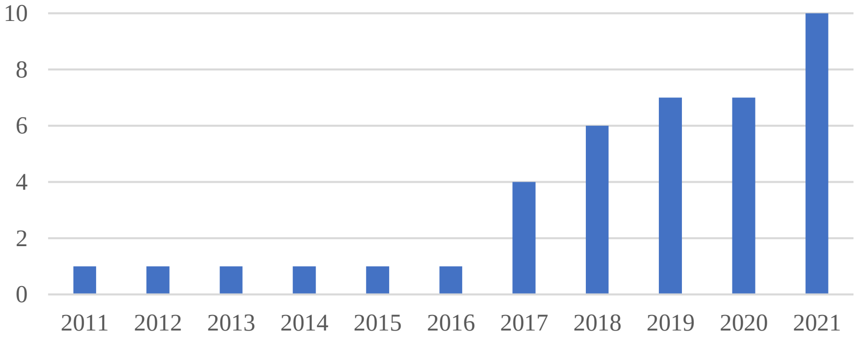

Figure 26. Number of recorded works on digital manufacturing of earth per year since 2011.

6.1. Remarks on manufacturing technologies

The technological development of digital tools and machines is critical to a successful integration of earth materials within a digital construction process. DMEC involves two main processes: first is the motion control system (e.g., gantry 3D printers, industrial robotic arms), and second is the material delivery system (e.g., extruders, pumps) (Gomaa et al., 2021a). The selected manufacturing method defines which type of these systems will be utilised in the construction process. Most research on DMEC to date focusses on additive manufacturing methods, while the use of other digital manufacturing techniques is considerably rare in the literature. Only 18% of the reported work in the study involve subtractive, formative or hybrid methods of manufacturing as can be seen in Table 2 and Figure 27. In addition, almost 60% of the work is concentrated on adobe and cob followed by 22% clay, which are all 3DP-friendly methods considering their wet processing nature.

Rammed earth, which is extensively investigated as a modern conventional construction (Hall et al., 2012), places last along with sand as the least investigated methods in DMEC (Figure 28). The work presented by Kloft et al., (2019) on robotic rammed earth, while considered an innovative hybrid digital approach, still has major limitations in terms of the feeding system and speed, in addition to the imposed geometry constraints by the mobile formwork system. However, involving innovative digital approaches in rammed earth construction presents immense potential for the future, and opens further possibilities to leverage the qualities of rammed earth on wider scale. On the other hand, the work by Öztürk et al., (2017) also shows an innovative hybrid approach to free-formed rammed earth components, yet, the process does not qualify as “automated” as it depended greatly on manual material feeding and compaction.

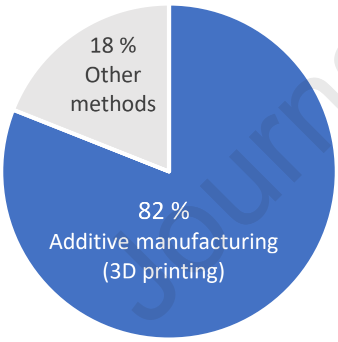

Figure 27. Percentage of usage per fabrication method.

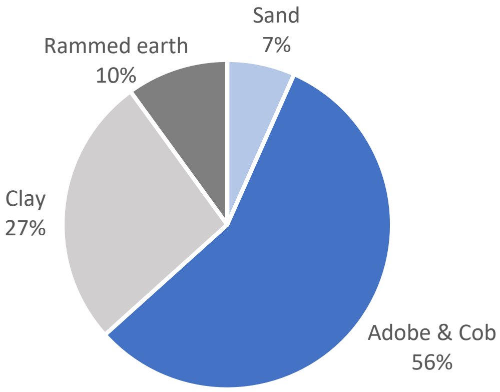

Figure 28. Percentage of usage per construction methods.

In general, the review of the literature showed that material delivery systems have been the major challenge facing the progress of earth-based construction; hence, it received a concentrated development effort to deliver the following benefits:

i. Improved integration with 3D printers and robotic arms, leading to better controllability over manufacturing processes and wider degrees of freedom;
ii. Enhanced consistency and quality of the built outcome;
iii. Reduced need for manual processing tasks (e.g., manual material preparation and mixing).

The special focus on AM/3D printing systems for earth materials led to a significant development in extrusions systems for wet-based earth construction method in terms of speed, quality and size. This is clearly observed, for instance, in the 3DP prototypes by WASP, IAAC and 3D Potter since 2016.

Nonetheless, there are still significant challenges facing 3DP of earth, as well as the other digital methods for earth construction. The remarked challenges in 3D printing methods divide into 2 lines:

6.1.1. Challenges in motion control system

It is noticed that the 3D printing process in most prototypes is dominated by the conventional 3 axes of movement, where the printing happens only in the vertical direction (Z axis). Despite the several examples in the literature of using 6 axes industrial robotic arms in the 3D printing process, little has been done on investigating other modes of movement that involve multi-directional mode of printing (e.g., printing over double-curved surfaces). In addition, there are still several limitations on other modes of 3D printing, like the point-to-point style. While less noticeable in 3DP clay, it is clearer in 3DP cob/adobe, where the rheological properties of the mixtures reduce controllability. This limitation forces the printing path planning to always adopt a continuous printing path line, which may limit the design possibilities and reduce efficiency. Path line design and planning also play an essential role in enhancing the product quality, material consumption and energy efficiency (Jiang and Ma, 2020). Developing an integrated shutter mechanism to the printing nozzle, similar to 3DP concrete systems, could be an efficient a solution for this problem. Furthermore, solving this issue is expected to deliver benefits for other limitations facing the constructing of certain components on large scale in terms of shape and topology, like large non-supported horizontal structures (i.e., ceilings and roofs) as well as vertical openings (i.e., windows and doors). 3D Printing of inclined and horizontal geometry with earth persist as a critical limitation, where the common approaches of using support structures in AM industry do not always suit earth materials. There are several examples where timber formwork has been used with 3DP earth (Figure 21) (Ganem Coutinho et al., 2021). Yet, the excessive use of formwork leads to material, time and energy waste (Jiang et al., 2018). Further research on smart integration of support structure with 3DP earth is needed. Other approaches that use topology optimisation for self-support form-finding can offer great and innovative solutions (Bi et al., 2020).

6.1.2. Challenges in material delivery system

The current manufacturing systems still require further upgrades to the material delivery/feeding system. The manufacturing system, as they are now, still not considered fully automated. It has a rather limited human interference with the digital construction workspace through focusing the human role on material mix preparation, material refilling, reloading and some assembly tasks. Automating the material delivery process can save time and increase the efficiency of the entire process in the future. There are several promising attempts to fully automate the material delivery system by Kloft et al. (2019) for rammed earth and Gramazio Kohler (2021) for clay. Gomaa et al., (2021a) also demonstrated in his study an envisaged fully automated material delivery system which adopts a collaborative robotic set up for material refilling and reloading. However, they are still considered in the early stage of development and require further enhancements to their accuracy and efficiency.

6.2. Remarks on performance aspects

Building performance analysis provides stakeholders with the essential information to improve the efficiency of the building for occupants and their surrounding environment. Building performance aspects, from an architectural point of view, cover a wide domain of technical aspects such as structural and thermal performance (Kolarevic and Malkawi, 2005). Moreover, the growing concerns of diminishing natural resources have brought several other performance aspects to light, such as energy and environmental performance, which together play a key role in a building's LCA (Hitchcock, 2002). Therefore, several studies on digital earth construction involved assessments of mechanical/structural, thermal, and environmental properties.

The conducted studies on the mechanical and structural properties of DMEC have demonstrated its promising capabilities for use in low-rise buildings, where it can exhibit higher material efficiency and design flexibility (Gomaa et al., 2021b; Perrot et al., 2018). There are several existing large-scale prototypes of earth constructions, which implies the feasibility of digitally manufactured earth walls to act as load-bearing elements. There are also promising examples of integrating timber systems in earth walls to support floors and staircase systems (Chang et al., 2018; Chiusoli, 2019). Yet, the published details on the mechanical and structural properties of earth construction have so far been based on small-scale test specimens (Gomaa et al., 2021a; Perrot et al., 2018). It is important to conduct a full-scale systematic structural testing of earth walls to provide a roadmap for standardisation. In addition, since earth material mixtures used for 3DP methods have high water content, it is expected that the built elements will undergo shrinkage during the hardening process, leading to possible cracking and other technical issues. This behaviour must be carefully considered in designing the structural components of digital earth construction. However, so far there have been no systematic studies that address this aspect.

The studies on the thermal properties and the environmental impacts of digital earth constructions demonstrate great potential, especially when compared to the rapidly spreading 3DP concrete construction. The reported studies show that 3DP earth walls have low thermal conductivity due to their design flexibility which enables efficient integration of insulation techniques, leading to an improved thermal comfort. Moreover, the preliminary LCA studies on 3DP earth walls show superior environmental performance over their concrete counterparts due to their lesser global warming effect. However, it is important to highlight that the studies on assessing thermal properties of 3DP earth walls were conducted by either using small scale prototypes or adopting a simulation-based approach (Dubor et al., 2018; Gomaa et al., 2019). To date there exists only one published study that assessed the LCA of 3DP cob (Alhumayani et al., 2020), which was limited in prototype size (1 m × 1 m wall) and focused only on the *cradle to site* processes of LCA. It is therefore important to consider further explorations on full-size constructions for a complete *cradle to cradle* LCA of several types of digital earth construction. A recent study by Schweiker et al. (2021) has also demonstrated several environmental and economical potentials of DMEC, while also highlighted the need for further robust investigations beyond the prototyping stage.

6.3. Remarks on research reliability, validity and visibility

Despite the noticeable increase in the adoption rate of DMEC in the recent years (Figure 26), the current recorded experiments are still considered nascent compared to other well-established digital construction methods (e.g., 3DCP). While these experiments present promising claims of improved productivity, quality and performance (i.e., thermal, structural, environmental), they rarely provide reliable information on the systematic assessment of these aspects. Most of the recorded studies to date are student projects, proof of concepts or commercial prototypes, such as the work by WASP and Emergent Objects. Very few projects are published in peer reviewed journals or refereed conference papers. Out of the 37 reported studies in this review, only 30% provided sufficient details that enable systematic replication of tests on the assessment of the performance-related aspects. Furthermore, there are limited details on material processing and workability aspects within the digital systems. To date, only 15 % of the published studies have actually provided details on the systematic investigation of the engineering properties of the digital manufactured earth components. Such lack of information leads to genuine concerns about the validity of results, which consequently creates reluctance in adopting the method on an industrial scale and hinders the ability of other researchers to replicate and verify the work.

On a different note, there is a clear fragmentation in the overall research on DMEC. It is easily noticeable that many research groups/institutions work within separate research silos with no real continuity of the knowledge thread. This is reflected by the recurrence of work, where different teams present remarkably similar work at the same time. There is also an issue of standardisation in the expressions, terminologies and keywords when describing the materials and processes of digital earth construction. For instance, some projects refer to the 3DP earth mixture as 3DP adobe, where others refer to it as 3DP cob, while in fact, in the context of 3DP, they are similar. This issue, while seemingly less significant, actually reduces the visibility of the new research, leading to a complicated process of information finding and prevents proper data collection. A potential solution for this problem is to create a list of glossaries that can serve as a standard reference for abbreviations in future research papers (Table 3). It is also worth noting that there is a significant contrast between the map of the traditional earth-construction regions and the new map of DMEC (Figure 28). Currently, most of digital earth construction research is taking place in Europe, while regions with historical abundance of earth construction still lag behind.

Table 3. Suggested list of glossaries to be used in the field of digitally manufacturing for earth construction.

DMEC	Digitally Manufactured/ Digital Manufacturing for Earth Construction
AME	Additive Manufacturing of Earth
3DEP	3D Earth Printing

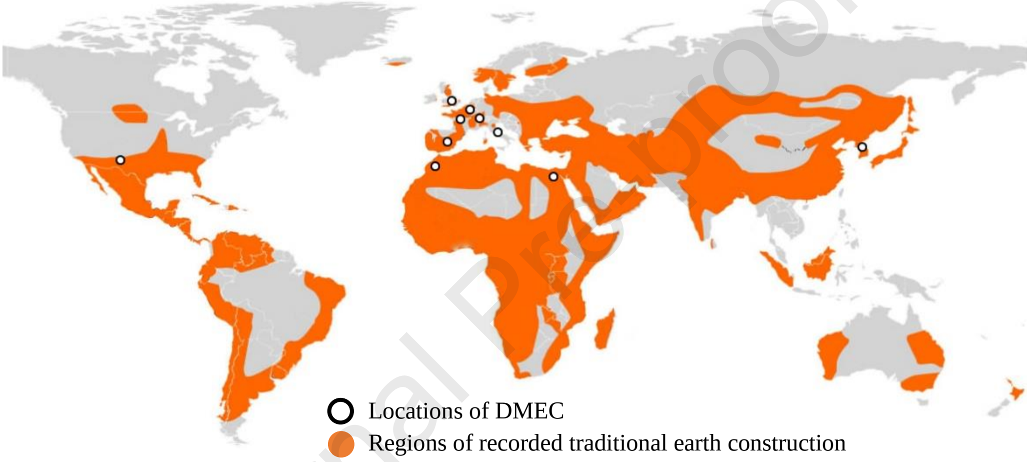

Figure 29. Map of reported DMEC projects around the world between 2011 and 2021

7. Concluding remarks

Originating from the aim to combine low cost and sustainable materials with the emerging digital construction sector, a new construction ethos has been growing steadily, founded on a digital research methodology that embraces vernacular knowledge as grounds for contemporary digital innovation. The development of the digital earth construction framework during the past 10 years, from early proof of concepts up to full-scale physical prototyping, has managed to explicate the potential of earth construction and expand the scope of digital manufacturing in construction beyond cement-based materials that are environmentally less friendly. The work done so far collaboratively offers a roadmap capable of bringing digital earth construction closer to an industrial scale and narrowing the gap between earth construction and contemporary digital practice. The systematic review of works in this study has not only provided a broad understanding of the undergoing developments of digital manufactured earth construction but also shed light on the disparity and fragmentation plaguing the research in this area. It is hoped that the comprehensive review in this paper and the standardisation of terms will bridge the gaps in knowledge among disparate research threads and collectively provide critical and consistent information for an enhanced utilisation of digital techniques in earth construction in the future.

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9. Declaration of competing interest

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

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Highlights

- *State-of-the-art of digital manufacturing for earth construction is critically reviewed.*
- *Potential and challenges of digital earth construction are presented and discussed.*
- *Information for enhanced utilisation of digital techniques in earth construction is provided.*
- *Concluded insights bridge the fragmented research threads on digital earth construction.*

Declaration of interests

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

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: