The Bryn Celli Ddu Minecraft Experience: A Workflow and Problem-Solving Case Study in the Creation of an Archaeological Reconstruction in Minecraft for Cultural Heritage Education

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This article explores the technical and interpretative issues surrounding the creation of a Minecraft Education Edition world for use by primary age school children (5–11 years). The project team undertook to create a Minecraft version of the prehistoric landscape surrounding the Neolithic passage tomb of Bryn Celli Ddu, Anglesey, Wales, United Kingdom. The workflow described here details the process from the initial aims of the project, designed to integrate heritage and STEM education; through the processing of lidar data to create the topography of the world; through the archaeological reconstruction; and then final release. An understanding of the workflow is particularly important for researchers and educators because the successful delivery of our aims resulted in a number of technical obstacles inherent in creating a Minecraft world when a designer is required to navigate several versions of the program—Java architecture, C++ architecture, and the Education Edition—and explains workarounds developed to overcome these issues. The article also considers the interpretative compromises required to translate complex archaeological remains into an accessible and engaging experience for school children set within the strictures of a program that allows a maximum physical resolution of a 1×1 m voxel block.

CCS Concepts: • **Applied computing → Interactive learning environments**; *Computer games*;

Additional Key Words and Phrases: Minecraft, cultural heritage, STEM education, archaeology

1 INTRODUCTION

Since 2015, the Bryn Celli Ddu Public Archaeology Landscape Project has been working in the environs of the Neolithic Passage Tomb of Bryn Celli Ddu, Anglesey, United Kingdom. The project has undertaken original archaeological excavation and survey work. Most importantly, it has engaged members of the public in every stage of the archaeological process, including education and outreach around the results of these investigations. Unfortunately, the field season planned for June 2020 was cancelled due to the coronavirus pandemic; this article focuses on one element of the response to this cancellation. A significant part of the outreach and education work that we undertook as part of the project was the creation of learning resources for local schools and providing opportunities for site tours and excavation by local children, mainly of primary school age (5–11 years) in both Welsh and English media. Social distancing and the closure of primary schools meant that this education opportunity was unavailable. We therefore turned to Minecraft as a means of engaging school-age children with the prehistoric landscape that we study, a means of communicating the results of our archaeological work, and a means of interlinking heritage and Science, Technology, Engineering and Mathematics (STEM) subject learning.

This article focuses on the process of moving from a deep physical and archaeological understanding of a landscape through the design and development process required to render this landscape into an educational experience in Minecraft. A particular focus is on the workflow and challenges that arose during the creation of the world so that subsequent researchers and educators can move through the process with more assurance. Particular problems were encountered when translating data between the various third-party programs needed to build a topographically accurate world; then navigating different release versions of Minecraft, Java, and C++ to import data; and, finally, moving to the Education Edition that schools in Wales can access for their STEM teaching. Detailed consideration is also paid to the interpretative challenges and the compromises required when simplifying highly complicated physical remains, subsurface sensing data, and nuanced archaeological interpretations so that they can be presented in an accessible and engaging digital format. The ultimate aim of this article is to provide a case study in the reflexive methodology developed by the project team, one which was forced to make balanced judgements between the complex nature of our research findings, education, and accessibility. It should also be noted that, whilst highly computer literate in three-dimensional (3D) modelling and spatial analysis, no member of the project team had any experience in the ‘modding’ of Minecraft or programming in C++. The successful creation of the world is therefore also a testament to the flexibility and accessibility of Minecraft as a platform.

Finally, it should be noted that the focus of this article is primarily technical and methodological. It is not our intention to review wholesale the practical and theoretical developments in archaeogaming more broadly; we focus instead on the specific development and utilization of Minecraft. However, over several years, the use of computer games in (and for) archaeological interpretation and communication has risen dramatically [1]. This practical case study should therefore be read in the context of the important work by Andrew Reinhard, *Archaeogaming* [2], but also against the background of key theoretical developments pioneered by researchers at the universities of Leiden and York [3]. This article will begin with a brief introduction to the Neolithic site of Bryn Celli Ddu and a short summary of our work to date to provide background to the elements chosen for incorporation within the Minecraft world. The detailed workflow of creating an accurate reproduction of the landscape and the archaeological remains will then be discussed, including workarounds for problems likely to be encountered by researchers undertaking similar projects.

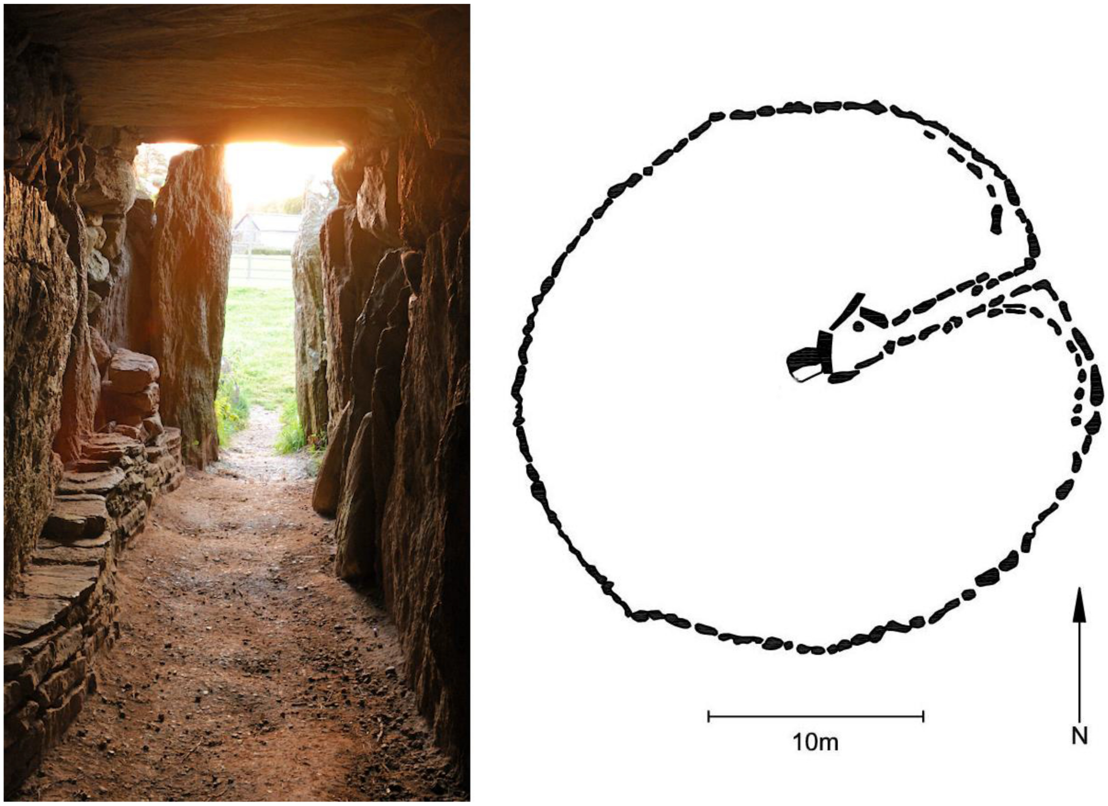

Fig. 1. Left: The summer solstice sunrise shining down the passage (courtesy Adam Stanford). Right: Plan of Bryn Celli Ddu.

2 BRYN CELLI DDU AND THE LANDSCAPE PROJECT

Bryn Celli Ddu is one of only two certain Neolithic passage tombs on the island of Anglesey, a distinction it shares with Barclodiad-y-Gawres [4]. There are a variety of other Neolithic burial monuments on the island, but only these two sites represent the passage tomb style of architecture—a style more commonly associated with the Neolithic of Ireland, in particular, the Boyne Valley [5]; the Orkney Isles, Scotland [6]; and Brittany, France [7]. Bryn Celli Ddu also possesses a series of other unique distinctions of interest to the prehistorian. First, radiocarbon dating indicates that the tomb was built circa 3000 BC [8], but it appears to have been constructed over an earlier henge and stone circle, implying a dramatically early date for these typically later Neolithic monuments. Second, the passage into the tomb is deliberately aligned so that on the summer solstice the first light of the rising sun shines directly down to the very back of the central burial chamber (Figure 1). The complexity of Bryn Celli Ddu, the rarity of these monuments on the British mainland, and their place in a pan-European architectural repertoire centered on the Irish Sea and the Atlantic coast led to the formulation of the Bryn Celli Ddu Landscape Project in 2015. Despite the importance of the site, no sustained new investigations had taken place since the first modern excavation in 1930, undertaken by Hemp [9] in advance of the stabilization and reconstruction of the monument. The burial mound itself was not the focus of our project, however. After Bryn Celli Ddu was excavated by Hemp, it was reconstructed by the Ministry of Works, which meant that little was to be gained by further digging into what is now a 20th-century monument on Neolithic foundations. Furthermore, as a legally protected Scheduled Ancient Monument [10], permission for such work, even if desirable, was unlikely to be granted. Instead, our project aimed to address the real lacuna in our understanding of the monument:

the landscape context of the site. This context is critical—without the location of the monument in this specific topographic context, the solar alignment would not be achieved and, our research suggests, other aspects of this elaborate ceremonial complex would not exist. The *landscape* is therefore critical to understanding the site. Yet no detailed excavation, geophysical, or remote-sensing surveys had ever been focused on the immediate surroundings of the tomb. As a result, beyond its existence as an impressive if reconstructed monument, Bryn Celli Ddu was divorced from its prehistoric context.

In response to this lack of knowledge around an internationally important site, the Bryn Celli Ddu Landscape Project deployed a mixed strategy of investigation: new geophysical prospection, laser scanning and photogrammetric recording of open-air rock art panels, lidar analysis, and traditional excavation. Over the 2015 to 2019 field seasons, the project uncovered an Early Bronze Age cairn group to the south of Bryn Celli Ddu and excavated two of the monuments; excavated a Grooved War pit cluster; undertook 21 hectares of geophysical survey; and recorded in 3D several panels of rock art, potentially tripling the number known on Anglesey. The discovery of these new features in the landscape has allowed the passage tomb and its preceding henge to be placed back into a Neolithic temporal and physical context, see Figure 2. Radiocarbon dating has demonstrated that the landscape was in use from the middle Neolithic to the early Bronze Age, representing over 1,000 years of monument construction and use [11].

Whilst these findings are interesting, they only provide the background to the work reported in this article because, from the outset, the Bryn Celli Ddu Public Archaeology Landscape Project was envisaged as more than a traditional academic research program. As a partnership between archaeologists working in universities, archaeologists in Cadw (the Welsh Government's historical environment service), archaeologists in developer-led practice, and with heritage specialists in the local museum, the project had always held public archaeology and heritage as a central theme in its research. Public engagement was central to the design and delivery of the scheme: these would not be 'extras' or 'benefits' from the project—they would define its form and execution [12]. From 2015 to 2019, every season of work in the field involved local volunteer excavators, school tours in Welsh and English, and a large public open day with reenactors, experimental archaeology, site tours, educational activities, finds displays, artists in residence, and visiting specialists. As the project developed, the scope of our engagement activities also grew, with a partnership with the local museum, Oriel Ynys Môn, resulting in temporary exhibitions, Lego resources for reconstructing the monument (an interesting harbinger of Minecraft), a series of free local lectures, and a treasure trail with a pin-badge reward, all at no cost to participants. However, with the outbreak of the coronavirus pandemic and the subsequent controls on movement, social distancing, and the almost total closure of schools, it became impossible to undertake any form of excavation, survey, or public outreach in 2020. Whilst this cancellation was disappointing, what became clear through the national media was the intense pressure on schools, teachers, and parents to deliver engaging education opportunities from home. The Bryn Celli Ddu Minecraft Experience was our response to this situation—an attempt to contribute positively in however small a way. Yet, from inception to delivery, this concept required a series of methodological and interpretative innovations that belied the initial simplicity of the idea.

3 MINECRAFT AND CULTURAL HERITAGE EDUCATION

3.1 Development

It is not the intention of this article to once again explain the history and development of the Minecraft platform, as almost every citation listed does this to some extent, and as the most downloaded game of all time [13] it has entered the general public consciousness. One point is worth highlighting here, however, of relevance to the educational aims of the Bryn Celli Ddu project. Minecraft's first full release took place in 2011, but it was with the launch of the Minecraft Education Edition in 2016 that the game's designers self-consciously developed a platform to facilitate easier use in an educational setting. This was based on the 'Bedrock' edition of the commercial game, developed by Microsoft after they acquired Mojang in 2014 and programmed in C++. Earlier releases, developed in Java, had been unofficially modded to create MinecraftEDU, which had seen success

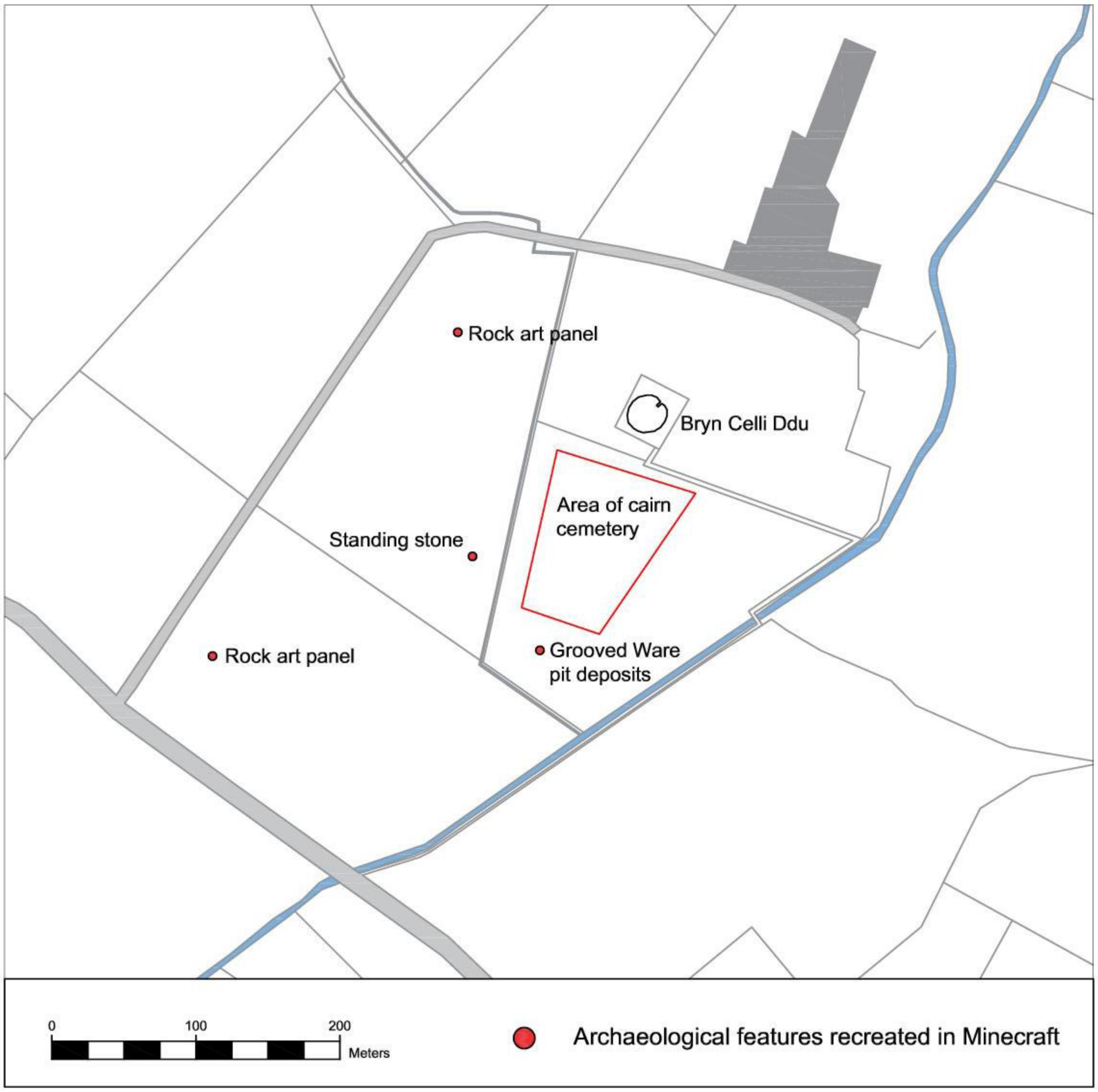

Fig. 2. The location of prehistoric archaeological features included in the Minecraft world.

amongst educational professionals. The Java edition is still available for those without Windows 10. There are differences in functionality and in-game items and textures between the educational and commercially available versions, explored in more detail below. There are also compatibility issues surrounding world-design as a result of moving from Java to C++-based editions of the game that necessitates the use of third-party software, as we shall see.

The use of Minecraft to explore themes in digital heritage, or facilitate the representation of heritage, is not a new concept, although built heritage tends to be overrepresented in comparison to other forms, such as the reconstruction of archaeological or other heritage sites that are now altered or lost. Several synthetic studies have validated the use of Minecraft for heritage interpretation: Garcia-Fernandez and Medeiros, in a comparative study of a variety of gaming platforms, noted that Minecraft was the most useful based on the levels of immersion and motivation for players, particularly self-authoring, despite the lack of 'fidelity' resulting from the 1×1 m voxel limitations [14]. Similarly, in a more focused comparison between paper-based modelling and Minecraft modelling of public sculpture as a means to connect students with art heritage in the built environment, the majority of participants found the Minecraft experience more engaging [15]. That said, Minecraft, as with any other digital platform for learning, must be used in an intelligent manner with a clear idea of aims, audience, and methodology—essential in any attempt to create a usable educational resource [16]. One of the earliest adopters of Minecraft for cultural heritage engagement was the museums sector. A particularly successfully project, *Tate Worlds*, was developed by Tate Britain and saw the digital interpretation of landscapes based on works in the museum's collection [17]. The *Tate Worlds* project was cited as an inspiration for an incredibly successful collaboration between educators and heritage professionals in Scotland called *Crafting the Past*, which saw communities undertake digital archaeological excavations and reconstruct historic buildings in Minecraft, attracting audiences of over 100,000 people [18]. Colleen Morgan of the University of York led a pioneering project introducing school children to the Mesolithic site of Star Carr through a Minecraft reconstruction in 2015 [19], which itself was built on the work of Shawn Graham that demonstrated the possibility of using landscape-scale DEMs to reconstruct the prehistoric environment [20]. Also beginning in 2015, the RoMeincraft project, coordinated by the VALUE foundation of the Netherlands, set out to collaboratively reconstruct elements of the Roman landscape with school children. The success of the project and the effectiveness of using Minecraft as an educational tool is demonstrated by the number of participants (over 1,000) that had engaged with the activities by 2020 [21]. Indeed, the potential benefits of Minecraft and video-gaming for heritage visualization more generally has been recognized by UNESCO [22]. The pioneering work discussed above has most recently been developed by Shawn Graham through an explicitly archaeological walkthrough of Minecraft [23]. Whilst his particular focus on the ethics of archaeogaming are outside the scope of this more technical article, his observation that the ethics of Minecraft in its 'survival' mode—particularly, the looting of temples—are explicitly drawn from the popular culture of the physical world is very important. Therefore, an archaeological engagement with Minecraft should not encourage unethical behavior in the physical present amongst users.

3.2 Challenges

There have been technical challenges in the creation of Minecraft representations of physical heritage. These can be identified with two broad themes, which can often overlap: modelling at scale and ensuring accurate representation. An ambitious attempt to recreate the entirety of Norway by Kartvertet, the national mapping authority, was limited by available computational power to a resolution of 8:1 (i.e., each 1×1 m voxel block in Minecraft represents 8×8 m in the real world), and a reported attempt to represent both landscapes and the built environment in Denmark is reported to have captured only the topography [24]. In both these cases, the underlying data transformed into the Minecraft world was derived from digital terrain models originating from lidar data. The issue with using lidar data to reconstruct the *built* environment is the lack of spatial resolution and texture. A successful workflow was developed by Garcia-Fernandez and Mateus [24] but this relied on a blending of airborne lidar and ground-based sensing at a higher resolution; texturing, that is, converting the buildings from single-color blocks to entities with brick walls and glass windows, still had to be undertaken manually. Similar issues were experienced by the *Crafting the Past* team, where the landscaping alone took 72 hours in the case of Penicuik House [18]. The RoMeincraft project overcame issues of landscape scale and travel-time within the online environment by recreating the whole of South Holland at 1:4 scale, but the areas around Roman sites at 1:1 where their collaborative reconstructions were to be undertaken [25]. Thus, automated workflows can be adopted for the accurate recreation of landscapes (see below for issues concerning vegetation coverage, however), but recreating the built environment is still largely a manual task. The construction of buildings is therefore where the desire to ensure accurate representation becomes exponentially more time-consuming as the desired scale of the modelling increases. The accurate representation of structures in terms of their texture is actually less of an issue than one might first assume. Whilst the named Minecraft entities, such as 'birch log', birch planks', 'oak planks', etc., may initially seem limiting in terms of accurate construction materials, in actuality because casual users of the worlds *do not know* what entities have been used to create the particular texture the modeler desires, a correct color block may be a more sensible choice than the correctly defined material. For example, there is no block for thatching a roof, but sandstone blocks provide the right color. There is no doubt that the 1×1 m voxel format of the world limits the resolution—and, therefore, accuracy—of a heritage reconstruction. However, there are blocks that can be used to mitigate this issue. Pitched roofs, for example, can be created using the 'wooden steps' entity, which creates a 0.5 m–deep treaded stair. Place these correctly and one has a 0.5×1 m resolution diagonal roof. Naturally, one can not alter the pitch of this incline; therefore, roofs are always pitched at 45 degrees unless an inconsistent slope is acceptable.

3.3 The Choice of Minecraft

All of the above limitations are of concern to those attempting to reconstruct the built heritage environment as accurately as possible. Thus, they naturally raise the question of why one would use Minecraft for a project of this type. First, concerning accuracy, the benefits of the platform lie in its accessibility and quality of engagement, not real-world accuracy of reproduction. If fidelity were the overriding aim, then a world based in the Unreal engine, for example, would be a better choice. Minecraft has an array of advantages for the production of an educational experience, many of which have been alluded to already, but it is worth making them explicit. Market penetration is a massive advantage: we have discussed the record sales of the game, but it is also worth noting the multiplatform compatibility of the Bedrock Edition with PC, tablet, and console editions now available. As a result, many of the potential users of an educational experience in Minecraft will already have used the program either through purchasing the commercial edition or via free access to the educational version. The latter point was particularly important to the Bryn Celli Ddu project which, being based in Wales and initially targeted at locked-down Welsh school children, was able to rely on the fact that the Welsh Government, through its 'Hwb' platform, already gave free access to Minecraft Education to all Welsh school children and teachers. The accessibility of the gameplay is also a great benefit in this context. Minecraft is a very simple game to learn to play, with instinctive keyboard and mouse controls, and similarly simple tablet and console editions. For new users, the Education Edition also displays all keyboard controls on-screen. Despite the challenge, noted above, of the time-consuming nature of constructing buildings in the Minecraft environment, this too can be set against the accessibility of the program for us as inexperienced developers. With little knowledge of commercial 3D modelling applications and no experience with C++ programming, it would have been far more difficult, if not impossible, to produce a meaningful world in any other gaming engine. In the overall context of developing an education tool, time was thus *saved* given the impracticality of learning a new, more complex gaming package.

4 BRYN CELLI DDU MINECRAFT EXPERIENCE: AIMS AND WORKFLOW

We will now turn to a consideration of the crafting of the Bryn Celli Ddu landscape and the reconstruction of its archaeological remains in Minecraft; see Figure 5 for a summary of the workflow. In addition to the steps taken to create the world, where technical issues arose, these issues will be examined in detail in order to provide potential solutions for other developers. Throughout the description of the workflow, problems encountered will be sequentially numbered and their resolution described. Some are the result of the project's stated aims; others of a technical nature relate to the design of the Minecraft platform.

4.1 Aims

The three aims behind creating the Bryn Celli Ddu Minecraft Experience were to produce an accurate reconstruction of the archaeological remains and the landscape around Bryn Celli Ddu during the late Neolithic and

Early Bronze Age; to embed interpretative elements that could be used by primary-age school children, their teachers and parents for educational purposes, integrating heritage and archaeology with STEM teaching; and to do this bilingually in Welsh and English. These aims immediately demand compromises before Minecraft has even been booted up. Our list of problems begins here:

- Chronology: Not all archaeological remains excavated or surveyed during fieldwork would have been visible at a given point in time, as the period studied is approximately 3000 BC to 1600 BC.
- The inclusion of paths, way-markers, lighting, and interpretative signage immediately introduces elements into the world that are not 'of' prehistory.
- Any element of the reconstructed world is *a priori* limited to a resolution of 1×1 m and must be aligned on cardinal points, as all blocks are square.

Thus, tensions arose between the representational aim and the educational aim. The educational aim took precedence. Minecraft was chosen due to its market penetration into the education sector, so any limitations with orientation and resolution (problem 3) were accepted from the outset. As discussed above, if the aim were to produce a representational world, an industry standard 3D modelling package would have been chosen. The chronological question (problem 1) was more concerning: by reducing a diachronic past to a synchronic representation, we ran the risk of *limiting* the educational potential of the world by introducing confusion around temporality. However, the inclusion of interpretative signage and pathing (problem 2) was designed to counter the issue of synchronicity by providing the user with information. Whilst this did introduce non-prehistoric elements into the landscape, we had already accepted the fact that education held precedence over accurate representation. Moreover, the use of signage and defined paths does not restrict the user—they are suggestions for paths of movement only—thus, the experience can still be self-authored.

4.2 Topographic Representation

The first stage of creating the world was reconstructing the prehistoric topography of the valley of the Afon Braint in which Bryn Celli Ddu is located. This was important because the specific landscape position of the monument, on a low gravel rise in the center of the valley, appears to have been chosen to avoid lower, boggier ground to the east and west. Other monuments in the landscape, such as standing stones and rock art, are also believed to have been sited with specific viewsheds in mind [26]. A group of early Bronze Age cairns was clearly located on the same gravel ridge as the passage grave from a concern with physical proximity to the earlier monument.

Publicly available lidar data was acquired for the landscape surrounding the monument from the Environment Agency of the UK government [27] at a 1 m spatial resolution. This was provided as a geoTIFF file with 1×1 m raster pixels containing the height data, conveniently the same maximum resolution of a Minecraft voxel. Developers in regions of the world without free public lidar could instead consider using the archive of Landsat images provided free by the USGS, or the Shuttle Radar Mission, although these are of lower resolution. In order to create a Minecraft map from this data, the third-party open-source software package *WorldPainter* was used in the same manner as the RoMeincraft project [25], which allows height maps to be imported, edited, and converted to *.mcworld files that are used in Minecraft [28]. However, an immediate problem presented itself:

- WorldPainter does not, at time of writing, support the import of *.tiff format image files despite this being an industry standard raster format for digital terrain modelling.

The solution was to convert the geoTIFF into a *.bmp image of the same size and resolution, where each shaded pixel could be read as a height map in WorldPainter. For the rapid creation of landscapes in Minecraft, WorldPainter is a useful tool: having successfully created the basic topography, it was also necessary to paint in the course of the local rivers—important for the specific siting of the monument, as we have seen—a task

Fig. 3. The WorldPainter contour model created after DTM import and addition of river features. Note colored blocks used to indicate locations for archaeological reconstruction.

that can also be accomplished quickly (Figure 3). WorldPainter could also be used to create different landscape types within the world, known in Minecraft as 'biomes', that is, marsh along the water courses, areas of deciduous forest, and grassland, although there were limitations, discussed below. It was recognized at this point that WorldPainter was not an appropriate package for the fine work of building individual monuments but that columns of blocks could be placed in the landscape where monuments could later be reconstructed in Minecraft itself. This was an important step, as WorldPainter provided a map view of the entire landscape, allowing the accurate spatial location of points for the monuments, which would have been impossible from within the confines of the Minecraft interface. Once the topography, water courses, and vegetation biomes were modelled, a *.mcworld file was exported from WorldPainter for use in Minecraft.

4.3 Exporting the Landscape Model

Initial attempts to open the newly generated landscape model immediately in Minecraft faced compatibility issues. This was because WorldPainter creates maps in the original Java-based game engine, not the C++ version used by the Minecraft Education Edition and the Windows 10 'Bedrock' edition. Thus:

- Java-based maps cannot be opened directly in the educational version of Minecraft.

Fig. 4. Screenshots of the reconstructions, clockwise from top left: airborne view over the cairn group; the entrance to Bryn Cell Ddu passage tomb; the rock art outcrop showing blocks used; the Neolithic house from Llanfaethlu.

However, a further third-party application MCC Tool Chest PE can be used to convert Java to Bedrock edition worlds [29], thereby allowing editing in-game. The *.mcworld file created was then opened, not in the Education Edition but in the current commercially distributed (paid for) version of the game. This decision was taken because the full version contains a wider array of block types for modelling, which remain visible in the Education Edition even though they cannot be created within it. However, the conversion from Java to Bedrock had a further unintended consequence posing a time-consuming problem for the design team:

- Conversion from Java to Bedrock kept the 'biome' definitions from the original WorldPainter map but did *not* create deciduous trees where they had been placed in the initial design.

An automated workflow solution to this problem could not be found; its consequences are discussed in Section 4.5.

4.4 Reconstructing the Archaeological Remains

The limitations on block textures, discussed in Section 3, were not an issue for the reconstruction of Neolithic and Early Bronze Age archaeological remains, as the only substances used for construction on any of the sites in the Bryn Celli Ddu landscape were stone and wood (see Section 3.2). As discussed in Section 2, the current appearance of Bryn Celli Ddu is the result of reconstruction after the excavations of Hemp [6], but his site plan of the original form of the monument allowed accurate modelling. Thus, the size of the burial mound, the length and size of the burial chamber, the location of kerbstones, and the encircling ditch could all be placed with a precision of 1 m (the 1×1 m voxel limitation of the world). Compromises were necessary with the width and height of the passage into the mound, as in order to allow the movement of avatars it had to be 1×2 m in profile. The overall height of the mound was also the result of interpretation, as this had been completely removed by the time of Hemp's excavation. See Figure 4 for views of the various reconstructed elements in the world.

The Early Bronze Age cairn group was reconstructed using two different sources. The largest cairn in the group was excavated by the project team during the summers of 2018 and 2019. This allowed the accurate reconstruction of the shape of the central stone-built mound and the encircling double kerb rings. A stone-built cist grave was also buried in the center of the cairn, should any user choose to dig into it, in the location of the primary burial discovered during the excavations. A 'flowerpot' object was placed between the kerb rings to mimic the Collared Urn cremation burial discovered at this point. Although the object is designed to be decorative, it serves as an appropriate analogue for simple prehistoric pottery given its similar form. The rest of the cairn group was less accurately reconstructed, being based on our geophysical survey results, which provided only the location and diameter of the remaining stone monuments. Their height was thus based on experience of the size of undamaged monuments of this type, and no burial objects were included within or near them.

New panels of rock art, dating to the Neolithic, were a major success of the project's fieldwork and clearly an important element of the prehistoric landscape. A large panel of cup-marked rock art was known prior to the start of the project on the upper surface of a large rock outcrop 150 m to the northwest of the passage tomb [30]. This was reconstructed using the 'bedrock' entity for the rock outcrop in order to distinguish this feature from the other stone textures used in the world, but the art was more problematic. It was decided to use the 'grey-glazed terracotta' block type for this purpose, as it was the closest in visual appearance to the arrangement of shallow cup-marks that form the art. This was a difficult compromise, but a necessary one, as we were committed to using only standard Minecraft entities to avoid users having to download an additional texture pack. We had also discovered a large number of new panels, but they were spread some distance over the surrounding landscape, which posed an additional interpretative problem:

- The educational aims of the project required as full a reconstruction of the landscape as possible, including its size, meaning that distances between features would be accurate. Therefore, a user visiting all the new rock art panels would require extended 'travel time' within the game.

The resolution to this issue was a compromise between educational aims and a necessity for the game to remain accessible in the widest sense of the term. Forcing users to walk significant distances in the game would have a number of negative consequences that would ultimately also impinge on the very same educational aim: walking would likely be boring to the average primary school user, creating the necessary pathing and surrounding vegetation for a much larger land area would be time-consuming for the design team, and the additional rock art panels added would not be significantly different from one another to create an interesting experience for the user. The compromise position was the creation of the single nearest panel to Bryn Celli Ddu, which was also close to one of the Neolithic standing stones. The reasoning behind this decision was that the accessibility of the world—which, alongside availability of the necessary software and hardware, includes the degree to which it is *engaging to the user*—was in this instance more important than representing 'all' the prehistoric remains that we had discovered.

Additional archaeological remains were also added, including the nearby standing stone and the Grooved Ware pits excavated in 2017, but a further interpretative decision was necessary. During site tours and educational visits by local school children, one of the most common questions was 'where and how did the prehistoric people live?' This was impossible to reconstruct if the Minecraft world adhered to the aim of accurate representation, as no Neolithic or Early Bronze Age settlement activity has been located or excavated in the environs of Bryn Celli Ddu. However, there was clearly value in visualising this activity. Thus, once again, the educational aim of the project was given greater significance than the desire for accurate reconstruction. A large early Neolithic longhouse excavated in the north of Anglesey at Llanfaethlu was chosen for reconstruction due to the quality of the excavation and its detailed reporting [31]. The ground-plan of this structure was well understood, including internal divisions separating areas for human and animal occupation. Yet, as it was discovered beneath ploughed farmland, everything modelled in Minecraft from the ground level up was an interpretative decision, based on extensive reconstruction of Neolithic longhouses from the European Linearbandkeramik [32] that, whilst often larger, share basic construction techniques and ground plans. Indeed, LBK examples have been discovered that were smaller than the Llanfaethlu structure.

4.5 Narrative and Interpretative Elements

The education aims of the project demanded that some interpretative signage was required within the world that should be discoverable whilst still retaining the possibility for self-authored exploration, identified as a key benefit of VR technology in education [16]. Minecraft 'signs' were placed at each reconstructed element providing information designed for consumption by children below the age of 11. As the site is located in an area with a high percentage of Welsh language speakers, all of our public engagement work has been bilingual. Most of our local partner schools provide education in the Welsh-language medium. It was therefore essential that both 'English' and 'Cymraeg' versions of the application were created. We choose to produce these as separate worlds to limit the size of explanatory signage within each. 'Path' blocks were used to suggest routes through the landscape to the various elements. However, these were deliberately nonlinear, with the user entering the world (spawning) immediately in front of the passage tomb and presented with four possible routes to different parts of the world. Furthermore, it was recognized that some element of 'discovery', or 'enchantment', following Sara Perry [33], had to be incorporated to ensure continued engagement by children. Thus, the decision was taken to use vegetation to obscure our reconstructions and design our paths so that monuments would be 'revealed' suddenly to the user. In this sense, the failure of MCC Tool Chest PE to successfully import the deciduous woodland prepainted onto the landscape (see Section 4.3) became an unexpected benefit. The team was forced to manually plant tree Minecraft 'saplings' and then use 'bone meal' on them to create instant growth. This was an extremely time-consuming process but did allow areas of woodland to be created in exactly the right locations to obscure critical views and to allow 'discoveries' to occur when winding paths through woodland revealed a monument. Minecraft contains silver birch and oak tree entities as standard, which were chosen to represent mixed deciduous woodland closest to Neolithic vegetation.

4.6 Publishing the World

Having created the world in the commercial version of Minecraft in order to take advantage of additional block-options (critically, the path block) it was necessary to export the world as a *.mcworld archive that could then be opened in the Education Edition, presenting a new problem:

- Despite being based on the same 'Bedrock' underlying C++ architecture, Minecraft Education Edition would not accept imports from the commercial version of the software.

The commercial and education editions of the program do not share the same version numbers, being updated at different speeds and with different features. As a result, when imported into the Education Edition, the following error message was displayed: 'A newer version of the game has saved this level. It cannot be loaded'. The solution to this workflow problem is to edit the *.mcworld file within MCC Tool Chest PE. Opening the world in this application allows the interrogation of the [level.dat] file that sits within the *.mcworld archive (note: *.mcworld files are simple ZIP archives with a renamed file extension). The level.dat is the top entry in the navigation pane of the application. The second entry within the DAT file is the tag [lastOpenedWithVersion]. Deleting this entry and saving the changes to the file will then allow the world to opened in the Education Edition. It is recommended that MCC Tool Chest PE is used for all file editing rather than editing the DAT through a text editor due to the additional tools for checking and exporting the *.mcworld file upon completion. Designers could also take this opportunity to delete all active players saved within the world to ensure a clean version for distribution. This is not essential, but if desired [players] is the second entry in the hierarchy of the navigation pane, and players can be deleted by right-clicking their entries. A final and important note, one cannot use this work-through to convert Education Edition worlds back for use in the commercial version.

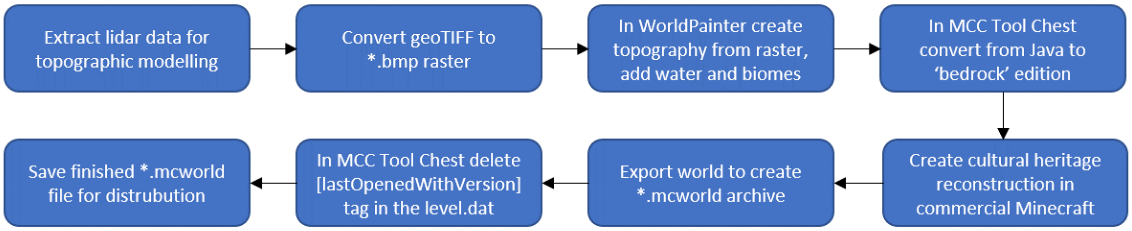

Fig. 5. Summary workflow for the creation of a cultural heritage experience in Minecraft Education Edition.

No satisfactory explanation or solution was found for this issue—a further reason to design worlds in the commercial version to allow continued usage if more general distribution of a world was desired.

Once saved as a *.mcworld file, the Minecraft experience was ready for distribution. Initial beta testing was undertaken at a single school with access to the Minecraft Education Edition; no technical issues were uncovered that required resolution. Final distribution was undertaken in two ways. Having worked in partnership with Cadw throughout the Bryn Celli Ddu Public Archaeology Landscape Project, we were able to share the educational version through the Welsh Government's online learning platform, HwbCymru [34]. This platform also has the advantage of providing the Education Edition of Minecraft free to all pupils at Welsh schools who possess a username. Wider distribution and permanent archiving was assured by sharing the world through the Manchester Centre for Public History and Heritage (MCPHH) website. Links to both the bilingual Education Edition and a version for use on the commercial edition of Minecraft are provided [35].

5 AUDIENCE RECEPTION

Following publication in June 2020, concerted efforts were made to publicize the existence of the Bryn Celli Ddu Minecraft Experience as widely as possible. This was aided significantly by interest from Welsh-language broadcaster S4C, which featured the experience on a child-orientated current affairs program, and by coverage on the BBC News website, with international coverage. Download statistics are not available for distribution through HwbCymru, but the MCPHH website registered 982 additional hits in the first month of availability. In addition, positive feedback was received from teachers at the primary school used for beta testing and from children themselves. Three interesting quotes are presented here (all translated from Welsh): "I really like the Minecraft World. I hadn't heard of Bryn Celli Ddu but now I'm looking forward to seeing it"; "It reminds me of all the places I can go and see when lockdown is over"; and "It's a lot of fun because even though we can't go there now, you can see what it looks like without leaving the house". The most striking element of these three quotes from primary school-age children is the recurrent theme linking the digital experience of the Minecraft world to *future* experiences in the physical reality. This came as a surprise because the aim of the project was to allow a continuation of school outreach during lockdown, not to publicise or encourage visitors to the site. Naturally, this is a very positive if unforeseen benefit, but it also highlights the effect of severe coronavirus lockdown on primary-age children. Clearly, whilst a positive experience for the children, the Minecraft world could not be taken as a replacement for actual physical presence in the landscape.

6 SUMMARY OF THE WORKFLOW AND CONCLUSIONS

Having considered in detail the process of creating a Minecraft world for public heritage education, it is useful to summarize the workflow in its entirety (Figure 5).

By its nature, this is a manual process with few opportunities for automated workflow, but the majority of the steps are not time intensive. The two exceptions are the addition of landscape elements in WorldPainter beyond the basic topography and the actual reconstruction of the cultural heritage elements desired. Both are dependent on the size, in real terms, of the reconstruction being attempted. The Bryn Celli Ddu Minecraft world required some addition of rivers in WorldPainter, but it was the manual 'planting' of the trees that actually occupied the most time, beyond even that of 'building' the archaeological features. This was not unexpected, as previous work, discussed in Section 2, had failed to find an automated workflow for the accurate reconstruction of built heritage [24]. It is estimated that the entire world required the equivalent of three working days to produce, excluding the time taken to find workarounds for the eight issues detailed in Section 4. For the sake of future comparison, the final world occupies 0.4 sq km, excluding the large areas of the topography that were not developed with vegetation because they fell outside the area of archaeological interest.

Focusing on the technical problems that arose during the creation of the world, it is clear that there are those that originated in limitations of the file formats used in Minecraft and those that were more pertinent to the educational aims of the exercise. The creation of the 'Bedrock' C++ edition of Minecraft—designed for education, Windows 10, iOS, and Xbox following the purchase by Microsoft—presented the most obvious bar to ease of development, as third-party world designers have not yet been developed to directly support this format. Therefore, conversion from Java was required. Similarly, lack of consistency in version updates between the Education Edition and commercial edition required further use of third-party software. The issues around importing biome information from the Java edition—in this case, the lack of automated tree planting whilst adding considerably to the time required to build the world—actually allowed the more considered creation of the user 'experience' of the world, essentially synonymous with 'accessibility'.

There were also clear issues in terms of how to represent complex, multiperiod archaeological landscapes, incorporating the STEM and heritage learning aspects but without limiting the enjoyment of the world for young learners. Our choice to use the program was deliberately centered on its worldwide user base and the free access to the Education Edition provided to Welsh schools. The physical limitations of 1×1 m voxels must be accepted in this context; moreover, any end user of the world will know Minecraft and not *expect* high-end graphical realism. We chose to select specific elements of the archaeology to augment player engagement, self-authored discovery, and signage as in-game work-round. Similarly, pathways and the use of vegetation to create 'encounters' in the landscape were important for the fostering of learning and engagement.

We hope this article will simplify future attempts to create Minecraft worlds for public heritage education by detailing the problems encountered during development and suggesting solutions. At the time of writing, there are no workflows for fully automated building and texturing of worlds and no direct compatibility between the various versions of Minecraft. However, as a reflexive process, the creation of the world was an illuminating experience, specifically in terms of the compromises it required in communicating complex archaeological research findings, accessibility, and learning outcomes in terms of heritage, archaeology, and STEM subjects for primary school students (5–11 years old). Communicating complex landscapes and archaeological findings without compromising on creative learning represents a challenge. Here, we have used a popular gaming platform to incorporate STEM learning outcomes and new archaeological research findings. Minecraft provides primary school children with a platform to combine archaeology and heritage learning in a self-authored, discovery-focused context. As such, Minecraft represents a unique opportunity for digital legacy of the project and remote learning, even when current pandemic circumstances mean that our traditional public archaeology program has not been possible. We hope to develop this approach to distance learning and digital public archaeology engagement in the future whilst acknowledging the interesting feedback from children that indicates digital experience is not necessarily preferable to physical encounters with the past.

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