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Article information:

To cite this document:
John David McEwen Arnold, Don Lafreniere, (2018) "Creating a longitudinal, data-driven 3D model of change over time in a postindustrial landscape using GIS and CityEngine", Journal of Cultural Heritage Management and Sustainable Development, Vol. 8 Issue: 4, pp.434-447, https://doi.org/10.1108/JCHMSD-08-2017-0055
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Received 9 August 2017
Revised 1 October 2017
Accepted 22 December 2017

Creating a longitudinal, data-driven 3D model of change over time in a postindustrial landscape using GIS and CityEngine

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Abstract

Purpose – The purpose of this paper is to create a longitudinal data-driven model of change over time in a postindustrial landscape, using the "Copper Country" of Michigan's Upper Peninsula as a case study. The models resulting from this project will support the heritage management and public education goals of the contemporary communities and Keweenaw National Historical Park that administer this nationally significant mining region through accessible, engaging, and interpretable digital heritage.
Design/methodology/approach – The paper applies Esri's CityEngine procedural modeling software to an existing historical big data set. The Copper Country Historical Spatial Data Infrastructure, previously created by the HESA lab, contains over 120,000 spatiotemporally specific building footprints and other built environment variables. This project constructed a pair of 3D digital landscapes comparing the built environments of 1917 and 1949, reflecting the formal and functional evolution of several of the most important copper mining, milling, and smelting districts of Michigan's Keweenaw Peninsula.
Findings – This research discovered that CityEngine, while intended for rapid 3D modeling of the contemporary urban landscape, was sufficiently robust and flexible to be applied to modeling serial historic industrial landscapes. While this novel application required some additional coding and finish work, by harnessing this software to existing big data sets, 48,000 individual buildings were rapidly visualized using several key variables.
Originality/value – This paper presents a new and useful application of an existing 3D modeling software, helping to further illuminate and inform the management and conservation of the rich heritage of this still-evolving postindustrial landscape.

Keywords Industrial heritage, Cultural landscapes, 3D modelling, CityEngine, Historical GIS, Historical spatial data infrastructure

Paper type Research paper

Introduction

This study integrates a high-resolution, big data, historical geographic information system (HGIS) (known herein as the Copper Country Historical Spatial Data Infrastructure (CC-HSDI)) with procedural modeling to recreate a pair of temporally comparative 3D models of an entire industrial landscape.

Background

The use of 3D digital modeling technologies today is widespread in the design and analysis of new buildings (Eleftheriadis *et al.*, 2017; Szalapaj, 2014) and in the study of contemporary cities for land use planning and management (Billen *et al.*, 2014; Miller and Tolle, 2016), and a variety of archeological undertakings (Biljecki *et al.*, 2015; Meyer *et al.*, 2016). Furthermore, the role of computer graphics extends beyond the needs of designers, planners, and managers, and has secured a role in the study of cultural heritage (Arnold, 2014). In particular, the use of building information modeling has expanded greatly

Journal of Cultural Heritage
Management and Sustainable
Development
Vol. 8 No. 4, 2018
pp. 434-447
© Emerald Publishing Limited
2044-1266
DOI 10.1108/JCHMSD-08-2017-0055

from its original application as a design tool, and is being increasingly employed in the study of historical buildings as heritage building information modeling (HBIM) (Arayici *et al.*, 2017), often employing data procured by laser scanning and photogrammetry (Dore and Murphy, 2015) to recreate digital emulations of historic buildings. Others have built on this approach, semantically enriching an HBIM by coupling it to a database of non-architectural attributes including landscape information by using GIS both broadly (Yang *et al.*, 2016) and to investigate in depth a single building at a particular point in time (Baik *et al.*, 2015). In particular, such 3D digital models have a particular utility to an evolutionary study of historic buildings (Casu and Pisu, 2015).

Only recently have the significant time and computational challenges of modeling at the city scale been somewhat diminished with technological progress in data capture and processing power (Dell'Unto *et al.*, 2016). A further advancement has been the advent of commercially available procedural modeling software. Unlike traditional 3D digital modeling in which individual building volumes must be independently modeled; procedural modeling, a computing technique for creating models from sets of rules can quickly and easily be deployed for the creation of entire cityscapes through the application of rule-based code to simple, pre-existing geometries. Procedural modeling has been used for digitally replicating a single historical building (Danielová *et al.*, 2016), for modeling a historical city center in its current state (Almeida *et al.*, 2016), for the virtual reconstruction of several buildings (Rodrigues *et al.*, 2014) or a portion of a city at a selected time period in the past (Dylla *et al.*, 2008), and as a tool for research and data recording in an active archeological site (Piccoli, 2016). Procedural modeling has additionally been demonstrated to be valuable for testing alternative architectural reconstructions of past built environments, both in examining various interpretations of a single time period (Saldana and Johanson, 2013) and directly modeling different time periods in a discrete location (Botica *et al.*, 2014). However, the power of procedural modeling has yet to be applied to a wide, near-complete representation of a built environment over time.

This paper unites the limited existing scholarship in procedural modeling with recent developments in the field of historical GIS that has demonstrated the ability to model historical environments using longitudinally linked high-resolution "big data" spatiotemporal data sets (Lafreniere and Gilliland, 2015) and "deep mapping" (Ridge *et al.*, 2013) to recreate historically representative 3D models for an entire industrial landscape over time.

Methodology

Case study

The case study selected for this project is a 130-square-mile area that encompasses the present-day Michigan communities of Houghton, Hancock, Calumet, Laurium, Lake Linden, Hubbell, and Dollar Bay, in addition to numerous small, scattered settlements. Located in the Keweenaw Peninsula, these towns and villages of the historic "Copper Country" comprise a nationally recognized example of the profound and lasting effects of industrialization in a semi-rural landscape. Industrialized copper mining of the region began in the 1840s, and ultimately ceased in the late 1960s. While the area's population today is only 40 percent of its peak (38,784 in 2010 and 95,254 in 1910), the living postindustrial landscape continues to evolve.

Keweenaw National Historical Park (KNHP), established in 1994, is charged with the preservation and interpretation of resources that relate the area's nationally significant story of copper. In addition to the work of KNHP, the Copper Country benefits from the attention of numerous local heritage sites, historical societies, and governing agencies including Isle Royale National Park. Further, there is an astonishing depth and richness of historical documentary evidence in the care of two archival collections, the KNHP Archives and Michigan Technological University Archives. Despite the widespread involvement of an engaged and caring populace, much of the remaining historic fabric is highly endangered due to ongoing depopulation and divestment, and very limited local financial capacity to stabilize or reverse the trend of deindustrialization, blight, and property loss. Furthermore, the area has neither an indexed historical building inventory nor a consolidated repository of historical building data, both of which would serve local and regional heritage conservation and interpretation efforts. This study attempts to digitally preserve a record of the industrial past as well as serve as a tool for the use of local preservation professionals in managing today's cultural landscape.

Copper Country historical spatial data infrastructure

We began construction of our historical spatial data infrastructure, the Copper Country Historical Spatial Data Infrastructure (CCHSDI) in 2015. The CCHSDI applies the concepts of the contemporary SDI to the creation of a big historical data set for use in an HGIS. Using an approach pioneered by Lafreniere and Gilliland (2015), our HSDI consists of a series of high-resolution, longitudinally linked data sets that track changes in the social, economic, and built environments of Michigan's Copper Country from the middle of the nineteenth century to the recent past.

The HSDI incorporates a range of data on the historical built environment, and is designed to ultimately serve as the basis for a publicly accessible clearinghouse of the vast but currently physically dispersed stores of Copper Country historical spatial data. The HSDI presently contains more than 120,000 digitized building footprints, traced to over 1,300 scanned and geo-referenced historical maps of the region. This paper employs a select subset of this HSDI, working with a total of over 48,000 buildings across two years (1917 and 1949) for this longitudinal comparison.

CityEngine

Our HSDI data sets are exceptionally well suited to test the capacity of Esri's 3D modeling software CityEngine to create high-resolution, data-driven, temporally, and spatially accurate models of the industrial mining communities in Michigan's Copper Country. This software is available as a free trial, and both single-use and educational site licenses can be purchased. We used a PC with a quad-core processor running at a clock speed of 4.4 Ghz and a dedicated graphics processing unit to run CityEngine, which exceeds recommended requirements but resulted in extremely rapid modeling – averaging around a 20-second refresh time for a fully rendered landscape of 48,000 structures. Numerous characteristics for each building are recorded in the CC-HSDI, including spatial location, building footprints, civic addressing information, number of stories, exterior finish, and building use.

CityEngine is designed to quickly transform 2D GIS data into 3D models by employing procedural modeling to rapidly generate buildings and landscape features through the implementation of coded rulesets to predefined geometries. The software features dedicated tools for the import of polygonal tax lot or building GIS shapefiles created in ArcMap which are often made available by the local municipalities. We utilize linear roads and pathways from OpenStreetMap (OSM), and digital elevation models (DEMs) from the US Geological Survey to provide the needed topography for our industrial landscape model. The user interface is clear and legible, and the importation of the various data sets is straightforward, as is the application of predefined CGA rulesets. Indeed, learning the basics of CityEngine and its overall functionality is not particularly difficult when hewing closely to Esri's own tutorials, employing associated data sets and rulesets as provided. Furthermore, making parametric changes to model primitives is easy via user-friendly selection palettes that feature drop-down menus of available settings. For our project however, few presets proved directly applicable as most presets are for modern cities rather than the historical industrial environments we aimed to model.

Data import

Virtually every stock step outlined above required some degree of modification to meet our demands in modeling historic industrial landscapes from the generation of the underlying terrain to working with existing street networks and to the writing of historically accurate rulesets. This process required significant iterative learning but did result in a viable product that met our requirements and, while challenging to this novice CGA coder, did not overtax the capacity of the (very flexible) software itself.

Although we are modeling historical data, contemporary digital data could serve the project well as a basis for the construction of our historical data sets, either through simple comparison or more directly through modification. However, the small municipalities (most with less than 1,000 residents) within our semi-rural case study do not have the capacity to produce GIS-ready tax lot or building footprint shapefiles, requiring our team to build the spatial data from scratch. Procuring, scanning, geo-referencing, and digitizing many hundreds of historical maps was itself a significant task.

As noted earlier, CityEngine has a specific and user-friendly interface for the importation of third-party terrain data. For this project, we outlined an area slightly larger than that required to encompass the communities selected for modeling, and downloaded and imported a texture-mapped DEM and contemporary street network of our case study site with just a few clicks. Although we are working with a postindustrial extractive landscape, due to the scale of our subject site we did not elect to modify the DEM for this project. However, because we are modeling historical data specifically, using either the provided contemporary cartography or the high-resolution orthoimagery as a texture for the terrain would invite unnecessary inaccuracy into the model. Instead, we duplicated the grayscale heightmap provided with the DEM download, posterized, and colorized it in Adobe Photoshop, and applied this new texture to the DEM as a gestural topographic overlay emulating a familiar elevation color ramp.

Similarly, the street network imported from OSM is contemporary, not historical. CityEngine again provides easy-to-use tools for the direct creation, deletion, and modification of linear elements that are modeled as roadways when an appropriate CGA ruleset is applied. We did correct the imported street network to more closely approximate historical conditions. Because we built our own historically accurate feature classes for our HSDI, no further modifications to building footprint polygons were required within CityEngine. Both were imported into CityEngine and automatically fitted to the previously imported DEM (Figure 1).

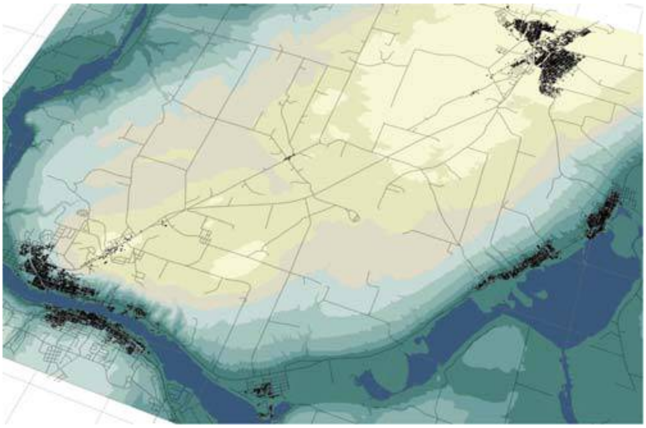

Figure 1.
24,000 imported building footprints and contemporary roadways are aligned to our customized terrain DEM for 1949

Rulesets

The power of procedural modeling lies in its capacity to very quickly generate a large and complex 3D model from a relatively small and simple set of easily modifiable rules. For this project, we required four rulesets: one each for buildings and for roadways, for each study year (1917 and 1949). Each object (polygon or line segment, respectively) is associated through a relational database to key attributes that are called by the CGA coding for 3D expression.

While we began our research by attempting to modify the existing rulesets created by others, we soon determined that writing new CGA script from scratch would result in cleaner, more legible, code and better satisfy our unique demands for a comparative virtual reproduction of the postindustrial landscape of the Copper Country at two points in time. It was our goal to write the script in a fluid manner, with the code designed to readily accommodate predicted modifications. This structuring would allow us to replicate and reuse portions of the code as similar subroutines in the same script (e.g. the code for "lower front wall" is very similar to the code for "upper rear wall"), as well as to duplicate the entire script used to generate one year (1949) for modification and application to our comparative year (1917).

To reiterate, when we created the building footprint shapefiles in ArcMap, we assigned three key variables to each polygon in the attribute table: the building's height, material, and use, as determined from the underlying historical fire insurance plans. Height is a value, recorded as number of stories, and may include a decimal fraction; material is a text string, recorded as either wood, brick, stone, iron, "special," or a combination thereof. Building use, also text, is recorded as dwelling, porch, garage, store, public, or industrial. We designed our buildings ruleset in CityEngine to incorporate all three of these variables in producing the 3D model, using facade material and roof type to illustrate various typologies, and volume – derived from the building footprint and a vertical height extrusion – to indicate massing. Because the few "iron" and "special" buildings present were a fairly even mix of just two (industrial and public) building types, we were able to consolidate these two materials categories and narrow our scope to just 18 combinations requiring CGA scripting (Table I).

In general terms, our buildings CGA script extrudes a footprint vertically in accordance with its height attribute, decomposes the volume into faces, and subdivides the faces into stories. The CGA script then pulls an appropriate texture map from a collection we have assembled (e.g. brick, shiplap siding, and so on) in response to the facade material recorded for that polygon, and applies it to the extruded volume's walls. CityEngine can automatically model a number of familiar roof types (shed, hip, gable, etc.), and our script tops the textured volume with a roof type based on the original polygon's designated use-type. The resulting 3D digital buildings immediately communicate the values of their three key variables clearly and directly (Figure 2).

The imported Open Street Map data retain the attributes of its components; in this project, the crucial variable is the class of roadway assigned to each segment and node. CityEngine recognizes ten different classes by default, but for this project we limited the

Table I.
The 18-material-use combinations that we wrote CGA script for

	Wood	Brick	Stone	Iron	Special
Dwelling	✓	✓	✓		
Auto	✓	✓	✓		
Store	✓	✓	✓		
Industrial	✓	✓	✓		
Public	✓	✓	✓		
Porch	✓				
All types				✓	✓

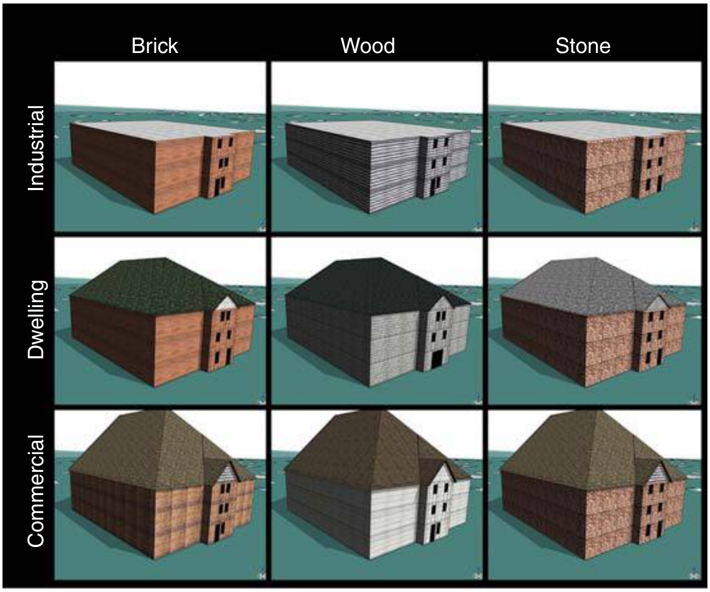

Figure 2.
Nine examples of the three key variable combinations, modeled on the same building footprint

possibilities to just three: residential, secondary, and primary roads. After CityEngine automatically generates road and sidewalk widths based on this attribute, our roadways CGA script – again, as directed by class – extrudes sidewalk height, decomposes the street assembly into faces, and applies appropriate texture maps to each surface.

However, because these subtle differences are difficult to discern visually from a distance, we evolved our roadway modeling to an additional level by introducing object (.obj) files representing plantings and streetlights (downloaded and exported with Trimble Inc.'s SketchUp Pro modeling software) to more clearly articulate street classes. In addition to the surficial texture maps, we employed four lamp types and four planting types to describe the three different classes of roadway in our models (Table II).

We initially wrote both of our CGA scripts (buildings and roadways) to visualize a representative historic streetscape of the Copper Country, as it appeared in 1949. Again, we intentionally wrote our code to be easily modified to model other data years from our HSDI. This provided us the ability to copy the script wholesale, and simply make adjustments to key variables to illustrate our comparative study year, 1917. For both buildings and roadways, we drew upon different sets of surface textures (including the siding of wood buildings and paving patterns) and applied them in different proportions to ensure that we were creating a model that was a better representative of the earlier time period. For the roadways CGA, we called additional object files that were more accurate to 1917, including earlier-style street lights and young street trees; since the entire region was heavily deforested at settlement, any street trees were still small, having just been planted in the early twentieth century (Figure 3).

Discussion

Opportunities

Esri's CityEngine presents a highly useable interface for architects, planners, designers, and researchers to apply the power of procedural modeling to the built environment, and to

Table II.
Textures and objects referenced by our 1949 Roadways CGA script

	Curb texture	Street texture	Street lights	Street trees
1917				
Primary streets	50% concrete 50% sandstone	50% concrete 40% brick 10% wood block	80% acorn style 20% early globe	10% young maple 10% young oak
Secondary streets	70% concrete 30% sandstone	30% concrete 50% brick 20% wood block	30% acorn style	30% young maple 30% young oak
Residential streets	10% concrete	100% earth	50% acorn style	45% young maple 45% young oak 5% mature maple 5% mature oak
1949				
Primary streets	90% concrete 10% sandstone	80% concrete 20% brick	10% acorn style 10% early globe 60% late globe 20% mast arm	10% young maple 10% young oak 10% mature maple 10% mature oak
Secondary streets	70% concrete 30% sandstone	50% concrete 50% brick	30% acorn style 30% late globe 20% mast arm	20% young maple 20% young oak 30% mature maple 30% mature oak
Residential streets	60% concrete	45% concrete 45% asphalt 10% earth	10% acorn style 40% late globe 30% mast arm	5% young maple 5% young oak 45% mature maple 45% mature oak

Figure 3.
The CGA scripting provides a clear and meaningful visual distinction between the 1917 and 1949 roadways

quickly do so at a truly remarkable scale. For comparison purposes, creating simple 3D models of 48,000 imported building polygons using Trimble Inc.'s SketchUp, working at an average rate of 45 seconds per footprint, would take 600 hours; that is 15 weeks of full-time work at an uncomfortably relentless pace. For this proof-of-concept project, we taught ourselves the software and CGA scripting, and built the finished comparative models with a much higher historical accuracy and precision than would a simple SketchUp model in just under 200 hours. The functional and transferrable product can be applied to the other 60,000+ building polygons in our HSDI requiring only minimal additional scripting time to adjust the CGA to reflect temporal differences. Procedural modeling in general, and CityEngine in particular, provides an unparalleled opportunity to quickly and easily visualize big GIS data sets as part of a complete 3D landscape over time.

However, 200 hours is still a considerable commitment to make, and it must be noted here that this requirement would be substantially decreased were we simply creating a single, contemporary city model rather than a pair of historical models of an entire postindustrial landscape. Working with CityEngine on this historical project required the development of a moderately robust understanding of CGA scripting, as the code that was available for our training (and potential use as the basis for subsequent modification) was highly developed for present-day urban applications. However, because of CityEngine's heavy reliance on CGA scripting to produce useful and meaningful output – rather than limiting user-initiated changes to existing preset values, toolsets, and menu options, for example – we were able to adapt the software to meet most of our needs fairly readily.

The degree of customization made possible by writing our own script meant that we were able to employ data directly from our HSDI's building shapefile attribute table, completed long before we had developed an understanding of the working parameters of CityEngine. Writing our own buildings CGA script also meant that we could choose precisely how to combine these data for modeling and display; in particular, to model just 18 of the 30 possible combinations of material and use-type, and to specify graphical distinctions between lower and upper stories and between street facade and other building faces. The benefits of creating our own CGA script was similarly apparent in writing the streetscape rulesets; we selectively incorporated an existing segment of code (to randomize the location of objects) into an otherwise uncomplicated script whose simplicity allowed us to emphasize just those few variables we wished to demonstrate. The inherent flexibility of custom CGA scripting is CityEngine's strongest feature, and offers tremendous opportunities for the 3D visualization and presentation of built environment data.

Challenges

Despite CityEngine's power and adaptability, we did encounter several important challenges in modeling historical landscapes. As noted earlier, there are complexities of representing historical space that are entirely independent of CityEngine, such as procuring or producing accurate historical building footprints, street networks, textures, and objects. Yet the software itself, designed as it is for modeling contemporary urban settings, necessarily makes assumptions that advance efficient user progress towards that goal.

Rule-based modeling such as CityEngine's CGA is applied iteratively to generate successively less symmetrical forms. For example, our buildings CGA script first extrudes a 2D polygon into a 3D massing, which establishes a top side and a bottom side. Second, it divides this volume into stories, and differentiates between the ground floor and any upper floors. Third, our script recognizes the distinction between the front facade and the other faces of these stories. These three rules, applied in order, transform a directionless plane into a three-dimensionally oriented volume that may be textured as (say) a first-floor storefront with walkup apartments above. The crucial step in this triad is nearly invisible, and is the one that bedeviled us in our work: automated recognition of the front facade.

The front of an extruded volume in CityEngine is defined by the "first edge" of its generating polygon; by default, this first edge is the first segment that was originally drawn in ArcMap. Since we created our shapefiles with no forethought of this possibility, the first edges are essentially random – meaning our rendered buildings would have no coherent orientation. The first edge of each polygon can be reset manually without difficulty, but doing so would obviously be extremely time-consuming. Because this is a predictably common possibility for shapefile imports, CityEngine provides a dedicated tool that automatically reassigns the first edge as that edge closest to the nearest street (Figure 4).

While this automated command can save quite a lot of time, it is designed to work with single-polygon buildings with a primary street face – which the contemporary urban landscape largely consists of. However, in following our research design in creating the HSDI, we had drafted our historical building footprints as multiple polygons, subdividing a single building into its varied parts for the purposes of documenting substantial additions or modifications to buildings over time (i.e. the enclosure of porches or the additions of garages or workspaces). Furthermore, much of our built historical landscape is simply not oriented toward a common roadway; many industrial buildings are sited facing waterways or railroads, and the rapidly established and densely inhabited residential areas frequently contain numerous small dwellings that are approached not by the main road but by alleyways or even footpaths.

The second of these two challenges can be most directly addressed by faithfully recreating the critical elements of the historical transportation network (including railways, alleys, and pedestrian paths) before its import into CityEngine; the automated first edge reassignment would be more accurate, and the rendered volumes require less subsequent manual correction. While this solution also provides the added benefit of resulting in an even more detailed and accurate recreation of the historical industrial landscape, it does not solve the first problem – our use of multiple polygons to represent a single building. Many of the buildings in our case study site feature multiple additions, a common practice in rapidly changing localities, such as rapidly industrializing landscapes. CityEngine automatically models shed roofs with the low eave at the first edge, and gable roofs with the ridge parallel the longest axis of the root polygon (Figure 5). Again, while these assumptions may work

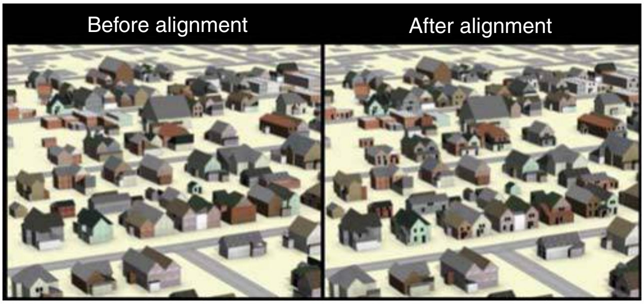

Figure 4.
Note the randomized entry façade orientation before (left) and after (right) executing automated alignment command

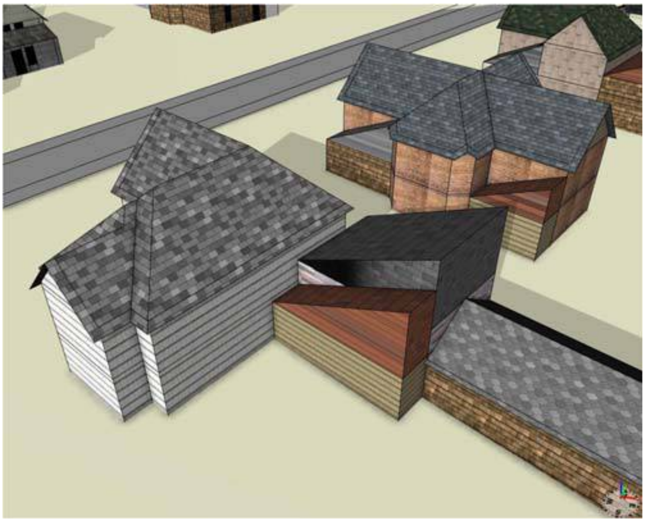

Figure 5.
Automated roof development modeling errors

Note: Stock CGA script orients sheds from the primary face as described by street proximity quite well in for single-polygon building footprints in a contemporary urban setting with a strong primary axis, they result in pronounced modeling errors for clusters of polygons representing historic building elements that serve a diversity of orientations.

Of course, these challenges can be surmounted through fine-grained, manual modification, and doing so would not be an inappropriate part of final model cleanup of even a few hundred building footprints. However, doing so mitigates much of the efficiencies of this procedural modeling approach. CityEngine, as its name clearly suggests, preferences the automated modeling of the urban landscape, not the rural industrial landscape; it relies heavily, and stubbornly, on the presence of road networks to determine building orientation. Finally, like all evolving digital technologies, the ongoing usability of the code written today depends on maintenance and adjustment for it to continue to be useful tomorrow. Despite these challenges, the power of CityEngine and the flexibility of CGA scripting offers new and unparalleled opportunities for heritage management and interpretation.

CityEngine for heritage management

Harnessing CityEngine to HESA Lab's CC-HSDI data sets holds great promise for advancing the public education and preservation goals of the many local heritage sites, historical societies, municipalities, and governing agencies engaged in the conservation and interpretation of the Keweenaw Peninsula's historic industrial landscape. Historically, this industrial landscape was woven together in a vast network of functionally interconnected buildings, structures, and sites. Much of the earliest activity on the historic industrial landscape been superseded by more recent construction, and much else has fallen to decay or been deliberately removed; today's landscape retains evidence of those systems largely as little more than isolated nodes and broken paths. Still, even remnants of this history confer meaning to the contemporary postindustrial landscape, if their message can be heard.

While the sparse historic remains scattered across today's descendant landscape may be understandably overlooked by heritage professionals seeking to relate a compact and coherent story, they are nevertheless significant. These vernacularly preserved remnants were once vital components of now largely vanished landscape scale industrial mechanisms for the extraction, refinement, and movement of copper; furthermore, many of these vestiges have compelling stories to tell about their material and functional evolution over time (Arnold and Lafreniere, 2017). Importantly, neither component significance nor evolutionary significance is necessarily visible at the scale of any single building or at any single time period. To understand the historical meaning of those remnants populating today's postindustrial landscape, it is crucial to situate them within their greater spatiotemporal context. The perspective provided by a longitudinal landscape study such as this provides a useful and much-needed viewpoint for historians, planners, and preservationists to evaluate and prioritize historical properties for the targeted application of always-limited human and financial resources for historic preservation.

Whatever significance or value may be ascribed to the remnants of the Copper Country's industrial past, it is simply not feasible – and perhaps not even desirable – to physically preserve everything. It is, however, possible to do so digitally, in a manner of speaking. That is, while digital recreations of historical buildings or past environments cannot replace the original material evidence, they can supplement and expand upon that which remains, both over space and across time. Working at a landscape scale means that we exchange a focus on individual character and fine-grained architectural detail for an aggregate perspective and a broad and collective overview of spatial relationships that integrate the built world and the natural. Working on a timeline spanning a century means that we trade daily narratives of work and rest for generational transformations of space and place. CityEngine provides the opportunity to do both well, to the ultimate benefit of the people and heritage of Michigan's Copper Country.

Future applications and next steps

All additives to the CityEngine model can be refined independently: the terrain, the roadways, the buildings shapefile, and its associated attribute table, and of course the rulesets themselves. This structural autonomy means that the overall model can be evolved iteratively, as more or better data is developed or discovered. In a real and important sense, the 3D model is nothing more than data visualization – this visible output is the product of its constituents, and a better model can be produced by the improvement any of its factors.

Conceptually, it is critical to consider CityEngine not as recreating a replica of the historic industrial landscape, but rather producing a useful abstraction: in essence, a 3D data-rich map. In the present study, we are visualizing historical map data of our subject area at two points in time, displayed as moderately realistic texture-mapped volumes that express our selected attributes. CityEngine's CGA scripting can easily be written to produce output at various levels of detail depending on the purpose, audience, and the way that users will access the model.

In the future, there will be opportunities to use CityEngine to graphically represent aspects of our ever-growing HSDI that are not actually manifest in the built world, while retaining the spatial relationships established therein. For example, using employment data records and the decennial census linked to building footprints, we will be able to visualize non-architectural social attributes in a three-dimensional landscape, similar to how cartographers use proportional symbology in 2D maps. Imagine that a building's height represents the level of income or wealth of the homeowner, while the envelope texture could indicate ethnicity, and the roof color the housing tenure status (rent vs own). This technique was suggested by Lafreniere and Gilliland (2015) to model the social environment of a nineteenth-century journey to work. Furthermore, the software holds promise for spatiotemporal data visualization of even more abstract paradata, which could act as a kind of primitive or introductory version of the "complex object" as detailed by Bonnett *et al.* (2016). The whole of the Copper Country's population for which we have employment data might be displayed, across a century of continuous and sometimes dramatic social change.

Currently, there are a number of refinements that can be made to our current models. Our terrain, while a fair approximation of the historical landscape, is not truly accurate to either the 1917 or the 1949 landscape. The waterways in particular were demonstrably altered by the addition of millions of cubic meters of mine waste over the decades, and the DEM will be adjusted to demonstrate this. Similarly, our texture map for the terrain graphically illustrates elevation change, but the color fields do not tightly correspond to numerically meaningful contour lines; we will soon create a more accurate and useful cartographic overlay for our terrain model.

Furthermore, as we continue to grow our HSDI and incorporate new information from additional sources, we will extend and rework the CGA scripting to take advantage of the increasing abundance of our available data sets. For example, while we can currently model with confidence the location and basic massing of various tracts of worker housing, the assigned roof types are merely approximate. However, once we ingest mining company housing data into the HSDI, we will likely learn the actual roof types, original finish siding, and paint colors used, and edit our script to increase the visual accuracy of our model. This iterative refinement of the model can be continued indefinitely, bounded only by available data and time.

Conclusions

We will continue to model our high-resolution spatiotemporal data sets as they evolve over time. Historical GIS generally, and our HSDI specifically, offers an unparalleled opportunity to consolidate historical information spatially, and CityEngine provides a currently underutilized capacity to visualize these big historical data sets. Landscape visualization at the scales we are exploring – both spatial and temporal – can benefit not only academics and researchers, but to the public as well, presenting high-quality historical geographical interpretive and educational opportunities.

The historic industrial landscape of Michigan's Keweenaw Peninsula has been studied extensively (Gohman, 2013; Hoagland, 2010; Lankton, 2010; Martin, 1999; Quivik, 2007; Scarlett, 2014) and much of it is the fortunate ward of numerous local heritage sites, historical societies, and administrative entities working to protect and share its rich history (Liesch, 2014; See, 2013). Many of these studies and those in other, similarly dynamic historic landscapes would benefit from the addition of 3D data visualizations; the robust and flexible CGA code developed here is modifiable and applicable to a diversity of historic landscapes. Much of what remains of the industrial past in the Copper Country is only coherent at the landscape scale, and is only significant when understood as the evolutionary phases of a great historical narrative.

It should be emphasized that CityEngine, as a sophisticated and highly customizable software package, requires dedicated and focused commitment to master. It requires a high level of computer literacy and experience with basic programming to implement as demonstrated in this paper, and the licensing fees are not inconsequential. However, given its power and versatility, it is well worth these costs, especially for planning organizations responsible for heritage landscapes, districts, or any site where the focus is expanded beyond a single resource. When working at these large scales, fostering a holistic understanding of a historical resource's temporospatial context can assist in the often-difficult processes of evaluating the National Register qualities of significance and integrity of remnant buildings, structures, and sites, and how to best allocate always-limited human and capital resources.

The broad spatiotemporal overview provided by this longitudinal landscape study offers an additional evaluative tool for heritage professionals, including historians, planners, and preservationists to study the changing industrial landscape and assist in informed, prioritized decision-making. Understanding the industrial vestiges as remnants of once vast and vital industrial networks – of materials, of people, of energy, and of waste – will further illuminate the meaning and importance of that which remains. Authorship of National Register nominations for a variety of features in the contemporary postindustrial landscape would be directly served by these 3D data visualizations, both in terms of demonstrating the association of a property with significant historical events, as well as investigating and communicating its integrity of setting. The exploration and interpretation of these important places is strengthened through the use of CityEngine and 3D spatiotemporal data visualization, and will benefit both the people and places of the historic industrial landscape that has evolved into today's Copper Country well into the future.

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