More Than One Twin:
An Ecology of Model Applications in East London*

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20th October 2021

Abstract

There is considerable ambiguity about the term 'digital twin' which is used to portray a digital model of a real system where the twin and its system interact with one another. Such interaction enables the twin to contribute to the operation and performance of the real system while the real system provides processes that enable the twin to come closer to the system itself. In this way, a two-way dependence augments both and provides a framework for control, management and design that is better than keeping the model and system separate. The problem of digital twining is that were the twin to be an identical copy of the real system with digital replacing physical components, in the last analysis, it would be the same. Moreover in practice many different models, hence twins, exist, and the focus then becomes how twins are linked to one another, thus forming an ecology of digital model applications. We illustrate these ideas by describing three very different applications in East London using data from the Olympic Park area where there is a rich constellation of entertainment, recreational, and educational activities. We introduce a land-use transport model that predicts activities at different locations, a three-dimensional (3D) model using virtual realities which are augmented by adding mobile data associated with the objects' functioning, sometimes moving in time, and a building complex in which we have planted a network of sensors enabling us to monitor its performance. These three examples are clearly different from one another but they are all based on the same physical area. We thus conclude by sketching ways in which these twins can be linked to one another and how the idea of the twin is linked to its users in the wider context.

*To be published in: Li Wan, Timea Nochta, Junqing Tang & Jennifer Schooling (Editors) (2022) *Digital Twins for Smart Cities – Conceptualization, Challenges & Practices*, Institution of Civil Engineers, London.

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A Cornucopia of Digital Twins

Digital twins are essentially computer models of real systems that not only simulate their functioning but interact with a real system so that it can be managed, designed, and operated to achieve its basic purpose. Such twins are organised like any model to mirror the dynamics of the real system and there is a general consensus that a good digital twin is ‘as close as possible’ to the system itself. This is to enable the twin to interact with the real system forming a synergy that augments its functioning in various ways. The twin monitors and can change the real system while the system can learn and improve its own functioning from the twin. The basic conundrum, of course, is that the closer the real system and the twin come to one another, the closer they are to ‘merger’. But as the twin is composed of digital media , it can never replace the physical components of what is being modelled, what is being twinned.

There is an important debate about whether or not a twin can be a model using the usual definition of a model as a simplification or abstraction of the real thing (Batty, 2018). Any simpflication of course cannot be the same as the real thing and this suggests that a digital twin can never be a model. But a twin can never merge either with the real thing and this inherent contradiction simply limits the power of language in thinking about models. In fact, the power of the digital twin is the way it evokes the idea that the virtual and the real world are able to interact with one another, while always remaining separate. In some senses, it is possible to think of the twin as virtual copy or mirror of the real thing in the sense first suggested by Gelernter (1993) and related to virtual city models by Dawkins (2017). Just as there can be more than one model of a real system, there can be more than one digital twin and this complicates the notion even further. It is thus possible to have strings of digital twins that mirror one another in different ways all relating to a particular system which is the focus of twinning (Hudson-Smith et al., 2008).

The other key issue is the extent to which the real system is physical. Strictly the concept of twinning links one media with another, one tangible and the other virtual, but there are many if not most systems that are not entirely physical. As soon as humans enter the process, in operating the system for example, then the system is no longer physical in the classical sense and elements of human behaviour begin to creep in. In fact when it comes to city systems, there is a very strong schizophrenia between cities as sets of physical objects and cities as systems of human behaviour. Their design and planning usually involves both but many of their elements are ill-defined and there are often several different models of their form. In this sense, they are non-physical models in that they describe how people behave and are thus not easy to link to the real system which may be physical but is often not articulated as such. In this chapter, we will focus on one location and examine several different models of and at that location, that is, different twins that can be related to one another but have different degrees and/or types of interaction with the real place and its activities.

The term digital twin came from thinking about how digital models could replicate manufacturing production whose physical elements are sufficiently close to computable processes that very good models of such functionality could be built. These models – twins – did not need to embrace any qualitative understanding and in many senses represent one-to-one virtual equivalents of the real thing. It was Grieves (2014, 2003) who seems to have been the first to coin the term and he was very clear in his definition that a digital twin is a “virtual, digital equivalent to a physical product”. This seems to rule out many socio-economic systems, or even physical systems that involve human operations. But as we will argue here, it is virtually impossible to separate the sorts of digital twins that pertain to the physical elements of the city from more abstract conceptions of cities which originate from human behaviours across many scales. As we develop our argument, we will demonstrate that even though the idea of the digital twin is ambiguous and blurs into many other representations, it represents a powerful concept. It is able to show how we can build dramatic improvements into our models of cities for increasing our understanding and producing better informed speculations about their future in terms of our predictions and prescriptions.

How A System and Its Model Are Twinned

The core requirements of a digital twin reflect the connections that the twin has with the system that it is linked to. A perfect twin would be one in which every part of the original system were some digital element of the equivalent physical component so that there was a one-to-one correspondence between each. However any physical system also contains relations between its own physical components that are integral to its functioning and these too must be replicated within its model for it to be considered a twin. To an extent, the system and its twin are identical except for the media in which they are embodied – that is, their physical materialism versus their digital representation. This still does not define the way the system and its twin connect to one another but it is easy to see that if this perfect correspondence exists, then simply by associating the components of the original system with those of its twin, then one can study the properties of the twin without worrying about interacting with the physical system itself. This of course is the logic that has surrounded the use of computers to model human systems for many years where experimentation on the virtual system replaces experimentation on the actual system, due to ethical as well as organisational limitations.

A very simple example of this is a basic mechanical engine that is used to power a system whose parts involve movement of some kind which enables work to take place. The components of a steam engine, for example, involve burning some fuel (the energy source) that creates steam that is then cooled to create pressure that controls the parts that move the object in question. Each of these has an equivalent that can be represented virtually and if it was required to control the parts in some other way via digital means, then this could be done by developing a control mechanism within the twin. In this way, the real system might be managed coupling a digital controller to the mechanical device. In a similar way, the digital twin might be controlled from the mechanical device. In fact, for the most part the coupling is never as tightly controlled as in this simple example. Usually there are many human interventions that control such processes of coupling. In this sense then, although the twin interacts with the real system, there is a good deal of room for discretion on the part of how the human operator (or model-builder) acts to manage the system. Thus the interaction is usually much looser.

We have already noted that there might be many different models of the same system and in this sense, there can be many digital twins, in fact an ecology of digital twins as Enzer et al. (2020) have characterised. To some extent, this is also a contradiction in that if a twin is designed to be as close as possible to a system, then the implication is that there is only one twin. However as soon as we broach the idea of many or multiple twins, then the power of language breaks down. We begin to think of triplets, quadruplets, quintuplets and so on; and then we begin to think about a twin of a twin of a twin, and so on. In fact, we can even think of sequences which are dependent on how many models are sequenced in causal chains or loops as the system and its twin, and then another twin which makes the sequence a triple and so on. The possibilities are endless (Waern, 2021). This is particularly relevant when we focus on some particular place and begin to think about the variety of models and theories that pertain to its understanding, for then there are many different models that can be built. In fact, if we accept the pragmatic stance that there can never be a definitive or unique digital twin, then any twin will contain parameters that can be manipulated or tuned, suggesting that these variants are different from one another. We will not develop such variants here for our twins of the same place will be quite different from simple variations on one model with respect to its parameter values. In fact, we will introduce models that are based on different scales of the same place and in this sense, our focus is on a much wider set of twins than is implied in terms of a particular twin getting closer to a single system. Our real systems in this sense will be based on different realisations of the real thing which are constituted from different theoretical, disciplinary, and professional perspectives.

Multiple Models of Single Locations

In 1964, the geographer Brian Berry introduced a particularly simple representation of location which he defined in terms of three dimensions – *space*, *time* and their characteristics which we call here *sectors* – and this trio has come to dominate discussion of how we might model the built and indeed natural environment ever since. In fact his representation is a 'data cube' which in fact has appeared in many other contexts since then. If we pick any location, then we can describe it in Berry's terms as follows. The *space* at a location reflects its scale and this focuses on the resolution of the place in question. It might be an area as large as a country or as small as a building or even the point at which an individual or some other object with near zero dimension locates. Its density thus depends on the extent of this location. *Time* reflects the particular cross section or sequence thereof that describes the actual time at which the system is observed and can embrace its temporal dynamics, while *sector* pertains to the features and attributes that describe the location. For example, a building and its components can be geo-coded to fix their location, the time at which the building is being constructed, and the processes involved in its maintenance which define its functioning; its characteristics or sectors relate to the activities that take place in the building and define its purpose. These three dimensions blur into one another and can be expanded in countless ways but in terms of the examples of digital twins that we develop here, they suffice to make the requisite distinctions between each.

We will choose a particularly diverse location to illustrate three rather different digital twins pointing out the way they might be connected to the real systems of interest. The general location is in east London at the Olympic Games Park in Stratford which is some 6 miles east of the financial quarter in the City. This is essentially an area of intense urban regeneration which we will model in three ways: first we will build an urban land-use transportation model to examine the locational potential of the area around the Olympic Park for residential and educational development using well-developed and established methods for primarily simulating the effects of transportation on location (Yin et al., 2022). Second we will describe the urban form of this area using a 3D rendition of the area into which we have embedded real time data pertaining to movement on local transport; and third we will take one of the buildings in the area – **HE** (**H**ere **E**ast) – which is an academic and training centre which we are currently wiring with various sensors so that we might monitor its performance. Each of these examples represents very different characteristics of the location, developed for rather different purposes but each represent an important perspective on the location itself. In fact, we might even argue that these three 'twins' or 'models' are simply the tip of the iceberg when it comes to developing such models for any single location; in short there are multiple models that can be developed for any location and the way in which these are linked represents an important research dimension in itself.

We will not explore in any detail how these three types of model can be linked together for our purpose is to illustrate their variety and how they might be connected to the real systems, which consist of activities that define the place itself. As we will show, the twins can be linked to one another through the way they are each connected to their real system of interest but there are multiple ways in which this can be done and thus what we will show represents a new direction which we would argue is essential to exploring the way an ecosystem of digital twins might be developed. The models that we have built for this area were not designed to interface or link with one another for they were built by different researchers at different times. But they are very typical of how any location has multiple representations that lead to models that can be used for a multitude of purposes in urban planning, design and management as well as for the operation of the very systems that define how buildings and cities function. The various purposes which these models are designed to inform open the door to ways in which they might be connected to each other as well as to the real systems that they attempt to twin.

The three models deal with three related scales that are nested from the largest extent, from the districts that comprise east London down to the Olympic Park itself and then to the particular building in question, **HE**. This reflects a disaggregation of activities that illustrate how cities are conceived from the top down as well as the bottom up. The first models that we will explore are those that simulate how aggregates of employment in small areas of roughly 2 to 3 square kilometres interact with similar aggregates of residential population through flows such as the journey to work, school, shop and so on. These enable us to make predictions about how much activity is able to locate in different places, in the case of the models here, across the Olympic Park area. This includes ‘Westfield East’, a major regional shopping centre, several entertainment zones based on facilities provided for the Olympics and a new higher education hub based around University College London East but also including “ … the University of the Arts in London’s (UAL) College of Fashion, a mid-scale dance theatre for Sadler’s Wells, and two new Victoria & Albert Museum sites on the Stratford Waterfront including a partnership with the Smithsonian Institution. The project will be the most significant single investment in London’s culture since the legacy of the 1851 Great Exhibition ...”, says the Mayor Sadiq Kahn[1].

This model which is called **QUANT** (**Q**uantitative **U**rban **AN**aly**T**ics) which has been under development for several years in different forms is essentially non-physical dealing with zones of different land use. To an extent, these are abstracted from the buildings and other infrastructure layers that compose the area at the physical scale. These models simulate aggregates in a statistical sense which are sometimes based on social physics but when disaggregated embrace individual populations, often called agent-based models, that embody specific behaviours associated with the human scale. It is in the same tradition as that developed for the Digital Twin of Cambridge and the West Cambridge Campus[2] which is being developed under the auspices of Centre for Digital Built Britain (Lu et al., 2020)

Our second approach involves much the same scale as in our land use transportation modelling with respect to the east London location. But this second model represents the city in physical terms, at the level of building blocks and communications infrastructure relating to other phenomena such as pollution, weather, traffic congestion, and so on. The **ViLo** (**Vi**rtual

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[1] https://www.queenelizabetholympicpark.co.uk/news/news-articles/2019/07/mayor-breaks-ground-on-new-culture-and-education-powerhouse

[2] https://www.cdbb.cam.ac.uk/news/research-profile-west-cambridge-digital-twin-facility and https://www.cdbb.cam.ac.uk/news/publication-final-report-local-governance-digital-technology-implications-city-scale-digital

London) model is a 3D representation of all buildings and physical assets at the scale of block models of the objects in question. The blocks are not detailed; they are not rendered nor do that contain any of the physical assets that define a building and in many respects, these simply act as 3D filing cabinet or data-base for a multitude of attributes. With this representation, we are able to add or change buildings very easily, and we are able to add transport links for the model is web-based and can access real time data such as that pertaining to movement. All the locational elements can be tagged from surfaces which are interpolated from physically diffusive data such as pollution. **ViLo** is much easier than **QUANT** to disseminate with respect to the visualisation of future scenarios and although both these models can be used in public participation, **QUANT** is more likely to be useful to technical experts whereas **ViLo** is more suited to a non-expert public.

Our third twin takes the scale down physically to the building itself (or possibly the building complex when a group of buildings are designed and/or function together). The building **HE** (**H**ere **E**ast) is " … an innovation and technology campus situated in the Olympic Park in Hackney, East London. The former Olympic Media Centre was left in the wake of the 2012 Games, and in 2014 was reinvented, courtesy of a privately funded, £120m regeneration project. Today, the architectural masterstroke unites culture, enterprise, entrepreneurship and education under one roof, whether the focus is dance, digital technology or game development."[3] This was not a wired building when it was first constructed but our group in CASA-UCL has been planting sensors in the space so that various key performance indicators pertaining to the operation of the building, particularly with respect to energy, can be captured. In fact, the sensing operations and infrastructure enable a stripped down building information model (BIM)[4] to be constructed. This can be used in much the same way as one can use **ViLo**, where it is possible to change the elements that define the building – its component parts as well as the human activities that define what goes on there – so that its performance, liveability and sustainability can be improved and optimised.

*Aggregate Location Modelling Using **QUANT***

We will not present our various models in the sort of detail that a reader might wish if they were to implement the models for themselves in different locations although we will point to online resources that may help take our descriptions here little further. We have been building land-use transportation models of the London metropolitan region for two decades or more and in 2012 we explored the impact of a new high speed subway line across London connecting Heathrow airport in the west, through the centre connecting up to the Olympic Park, and thence east, beyond to Shenfield which is on the edge of Greater London. We have used these models to simulate and predict the impacts of new transportation proposals as well as new locations for population and employment, and in particular the development of new housing and the attraction of new employment to the Olympic site has been a major goal of development there ever since the Olympics was held in 2012. In fact the wider area was chosen largely for its potential for regeneration.

The model originally called **SIMULACRA** (Batty et al., 2013) which divides Greater London into 633 zones (based on political wards) is able to simulate the impact of the new high speed line across London focussed on the Olympic site. If you click on the footnote (number 5), then

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[3] https://hereeast.com/about/

[4] BIM – Building Information Model: https://en.wikipedia.org/wiki/Building_information_modeling

you can access a short movie that gives you some sense of how the model works and what it predicts[5]. We first show the distribution of population and the link between employment and population across London in Figure 1(a) which illustrates the pattern of employment location and the location of the Olympic site with respect to the flows to all other residential areas in London. Figure 1(b) shows the Crossrail link and Figure 1(c) the same link but related to the pattern of employment accessibility on the subway (tube) in London. Note the lower accessibility in the centre of the city due to the congestion charge. The last illustration in Figure 1(d) shows the location of employment in blue and associated population in red. In essence, the purpose of the model is to predict how successfully the new employment at the Olympic site retains its population of workers to live near the Park rather than using the fast new tube line to 'escape' to other locations in London. A summary of these issues is given in Batty (2012). The connection between this model and the real system is quite abstract but it is clear that this sort of tool is twinned with the wider strategic plans that cover the area of the Olympic Park. This links the wider London Plan to the various local plans and master plans that bring a wide variety of stakeholders together to debate the best locations for new activities.

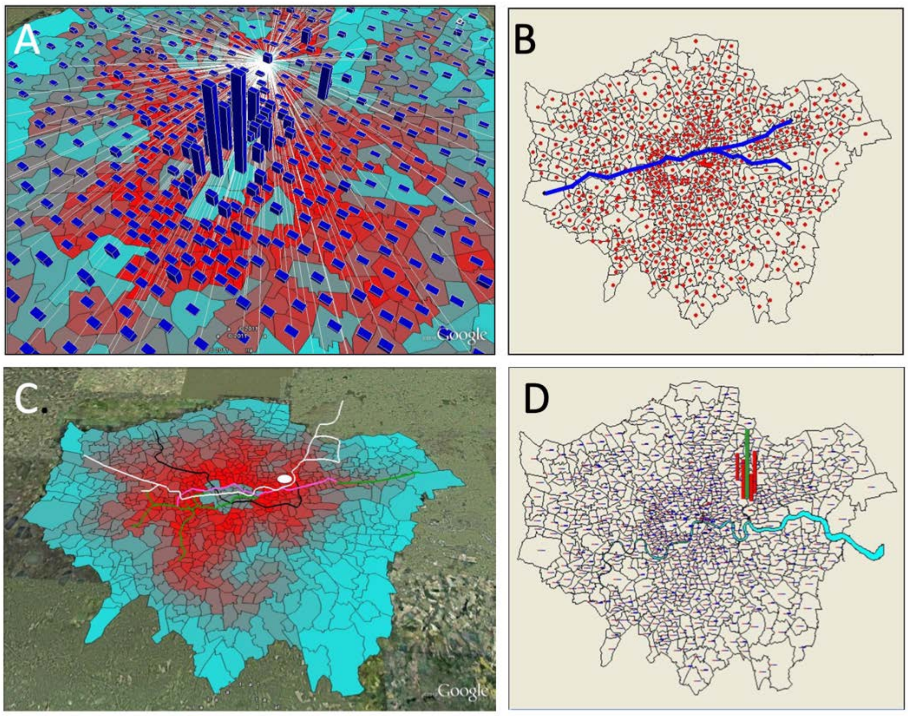

Figure 1: The Impact of Crossrail on the Olympic Park

A) Employment and Population in Greater London B) Crossrail C) Rail Accessibility and the Olympic Park D) New Housing and Employment In the Stratford Area

This model was developed prior to the national model we have built. The later model **QUANT** scales these functions up to the level of the nation, in fact to England, Scotland and Wales, based on the premise that many of the major infrastructure changes and plans have much wider repercussions than simply on the local area where they are located. For example we can see from Figure 1 that the implications of locating activities at the Olympic site go much wider than the site itself and the impact of Crossrail for example, spreads out across the rail network

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[5] A movie showing a simple sequence of operations in the **SIMULACRA** (**S**trategic **I**ntegrated **M**odel for **U**rban **La**nd, **C**ommercial and **R**esidential **A**ctivity) desktop model: http://www.casa.ucl.ac.uk/movies-weblog/TYndallLUTImovie.mov

in the whole of great Britain. We show this in our summary of the detailed model in Batty and Milton (2021). A movie explaining the model can be downloaded from footnote (number 6)[6] and the model itself can be run online at http://quant.casa.ucl.ac.uk/.

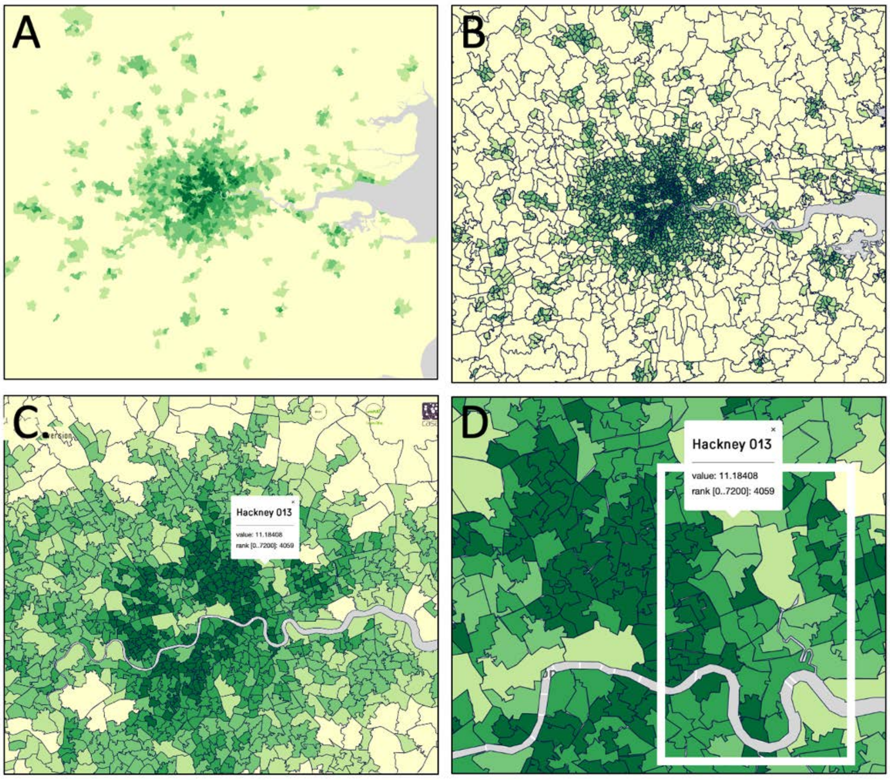

Figure 2: Zooming in on the Olympic Park

A) Population Density in the Wider London Region B) The GLA Area C) Hackney East London D) The Olympic Park Area

The predictions from this model which capture nationwide repercussions goes much wider than our London model. The Olympic Park is a national location which has had ploughed into it massive investment and it is designed not merely for local regeneration but as national venue for many educational and recreational activities as well as for new housing. In Figure 2, we show output from the **QUANT** model that scales down from the southeast into the Stratford area which we visualise in more detail in Figure 3. The location is in fact on the western side of the eastern Greenbelt and in fact follows the River Lee which is the biggest tributary of the River Thames in London. This provides the open floodplain land in a location needed to locate various sites of national importance. The location of the area which is immediately east of the City lies in its shadow but to regenerate the area, the **QUANT** model illustrates how we can take different combinations of jobs and populations and manipulate them to generate various win-win situations that will depend on how various locations might interact with one another. Figure 3 implies that the cluster of new facilities within the City's shadow has the potential to regenerate the area but to explore this completely requires many more models than the land-use transportation model presented here.

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[6] A movie of **QUANT** at https://www.youtube.com/watch?v=fVJ-l5MAXS8. You can run **QUANT** for yourself at http://quant.casa.ucl.ac.uk/

These models are largely spatial rather than physical but there are many other models of the same kind that need to inform regeneration in this area. There are spatial economic models of various sorts, retail models, housing market models, land development methods such as those involving geodesign, and demographic models. These models can be developed in cross sectional or dynamic form. They can deal with aggregates or disaggregate realisations of different scales of the Olympic site area, where transport can be in aggregate flow terms or in disaggregate agent-based form. The list of possibilities is endless and these all represent different perspectives on any place or set of places. Multiple models, to an extent, undermine the idea that there are a very limited number of digital twins and the challenges that we will pose in the rest of this chapter involve ways in which one can work creatively with an ecology of digital twins that consist of multiple models at different spatial, temporal and sectoral scales. Our next model illustrates another perspective on this question.

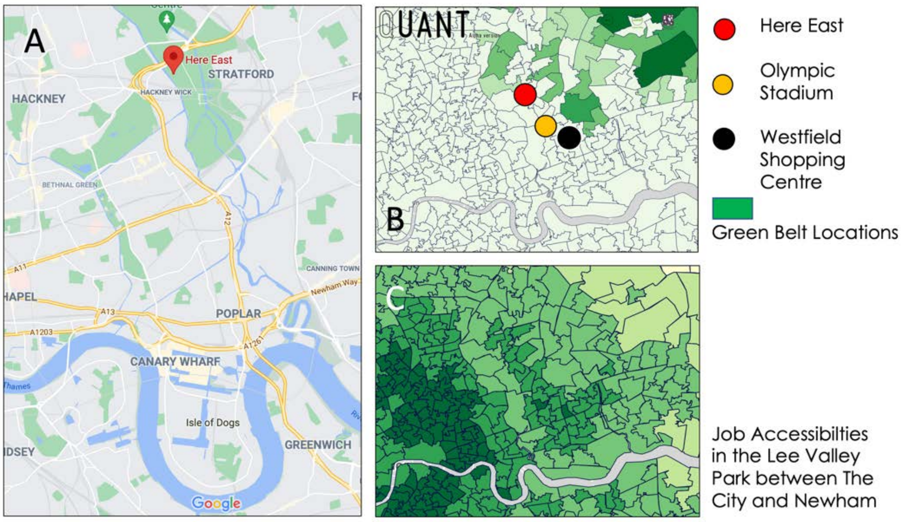

Figure 3: Local Facilities in the Olympic Park

A) left: The Morphology of the Area B) The Green belt and the Location of Here East, the Olympic Stadium and the Westfield Retail Centre C) Job Accessibility in East London, Noting the Lee Valley

Visual Modelling Using **ViLo**

Although **ViLo** is a 3D model of East London which is extensible to the entire city, we refer to this as a platform rather than a model or twin in that we use the platform to engage in experimentation where the user can be both the modeller and the stakeholder. We have built a very fluid interace between user and model which enables a rich set of experiences in thinking about the future city and ways of exploring what this might be like. The platform enables visualisation of both real-time and offline spatio-temporal data sets in a digital, three-dimensional representation of the urban environment. The platform uses both OpenStreetMap data and the MapBox API for the creation of the digital environment. It enables us to visualise the precise locations of buildings, trees and various other urban amenities on a high resolution digital terrain model. The buildings, which are generated at runtime from OpenStreetMap data, retain their original identifiers so that they can be queried for semantic descriptions of their properties. **ViLo** can also visualise customised spatio-temporal data sets provided by the user in various file formats. Custom 3D models can be provided for landmarks and it is possible to switch from the OpenStreetMap generated geometries to a higher detailed CityGML model of the district at the scale of Level of Detail 2.

Dynamic data sets stored in CSV file format can also be visualised alongside real-time feeds. A specific emphasis has been placed on the visualisation of mobility data sets. Using Transport for London's APIs, **ViLo** has the capability to retrieve and visualise the location of bike sharing docks and the availability of bikes along with the entire bus and tube networks including the locations of bus stops and tube stations along with the position of buses and trains updated in real-time. The **ViLo** platform also integrates real-time weather information from Wunderground's API, a three dimensional visualisation of Flickr photos relating to points of interest, and a walking route planner for predefined locations using MapBox API.

An innovative aspect of the **ViLo** project is the possibility of conducting real time urban analysis using the various data sets loaded into the digital environment. At the current stage it is possible to conduct two-dimensional and three-dimensional visibility analysis (intervisibility; area and perimeter of the visible surfaces; maximum, minimum and average distance; compactness, convexity and concavity). While originally conceived as part of an effort to visualise London in 3D, the **ViLo** platform can be used to visualise any urban area across the globe. The first version of the platform demonstrated here focuses on visualising the Olympic Park in East London, and surrounding area as the illustrations in Figure 4 demonstrate.

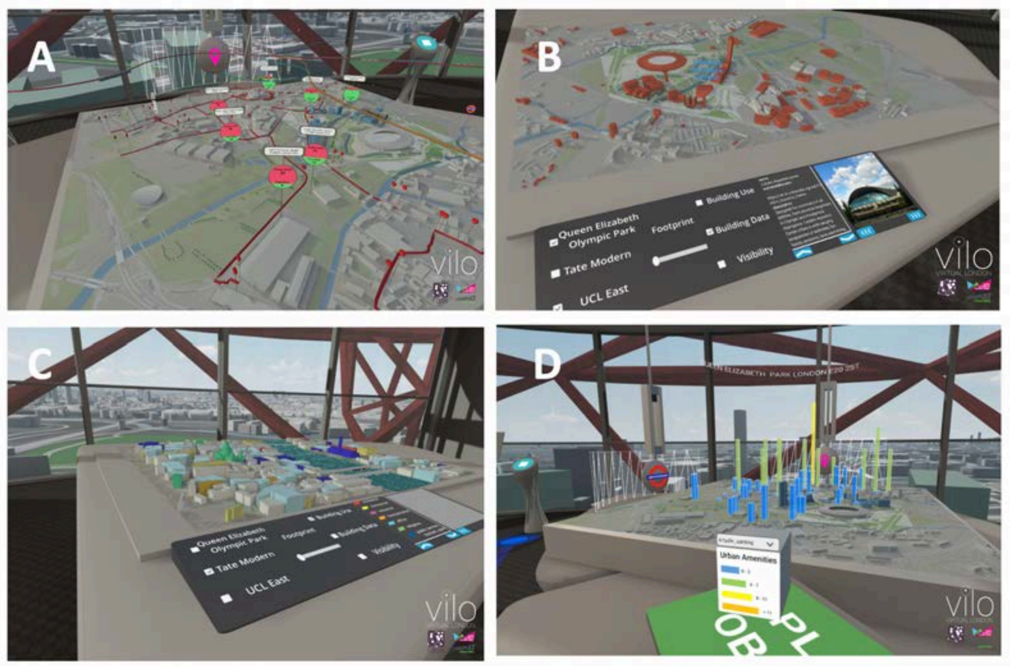

Figure 4: ViLo: Virtual London

A) Detailed Facilities B) Identifying Key Buildings Through the Interface C) The Urban Landscape D) Locating Different Facilities within the Virtual Environment

Using virtual reality technologies such as the HTC Vive, we can create data rich virtual environments in which users can freely interact with digital representations of urban spaces. In this demonstration we invite users to enter a virtual representation of the ArcelorMittal Orbit tower, a landmark tower located in the Olympic Park[7]. Using **ViLo**, it is possible to recursively embed 3D models of the surrounding district within that scene. These models can be digitally coupled to the actual locations they represent through the incorporation of real-time data feeds.

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[7] There are a number of visualisations of the **ViLo** platform on the Virtualarchitectures Blog, the most general of which can be accessed here https://virtualarchitectures.wordpress.com/2017/09/18/*vilo*-and-the-future-of-planning/ which is at ***YouTube*** https://www.youtube.com/watch?v=6OrwitlvOxk

In this way events occurring in the actual environment, the arrival and departure of buses and trains for example, are immediately represented within the virtual environment in real-time. We imply some of these in Figure 5. VR is a technology which typically uses a head mounted display to immerse the user in a three dimensional, computer-generated environment, regularly referred to as a 'virtual environment'. In this case the virtual environment is a recreation of the viewing gallery at the top of the ArcelorMittal Orbit tower, situated at the Olympic Park in East London. The **ViLo** platform is then used to embed further interactive 3D models and data visualisations within that virtual environment. The footnote (number 8) accesses two movies that illustrate all this content and the way a user can explore the virtual and augmented environments that have been constructed.[8]

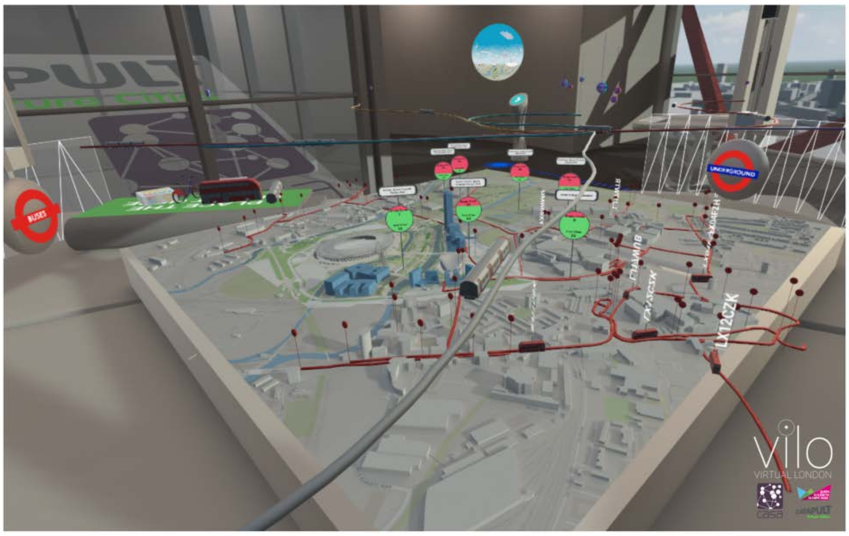

Figure 5: Transportation Facilities in the Stratford Area Within the Virtual and Augmented Environment

The way one interacts with the platform can be seen in the videos accessible in footnote (number 8). Visitors can watch 360 degree videos and high quality architectural visualisations, but they can also interact with the 3D models featured in that content more actively using virtual tools like the cross-sectional plane seen in the videos. The **ViLo** platform provides further flexibility by enabling us to import interactive models of entire urban environments. The Olympic Park is visualised with different layers of data provided by live feeds from Transport for London's bus, tube, and bike hire APIs. Different layers are selected and removed here by the placing of 3D icons on a panel. Virtual reality affords the user the ability to choose their own view point on the data by simply moving their head. Other contextual information like images from Flickr or articles from Wikipedia can also be imported.

A further feature is the ability to quickly swap between models of different locations. In our development at the east London site, the model of the Olympic Park can be immediately replaced by a model of the area of the Thames in Central London between St Paul's Cathedral and the Tate Modern gallery. The same tools can be used to manipulate either model. Analysis of building footprint size and building use data are combined with real-time visibility analysis depicting viewsheds from any point the user designates. Wikipedia and Flickr are queried dynamically to provide additional information and context for particular buildings by simply

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[8] The VR (virtual reality) is captured in the movie at https://vimeo.com/226303585 while the AR (augmented reality) is accessible at https://vimeo.com/226279487

pointing and clicking. In this way many different aspects of urban environments can be digitally reconstructed within the virtual environment, either in miniature or at 1:1 scale.

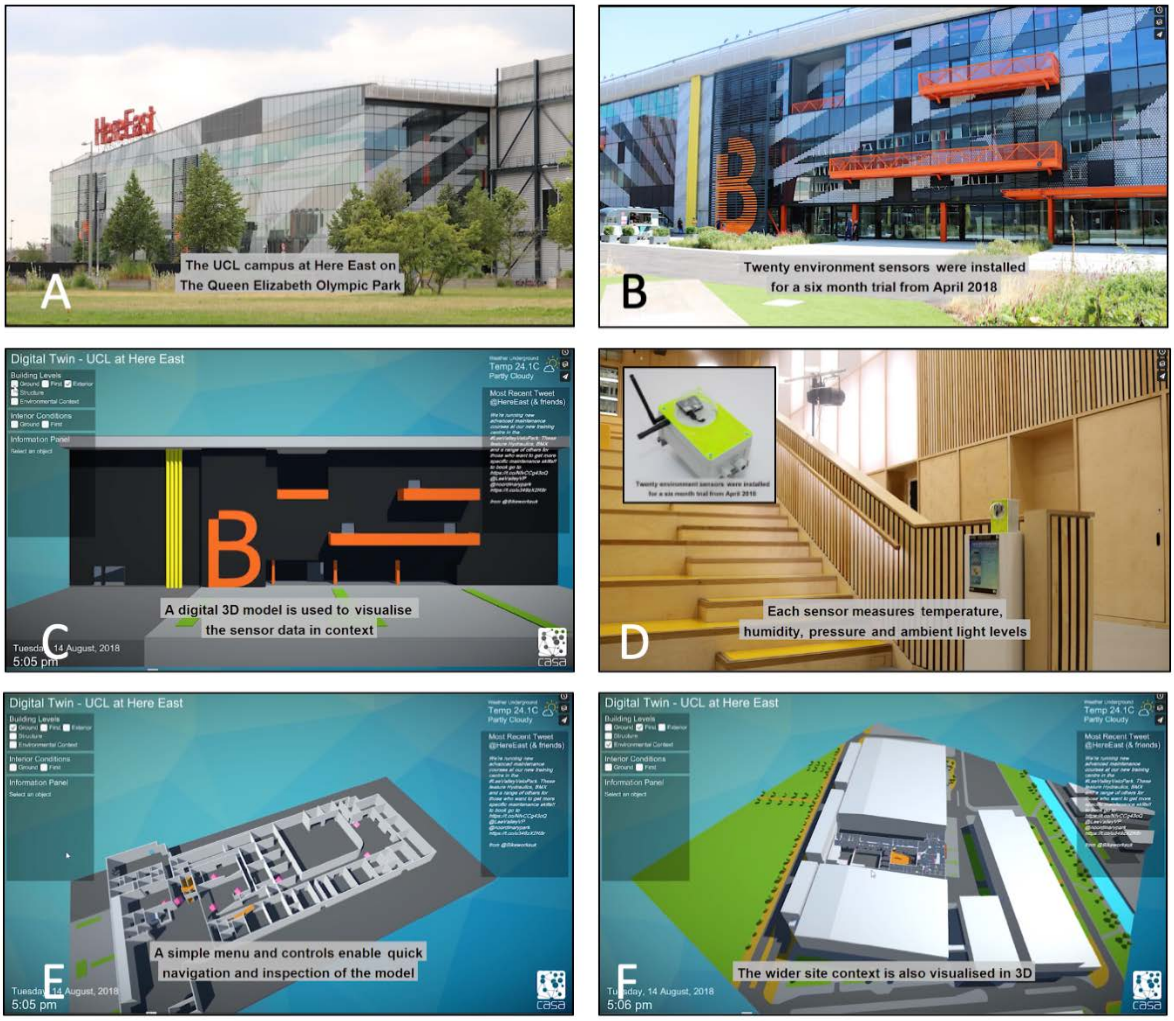
3D physical models such as those developed here can be quite easy to link to urban land-use transportation models through their spatial geocodes, and as we will show in our third model, **ViLo** can easily incorporate the **HE** model which can also be extended down to much greater detail as a BIM. There are in fact many 3D models now in most world cities and the connections to these from platforms like **ViLo** are relatively straightforward. We will reserve our analysis of the way these twins can be linked to one another and in particular to the real systems that they are articulated around until a little later. But there are many connections and one of the main challenges facing the development of the digital twin concept is how to build a robustly connected system where the links are clear and where there is real progress on linking what in the first instance tend to be standalone models, standalone twins to their real system, to one another. These provide wider environments and ecologies that define a world where multiple networks and increasing complexity dominate any set of technologies relevant to planning and design.

*Sensing Performance in Buildings: The Here East (**HE**) Model*

The most detailed scale our group have dealt with in the Olympic Park involves a project to 'wire' or rather 'sense' the Media Centre established for the Games, and now converted to a building complex that deals with new technology applications such as game development, digital music, and built environment applications of which this project is one. The **HE** Digital Twin was a six month trial of a real-time 3D data visualisation platform, designed for the purpose of supporting operational management in the building and its wider environment. As in the case of **ViLo**, this was more an extensible platform than a model *per se* or than the narrower notion of a twin close to the real thing. In fact there are many features of **HE** that were not modelled as the focus was on the introduction of an energy-based sensor network in the complex and no attempts were made to move the twin to a complete sensing of the many different operations that control the building.

The trial used twenty custom sensing devices created by the Intel Collaborative Research Institute (ICRI) for Urban IoT. Data from the sensors were aggregated in a cloud-based platform which then transmitted the data to specially designed client applications. The Unity game engine was used to visualise the real-time data in the context of an interactive 3D model representing the site. This real-time 3D model which we called a 'Digital Twin' was also accessible to site occupants and visitors *in situ* using WebGL. In this way, a shared view of site operation was made available to building managers and visitors alike, just as **ViLo** was designed to be available to a spectrum of experts as well as to the general public. Integration with social media provided one potential mechanism for visitors to interact with each other and explore the site's wider context. The Digital Twin also provided further opportunities for the investigation of data analysis, simulation and agent-based modelling within the context of Building Information Modelling (BIM).

For this study, 20 environmental sensor boxes were first installed as part of the UCL campus at the **HE** building complex. The initial experiment was for a duration of six months from February to July 2018. The data obtained is being used to perform longitudinal analysis which seeks to identify patterns and relationships between environmental parameters over time. Access to data from the **HE**'s Building Management System is being used for the purpose of cross-correlation with sensor outputs in order to test their ability to provide additional intelligence for sustainable operational management. Visual analysis of the data enables us to explore the data and building performance over several attributes using the three dimensional model in near real-time by leveraging the rendering capabilities of the Unity game engine used for visualisation on the platform. This enables timely visual inspection of otherwise invisible aspects of the building's daily performance. The 3D model of the site has been constructed from BIM data, secured from the construction process, and LiDAR data captured in collaboration with UCL's Bartlett scan group. Illustrations of the sequence of steps in building the twin are shown in Figure 6.


The UCL campus at Here East on The Queen Elizabeth Olympic Park

Twenty environment sensors were installed for a six month trial from April 2018

A digital 3D model is used to visualise the sensor data in context

Each sensor measures temperature, humidity, pressure and ambient light levels

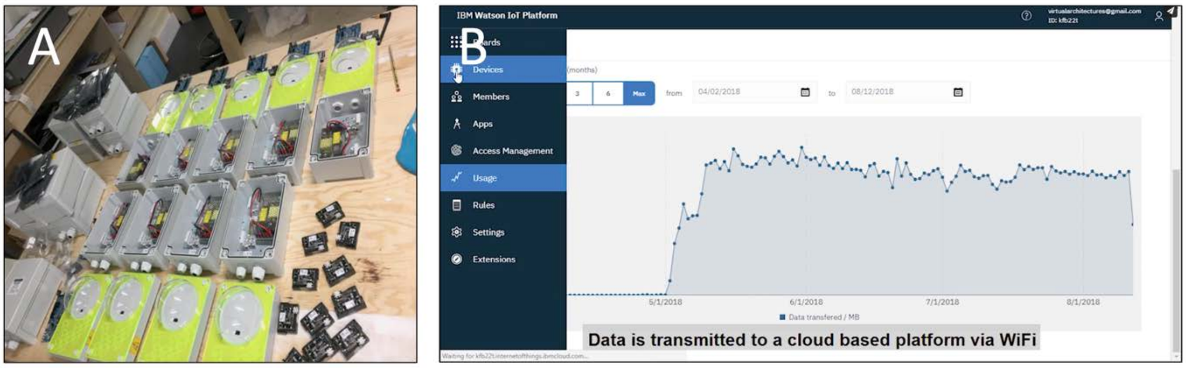
A simple menu and controls enable quick navigation and inspection of the model

The wider site context is also visualised in 3D

*Figure 6: The Interface to the **HE** Sensing Network*

A) The Real Outside Environment B) Zooming Into the Actual Building Which Contains the Network of Sensors C) The 3D CAD Model of **HE** D) The Interior Showing a Sensor and Its Placement E) The Tool Box for Exploring the 3D Model F) The Exterior View of the Model

The 20 sensor boxes being used in this study are each equipped with a Texas Instruments CC2650STK sensor tag which has been programmed to capture separate readings for temperature, humidity, barometric pressure and ambient light levels once every 60 seconds. The readings are then processed by an Intel Edison which posts them to the Open Sensors platform for open IoT data. The Edisons, programmed using Python, are connected to the internet via the Olympic Park's WiFi network. These components are housed in robust weather proof boxes, originally designed for outdoor deployment. In order to facilitate interaction with the Digital Twin, the sensors are presented in the form of an exhibit. Interaction with the Digital Twin will be enabled using Google Beacon technology embedded within each sensor box. These provide a link from a physical object, the sensor box, to online resources which can be accessed via mobile devices and can include links to the 3D representation of the **HE** Digital Twin. The boxes are pictured in Figure 7 where a typical process of data collection is illustrated using software that enables the operation of the sensing network to be monitored.



Data is transmitted to a cloud based platform via WiFi

Figure 7: Monitoring the Building

A) The Array of Portable Sensing Components B) The Transmission of WiFi Data

The best way to explore **HE** and its potential in twinning with a real building is through the sequence of operations captured in the movie footnoted[9] here as number 9. We show a sample of screen shots of the use of the system in terms of the way we visualise and explore the building's performance starting with the building from the outside, defining the sensor technology and then illustrating how we can query the 3D model to evaluate different performances. Some of the pictures from the movie are shown in Figures 6 and 7 and although we are not able to completely communicate the richness of this interface, it is clear that the array of functions illustrated in the 3D model interface offers users a framework for exploring many different experiments. These can then be used to enable the various changes to be made to the positing of many different components within the building structure that are able to help conserve energy.

Building an Ecology of Linked Twins

We have argued that any spatial or locational context requires many different theories to enable our understanding and to then devise models that translate these theories into digital forms that help us explore their future – to predict insofar as this is possible in complex systems (Arcaute et al., 2021) and to inform our speculations that are often cast in terms of design and policy. In the examples that we have developed here for a single location, the models were developed quite separately each with a. different purpose in mind but they are joined implicitly by a variety of stakeholders who not only construct the models in the first place but use them to help in improving the functioning of the real systems to which they are applied. In terms of **QUANT**, the model is used to figure out best locations for new employment, population and transport links within the Olympic Park area while **ViLo** is used to give physical form to these locations in terms of the physical objects – buildings, transport routes, green spaces and so on that enable high quality new development. At the level of the buildings of which we develop

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[9] The **HE** movie https://vimeo.com/311089492

only one, that is **HE**, new developments surrounding the precise locations, changed volumes of traffic, pedestrian access, the location of different activities in the building, and the juxtaposition of these within the complex, can all be generated from the other models; from **QUANT** and realised physically by **ViLo**. These models can be used together if not actually joined and integrated in digital terms.

To an extent what we are implying here that in the development of any model or model system involving digital twins, human beings – ourselves – are always in the loop and this is enough to provide a rich network of associations between the problems, their models, and their twins. This association can enable formal organisation and this can be done quite easily through networked software on their web sites. It is however harder to join different models together that operate on different variants of the same system. For example in **QUANT**, there are no formal functions that generate energy use at the level of buildings which is what **HE** is focussed upon, and it would require extensions of the theory for both land-use transportation models and building information modelling of which **HE** is a variant, to be able to pursue this. In short, what is urgently required is a discussion of how we can integrate very diverse models that have a common benchmark. This provides a core for integration but the very wide and diverse elements of the twins we attempt to link together, tend to make integration very difficult, if not impossible at the present time. In short, we need to explore in much more detail the formality of linking through decentralised and federated digital twins.

Location and space which reflect scale is one of the key anchors of the three digital twins we have described but the temporal dimension complicates their integration. The **QUANT** model deals with longer term locations – that is the impact of new development and regeneration in the Olympic Park area over years and decades, not days or months. This is contrasted with the other extreme of digital twins we have presented which is **HE** where the temporal dimension is central with the sensors producing data in near real time, every 60 seconds. In turn, such rapidity in data production provides the opportunity for real-time monitoring and intervention in the control of energy use in the building. **ViLo** is an intermediate between these two twins as it can be used to explore real time change in the various VR and AR interfaces in the 3D London model but it can also be manipulated to show the visual impact of longer term change in land uses and activities that define the area. To really begin to integrate these three types of digital twin, then new functions need to be added to each to enable their input and output data to be shared. This exists at the level of information flows that are the raw material connecting digital twins to each other and to the real systems that define the particular locations in question. One of the problems with these twins involves the very different time scales over which they operate and this reflects the different problem contexts relevant to each.

To conclude, there needs to be an enormous effort involving theory and computation in developing digital twins for social and economic systems that interact with their physical equivalents. There are many different ways of linking through space, time and sectors across different time intervals and instants, and once one admits the fact that a digital twin can interchange with its real system and with other digital twins that pertain to different realisations of the same system, then there is a veritable explosion of possibilities. A detailed mapping of this terrain is urgently required for the momentum is now on defining more than one twin for more than one realisation of the same system where multiple models are the norm.

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