Towards a Digital Landscape Twin: Insights from the Healthcare Industry

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Abstract: Adapting the Digital Twin concept, initially conceived within the aerospace industry, to the realm of landscape poses a big challenge. This difficulty stems from the unique intrinsic characteristics of landscapes, primarily composed of organic elements and materials. In order to shed light on the viability of such an adaptation, this paper undertakes an examination of three instances wherein the Digital Twin concept has been successfully incorporated into the healthcare industry. These instances include the creation of virtual patients through advanced imaging, the application of simulation in surgical practice, and the integration of precision medicine. Through a comparative analysis of these cases, this paper explains how the landscape discipline could emulate the adoption and framework of the Digital Twin concept, thereby enhancing current landscape practices.

Keywords: Digital twin, digital landscape twin, health digital twin, process modeling

1 Introduction

Since the inception of the Digital Twin (DT) concept by Dr. Michael Grieves in 2003 as the foundational model for Product Lifecycle Management (PLM), the concept was quickly adopted by NASA and the broader aerospace industry. The Digital Twin concept was further highlighted in the widely adopted "Industry 4.0" initiative where it is defined as an evolving digital profile of a physical object or process that helps improve business performance (GRIEVES&VICKERS 2017 DELOITTE 2017).

In recent publications and conference presentations introducing Digital Landscape Twin (DLT) in the field of landscape architecture and its related disciplines, this industry 4.0 concept and practice have been frequently used as a benchmark and pioneering example for implementation (ZOU 2022; MA & PATRICK 2023). At the 2021 Digital Landscape Architecture Conference, Professor Kolbe's introduction of the emerging Digital Landscape Twin with reference to established Digital Twin in aerospace industry (KOLBE 2021) allows scholars and practitioners to gain a comprehensive understanding of the Digital Twin concept and its important benefits in the realms of landscape design and planning.

However, when we try to adapt Digital Twin concept to landscape, such reference and comparison have the following limitations due to the inherent characteristics of Digital Twin applications in the aerospace industry:

1) Nature of materials: Unlike industrial products, which can be designed and improved using mathematical models, scientific formulas in physics, chemistry, and similar fields, a substantial portion of landscapes consists of organic materials and elements, ranging from soil microbes to fauna and flora within the biosphere. The behaviours of organic elements and living systems, including broader ecological dynamics, defy easy quantification and replication within the existing Digital Twin framework as we see in the aerospace industry.

Journal of Digital Landscape Architecture, 9-2024, pp. 873-880. © Wichmann Verlag, VDE VERLAG GMBH · Berlin · Offenbach. ISBN 978-3-87907-752-6, ISSN 2367-4253, e-ISSN 2511-624X, doi:10.14627/537752081.
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2) Uniqueness: Each landscape is unique. Unlike industrial applications of Digital Twin that can be standardized, each landscape has unique combination of landscape elements with unique landscape processes. The potential interventions to landscape in the form of landscape design and planning also require a consideration of social and environmental factors in decision-making. Landscapes are not only physical entities but also serve as social spaces, affecting and being influenced by human interactions, environmental processes, cultural significance, and community well-being. Incorporating these dimensions into the Digital Landscape Twin adds a layer of complexity beyond the scope of industrial Digital Twin.

3) Goals and objectives: The primary objective of implementing Digital twin in the aerospace industry is to enhance performance, efficiency, and other measurable metrics through the adoption of new designs, materials, and energy sources. In essence, the focus is on continuous product improvement. However, landscapes are dynamic and delicate equilibriums, where intentional changes in design aim to achieve harmony, stability, and aesthetic balance rather than mere efficiency. The objectives in landscape design and planning extend beyond performance metrics to encompass the preservation and enhancement of the natural environment, as well as social well-being.

Expanding our scope to include the field of urban planning, where there is a growing literature on the adoption of digital twins in making smart cities, parallels can be drawn with the aerospace and manufacturing industries. In this context, the focus often centers on enhancing the efficiency and efficacy of specific urban systems. A recent study examined 131 peer-reviewed journal articles discussing digital twins of cities. It revealed that the majority of these studies investigated very small projects, or concentrated on data management, visualization, and situational awareness. Only a small number of studies developed simulations and decision support systems aimed at improving and optimizing urban functions such as mobility and risk assessment (SHAHAT et al. 2021). However, these efforts tend to lack a holistic approach towards achieving broader equilibrium.

Therefore, despite Digital Twin has found diverse potential applications in landscape, its adoption presents unique challenges because of the intricate and organic nature of the landscapes it aims to represent and enhance. The building of Digital Landscape Twin needs to find other reference points and inspirations. In a similar vein, the healthcare industry has made significant progress in the adaptation and adoption of the Digital Twin concept and framework. The concept of the Health Digital Twin (HDT) made its entry into the healthcare industry not too long ago and started gaining significant traction around 2016 (SUN et al. 2023), although similar practice has been going on for two decades. Thanks to substantial investments in cutting-edge fields such as brain surgery, cardiology, and cancer treatment, the healthcare industry has made strides in applying Digital Twin technology to real-world scenarios. More importantly, the healthcare industry shares many similarities with landscape management, design, and planning: First, the primary focus of the healthcare industry is the human body, which is a dynamic organic system with many subsystems interacting with each other, presenting intricate situations when intervention is needed. The industry relies more on statistics than strict mathematical rules in health care, primarily because there are many aspects of the human body as well as their interactions with social and environmental conditions that still elude our full comprehension and control. Formulas, equations, and mathematical models that successfully depict the behaviour of machines often fall short in representing the complexities of human physiology and biological processes. Additionally, health care recognizes that our human body, like any landscape system, has its limits and operates within a delicate equilibrium. Therefore, any treatment and intervention cannot endlessly push the system beyond its capabilities, a rule that has been observed for millennium in medicine and landscape management in different ancient cultures.

Because of all these reasons, the healthcare industry presents an additional comparison or reference point to the aerospace industry to help the landscape industry and discipline better understand and adopt Digital Twin into applications. Aided by the widespread use of advanced imaging technologies, advancements in biological computation, robust bio-statistical methodologies, and substantial investments in technologies like artificial intelligence (AI) in the healthcare industry, the Health Digital Twin has quickly transitioned from being a theoretical concept to a tangible reality in healthcare implementation. There are many insights we can learn from its successful adoption to refine our aspiration for Digital Landscape Twin.

2 Methods

This study adopts a comparative research approach to analyze and contrast the development of digital twins in the fields of healthcare and landscape. A systematic comparison enables a comprehensive understanding of the technological advancements, use cases, and implications within these two distinct yet similar domains. The aim of this study is to elucidate the similarities, differences, challenges, and opportunities inherent in the adoption and implementation of digital twins in landscape practices.

Three real-world instances of creating digital twins in the healthcare industry are selected to cover major advancements in implementation: representation, interaction, and customization. For each instance, a brief explanation is provided on the achieved outcomes, how the digital twin mimics the real physical twin, and the associated benefits. Scholarly articles, research papers, industry reports, and relevant literature discussing and reflecting on such practices are presented to illustrate the key concepts and mechanisms in each instance. Following qualitative analysis of each instance, its relevance and implications in creating a Digital Landscape Twin are discussed. Recommendations are provided to address challenges, leverage opportunities, and optimize the benefits of digital twins in landscape practice. The comparative study concludes with an aspirational summary of key findings and a recalibrated explanation of what a Digital Landscape Twin is and what it could achieve.

3 Learning from Digital Twin in Healthcare industry

3.1 Representation with Advanced Imaging Technologies

Any creation of Digital Twin starts with and relies on large quantity of quality data that can accurately represent the physical twin. Similar to large geographic data collections offered by many government agencies and research institutions, the healthcare industry also has large-scale biomedical databases such as UK biobank, as well as individualized database. In recent years, substantial advancements have been witnessed in medical imaging technologies, yielding highly detailed physiological data from sources ranging from Computer Tomography (CT) and Ultrasound to Positron Emission Tomography (PET), Magnetic Resonance Imaging (MRI), and even Bio-Nanosensors. In one example, the U.S. National Library of Medicine (NLM) under the direction of Michael J. Ackerman initiated a Visible Human Project more than 20 years ago. The team slices cadavers at 1-millimter intervals, then creates three-dimensional virtual model bodies by scanning and integrating each slice into digital representation. The data are supplemented with CT and MRI scans to be not only educational but also diagnostic (NLM 2023). In many similar practices, the data from these electronic, electromechanical, optical, and electrochemical sensors are not only used to reconstruct organs and bodies, they are also further analyzed by AI-driven algorithm to create detailed biomarkers (ARMENI et al. 2022). Although more studies are needed to be able to generate actionable links between data and physiology, the practice to create comprehensive digital twin with multi-omics, i. e. multiple data types derived from different research areas such as imaging biomarkers and patient-specific data, offers a good model of creating Digital Twin.

This is where Digital Twin in landscape lags behind. We do have data representing landscapes at different scales and dimensions, including high precision data such as LiDAR, and emerging subsurface imaging data from Ground Penetrating Radar (GPR). But the integration, as well as the study of interactions between landscape elements and features, are still far from the multi-omics approach used in the healthcare industry in terms of comprehensiveness and resolution. Part of the limitation comes from the current data models we have used to represent landscape and its subsystems for decades. For example, the widely available soil data is typically a vector polygon representation associated with attributes documenting various soil properties. However, soil is a continuous 3D entity full of interactions with other subsystems such as vegetation and hydrology. Soil properties vary at different depth. The highly generalized polygon representation is not capable of representing the rich 3D soil properties, let alone facilitating the study of interactions between landscape subsystems. In a foreseeable future, advanced imaging technologies used in landscape representation would demand a major update of existing data models for a better implementation of Digital Landscape Twin.

3.2 Digital Twin in Surgical Practice

Digital Twin has also allowed medical practitioners to test new surgical and treatment plans, or train surgeons to prepare for complex surgical procedure before the real surgery to be performed on the physical body of a patient. Many applications now also involve Augmented Reality (AR) and Virtual Reality (VR) in the process, and some even allow remote surgery or telesurgery to be conducted. At the core of these applications lie two technical concepts: cyber-physical systems (CPS) in which physical systems as well as their interactions are modeled in the cyber system, and closed-loop optimization (CLO) in which cyber systems provides instant feedback to surgeons or trainer for improvement (VENKATESH et al. 2022).

The French company Dassault Systèmes, a leader in the aerospace industry as well, has undertaken the development of the “Living Heart” project, which has received support from many doctors all over the world and endorsement from the U.S. Food and Drug Administration (FDA). This initiative seeks to amalgamate diverse process models of various cardiac functions into a comprehensive digital representation known as a virtual heart. Drawing upon an in-depth understanding of the underlying chemistry, physics, and physiology of distinct cardiac components such as veins, chambers, and muscles, the project facilitates the testing of novel treatments or cardiovascular devices within this virtual replication of a patient's heart. The project extends its utility to cardiac surgeons who can use immersive operating rooms to digitally simulate surgical procedures. This enables practitioners to explore and refine their techniques, obtaining valuable insights and circumventing the physical and legal constraints associated with traditional approaches (DASSAULT SYSTEMES, N.D.). Many other companies are also actively engaged in the development of Digital Twin for human brain, catering to the needs of neurosurgeons and students seeking to master intricate brain surgeries through immersive and simulated experiences.

While direct applications of these technologies and techniques, especially the ones with CPS and CLO, in landscape intervention are yet to be observed, the potential benefits they hold for the field are substantial. The integration of a Computer-Aided Design (CAD) environment with a virtual replication of the site affords the capacity to conduct pre-design site analyses and post-design impact assessments promptly and interactively. This capability empowers designers to formulate optimized design decisions grounded in a more thorough understanding of potential consequences. A case in point is the Huntington Library in San Marino, California, renowned for its exquisite botanical gardens featuring numerous rare plants. However, footsteps of half a million visitors every year and changing surface drainage pattern are impacting soil properties and the growth of precious plants. Gardeners and GIS analysts are contemplating the creation of a Digital Landscape Twin to facilitate the testing of various interventions before actual implementation, analogous to a surgeon experimenting with different operative plans in the Living Heart project. Although we are already engaged in process modeling at the geographic scale, there is still significant work to be undertaken at both the landscape and site scales, particularly in understanding how landscape subsystems interact and how local interventions might influence larger landscape systems. By envisioning the prospect of a Digital Landscape Twin providing real-time feedback on landscape performance, designers would have the ability to make immediate adjustments to their designs in the future. For instance, the Sustainable SITES Initiative has created a rating system that "guides, evaluates and certifies a project's sustainability in the planning, design, construction and management of landscapes and other outdoor spaces" (SUSTAINABLE SITES INITIATIVE 2015). If the evaluation could be turned into algorithm in the implementation of Digital Landscape Twin, landscape designers can use the instant rating feedback during the design process to guide their design thinking toward environmental sensitivity and sustainability.

3.3 Precision Medicine

Precision medicine represents an innovative approach to the design of medical treatments, taking into account individual variations in patients' genetic makeup, physiology, and living environments. This approach marks a significant departure from traditional practices that often provide generic treatments based on broad statistical data. In the realm of healthcare, the concept of individualized Health Digital Twin has emerged, which integrates generic Digital Twin with decentralized data derived from patient records, biological information, and data from mobile sensors. It can forecast how patients will respond to medications and various treatments (VENKATESH et al. 2022).

Atlas Meditech, a company specializing in the development of Digital Twin of the brain, has been collaborating with Nvidia, a leading manufacturer of AI chips, to establish the Atlas Platform. This platform introduces a customizable 3D model of the brain, equipped with advanced algorithms designed to facilitate surgeon training and test new surgical procedure. The initial generic 3D brain undergoes customization through the utilization of the AI algorithm "Atlas Pathfinder" which adjusts the model based on segmented views obtained from a patient's brain scan, allowing for an accurate representation of how a tumor deforms the normal structure of their brain tissue. Subsequently, surgeons engage in training on a virtual brain precisely tailored to match the size, shape, and lesion position of the patient's brain. The virtual model provides haptic feedback during the procedure, enhancing the realism of the training experience (NVIDIA 2023).

Just as every individual possesses a unique genetic makeup, each landscape is characterized by distinct soil, moisture levels, biome, and built-up conditions. Any intervention in these environments must consider their inherent uniqueness. Today, we still see examples like the "high line" being replicated elsewhere. Scholars have raised concerns about whether such standardized designs may result in landscapes devoid of meaningful character (HELLEMONDT et al. 2022).

The adoption of Digital Twin in landscape in the context of precision medicine is actually not such a novel idea. In landscape, one area stands out in effective use of similar approach: precision agriculture. Notably, low-altitude advanced imaging techniques with drones have gained extensive usage for monitoring crop growth, as well as facilitating subsequent mitigation or improvement measures. This approach establishes relationships between soil dynamics, water availability, and crop growth through foundational process modeling (BONGIOVANNI & LOWENBERG-DEBOER 2004). Despite these efforts, precision agriculture places a pronounced emphasis on profitability, affording limited consideration to the equilibrium of ecosystem. In a broader and more environmentally responsible sense, when landscape interventions are designed within a virtual environment, accounting for these distinct landscape conditions, it becomes possible to assess the impact of interventions on the particular natural and built environment. This approach can help raise awareness about the importance of considering the uniqueness of landscapes in the planning and development process.

4 Conclusion and Outlook

From these three instances of the adoption of Digital Twin in the healthcare industry, as well as the associated comparative analyses above, we can find many similarities and inspirations as we try to adopt Digital Twin in landscape. In the simplest terms, Digital Landscape Twin is the digital replica of landscape. But its meaning, functions, and objectives could be far richer as we examine the Health Digital Twin examples.

First of all, a Digital Landscape Twin is not merely for visualization or representation. As we integrate multi-scalar and multi-dimensional data into various virtual representations, the important properties of their real-world counterparts should be associated as well, similar to the multi-omics approach in healthcare. Each element within the digital replica of the physical landscape should be constructed with comprehensive, measured attributes to enable its proper functioning and interaction with other landscape elements in virtual simulation. When traditional data models representing landscape fall short of fulfilling 3D representation and spatio-temporal process modeling, new data models need to be developed.

Secondly, akin to the role of computational biology in establishing Health Digital Twin, Digital Landscape Twin also needs multi-scalar spatio-temporal process modeling that can help establish feedback mechanism between landscape elements and subsystems. Ideally, such feedback can be instant, real time, and predictive in the virtual replica. Understanding the anatomy of landscape and mechanisms of major subsystems could help us model consequences of unintentional changes or intentional interventions. This feedback loop, encompassing changes, impact assessments, and improvements, should remain at the core of Digital Landscape Twin. Similar to vitals and biomarkers used in the healthcare industry, landscape also needs vitals and benchmarks that can provide digital diagnostics on the condition of our landscape. We can even imagine a Digital Landscape Twin that provides warning based on statistical models and AI when something runs beyond the normal variation in a healthy equilibrium. One objective of a Digital Landscape Twin should be to facilitate more nuanced, location-aware, and evidence-based design interventions.

Finally, Digital Landscape Twin should facilitate engagements across various media platforms, incorporating emerging immersive visualization environments such as AR and VR. Given the acknowledged social dimension of landscapes outlined earlier in this paper, the manipulation of a Digital Landscape Twin should not be confined to only professionals. To account for the communal aspect, potential interventions and their repercussions must be interactively shareable with community members and the general public. In essence, Digital Landscape Twin should emulate its real-world counterpart as a virtual social space. This emulation is crucial for comprehending and gauging human interactions, and community well-being, ultimately enabling more informed and effective interventions in the real world.

In conclusion, the realization and incorporation of Digital Landscape Twin pose a challenging undertaking for members in the landscape discipline and industry. Nonetheless, insights gleaned from the examination of the Digital Twin concept's integration within the healthcare industry can serve as valuable guidance in crafting a more versatile and efficacious Digital Landscape Twin. This endeavour holds promise in assisting the profession and industry in realizing their lofty aspirations for a sustainable and equitable future in our living environment.

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