



AperTO - Archivio Istituzionale Open Access dell'Università di Torino

3D City Models in Planning Activities: From a Theoretical Study to an Innovative Practical Application

This is the author's manuscript
Original Citation:
Availability:
This version is available http://hdl.handle.net/2318/2035008 since 2024-12-08T18:11:11Z
Publisher:
CRC Press
Published version:
DOI:10.1201/9781003425724
Terms of use:
Open Access Anyone can freely access the full text of works made available as "Open Access". Works made available under a Creative Commons license can be used according to the terms and conditions of said license. Use of all other works requires consent of the right holder (author or publisher) if not exempted from copyright protection by the applicable law.

(Article begins on next page)

Handbook of Digital Twins

Over the last two decades, Digital Twins (DTs) have become the intelligent representation of future development in industrial production and daily life. Consisting of over 50 chapters by more than 100 contributors, this comprehensive handbook explains the concept, architecture, design specification and application scenarios of DTs.

As a virtual model of a process, product or service to pair the virtual and physical worlds, DTs allow data analysis and system monitoring by using simulations. The fast-growing technology has been widely studied and developed in recent years. Featured with centralization, integrity and dynamics, it is cost-effective to drive innovation and performance. Many fields saw the adaptation and implementation across industrial production, healthcare, smart city, transportation and logistics. World-famous enterprises such as Siemens, Tesla, ANSYS and General Electric have built smart factories and pioneered digital production, heading towards Industry 4.0.

This book aims to provide an in-depth understanding and reference of DTs to technical personnel in the field, students and scholars of related majors, and general readers interested in intelligent industrial manufacturing.

Dr Zhihan Lyu is an Associate Professor at the Department of Game Design, Uppsala University, Sweden. He is also IEEE Senior Member, British Computer Society Fellow, ACM Distinguished Speaker, Career-Long Scientific Influence Rankings of Stanford's Top 2% Scientists, Marie Skłodowska-Curie Fellow, Clarivate Highly Cited Researcher and Elsevier Highly Cited Chinese Researcher. He has contributed 300 papers including more than 90 papers on IEEE/ACM Transactions. He is the Editor-in-Chief of Internet of Things and Cyber-Physical Systems (KeAi), an Associate Editor of a few journals including *ACM TOMM, IEEE TITS, IEEE TNSM, IEEE TCSS, IEEE TNSE* and *IEEE CEM*. He has reviewed 400 papers. He has received more than 20 awards from China, Europe and IEEE. He has given more than 80 invited talks for universities and companies in Europe and China. He has given 20 keynote speeches at international conferences.

Review Copy Only – Not for Redistribution Gabriele Garnero - Università degli Studi di Torino - 26/06/2024

Review Copy Only – Not for Redistribution Gabriele Garnero - Università degli Studi di Torino - 26/06/2024

Handbook of Digital Twins

Edited by Zhihan Lyu



CRC Press is an imprint of the Taylor & Francis Group, an **informa** business

Front cover image: Gorodenkoff/Shutterstock

First edition published 2024 by CRC Press 2385 NW Executive Center Drive, Suite 320, Boca Raton FL 33431

and by CRC Press 4 Park Square, Milton Park, Abingdon, Oxon, OX14 4RN

CRC Press is an imprint of Taylor & Francis Group, LLC

© 2024 selection and editorial matter, Zhihan Lyu; individual chapters, the contributors

Reasonable efforts have been made to publish reliable data and information, but the author and publisher cannot assume responsibility for the validity of all materials or the consequences of their use. The authors and publishers have attempted to trace the copyright holders of all material reproduced in this publication and apologize to copyright holders if permission to publish in this form has not been obtained. If any copyright material has not been acknowledged please write and let us know so we may rectify in any future reprint.

Except as permitted under U.S. Copyright Law, no part of this book may be reprinted, reproduced, transmitted, or utilized in any form by any electronic, mechanical, or other means, now known or hereafter invented, including photocopying, microfilming, and recording, or in any information storage or retrieval system, without written permission from the publishers.

For permission to photocopy or use material electronically from this work, access www.copyright. com or contact the Copyright Clearance Center, Inc. (CCC), 222 Rosewood Drive, Danvers, MA 01923, 978-750-8400. For works that are not available on CCC please contact mpkbookspermissions@ tandf.co.uk

Trademark notice: Product or corporate names may be trademarks or registered trademarks and are used only for identification and explanation without intent to infringe.

ISBN: 978-1-032-54607-0 (hbk) ISBN: 978-1-032-54608-7 (pbk) ISBN: 978-1-003-42572-4 (ebk)

DOI: 10.1201/9781003425724

Typeset in Palatino by codeMantra Review Copy Only – Not for Redistribution Gabriele Garnero - Università degli Studi di Torino - 26/06/2024

Contents

Contributorsxi
Part 1 Introduction
1. Overview of Digital Twins
Part 2 Thinking about Digital Twins
2. What Is Digital and What Are We Twinning?: A Conceptual Model to Make Sense of Digital Twins
3. When Digital Twin Meets Network Engineering and Operations 30 <i>Pedro Henrique Diniz, Christian Esteve Rothenberg, and</i> <i>José Ferreira de Rezende</i>
4. Cognitive Digital Twins
5. Structural Integrity Preservation of Built Cultural Heritage: How Can Digital Twins Help?
Part 3 Digital Twins Technology
6. Key Technologies of Digital Twins: A Model-Based Perspective85 Serge P. Kovalyov
7. A Generic Deployment Methodology for Digital Twins – First Building Blocks
8. Automated Inference of Simulators in Digital Twins

Review Copy Only – Not for Redistribution Gabriele Garnero - Università degli Studi di Torino - 26/06/2024 vi Contents

9. Digital Twin for Federated Analytics Applications)
10. Blockchain-Based Digital Twin Design	7
11. Physics-Based Digital Twins Leveraging Competitive Edge in Novel Markets	5
Emil Kurvinen, Antero Kutvonen, Päivi Aaltonen, Jussi Salakka, and Behnam Ghalamchi	
Part 4 Digital Twins Design and Standard	
12. Digital Twin Model Formal Specification and Software Design 203 Yevgeniya Sulema, Andreas Pester, Ivan Dychka, and Olga Sulema	3
13. Layering Abstractions for Design-Integrated Engineering of Cyber-Physical Systems	1
 14. Issues in Human-Centric HMI Design for Digital Twins	_
	3

10.	Toward a New Generation of Design Tools for the Digital	
	Multiverse	256
	Chiara Cimino, Gianni Ferretti, and Alberto Leva	

16. A Service Design and Systems Thinking Approach to Enabling New Value Propositions in Digital Twins with AI Technologies 274 Shaun West, Cecilia Lee, Utpal Mangla, and Atul Gupta

17.	. Tokenized Digital Twins for Society 5.0	291
	Abdeljalil Beniiche and Martin Maier	

19.	Design and Operationalization of Digital Twins in Robotized	
	Applications: Architecture and Opportunities	. 321
	Tobias Osterloh, Eric Guiffo Kaigom, and Jürgen Roßmann	

Review Copy Only – Not for Redistribution Gabriele Garnero - Università degli Studi di Torino - 26/06/2024 *Contents* vii

Pa	rt 5 Digital Twins in Management
20.	Management of Digital Twins Complex System Based on Interaction
	Vladimir Shvedenko, Valeria Shvedenko, Oleg Schekochikhin, and Andrey Mozokhin
21.	Artificial Intelligence Enhanced Cognitive Digital Twins for Dynamic Building Knowledge Management
22.	On the Design of a Digital Twin for Maintenance Planning
23.	Organizational Barriers and Enablers in Reaching Maturity in Digital Twin Technology
24.	Digital Twin Development – Understanding Tacit Assets
25.	Digital Twins for Lifecycle Management: The Digital Thread from Design to Operation in the AECO Sector
Pa	rt 6 Digital Twins in Industry
26.	Digital Twins for Process Industries
27.	Digital Twins in the Manufacturing Industry
28.	Cognitive Digital Twins in the Process Industries
29.	Development of the Digital Twin for the Ultraprecision Diamond Turning System and Its Application Perspectives

Review Copy Only – Not for Redistribution Gabriele Garnero - Università degli Studi di Torino - 26/06/2024 viii Contents

30.	Conceptualization and Design of a Digital Twin for Industrial Logistic Systems: An Application in the Shipbuilding Industry 515 <i>Giuseppe Aiello, Islam Asem Salah Abusohyon, Salvatore Quaranta,</i> <i>and Giulia Marcon</i>
31.	Digital Twin Applications in Electrical Machines Diagnostics 531

Georgios Falekas, Ilias Palaiologou, Zafeirios Kolidakis, and Athanasios Karlis

32.	Building a Digital Twin – Features for Veneer Production Lines – Observations on the Discrepancies between Theory and Practice	549
	Jyrki Savolainen and Ahsan Muneer	
33.	Experiments as DTs Jascha Grübel	563
34.	Digital Twins–Enabled Smart Control Engineering and Smart Predictive Maintenance Jairo Viola, Furkan Guc, and YangQuan Chen	584

Part 7 Digital Twins in Building

35.	3D City Models in Planning Activities: From a Theoretical Study to an Innovative Practical Application
36.	Exploiting Virtual Reality to Dynamically Assess Sustainability of Buildings through Digital Twin
37.	Riding the Waves of Digital Transformation in Construction – Chances and Challenges Using Digital Twins
38.	A Framework for the Definition of Built Heritage Digital Twins 647 <i>Marianna Crognale, Melissa De Iuliis, and Vincenzo Gattulli</i>
39.	Digital Twins in Architecture: An Ecology of Practices and Understandings

Review Copy Only – Not for Redistribution Gabriele Garnero - Università degli Studi di Torino - 26/06/2024 *Contents* ix

40.	Developing a Construction Digital Twin for Bridges: A Case Study of Construction Control of Long-Span Rigid Skeleton Arch Bridge
	Chunli Ying, Long Chen, Daguang Han, Kaixin Hu, Yu Zhang, Guoqian Ren, Yanhui Liu, Yongquan Dong, and Yatong Yuan
41.	Urban-Scale Digital Twins and Sustainable Environmental Design: Mobility Justice and Big Data
Pa	rt 8 Digital Twins in Transportation
42.	Digital Twins in Transportation and Logistics
43.	Digital Twin–Driven Damage Diagnosis and Prognosis of Complex Aircraft Structures
44.	Digital Twins and Path Planning for Aerial Inspections
Pa	rt 9 Digital Twins in Energy
45.	Digital Twin Security of the Cyber-Physical Water Supply System
46.	Digital Twin in Smart Grid
47.	Digital Twins in Graphene Technology
48.	Applications of Triboelectric Nanogenerator in Digital Twin Technology

Review Copy Only – Not for Redistribution Gabriele Garnero - Università degli Studi di Torino - 26/06/2024 x Contents

Part 10 Digital Twins in Medicine and Life

49.	Digital Twins in the Pharmaceutical Industry	357
	João Afonso Ménagé Santos, João Miguel da Costa Sousa,	
	Susana Margarida da Silva Vieira, and André Filipe Simões Ferreira	
50.	Human Body Digital Twins: Technologies and Applications Chenyu Tang, Yanning Dai, Jiaqi Wang, and Shuo Gao	872
51.	Digital Twins for Proactive and Personalized Healthcare –	
	Challenges and Opportunities	388
	Sai Phanindra Venkatapurapu, Marianne T. DeWitt, Marcelo Behar,	
	and Paul M. D'Alessandro	

Review Copy Only – Not for Redistribution Gabriele Garnero - Università degli Studi di Torino - 26/06/2024

Contributors

Päivi Aaltonen

MORE SIM Research Platform, LUT School of Business and Administration LUT University Lappeenranta, Finland

Islam Asem Salah Abusohyon

Università degli studi di Palermo Palermo, Italy

Sofia Agostinelli

CITERA Research Centre Sapienza University of Rome Rome, Italy

Ashwin Agrawal

Civil and Environmental Engineering Stanford University Stanford, CA

Giuseppe Aiello

Università degli studi di Palermo Palermo, Italy

George Arampatzis

School of Production Engineering and Management Technical University of Crete Chania, Greece

Rebeca Arista

Industrial System Digital Continuity Specialist at Airbus SAS Leiden, the Netherlands

Zeynep Baysal Ostim Technical University OSTIM, Turkey Marcelo Behar

PricewaterhouseCoopers LLP New York, New York

Abdeljalil Beniiche

Optical Zeitgeist Laboratory Institut national de la recherche scientifique Quebec, Canada

Antonio Bono

Department of Computer Science, Modeling, Electronics and Systems Engineering University of Calabria Rende, Italy

Hui Cai

Department of Electrical Engineering and Information Technology Ilmenau University of Technology Ilmenau, Germany

Serdar Çelik

Ostim Technical University Ostim, Turkey

Marianna Charitonidou

Faculty of Art Theory and History Athens School of Fine Arts Athens, Greece

Dawei Chen

InfoTech Labs Toyota Motor North America Plano, Texas Review Copy Only – Not for Redistribution Gabriele Garnero - Università degli Studi di Torino - 26/06/2024 xii Contributors

Long Chen

School of Architecture, Building and Civil Engineering Loughborough University Loughborough, England

YangQuan Chen

University of California Merced Merced, California

Kai Cheng

Brunel University London Uxbridge, England

David Christopher

Brunel University London Uxbridge, England

Chiara Cimino

Associate Professor at University of Turin

Department of Management, Economics, and Industrial Engineering Politecnico di Milano Milan, Lombardia, Italy

Marianna Crognale

Department of Structural and Geotechnical Engineering Sapienza University of Rome Rome, Italy

Paul M D'Alessandro

Customer Transformation PricewaterhouseCoopers LLP New York, New York

Luigi D'Alfonso

Department of Computer Science, Modeling, Electronics and Systems Engineering (DIMES) University of Calabria Rende, Italy

João Miguel da Costa Sousa

IDMEC, Instituto Superior Técnico Universidade de Lisboa Lisbon, Portugal

Susana Margarida da Silva Vieira

IDMEC, Instituto Superior Técnico Universidade de Lisboa Lisbon, Portugal

Yanning Dai

School of Instrumentation and Optoelectronic Engineering Beihang University Beijing, China

Istvan David

Université de Montréal Montreal, Canada

Melissa De Iuliis

Department of Structural and Geotechnical Engineering Sapienza University of Rome Rome, Italy

José Ferreira de Rezende

Federal University of Rio de Janeiro (UFRJ) Rio de Janeiro, Brazil

Marianne T DeWitt

Customer Transformation PricewaterhouseCoopers LLP New York, New York

Pedro Henrique Diniz

Federal University of Rio de Janeiro (UFRJ) Rio de Janeiro, Brazil Review Copy Only – Not for Redistribution Gabriele Garnero - Università degli Studi di Torino - 26/06/2024 Contributors xiii

Leiting Dong

School of Aeronautic Science and Engineering Beihang University Beijing, China

Yongquan Dong

Chongqing Jiaotong University Chongqing, China

Ivan Dychka

Faculty of Applied Mathematics National Technical University of Ukraine Kyiv, Ukraine

Pavlos Eirinakis

Department of Industrial Management and Technology University of Piraeus Piraeus, Greece

Georgios Falekas

Department of Electrical and Computer Engineering Democritus University of Thrace Komotini, Greece

Giuseppe Fedele

Department of Informatics, Modeling, Electronics and Systems Engineering (DIMES) University of Calabria Rende, Italy

André Filipe Simões Ferreira

Hovione Farmaciência S.A. Loures, Portugal

Gianni Ferretti

Automatic Control Cremona campus of the Politecnico di Milano Cremona, Italy

Anselmo Filice

Department of Environmental Engineering, Afference to Department of Informatics, Modeling, Electronics and Systems Engineering (DIMES) University of Calabria Rende, Italy

Martin Fischer

Civil and Environmental Engineering Stanford University Stanford, California

Nikolai Fomin

V. A. Trapeznikov Institute of Control Sciences of Russian Academy of Sciences Moscow, Russia

Marco Francesco Funari

Department of Civil and Environmental Engineering University of Surrey Guildford, England

Shuo Gao

School of Instrumentation and Optoelectronic Engineering Beihang University Beijing, China

Gabriele Garnero

Interuniversity Department of Regional and Urban Studies and Planning Università degli Studi di Torino Turin, Italy

Vincenzo Gattulli

Department of Structural and Geotechnical Engineering Sapienza University of Rome Rome, Italy Review Copy Only – Not for Redistribution Gabriele Garnero - Università degli Studi di Torino - 26/06/2024 xiv Contributors

Behnam Ghalamchi

Mechanical Engineering California Polytechnique State University San Luis Obispo, California

Ning Gou Brunel University London Uxbridge, England

Jascha Grübel Cognitive Science ETH Zurich Zurich, Switzerland

Furkan Guc University of California Merced Merced, California

Dayalan R. Gunasegaram CSIRO Manufacturing Geelong, Australia

Atul Gupta Merative Ann Arbor, Michigan

Mohammed Adel Hamzaoui

Lab-STICC Université Bretagne Sud Lorient Lorient, France

Daguang Han

School of Civil Engineering Southeast University Nanjing, China

Zhu Han

Department of Electrical and Computer Engineering University of Houston Houston, Texas

Richard Heininger

Business Informatics-Communications Engineering Johannes Kepler University Linz, Austria

Anca-Simona Horvath

Research Laboratory for Art and Technology Aalborg University Aalborg, Denmark

Kaixin Hu

Smart City and Sustainable Development Academy Chongqing Jiaotong University Chongqing, China

Thomas Ernst Jost

Business Informatics-Communications Engineering Johannes Kepler University Linz, Austria

Nathalie Julien Lab-STICC

Université Bretagne Sud Lorient Lorient, France

Eric Guiffo Kaigom

Computer Science and Engineering Frankfurt University of Applied Sciences Frankfurt, Germany

Kostas Kalaboukas

Gruppo Maggioli Santarcangelo di Romagna, Greece Review Copy Only – Not for Redistribution Gabriele Garnero - Università degli Studi di Torino - 26/06/2024 Contributors xv

Vivek Kant

Human Factors and Sociotechnical Systems Studios IDC School of Design Indian Institute of Technology Bombay Mumbai, India

Athanasios Karlis

Department of Electrical and Computer Engineering Democritus University of Thrace Komotini, Greece

Dimitris Kiritsis

Sustainable Manufacturing Ecole Polytechnique Federale de Lausanne (EPFL) Lausanne, Switzerland

Zafeirios Kolidakis

Department of Electrical and Computer Engineering Democritus University of Thrace Komotini, Greece

Mariusz Kostrzewski

Warsaw University of Technology Faculty of Transport Warszawa, Poland

Serge P. Kovalyov

Institute of Control Sciences of Russian Academy of Sciences Moscow, Russia

Esra Kumaş

Ostim Technical University Ostim, Turkey

Emil Kurvinen

Materials and Mechanical Engineering Research Unit, Machine and Vehicle Design University of Oulu Oulu, Finland

Antero Kutvonen

LUT School of Engineering Science LUT University Lappeenranta, Finland

Cecilia Lee

Royal College of Art London, United Kingdom

Alberto Leva

Automatic Control at Politecnico di Milano Milan, Italy

Shangkuan Liu Brunel University London Uxbridge, England

Xiaocheng Liu

School of Computer Science and Technology Qingdao University Qingdao, China

Yanhui Liu

Southwest Jiaotong University Chengdu, China

Stavros Lounis

ELTRUN E-Business Research Center, Department of Management Science and Technology Athens University of Economics and Business Athens, Greece Review Copy Only – Not for Redistribution Gabriele Garnero - Università degli Studi di Torino - 26/06/2024 xvi Contributors

Paulo B. Lourenço Department of Civil Engineering University of Minho Minho, Portugal

Jinzhi Lu

Ecole Polytechnique Federale de Lausanne (EPFL) Lausanne, Switzerland

Zhihan Lyu Department of Game Design Uppsala University Uppsala, Sweden

Martin Maier Optical Zeitgeist Laboratory Institut national de la recherche scientifique Quebec, Canada

Utpal Mangla Telco Industry & EDGE Clouds IBM Toronto, Canada

Giulia Marcon University of Palermo Palermo, Italy

Roman V. Meshcheryakov

V. A. Trapeznikov Institute of Control Sciences of Russian Academy of Sciences Moscow, Russia

Andrey Mozokhin

Department of Automated Systems of Process Control of SMGMA Group Moscow, Russia

Petra Müller-Csernetzky

Design Management and Innovation Lucerne School of Engineering and Architecture Lucerne, Switzerland

Ahsan Muneer

School of Business and Management LUT University Lappeenranta, Finland

Andre Nemeh

Strategy and Innovation Rennes School of Business Rennes, France

Tobias Osterloh RWTH Aachen University Aachen, Germany

Busra Ozen Department of Civil Engineering Aydin Adnan Menderes University Aydin, Turkey

Gozde Basak Ozturk

Department of Civil Engineering Aydin Adnan Menderes University Aydin, Turkey

Hamide Özyürek

Department of Business Administration Ostim Technical University Ostim, Turkey

Ilias Palaiologou Department of Electrical and Computer Engineering

Democritus University of Thrace Komotini, Greece Review Copy Only – Not for Redistribution Gabriele Garnero - Università degli Studi di Torino - 26/06/2024 Contributors xvii

Andreas Pester Faculty of Informatics and Computer Science The British University in Egypt Cairo, Egypt

Heli Ponto Forum Virium Helsinki Oy Helsinki, Finland

Panagiota Pouliou CITA – Center of Information Technology and Architecture KADK Copenhagen, Denmark

Salvatore Quaranta Università degli studi di Palermo Palermo, Italy

Laavanya Ramaul School of Business and Management LUT University Lappeenranta, Finland

Guoqian Ren College of Architecture and Urban Planning Tongji University Shangai, China

Stefano Rinaldi Department of Information Engineering University of Brescia Brescia, Italy

Jürgen Roßmann Electrical Engineering RWTH Aachen University Aachen, Germany

Christian Esteve Rothenberg University of Campinas Campinas, Brazil

Jože Martin Rožanec

Information and Communication Technologies Jožef Stefan International Postgraduate School Ljubljana, Slovenia

Timo Ruohomäki

Forum Virium Helsinki Oy Helsinki, Finland

Jussi Salakka

Mechanical Engineering Oulu University Oulu, Finland

Ville Santala Forum Virium Helsinki Oy Helsinki, Finland

João Afonso Ménagé Santos

Hovione Farmaciência S.A.; IDME, Instituto Superior Técnico Universidade de Lisboa Lisbon, Portugal

Jyrki Savolainen

School of Business and Management LUT University Lappeenranta, Finland

Philip Scarf Cardiff Business School Cardiff University Cardiff, Wales

Oleg Schekochikhin Department of Information Security

Kostroma State University Kostroma, Russia Review Copy Only – Not for Redistribution Gabriele Garnero - Università degli Studi di Torino - 26/06/2024 xviii Contributors

Elena F. Sheka

Institute of Physical Researches and Technology of the Peoples' Friendship University of Russia Moscow, Russia

Muhammad Shoaib

Information Systems Department, King Saud University Politecnico di Milano Milan, Italy

Valeria Shvedenko

LLC T-Innovatic St. Petersburg, Russia

Vladimir Shvedenko

Federal Agency for Technical Regulation and Metrology ROSSTANDART The Russian Institute of Scientific and Technical Information of the Russian Academy of Sciences (VINITI RAS) Moscow, Russia

Seppo Sierla

Aalto University Espoo, Finland

Xinya Song

Department of Electrical Engineering and Information Technology Ilmenau University of Technology Ilmenau, Germany

Christian Stary Business Informatics-Communications Engineering Johannes Kepler University Linz, Austria

Nenad Stojanović

Nissatech Innovation Centre Germany

Oliver Stoll

Lucerne School of Engineering and Architecture Lucerne, Switzerland

Jayasurya Salem Sudakaran

Human Factors and Sociotechnical Systems Studios, IDC School of Design Indian Institute of Technology Bombay Mumbai, India

Olga Sulema

Computer Systems Software Department National Technical University of Ukraine Kyiv, Ukraine

Yevgeniya Sulema

Computer Systems Software Department National Technical University of Ukraine Kyiv, Ukraine

Eugene Syriani

Department of Computer Science and Operations Research Université de Montréal Montreal, Canada

Lavinia Tagliabue

University of Turin Turin, Italy Review Copy Only – Not for Redistribution Gabriele Garnero - Università degli Studi di Torino - 26/06/2024 *Contributors* xix

Chenyu Tang

Department of Engineering University of Cambridge Cambridge, England

Gloria Tarantino

Università degli Studi di Torino | UNITO · Dipartimento Interateneo di Scienze, Progetto e Politiche Del Territorio Politecnico di Torino Turin, Italy

Frits van Rooij

IDE Americas Inc. Carlsbad, California Salford Business School University of Salford Salford, England

Sai Phanindra Venkatapurapu

Customer Transformation PricewaterhouseCoopers LLP New York, New York

Jairo Viola

University of California Merced Merced, California

Juho-Pekka Virtanen

Forum Virium Helsinki Oy Helsinki, Finland

Annalaura Vuoto

Department of Civil Engineering University of Minho Minho, Portugal

Dan Wang

Department of Computing The Hong Kong Polytechnic University Hong Kong, China

Jiaqi Wang

School of Instrumentation and Optoelectronic Engineering Beihang University Beijing, China

Jie Wang

Beijing Institute of Nanoenergy and Nanosystems Chinese Academy of Sciences Beijing, China School of Nanoscience and Technology University of Chinese Academy of Sciences China

Bianca Weber-Lewerenz

Faculty of Civil Engineering RWTH Aachen University Aachen, Germany

Shaun West

Lucerne School of Engineering and Architecture Lucerne University of Applied Sciences and Arts Lucerne, Switzerland

Dirk Westermann

Department of Electrical Engineering and Information Technology Ilmenau University of Technology Ilmenau, Germany

Chunli Ying

School of Architecture, Building and Civil Engineering Loughborough University Loughborough, England Review Copy Only – Not for Redistribution Gabriele Garnero - Università degli Studi di Torino - 26/06/2024 xx Contributors

Yatong Yuan

China Construction Fifth Engineering Bureau Guangdong, China

Jiayue Zhang

Department of Mechanical Engineering State Key Laboratory of Tribology Tsinghua University Shenyang Architectural and Civil Engineering Institute Tsinghua University Beijing, China

Xiaochen Zheng

Sustainable Manufacturing (ICT4SM) Ecole Polytechnique Fédérale de Lausanne (EPFL) Lausanne, Switzerland **Yu Zhang** Shenyang Jianzhu University Shenyang, China

Xuan Zhou

School of Aeronautic Science and Engineering Beihang University Beijing, China

Yifei Zhu

Shanghai Jiao Tong University Shanghai, China

35

3D City Models in Planning Activities: From a Theoretical Study to an Innovative Practical Application

Gabriele Garnero Università degli Studi di Torino

Gloria Tarantino *Politecnico di Torino*

35.1 Introduction

During the last few years, digital 3D city models have achieved a high presence as valuable planning tools used by a large number of public administrations and private firms spread all over the world. Initially, the early use of 3D city models has been dominated by visualization only, and the main purpose was providing public access to users for an attractive view of the urban environment and all its geographic elements in a certain area, taking advantage of 3D models for tourism and marketing tasks. In recent times, by virtue of new software and new modeling technologies, 3D spatial and non-spatial information has been implemented in several cities. Consequently, 3D city models have become estimable for various domains beyond visualization and have been extended to larger number of tasks, such as urban planning, disaster simulation, virtual-heritage conservation and many others. However, on the one hand, the increasing number of different applications that employ 3D city models, where each of them requires its own specific LoD, and on the other hand, the complexity of 3D model generation process, have led to a fuzzy vision about the real possibilities of utilization that 3D city models have.

35.1.1 Outline

In light of that, the first part of this chapter (Section 35.2) provides a comprehensive inventory of use cases, where specific 3D data requirements are Review Copy Only – Not for Redistribution Gabriele Garnero - Università degli Studi di Torino - 26/06/2024 Handbook of Digital Twins

classified for certain applications, hence delineating which 3D models with their specific LoDs fit-for-purpose. Since visualization seems to be the only criterion that is suitable and can cover almost all fields of application, a wide range of use cases that employ 3D city models has been chosen and categorized into two groups. The first regards non-visualization use cases, where the visualization of 3D city models is not required and the results of the spatial operations can be just stored in a database. The second group concerns visualization-based use cases, where the visualization of 3D city model is essential and without it the use cases part of this group would not make much sense. Successively, the use of 3D models as support tools throughout the planning process is investigated in-depth. Indeed, 3D city models are commonly used to display virtually existing cities as well as publicly divulge three-dimensional visualization about future developments, plans and projects in a 3D environment. Furthermore, these visualizations can be used in two-way communication where citizens can comment back and propose better alternatives after having inspected the plan, providing either positive or negative feedbacks to local authorities, information to citizens about hypothetical new developments in a 3D environment. Subsequently, to better understand how much attention the opinion of diverse actors deserves throughout the whole process, two different approaches widespread among municipalities are described, which use virtual city modeling to make engagement of different stakeholders faster and easier during the decisions-making process: the User-oriented approach and the E-participation technology.

The second part (Section 35.3) regards the description of a project developed at Vaxholms Stad, the municipality office of Vaxholm, a small town of the Stockholm County in Sweden. The project aimed to create a system that allows 3D visualizations of Vaxön's urban structure, which is the most populated island of the whole municipality chosen as the area of study. By virtue of the software FME, and the combination of data source with different formats, a geo database has been created to represent and manage a virtual LoD2 3D buildings model of Vaxholm, which has been visualized on Google Earth, allowing citizens to easily read and view the 3D model into a free web-based mapping platform as Google Earth. In addition, the detailed planning and project of Vauxhall are added to the three-dimensional model, and the planning work is still in progress. Indeed, citizens had the possibility not only to inspect the 3D city model of Vaxön on GE but also, from the plans mapped on the earth surface, to have access directly by the model to the interested area and to all the detailed information about a certain plan on the municipality web page. Furthermore, thanks to Google Earth functions, citizens can leave a feedback by e-mail to the city administration, claiming for their needs about a specific plan or just providing their points of view about what has been mapped on the 3D model. Finally, based on the results obtained, the possible improvements of the adopted program are predicted, and other applications of the 3D building model that may be extended in the future are prospected.

35.1.2 Materials and Methodologies

The objective of this article is to investigate what the real potential of 3D city models can be for planning activities as well as for many other domains related to the city's development, in order to identify an efficient procedure to create 3D city models for municipalities, and which advantages they can get if equipped with this planning tool. To gather such information, the main methodology used in this essay was based on a survey and literature review of, mostly, online resources publicized in the last two decades, such as scientific journals, academic articles, theses and project reports. These documents were related in some cases, to the current application and utilization of 3D city models in diverse domains and in others, to the broad number of different approaches used today to create 3D city models at various levels of details. Most of the literature found about the topic debated includes cases of study taken as examples, in which cities were already equipped with 3D city models, and that were mainly chosen in Austria, Kenya and Sweden, where the 3D city model of Vaxholm has been developed. This study area was selected because it presents a mixture of historic and modern buildings with homogeneous architecture styles, which made easier the reconstruction of the 3D buildings, and where the highest building was about 20 m. Once all the documents were retrieved, a comprehensive and systematic synthesis was delineated through the sections of this essay, aiming to sort out the objectives aforementioned. First, an overview was reported about which application fields the use of 3D city models could be convenient for. Successively, a hypothetical procedure was proposed, already implemented in Sweden, to create a 3D city model, which in turn will be used as a tool for citizens' engagement throughout the decision-making process.

35.2 Theoretical Overview

35.2.1 Geometrics and Semantic Properties of 3D City Models

3D city models are digital representations of certain objects in the urban environment, which include earth surface, vegetation, infrastructure, landscape elements and buildings, created through a modeling process [1]. The third dimension indicates 3D GIS (Geographic Information System) data, where each dimension is geometrically defined. However, besides geometry, an important component of 3D city models is semantic information, which can be described as any information that is not visible as the geometry is, e.g., the land use of a building. Both geometric and semantic properties of 3D models are stored in diverse 'levels-of-detail' (LoD). The LoD approach, Review Copy Only – Not for Redistribution Gabriele Garnero - Università degli Studi di Torino - 26/06/2024 Handbook of Digital Twins

defined by the CityGML¹ standard, is a coherent modeling of geometric and topological properties at each level, where geometric objects get assigned to semantic objects. The LoD definition is mainly used for the details of the buildings, which are the most important items in a 3D city model, and it is a fundamental concept in 3D city modeling since it defines the degree of abstraction of real-world's elements [1].

35.2.2 Related Works

Nowadays, the development of new technologies has allowed the implementation of 3D geo-information data in several cities, which is rapidly growing and expanding in different research fields. The early use of 3D city models has been dominated by visualization only. However, by virtue of new software and new modeling methodologies, 3D city models have become estimable for several domains beyond visualization, and are currently used in a large number of purposes. During the past years, some researchers have studied the applicability of 3D geo-information, focusing on solving industrial and experimentation problems. For instance, Ross in 2010 [2], proposed a general taxonomy of 3D use cases, which relies on the type of data that each model contains: applications based on geometry (e.g. estimation of the shadow); applications based on geometry and semantic information (e.g. estimation of the solar potential); applications based on domain-specific extensions and external data (e.g. noise emission calculation). However, it is important to note that such categories are not 'exclusive' in all cases, but some applications might fit in more than one category. For example, to estimate the propagation of noise in an urban environment, only the geometry of buildings is needed. Furthermore, if hypothetically semantic information of geometries is also known, such as inhabitants or building's material, these data may represent important improvements for predictions and better assessment of noise consequences [3].

Biljecki et al. [3] conducted another study in 2015, where they argued that visualization might be considered as the only criterion that is suitable and can cover almost all categories of applications. Hence, the taxonomy of use cases mentioned above can be further categorized into two groups. The first concerns non-visualization use cases, where the visualization of the 3D model and the results of the 3D spatial operations can be visualized, but it is not essential to achieve the task of the use case since the results can be stored in a database. The second group regards visualization-based use cases, where instead, visualization is essential and the use cases would not make much sense without it. Based on these two groups, distinct use cases have been identified in several application domains.

¹ *City GML:* Today, the number of cities that are representing their 3D city models according to the CityGML standard is growing. This standard has been issued by the OGC (Open Geospatial Consortium) to decompose articulated objects [1].

Review Copy Only – Not for Redistribution Gabriele Garnero - Università degli Studi di Torino - 26/06/2024 3D City Models in Planning Activities 607

35.2.2.1 Non-visualization Use Cases

Environmental simulations part of this group are, for instance, the estimation of solar irradiation, where 3D data are used to evaluate the solar potential on rooftops in urban areas, and thus, to assess how much a building is exposed to the sunlight, in order to evaluate the suitability of a roof surface for installing photovoltaic panels above it. Another analysis concerns the energy demand estimation, where 3D city models are used to combine the data of the building's volume, number of floors, type of buildings, and other features to predict the energy demand for heating or cooling. A further estimation regards the distribution and shape of a building type in a neighborhood, which may help marketing and real estate management fields, forecasting its potential for taxation and valuation of buildings [3].

35.2.2.2 Visualization-Based Use Cases

Visualization is considered as one of the most used applications of 3D city models since it is able to provide panoramic views, web visualizations, profiling and other related works. Furthermore, it is generally used for an attractive presentation of the results from such analyses, which can be related to GIS, as in a visibility analysis, or which are not necessarily related to GIS, as economic activities [3]. Indeed, 3D city models are fundamental for various kinds of visibility analyses.

In light of the classification above mentioned, it is clear that 3D city models are currently used in a lot of domains for several purposes. The second group related to visualization-based applications is broader than the first one. This suggests that visualization is a fundamental feature of the contemporary workflows involving 3D city models. Therefore, this analysis has revealed some interesting patterns about the development and large utilization of 3D city models, and how a lot of use cases already prove the valuable role and their growth over time.

35.2.3 A Support Tool for Urban Planning and Facility Management

In recent times, 3D city models have been widely used by designer and urban planners as decision-making tools employed to explore, plan and actively act on cities. For instance, a visualization application of 3D city models can virtually display existing cities as well as may provide urban information to citizens about hypothetical developments in a 3D environment [4]. Furthermore, today's web technologies and availability of 3D city models, at different LoDs, enables local governments to communicate spatial plans to their citizens, but also it can be used in two-way communication where citizens can comment back and propose better alternatives, submitting either positive or negative feedbacks to local authorities [5]. This means that 3D city models can be useful to investigate local dynamics and best fitting urban indicators for a future enhancement [3]. Review Copy Only – Not for Redistribution Gabriele Garnero - Università degli Studi di Torino - 26/06/2024 Handbook of Digital Twins

35.2.3.1 User-Oriented

A useful method to achieve what is mentioned above might be a solution-oriented approach. This process starts with the collection of citizens' issues and needs, then understanding them carefully and subsequently, trying to figure out what the optimal solutions that solve citizens' problems might be. Therefore, user-oriented requirements may become helpful tools for a more transparent communication and a better decision-making process, which can improve the quality of the planning process. In Salzburg, Austria, a study has been accomplished thanks to the research project Digital Cities,² which Autodesk has conducted with Z_GIS and the City of Salzburg as a pilot city. The research was focused on the analysis of the impact that a future urban development could have in Salzburg. To do that, a combination of city data with realistic visualizations and simulation tools allowed Salzburg authorities to view and interact with the city landscape and analyze the impact of future urban planning, tourism, and economic development projects before they are built [6]. Successively, aiming to create an integrated tool for the working processes, a user-oriented approach was implemented. Indeed, users could express their needs that, in a second moment, have been structured in detailed requirements for digital cities. These requirements covered all the components of the digital cities working environment and aimed to embrace all the tasks that had value for the City of Salzburg [7]. Thus, this kind of analysis conducted, in order to be user-oriented, was context-oriented as well. At the end, two application areas have been selected: the first area concerns visual communication of planned development and navigation in the city model, considered at a different scale, from building modifications to planning the whole city districts, which represents the communication basis to involve stakeholders of different areas of expertise. The second application area regards the management of geographic objects that need to be represented in three-dimensions and that are spread over a big area of the city. In both application areas, respectively, planned modifications and geographic objects were integrated into their surroundings and could be analyzed by their spatial relations with other geographic elements [7]. In light of that, it can be argued that the digital cities environment may help cities like Salzburg to visualize and communicate proposed changes in urban areas to inhabitants. The data collected in Salzburg, especially about urban planning tasks, can be suitable for other urban contexts, such as cities with equal size, number of inhabitants, levels of development, social environment, and historical buildings structure.

² Digital Cities: 'The Digital City initiative is Autodesk's unique technology designed to provide a collaborative environment for visualizing, analyzing and simulating the future impact of urban design and development at a city-wide scale'. http://www.autodesk.com/ digitalcities.

35.2.3.2 E-Participation

During the past years, E-participation has been frequently used to involve citizens in urban planning and management [5]. Indeed, web technologies, today, facilitate the communication of citizens' feedbacks about development plans promoted by authorities in order to eliminate the need for citizens to gather together in a certain place and in a specific moment. Through these technologies, a citizen may choose how, when and where to take part, even anonymously if he wants, to the decision-making process simply using a web portal. Aiming to prove the feasibility of the E-participation approach in developing countries, a 3D model with a web portal access has been created for the city of Kismu, in Kenya. Experiments have been held to measure the ability of groups of people from different backgrounds. The 3D model created was visualized in a web portal, provided by ArcGIS online, and each participant had the possibility to take part remotely, without meetings to take part in the whole process. Essentially, each citizen could easily create an account, log in, view, navigate through and leave comments in the portal. Subsequently, opinions, proposals and various alternatives gathered have been discussed throughout plenary workshops [5]. To verify participants' abilities coping with the designed 3D model, two tasks have been identified: the first regards 2D maps on A3 sheets with road networks and a list of feature names, where each participant had to pick the name of a feature in the list, locate it and mark it in the 2D map within a time limit. The second task had the same process, but with a 3D city model stored in a web-based portal. The participants' performance has been measured calculating the time needed to complete the tasks and counting the number of correct objects identified. Considering these factors, the results have shown that for all groups, the 3D task has taken less time than the first one and also appeared in more correct answers than the 2D task [5].

35.3 A Practical Application of 3D City Models

35.3.1 Public Use of the 3D City Models in the Swedish Environment

Since 1970 in Sweden, after a decentralization process that has brought about a considerable power transition to counties and especially to municipalities, the fields of territorial and urban planning are managed by the public sector and municipalities, who are considered the main actors [8]. In light of that, the 3D industry in Sweden is increasingly developing thanks to the recurring employment of 3D models in public use and particularly in city planning applications widespread in many municipalities. Indeed, many Swedish cities are currently engaged in projects that aim to reinvent the Review Copy Only – Not for Redistribution Gabriele Garnero - Università degli Studi di Torino - 26/06/2024 Handbook of Digital Twins



FIGURE 35.1

From the left: Stockholm Royal Sea Port; *Min Stad* in Gothenburg; touchscreen of Linköping's 3D city model [10].

use of 3D city models for the promotion of the city development and public participation [9].

As shown in Figure 35.1, in projects like Stockholm Royal Sea Port, *Min Stad* and the Linköping's touch screen, the digital dialogue's structure consists essentially of a web portal or a touch screen, which uses an interactive 3D city model as background and encourages citizens to post ideas, according to their needs, that can be useful for the development and enhancement of several projects in certain contexts [10]. Therefore, the recent broad employment of 3D city models for public uses and stakeholders engagement have allowed many cities in Sweden to digitally promote the implementation of new projects in their territory as well as inviting an increasing number of citizens to take part in the decision-making process.

35.3.2 Study Area

The generation of a 3D city model for the city of Vaxholm will be carried out throughout this chapter as a case study to get firsthand experience with some of the available methods to create 3D city models. The whole process to create the model, the results obtained and the potential future applications and improvements that the model may reach will be presented in this chapter as well. The geographic area used in this case study, as aforesaid, is the municipality of Vaxholm, which is located in northwest of Stockholm and is often referred as the capital of its Archipelago [11].

35.3.3 The Generation Process

Throughout the next paragraphs will be presented the workflow generated to reconstruct a 3D building model with textured roofs at LoD2. The project developed aimed to create a system that allows 3D visualizations of Vaxön's urban structure, the main and most populated island of the whole municipality chosen as study area. Through the use of the software FME, and the combination of different data formats, LIDAR point clouds, 2D footprints in shapefiles and ortho images in ECW (Enhanced Compression Wavelet), a geo database handled in a FME workflow has been created to represent and manage the virtual 3D building models of Vaxholm, as shown in Figure 35.2.

Review Copy Only – Not for Redistribution Gabriele Garnero - Università degli Studi di Torino - 26/06/2024 3D City Models in Planning Activities 611



FIGURE 35.2

Workspace assembled to shape integrated 3D buildings models (Own elaboration from FMEDesktop).

The KML format was chosen because it is compatible with GE, and thus, allowing citizens to easily read and view the 3D model in a free widespread web-based mapping application as GE. Furthermore, the KML model has been spread out on the earth surface in GE, which, as in reality, presents the earth slopes according to the sea level, as shown in Figure 35.3.

Furthermore, *Detaljplaner* (Detailed plans) and *Projekt* (Projects) *pågående planarbeten* (with an ongoing plan work) have been added to the 3D buildings model, representing a zoning spread on the island of Vaxön in proximity to those buildings' part of the plans. Therefore, adding these plans has improved the usability of the 3D model, not only as a mere 3D visualization of the municipality, but rather as an effective urban planning tool. Indeed,



FIGURE 35.3

Visualization on Google Earth of the 3D models, detailed plans and projects (Own elaboration from GE).

Review Copy Only – Not for Redistribution Gabriele Garnero - Università degli Studi di Torino - 26/06/2024 Handbook of Digital Twins

these types of plans are legally binding in Sweden and thus, considered as the most incisive ones at the local level. They are planned for specific areas of the municipality where particular development process makes such plans fundamental. For instance, they can be adopted for: new buildings of an urban settlement; evaluation of the potential development in an urban area; and identifying a building with significant impact on the surrounding area and others cases [8].

35.3.4 Results Achieved

As aforementioned, only the plans where the planning process was still ongoing have been selected and added to the 3D model. The reason was to allow the municipality of Vaxholm, throughout the *iter* of approval, to take into consideration different alternatives proposed by citizens about those plans, and eventually, modifying some features before the approval of a certain plan. Indeed the plans mapped on GE can be easily switched on and switched off from the legend on the left side, according to the users' interest, and also present an URL link in the attributes content that from a clickable pop-up window connects each user directly to the plan information, published on Vaxholm municipality's webpage, as shown in Figure 35.4. In this way, citizens have the possibility not only to inspect the 3D city model of Vaxön on a GE but also to have access directly from the model, specifically on the interested area, to all the documents about analysis and studies conducted before drawing up the plan, planimetries and different types of maps about measures and quantities about the construction of new buildings and any other information about the area of interest, which are available on the webpage. In light of that, the integration between the 3D building models and the plans with pending approval may represent a helpful planning tool for those citizens who are not familiar with a web-GIS portal. For this reason, a free widespread program with an easy interface as GE has been chosen for the visualization of an interactive 3D building model.

Furthermore, the inhabitants of Vaxholm, besides the visualization of the 3D models and the connection that detailed plans have with the municipality's webpage, have also the possibility to login in GE with their private e-mail account and leave opinions, complaints and proposals about a building or a whole area, In order to attach a screenshot or KML of the subject they are interested in to the email, an email was sent to the Vauxhall Municipality.

Therefore, Google Earth, besides a simple visualization of the 3D model generated, provides a user-friendly tool to the citizens of Vaxholm, which allows them to have a clear and quick access to all the information about what is going to happen in certain areas, in order to give them a chance to have voice within the planning process of those plans with pending approval. Review Copy Only – Not for Redistribution Gabriele Garnero - Università degli Studi di Torino - 26/06/2024 3D City Models in Planning Activities 613



FIGURE 35.4

On the top: the pop-up window with the URL link (Own elaboration from GE) that connects users directly to the detailed plan information on the municipality's website, on the bottom [11].

35.4 Conclusions and Future Improvements

The evidence presented in this article clearly indicates that 3D city models have proved to be estimable for a large number of domains during the last few years and thus have been recently used in large number of application ambits and for diverse purposes related to cities' development that, throughout this chapter, have been classified according diverse criteria. These principles can Review Copy Only – Not for Redistribution Gabriele Garnero - Università degli Studi di Torino - 26/06/2024 614 Handbook of Digital Twins

regard the geometry of the building, if the task, for example, is the estimation of shadow; or semantic information stored in each building, if we refer to the estimation of solar irradiation. However, the most relevant criterion followed to individuate two main groups, concerns the visualization or non-visualization of 3D models. Indeed, besides being the first early-use domain of application for 3D city models, visualization is arguably an indivisible part of the workflows that involve 3D city models and it can be considered as the only criterion that is adaptable to almost all categories of applications mentioned in the last chapters. Successively, in examining how the utilization of 3D city models in purposes related to urban analyses is growing, some interesting patterns have been delineated. For instance, it has been revealed that, by virtue of new technologies and methods for data acquisition and processing that have enhanced the efficiency of 3D city models, the requirements of 3D city models have changed direction: from a mere realistic geographical representation of cities that provides to users public access for the exploration of 3D elements, currently, the goals that a city administration wants to achieve using a 3D city model go toward the realization of a detailed and attractive representation of the urban environment that, thanks to specific interactive functions, enables users to retrieve from buildings spatial and non-spatial attributes data when they interact with the model. As it has been shown in some case studies aforementioned, this information stored in the 3D model may regard the building features about its structure (e.g. height and number of households that live in the building), or on the other hand, may concern a future development plan drawn up for the area of interest that shows how the area would look like in the future, or as in the case of Vaxholm, the model visualized in a web-mapping platform can present some clickable pop-up windows that connect users directly to the municipality's webpage where all the documents related to the plans of interest are published and open for inspection. Another pattern emerged, regarding the recent increasing spread of 3D city models toward a larger number of public and private institutions, such as city administrations, mapping agencies, private firms, universities research departments and many others [12]. Most of the research papers and articles available on the web, documenting uses of 3D city models and integration of them as planning tools employed by several municipalities, have been published during the last decade. Hence, this fundamental support tool has been already adopted by every municipality that has a dense urban structure and a copious population or, for the cities where it is not yet, they are in the process of setting up 3D city models as part of their planning tools [13].

Given the results achieved, this research might be helpful for all stakeholders involved in 3D city modeling community with different level of decision-making, in the way that they may use it to make improvements to their product or at least understand the range of applications that 3D geoinformation can offer today. Also, it might be beneficial as a reference that provides a detailed insight defining use case scenarios and then according to the purposes that have to be achieved, setting the suitable requirements when procuring the 3D datasets. Even though the large number of cases of study that have been mentioned proves already the estimable role and the high demand of 3D city models, further technologies' improvements, new scenarios and cases of application, are expected in the following years. One of the biggest tasks related to the field of 3D city models is to find cost-effective and avoid time-consuming approaches to create models rich in semantic information. For instance, improvements toward the integration of computer graphics, GIS and BIM would allow on the one side, the realization of more detailed 3D city models, and on the other side, rich information stored in the model would allow new types of applications to be planned thereby increasing the possibilities associated with 3D city models.

The integration of 3D modeling with dynamic visibility analysis is being developed in order to allow users (citizens, planners, members of landscape commissions, ... up to students) to analyze the urban proposals presented using this key [14,15].

In conclusion, in light of the all above-mentioned considerations, it can be asserted that virtual city modeling for many municipalities is a new approach to manage cities' development and to encourage participation of the public within the planning process. A 3D city model can help cities, both similar to and different from Vaxholm, to visualize, inspect, and communicate proposed developments and changes of their urban environment. The approach followed to generate the model can be applicable in other contexts with similar characteristics, such as equal size, number of inhabitants, historical background and building structure, as a support tool for more transparent communication with the citizens that have the potentiality to improve the quality of the planning process. However, there is a lot more to investigate in this field that unluckily is outside the scope of this dissertation, but it is clear that the more detailed is the model and rich of semantic information, the greater are the possibilities to include additional applications with the model as a basis.

The tools developed are used in academic activities and represent a significant example to be promoted as best practices at various administrative levels.

Acknowledgments

This chapter is the result of a Master of Science Thesis handed-in to the Politecnico of Turin. The authors would like to acknowledge the support of the Building Law and GIS Unit (Bygglov- och GIS-enhet) of Vaxholms Stad, Sweden, for the development of the 3D city model used as case study.

References

- 1. Biljecki, F. The concept of level of detail in 3D city models. GISt Report No. 62. Delft University of Technology. **2013**. pp. 1–25.
- Ross, L. Virtual 3D City Models in Urban Land Management-Technologies and Applications. Ph.D. Thesis, Technische Universität Berlin (TUB), Berlin, Germany, 2010.
- 3. Biljecki, F.; Stoter, J.; Ledoux, H.; Zlatanova, S.; Çöltekin, A. Applications of 3D city models: State of the art review. *ISPRS Int. J. Geo-Inf.* **2015**, 4, pp. 2842–2889.
- Buhur, S.; Ross, L.; Büyüksalih, G.; Baz, I. 3D city modeling for planning activities, case study: Haydarpasa train station, haydarpasa port and surrounding backside zones. *Istanbul. Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* 2009, 38. pp. 1–6.
- 5. Onyimbi, J.R.; Koeva, M.; Flacke, J. Public participation using 3D city models. E-participation opportunities in Kenya. *GIM International*, **2017**, 31. pp. 29–31.
- 6. Autodesk. Autodesk Announces Salzburg, Austria, as First Pilot City of Its Digital Cities Initiative. Press Room Archieve, **2008**. Available online: https://www.autodesk.com/digitalcities (Accessed the 23rd September 2017).
- 7. Albrecht, F.; Moser, J. Potential of 3D City Models for Municipalities The User-Oriented Case Study of Salzburg. **2008**. pp. 2–8.
- 8. Solly, A. *The Europeanization of Spatial Planning: The Case of Sweden*. Master Thesis in Territorial, Urban, Environmental and Landscape Planning at Politecnico of Turin, **2013**.
- GIM International. Sweden Excels in Public Use of 3D in Smart City Applications. Mapping the world. 2015. Available online: https://www.gim-international.com/ content/news/swedish-cities-excel-in-public-use-of-3d-in-smart-city-applications (Accessed the 1st October 2017).
- Agency9. Swedish Cities Innovate 3D Use in Smart City applications. 2015. Available online: https://agency9.com/swedish-cities-innovate-3d-use-insmart-city-applications/ (Accessed the 14th of November 2017).
- 11. Vaxholms Stad. *Vaxholm skärgårdens huvudstad*. **2017**. Available online: https://www.vaxholm.se/turistwebb-startsida.html (Accessed the 3rd of December 2017).
- Salata, S.; Garnero, G.; Barbieri, C. A.; Giaimo, C. The integration of ecosystem services in planning: An evaluation of the nutrient retention model using InVEST software. *Land*, 2017, 6. 48p [DOI: 10.3390/land6030048].
- Minucciani, V.; Garnero, G.: Available and implementable technologies for virtual tourism: A prototypal station project. In B. Murgante et al. (Eds.): *ICCSA 2013*, Part IV, published in Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics), LNCS 7974 (ISSN: 0302-9743, ISBN: 978-3-642-39649-6), pp. 193–204. Springer, Heidelberg (2013) [DOI: 10.1007/978-3-642-39649-6-14].
- 14. Garnero, G.; Fabrizio, E. Visibility analysis in urban spaces: A raster-based approach and case studies. *Environment and Planning B-Planning & Design*, **2015**, 42. pp. 688–707 [DOI: 10.1068/b130119p].
- Fabrizio, E.; Garnero, G. Visual impact in the urban environment: The case of out-of-scale buildings. *Journal of Land Use, Mobility and Environment*, 2014. pp. 377–388 [DOI: 10.6092/1970-9870/2477].