Urban Solutions and Sustainability R&D Congress 2023

Science of Cities Symposium

5th October 2023, Thursday

Sands Expo & Convention Hall, Singapore

Abstract Proceedings

CENTRE for LiveableCities SINGAPORE

URBAN SOLUTIONS AND SUSTAINABILITY R&D CONGRESS 2023
BUILDING SUSTAINABLE, RESILIENT, AND LIVEABLE CITIES OF TOMORROW
4TH - 5TH OCTOBER 2023

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Introduction

The second run of the Science of Cities Symposium will be held in-person as part of the Urban Solutions & Sustainability (USS) R&D Congress. It will be held on:

Date: 5th October 2023, Thursday
Venue: Sands Expo Hall and Convention Centre, Level 3, 10 Bayfront Avenue, Singapore 018956

Convening research heads, academics, as well as city and industry leaders involved and/or keen on research developments in three panels, representing three emerging yet pertinent fields:

Panel 1: Science-based Approach to Future Scenario Planning

With increasingly unpredictable dynamics of cities and their development trajectory, planning cities can be a challenge. A systems level science-based approach can help reduce uncertainty by identifying the key underlying drivers of the urban system and its emergent behaviours, grasp the co-evolution of different systems, and simulate plausible future scenarios. By combining scientific urban science concepts such as circular causality and complexity sciences with advanced computational modelling and data, emergent patterns and trends can be detected at various temporal and spatial scales, helping to plan for the future of cities.

Panel 2: Science of Decarbonising Cities

The call for decarbonisation has intensified, requiring solutions to ease the phasing down of fossil fuels, develop clear funding frameworks and standards, and inform decarbonisation transitions within and beyond cities' consumption value chains, before 2050. Science can help address decarbonisation gaps in the built environment, such as by innovating low-carbon designs and practices, developing decarbonisation accounting tools, synergising strategies, and optimising trade-offs. These can devise city-specific pathways to accelerate the attainment of net-zero targets across their sectors and systems.

Panel 3: Regenerative Cities

Co-Curated by Singapore-ETH Centre (SEC) Future Cities Laboratory (FCL) Global

According to the recently released U.N. Intergovernmental Panel on Climate Change (IPCC) report on climate change, the world is likely to pass a dangerous temperature threshold within the next 10 years, pushing the planet past the point of catastrophic warming — unless nations drastically transform their economies and immediately transition away from fossil fuels. Estimates suggest that cities are responsible for 75% of global CO2 emissions, with transport and buildings being among the largest contributors. This is an urgent call for urban planners, policymakers, and researchers to take action and affect transformational change to shrink the urban environmental footprint, as the settlement footprints expand, the interconnections between them become even more complex. We require a sustainable and regenerative approach, creating a restorative relationship between cities and the context they are situated within. This session presents six such regenerative strategies.

Through the presentations, panel discussions, and posters, the symposium will serve as the academic platform of R&D Congress, where insights from scientific knowledge and research methodologies would complement the congress' theme in showcasing Singapore's R&D efforts in becoming a highly liveable, sustainable, and resilient city of the future. The Congress will also showcase innovations in

resource circularity, climate adaptation, building cities that nurture citizens' health and well-being, and building resilience in the built environment sector through automation and digitalisation.

Symposium Programme

Time (GMT+8)	**Programme**
9.00–9.10am	**Opening Remarks *by Ms Adele Tan***
Panel 1: Science-based Approach to Future Scenario Planning	
9.10–11.00am	**K1.1:** UrbanSense: Empowering Communities through Active Sensing for Sustainable Urban Development *LONG Ying* **K1.2:** Re-imagining Urban Futures: How Cities Can Leverage Strategic & Transformative Foresight *John A. SWEENEY* **O1.1:** A Case-based Search Engine for Mapping Urban Patterns & Cases Integrating Street View Imagery *Pieter HERTHOGS* **O1.2:** Urbanity: Automated Modelling and Analysis of Multidimensional Networks in Cities *Winston YAP* **O1.3:** A Digital Urban Climate Twin of Singapore to analyse Green Plan 2030 scenarios *Heiko AYDT* **O1.4:** Analysing Systemic Traffic Conditions in Singapore through Epidemic Spreading Models *Dake WU* **O1.5:** Understanding Active Mobility using Computer Vision and Data Visualisation *Sam C. JOYCE* **Panel discussion** (moderated by keynote speakers)
11.00–11.30am	Congress tea break
Panel 2: Science of Decarbonising Cities	
11.30am–1.30pm	**K2.1:** Design to Decarbonise: Effective Tools to Reduce Urban Building Emissions *Arno SCHLUETER* **K2.2:** Sufficiency, Justice and Urban Transport *Philipp RODE* **O2.1:** A Global Bottom-up Approach to create Urban Digital Twins (UDT): Mitigating Greenhouse Gas (GHG) Emissions *Pradeep ALVA* **O2.2:** Material stock-service and circularity prospects of buildings in Singapore *Anthony MEIJER* **O2.3:** Can New Urban Rail Transit Lines Reduce Car Ownership? — Evidence from the Opening of the Circle Line in Singapore *DAI Fangzhou* **O2.4:** Significant Carbon Mitigation Potential from Installed Rooftop Photovoltaics in Singapore: A GIS-integrated Life Cycle Assessment *ZHU Rui* **O2.5:** Accelerating PV Adoption in Singapore: The Potential of Advanced Energy Communities *KANG Jidong* **Panel discussion** (moderated by keynote speakers)
1.30–2.30pm	Congress Lunch

Panel 3: Regenerative Cities (Co-curated with FCL Global)	
2.30pm–4.30pm	**Panel Welcome Address** by *Professor Sacha MENZ* **Panel Opening Address** by *Professor Thomas SCHROEFFER* **Regenerative Cities: Circular Districts** **OF.1:** From Urban Mining to Urban Harvesting: Building Shared Frameworks for Circular Future Cities *Pieter HERTHOGS* **OF.2:** Integrating Renewables within the City *Francis B.S. LEE* **OF.3:** Dense and Green Cities for a Nature-Positive Future *Srilalitha GOPALAKIRSHNAN* **Panel discussion** (moderated by Dr. Gopalakrishnan) **Regenerative Cities: Transformative Strategies** **OF.4:** Long-term Solar PV Planning in High-Density Urban Systems *Alberto COSTA* **OF.5:** Cities as Social Reactors *CHEONG Siew Ann* **OF.6:** Adaptive Planning of Charging Infrastructure for Electric Vehicles *Prateek BANSAL* **Panel discussion** (moderated by Dr. Gopalakrishnan)
4.30pm–5.30pm	**Networking Evening Tea** **Poster Exhibition Presentations**

Opening/Welcome Addressees

Symposium Opening Addressee

Adele TAN

Acting Deputy Chief Executive Officer and Chief Planner, Urban Redevelopment Authority (URA)

Responsible for long-term land use planning for Singapore, she has been involved in a broad range of land use planning areas, ranging from planning for an aging population, to developing a master plan for our underground space. She also drove a range of important planning and policy workstreams in her 25 years of public service in URA, the Ministry of National Development, and the National Parks Board, ensuring that Singapore's land use plans effectively meet Singapore's diverse economic, social, and environmental needs, while also addressing its future challenges. With a background in civil engineering and operations research as well and public administration, Adele is well-versed in utilising a methodological and evidence-based approach in translating research to policy.

Co-Curated Panel Welcome and Opening Addressees

Sacha MENZ

Professor, ETH-Zurich
Programme Director and Principal Investigator, Future Cities Laboratory (FCL) Global

Sacha Menz is Full Professor of Architecture and Building Process at ETH Zurich and the Head and Co-Founder of the Institute of Technology in Architecture (ITA), Dean and Vice-Dean of the Department of Architecture at ETH Zurich. He is Director of FCL Global under the Singapore-ETH Centre. Sacha has over ten years of research experience in high-density, high-liveability urban development and transformation. He has been leading multi-disciplinary research projects in Singapore and Zurich, investigating buildings and urban planning performance in different urban contexts. He is also a Principal Investigator of the Dense and Green Cities research module in FCL Global Zurich. Additionally, Sacha is a practising architect and urban planner and co-owner of the architecture firm SAM Architekten und Partner AG in Zurich since 1997. He has various executive and strategic positions in the Federation of Swiss Architects (FSA) and the Swiss Society of Engineers and Architects (SIA).

Thomas SCHROEPFER

Professor, Singapore University of Technology and Design (SUTD)
Programme Co-Director and Principal Investigator, Future Cities Laboratory (FCL) Global

Dr Thomas Schroepfer is Full Professor of Architecture and Sustainable Design at the Singapore University of Technology and Design and Co-Director of the Singapore-ETH Centre Future Cities Laboratory (FCL) Global. His research and design projects relate to advances in environmental sustainability, materials, structure and form, performance and energy, digital fabrication and building processes. He has published extensively on his work that has been exhibited at important international venues including the Venice Architecture Biennale and the World Architecture Festival. His books have been translated into several languages and include Dense and Green Cities: Architecture as Urban Ecosystem (2020), Dense and Green: Innovative Building Types for Sustainable Urban Architecture (2016), and Ecological Urban Architecture (2012). He is the recipient of prestigious awards and recognitions including the President's Design Award, Singapore’s highest honour accorded to designers and designs across all disciplines; the German Design Award; and the Asia Education Leadership Award.

Panel 1: Science-based Approach to Future Scenario Planning

Abstracts – Keynotes

K1.1

UrbanSense: Empowering Communities through Active Sensing for Sustainable Urban Development

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Accurate monitoring of urban environments and their dynamics is essential for achieving the Sustainable Development Goals (SDGs) set by the United Nations. However, traditional sensing methods face challenges in meeting the needs of urban monitoring, including difficulties in balancing spatial and temporal granularity, high human and material costs, and a mismatch in study scope due to data-driven rather than demand-driven approaches. In recent years, active urban sensing methods have emerged as more flexible approaches that can adapt to varying demands. Three sensing paradigms — stationary sensing, mobile sensing and collaborative sensing — have been practiced in research. This paper proposes a framework for an active urban sensing approach: firstly, it categorises and aggregates literature on active urban sensing techniques, refines monitoring objects and sensing paradigms, and forms an evidence-based metrics library for active urban sensing. Secondly, in order to conclude the application conditions of different sensing paradigms, the metrics are further clustered according to volatility, spatial resolution and spatio-temporal coverage, and five application scenarios are further summarised to form a decision tree for sensing paradigm selection. This framework serves as a valuable reference for data refinement in less developed areas with missing or untimely data updates, as well as developed areas with insufficient data coverage and density, enabling active urban sensing to be applied in a wider range of demand scenarios and contribute to the achievement of SDGs in community research contexts.

K1.2

Re-imagining Urban Futures: How Cities Can Leverage Strategic & Transformative Foresight

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In recent years, cities have turned towards forward-looking approaches aimed at creating more resilient policies, plans, and strategies. This talk provides a framework and case studies centered on the usage of foresight within urban contexts with a particular focus on participatory futures tools and methods. From Mexico City to Płock, there are numerous case studies that demonstrate the value and impact of foresight, specifically how to include more citizens and residents in decision-making. Additionally, this talk puts forward a framework for distinguishing between strategic and transformative foresight, which situates the latter as focused more inward with an emphasis on perceptions, hopes, and fears. Designed for an audience with little or no exposure to foresight, this

talk offers an introduction to forward-looking approaches within the context of urban planning, policy, and strategy development, design, and delivery.

Abstracts – Oral Presentations

* denotes presenters

O1.1

A Case-based Search Engine for Mapping Urban Patterns and Cases Integrating Street View Imagery

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Cities are considered complex and open environments with multidimensional aspects that influence each other in irreducible and unpredictable ways. The urban design process highly relies on individual understanding and implicit knowledge that is case-based and experience-based. Linking city science and urban design is significant for progressing both sides. Both urban design and science can thus be enhanced by allowing individual knowledge as input to derive more generalizable evidence. Complex urban elements - the topics of science and design—need multi-source data and representations. However, we see a lack of digital modelling approaches for heterogeneous data integration, representation and interoperation. Therefore, we are working towards a methodology that integrates data streams, associates topical semantic urban elements, and enables a dialogue between users and machines, for mapping general urban patterns and specific cases. We present a case-based search engine for Nanjing that automatically collects urban semantic, spatial, and image data, extracts the geometry and image features, and enables easy case retrieval. Unsupervised learning and feature extraction techniques are applied to generate the general urban patterns, and the resulting patterns can be consulted by users using information retrieval techniques. We retrieved relevant cases using different combinations of geometry and imagery, illustrating both strong and weak relevance between urban patterns and cases. By enabling easy case retrieval, such a search engine could serve as an instrument for users to navigate among existing cases, and hence supports case-based reasoning related to urban design hypotheses about which characteristics make a particular case good (or bad), and would provide evidence to support or contradict case-based assumptions. This proposed framework can be expanded with additional data or combined with other urban search engines we developed. The model can help architects and urban designers with decision-making and supports the derivation of hidden rules in complex cities based on in-field, case-based experiences.

Keywords: Isovist analysis, Probabilistic modelling, Street view imagery, Self-organising map

O1.2

Urbanity: automated modelling and analysis of multidimensional networks in cities

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Urban networks play a vital role in connecting multiple urban components and developing our understanding of cities and urban systems. Despite the significant progress we have made in understanding how city networks are connected and spread out, we still have a lot to learn about the geospatial context and semantic attributes of these networks. The increasing availability of open data also offers opportunities to supplement urban networks with specific location information and create more expressive urban machine-learning models. In this work, we introduce Urbanity, a network-based Python package to automate the construction of feature-rich urban networks anywhere and at any geographical scale using open-sourced data. We discuss data sources, the features of our software, and demonstrate the utility using a set of data representing the networks of five major cities. We also test the usefulness of added context in our networks by classifying road categories within a single network. Our research results underscore the significance of considering contextual features when examining concealed patterns and spatial disparities within urban networks, as a means to bolster a systems-oriented approach in context-driven urban planning.

Keywords: Computer Vision, GIScience, GeoAI, Open-Source Software, Sustainability, Urban Planning

O1.3

A Digital Urban Climate Twin of Singapore to analyse Green Plan 2030 scenarios

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Cities are committed to sustainable development to reach 2050 targets of the Paris Agreement. Sustainable development requires an integrated approach that takes the cities infrastructure, its heat emissions, the vegetation and land use, the behaviour of people and the prevailing climate into account. These complex interactions have to be understood, requiring computational tools to support the analysis. The Digital Urban Climate Twin (DUCT), developed by the Cooling Singapore 2.0 project facilitates the coupling of relevant models together with the integration of required input data. We demonstrate the capabilities of the DUCT by assessing a set of Green Plan 2030 measures for Singapore. Time-resolved heat emissions of buildings, traffic, industry, and power plants are modelled and further integrated as gridded anthropogenic heat emissions into a meso-scale climate model of Singapore. Vegetation and land use is represented in the form of local climate zones. In total 16 Local Climate zones are used for representing differences in urban and rural configurations in the Meso-scale climate model. A base-representation of the current situation of Singapore is first

modelled and the contribution of different factors to the urban heat is evaluated. The analysis is conducted for a set of time periods in Singapore. Next, measures within the scope of the Green Plan's City in Nature, Energy Reset, Sustainable Living, and Green Economy pillars are translated into a set of scenarios using corresponding, adjustable variables such as electric vehicle share and vegetation cover, with the input data prepared. The impact of these scenarios on the urban heat for Singapore is then analysed, projecting that buildings and electric vehicle share can have a relatively large impact on UHI. This holistic analysis and visual interface can aid in deriving optimal urban climate adaptation solutions to improve outdoor thermal comfort, and the effects of potential future developments & policies on their effectiveness.

Keywords: Digital twin, Outdoor thermal comfort, Urban climate

O1.4

Analysing Systemic Traffic Conditions in Singapore through Epidemic Spreading Models

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Urban traffic is a highly complex system. While there has been extensive studies on the microscopic modelling of traffic jams at the local level, incorporating these microscopic features, such network structure and traffic condition, and the associated theories at macroscopic, urban-scale studies are often lacking. Given how such microscopic details of urban traffic system may affect the evolution of congestion, new models are needed to enhance the predictive capacity of traffic management systems. One promising direction is based on percolation theory related to network spreading dynamics, like the SIR model (Susceptible-Infected-Recovery) used in epidemics modelling. In this study, we analyse the traffic data in Singapore, and aim to extract the empirical dynamics of traffic jams in the framework of epidemic spreading over road networks. We treat a traffic jam or relatively slow vehicle movement in a road segment as an 'infected' node, and a high-speed flow road segment as 'susceptible' node. By analysing the spatial-temporal data of traffic movement, we recover the empirical dynamical properties of the spreading of traffic jams at the system level. Our results suggest that the spreading patterns do not fit into the commonly used SIR model, which assumes 'recovered' road segments being unable to experience jams again, but rather a 2-type competing SI model, where congestions and free-flow traffic movement are two types of 'infections' competing on one network. The spreading and recovery parameters calibrated on Singapore data also shows that the existing traffic dynamics operate well below the 'percolation threshold' of global spreading, meaning no large area of traffic jam can emerge, which is consistent with the general perception of traffic conditions in Singapore. This study demonstrates the utility of the SI models, and. if combined with land usage and network analysis, such systemic approach could be used as a simplified framework to facilitate urban planning in better manage traffic at the system level.

Keywords: Complex network, Percolation theory, Phase transitions**,** SIR/SIS model, Urban traffic

O1.5

Understanding Active Mobility using Computer Vision and Data Visualisation

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Active mobility, specifically walking and cycling, have been widely identified as key elements in promoting healthy lifestyles and creating liveable cities. As Singapore incorporates active mobility infrastructure like Park Connector Networks into its planning and policy goals, inter-user conflicts and spatial negotiation become inevitable. In particular, personal mobility devices (PMD) collision with pedestrians on shared paths have escalated safety concerns. Building up on William Whyte's work on improving public space design through observation and analysis, our study leverages computer vision technologies to automatically extract movements of pedestrians and PMD, for robust data collection and analytics. Our research aims to (i) deploy machine learning over long-duration video captures paired with spatiotemporal data visualisation techniques to gain data and insights on active mobility use patterns (ii) understand how different types of users behave and interact within these shared spaces and how the design of those spaces influences them. We deployed three CCTV cameras along Tampines Park Connector's shared walkway collecting a total of 169 hours of video footage over three consecutive days in July 2022.This data was then processed using state of the art object detection and tracking algorithms to identify over 20,000 unique instances of people, PMDs (bicycles, e-scooters), other objects (dogs, umbrellas, bags); and extract their movement patterns. Our findings show that most PMD users followed speed limits on shared paths, but a minority exhibited dangerous speeds. Focus should be given to minimise these Addressing this behaviour should be a top priority in planning solutions. Additionally, our findings highlight potential conflicts between pedestrians and PMD users on the cycling path, suggesting design and policy changes to minimise pedestrian presence on the cycling path. Furthermore, we show how design elements like overhead-cover and path design affect usage patterns and analyse temporal and environmental factors on the volume, direction, and distribution of different user groups. This study concludes with a discussion on the advantages of computer vision technology methodology and recommendations for future research.

Keywords: Active mobility, Activity monitoring, Computer vision, Machine learning, Smart cities, Video analysis

Panel 2: Science of Decarbonising Cities

Abstracts – Keynotes

K2.1

Design to Decarbonise: Effective Tools to Reduce Urban Building Emissions

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The urgent need to combat climate change has placed a spotlight on the decarbonisation of urban infrastructure, with a particular emphasis on building emissions. This keynote presentation delves into the ways in which scientific insights can be harnessed to achieve rapid and effective decarbonisation of buildings in cities. The presentation outlines a strategic approach that revolves around evidence-based decision-making and leverages analytical methods to address the challenges of urban building emissions. It underscores the pivotal role of science in driving rapid decarbonisation efforts. By adopting an integrated design process, harnessing the power of data to identify impactful interventions, and incorporating a life cycle perspective focusing on long-term dynamics, urban environments can make substantial strides in curbing overall emissions. The presentation imparts a call to action for a collaborative, evidence-driven approach that paves the way for a more sustainable and resilient future.

K2.2

Sufficiency, Justice and Transport

Philipp RODE

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This keynote considers the research and policy implications of applying the sufficiency principle to urban transport. It explores “enoughness” against a backdrop of increasing carbon emissions in the transport sector, inevitable ceilings for resource intense movement, and the essential requirement of providing access to opportunities in cities. Given the relative lack of progress, increasingly polarising political debate and urgent requirement for change, a more direct and open engagement with a sufficiency turn in urban transport is urgently needed. Most importantly, fundamental questions about a fair distribution of remaining emissions and finite street space within the transport sector must be considered. This engagement builds on the emerging field of transport equity while joining up social justice perspectives of the here and now with sustainability justice recognising global society, future generations, and nature.

* denotes presenters

O2.1

A Global Bottom-up Approach to create Urban Digital Twins (UDT): Mitigating Greenhouse Gas (GHG) Emissions

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Several nations have taken a stance to reduce greenhouse gas (GHG) emissions in their industrial processes and operations. Furthermore, these nations have committed to achieving carbon neutrality goals within a short duration. However, accounting for emissions requires technical support in the form of tools and applications that can prove use cases for effective city management. Urban Digital Twins (UDTs) integrate multiple disciplines to improve city system efficiency. Nevertheless, UDTs that explore decarbonisation initiatives for cities are limited, as the applications restrict themselves to the building level and have minimum access to authoritative 3D data at the city scale. We propose a methodology to build a UDT platform using a bottom-up integrated 3D city energy dataset based on OpenStreetMap and local public data portals in Singapore. Local datasets are used to gather building type, completion year, and energy consumption data. A linear equation is used to calculate the building's operational GHG emissions based on energy modelling and the dataset. Each building is assigned a Singapore Region, Planning Area, and Subzone, this information allows city-scale analyses and data exploration. An interactive web map application with User Experience (UX) is developed for rapid heterogeneous data streaming. The UDT platform has a query system with three input scrollbars for quick access to the information—Planning Area, Built Year, and Building Typology. The UDT dashboard generates charts and visualisations based on GHG emissions calculation output. New scenarios such as low/high energy use and low GWP refrigerants in the future are created on top of the baseline (current energy use and technology). By using various interactive what-if scenarios for future scenarios, the UDT use case demonstration will help stakeholders develop GHG emission reduction and carbon-neutral strategies. The research provides a guideline to develop UDT applications around the world without or with limited authoritative open 3D datasets.

Keywords: Climate change, Energy modelling, Smart cities semantics, Urban analytics

O2.2

Material stock-service and circularity prospects of buildings in Singapore

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The buildings and construction sector plays a vital role in socio-economic development, while being a primary consumer of resources. In Singapore, this sector is highly reliant on imports, and the city-state is expected to double its building stock by year 2050. Estimates of city-scale building material stock and flow can contribute towards local resource circularity opportunities and decarbonisation. To examine this, we apply a bottom-up, retrospective material flow analysis to track concrete and steel stocks, flows and embodied carbon in Singapore buildings, from 2010 to 2020. The model operates on age-type specific gross floor area (m2 of floor area) which are complemented by building-type specific material intensities (kg/m2). Investigating seven building typologies, covering all public and private residential, commercial, and industrial buildings, we show that most inflows are directed to residential sector demand, while the largest outflow originated from the demolition of private industrial buildings. In 2020, 257 million tonnes of concrete and steel stocks were embodied in buildings. The cumulative material outflows for the next 10 years can meet around 37% of total annual material demanded for the past 10 years. As of 2020, embodied carbon in public residential buildings is the highest (93.04 MtCO2e) among all building types, followed by private residential buildings at 64.67 MtCO2e and private industrial buildings at 45.42 MtCO2e. Resource efficiency of residential and industrial buildings, in terms of material use per service index, has remained unchanged over the past decade, while that for commercial buildings has risen. Focusing on secondary resource utilization and reuse can contribute to low carbon and circular built environment.

Keywords: Built environment, Circular economy, Embodied carbon, Material flow analysis, Sustainable cities

O2.3

Can New Urban Rail Transit Lines Reduce Car Ownership? — Evidence from the Opening of the Circle Line in Singapore

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The existing empirical studies have presented conflicting arguments on whether investments in urban rail transit can restrict car ownership, and some of them face methodological challenges. In this research, we regard the opening of the fourth Mass Rapid Transit (MRT) Line in Singapore, the Circle Line (CCL), as a quasi-natural experiment to assess the treatment effect of rail transit on car

ownership within a difference-in-differences modelling framework based on Household Interview Travel Surveys. We also employ a two-dimensional propensity score matching approach to creating matched samples with controlling for the spatial and temporal heterogeneity. We find that the CCL reduces the car ownership per household by 3.2 percentage points and 2.5 percentage points for those living within 500 m from the CCL stations with considering only individual characteristics and both individual and household characteristics, respectively. With matched samples, the treatment effect on car ownership level increases, suggesting that there could be gentrification process in station areas. Moreover, the CCL can significantly reduce the car ownership of households both living and working close to CCL stations than those only live close to CCL station or didn't report their fixed workplaces. Furthermore, the opening of the CCL shows a significant impact on households' decisions on whether to purchase their first car, but its impact on the number of cars given car ownership is insignificant. The research findings provide more robust estimations of the treatment effect and new evidence that supports the effectiveness of urban rail transit in restricting car ownership, which strengthens the justification of building more accessible MRT system. In addition, when designing new rail transit lines, the policy makers should attach importance to the role of MRT, individual and household factors, and heterogeneity issues to better restrict car dependency and achieve sustainable transportation.

Keywords: Car dependency, Difference-in-differences, Public transportation, Treatment effect, Two-dimensional propensity score matching

O2.4

Significant Carbon Mitigation Potential from Installed Rooftop Photovoltaics in Singapore: A GIS-integrated Life Cycle Assessment

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Solar farming has been increasingly being used for decarbonisation in cities. However, it is challenging to accurately quantify the life-cycle carbon mitigation potential of installed photovoltaic (PV) systems at a city-scale. This is because conventional methods relying on individual surveying are time-consuming and labour-intensive, while large-scale estimation confronts the data unavailability for installed PV size and location, the spatiotemporally heterogenous distribution of solar PV potential, and the complexity of carbon emission during the whole life cycle. To effectively support government decision-making for renewable energy transition, this study develops a deep learning-oriented Remote Sensing and Geographical Information System (GIS) integration model to estimate life-cycle carbon mitigation potential of all the installed rooftop PV systems. Specifically, the model is built by three interconnected modules: (i) an advanced semantic segmentation network is used to segment PV areas from satellite imagery, (ii) the segmented PV areas that quantify installed capacity, historical weather that determines land-surface solar irradiation, and three-dimensional building data for modelling shadow effects are combined to quantify the annual PV electricity generation capacity, and (iii) a life cycle assessment is adopted to estimate carbon mitigation potential of rooftop PVs from manufacturing, transportation, installation and maintenance, and finally

deconstruction. The proposed method can be generalised and used for global cities. As a case study in Singapore, the results show that, for the installed rooftop PVs, the carbon emission rate is considerably small, and the carbon reduction benefit is significantly large, which makes the carbon payback time equalling 1.51 years and the energy payback time equalling 1.29 years only. The net carbon reduction benefit was also estimated, suggesting that 4687774.5 tons CO2 emission could be reduced. This demonstrates a rapid offset of the carbon emission and a large reduce of energy consumption of rooftop PVs during the whole life cycle in Singapore.

Keywords: Building-integrated photovoltaics, Carbon mitigation, Geographical information science, Geospatial artificial intelligence, Life cycle assessment, Remote sensing

O2.5

Accelerating PV Adoption in Singapore: The Potential of Advanced Energy Communities

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Solar energy stands out as the most promising among the available renewable resources in Singapore. However, solar photovoltaic (PV) installations in Singapore are still far from sufficient due to limited land space, a low feed-in tariff, and significant investment costs. To overcome these challenges, the concept of the Advanced Energy Community (AEC) has garnered attention as an innovative business model that can potentially accelerate the PV adoption rate (i.e., fraction of energy demand met by local solar supply), through solutions like local energy sharing via microgrid, demand flexibility, the utilisation of public spaces, and the introduction of district cooling systems. While the economic and environmental benefits of AEC have already been extensively examined in literature, the potential of AEC to expedite the PV adoption rate in densely populated tropical urban centres, such as Singapore, remains inadequately evaluated. To address this gap, we develop an optimisation-based framework to assess the potential and drivers of the AEC model to accelerate PV adoption across Singapore. The simulation covers nine representative district areas, ranging from Housing and Development Board (HDB) residential areas, condominium complexes, central business districts (CBDs), industrial parks, university campus, to landed housing zones. The study's outcomes demonstrate that the incorporation of the AEC model can significantly reduce the Levelized Cost of Energy (LCOE) and therefore increase the PV adoption rate compared to the solar-leasing model and ownership model. Residential areas exhibit notably higher solar adoption rate by leveraging AECs compared to other district types because of the high PV generation potential and low energy demand. Among the various solutions incorporated by AEC, district cooling, utilisation of public space (e.g., carpark and corridor rooftops), and demand flexibility can substantially increase PV adoption rate. The results could inform the design of AECs in a high-density tropical city on various aspects, such as building mix, technological portfolio, and system operation.

Keywords: Advanced energy community, Distributed energy resources, Photovoltaic adoption

Panel 3: Regenerative Cities (Co-curated with FCL Global)

FCL Global is an international research collaboration between ETH Zurich and the Singapore universities NUS, NTU, and SUTD, supported by the National Research Foundation Singapore (NRF), and pursues a transdisciplinary approach that combines design, technology, science, and governance. With its data-driven research based on evidence-based strategies and empirical findings, FCL Global provides the foundation for resilient future urban planning and design.

Abstracts – Oral Presentations

Regenerative Cities: Circular Districts

OF.1

From Urban Mining to Urban Harvesting: Building Shared Frameworks for Circular Future Cities

Pieter HERTHOGS

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In this talk, the importance of establishing a common understanding and language for socio-technical transitions, such as our vision to design regenerative cities, will be discussed. Clear frameworks and definitions help shape knowledge and identify innovations. The talk will illustrate these using examples from the research, focussing on differentiations between Urban Mining and Urban Harvesting, and between Circular and Regenerative Cities.

OF.2

Integrating Renewables within the City

Francis Bu Sung LEE

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Over 80% of the world's energy consumption occurs in urban areas, making the transition to renewable energy a critical step in reducing carbon emissions. Singapore is placing a strong emphasis on solar energy as a key component of its renewable energy strategy. Building Integrated Photovoltaic (BIPV) technology is particularly promising in Singapore due to limited land space. This approach is often regarded as holistic, as it combines data-driven analysis with modelling and simulation to support evidence-based decision-making in the design and planning of the city.

OF.3

Dense and Green Cities for a Nature-Positive Future

Srilalitha GOPALAKRISHNAN

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A nature-positive approach seeks to move beyond simply reducing the negative impact of cities on the natural environment to actively restoring and regenerating ecosystems and promoting biodiversity. Nature-positive urban solutions recognise that nature is not just a resource to be exploited but a valuable partner in creating healthy, resilient, and sustainable cities. The talk will capture important aspects of the urban planning and design, architectural, social, environmental, economic and governance systems performance of the selected cases in Singapore, to allow for the evaluation, comparison, and mutual learning on how urban density, greenery, and sustainability can become mutually dependent and synergistic.

Regenerative Cities: Transformative Strategies

OF.4

Long-term Solar PV Planning in High-Density Urban Systems

Alberto COSTA

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During this session, a robust optimisation model will be presented for solar photovoltaic (PV) planning under uncertainty, considering the impact of land use and national adoption targets over the medium and long term. This model can facilitate the derivation of incentives needed to achieve such targets as well as the generation of what-if scenarios, which can serve as a decision-support tool for agencies.

OF.5

Cities as Social Reactors

CHEONG Siew Ann

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Cities play a role similar to the cell membrane in cells, in that they intensify the interactions of constituents within small spaces. This intensification gives rise to myriad processes that make biological life possible in a cell. We believe the same is true for urban and cultural life in a city. In fact, in cities the outcomes of these interactions are highly desirable, in that they lead to diversification and innovation. However, we also believe that rewarding intensification of these

social interactions cannot be achieved by simply making a city larger in geographical size, or in Singapore's case, make uniformly increasing the population density. We argue that intensification is best done by creatively scheduling the self-organised hierarchy of social interactions over their enabling spaces, so that we achieve the desired interactions as the result of intensifying over time, without making too much demand of space.

OF.6

Adaptive Planning of Charging Infrastructure for Electric Vehicles

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Electric mobility is paving a path towards sustainable transportation by reducing air pollution and dependence on fossil fuels. Governments across the globe have offered financial incentives such as tax exemptions and purchase subsidies to increase the uptake of electric vehicles. While these benefits could encourage first-time electric vehicle buyers, the repurchase decisions will considerably depend on the accessibility to charging infrastructure. Prateek's talk will focus on how to develop adaptive plans to deploy charging infrastructure across space and time while considering its bidirectional relationship with market-level adoption of electric vehicles.

Poster Abstracts

Topics within Panel 1: Science-based Approach for Future Scenario Planning from P1–P20, and Panel 2: Science behind Decarbonising Cities from P21–P32. Poster presenters during the 4.30–5.30pm Poster Showcase are indicated with an asterisk next to their names.

P1

Urban Heat Island Scenario Exploration: A Generative Design Approach for Optimally Cool Urban Plans

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Anthropogenic climate change is exacerbating Urban Heat Island (UHI) effect in many cities, with planners asked to anticipate and mitigate this effect decades ahead of time. There is a well-documented causal link between increased density of urban construction and increased UHI intensity, however, how urban designers can control density in response to UHI has yet to be explored and assessed. To understand the impact of urban design density, layout, and greenspaces on UHI, this study employs a generative design and optimisation approach, exploring many planning scenarios to search for best outcomes. The case study site was selected from one of Singapore's current redevelopment sites, Jurong Lake District (116 ha) and is simulated in this study with a focus on residential settlements. The implemented two-step experimental methodology seeks to minimise UHI intensity simulated with Urban Weather Generator (Bueno et al. 2013) while minimising total view obstruction associated with URA's building allocation guidance (URA: Building Length, Building

Height and Building Setback). The impact of UHI on planning parameters (land parcel size, building height, and gross floor area) was investigated, resulting in 27 models. Next, urban massing alternatives were identified based on the selected best-performing model and by optimising for three objectives (view obstruction, building orientation, and UHI) using five building design parameters (footprint width, footprint depth, grid angle, grid spacing, parcel storey scale (PSS)), resulting in 320 models. Lower settlement patterns (parcel storey scale closer to 1) within higher density (from 250 ha to 350 ha) are found to be positively associated with UHI. Prioritising fewer blocks with taller structures is advantageous to mitigate both UHI and view obstruction in the optimisation process. More broadly, the two-step performance evaluation method developed in the experiment provides a step toward the integration of computational optimisation and environmental performance simulation for science-based urban planning scenarios targeting improved sustainability of future cities.

Keywords: Generative design, Optimisation, Planning, Urban design, Urban health island effect

P2

An Ontological Framework to Model Urban Metabolisms for Future Urban Scenarios

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Cities are complex systems characterised by evolving dynamics, interdependencies, and feedback loops. To effectively plan for their development, it is crucial to model their uncertain futures, considering natural shifts such as climate change, or societal ones such as changing demographics and remote work. Urban and systems planners hence require a common language to describe cities and their metabolism (i.e., urban processes that are supported by several interdependent domain systems, such as energy, water, waste management, or urban transport). Furthermore, to enhance understanding of the impact of planning decisions on future urban processes, and hence, future city scenarios, modelling tools are required to leverage accessible data sources to incorporate city metabolism knowledge across temporal and spatial scales. This work presents a framework that addresses this using semantic representations of urban domain knowledge. The framework comprises three ontologies that provide a comprehensive knowledge base to modelers: one describing an urban area in terms of its built environment content, one defining key concepts and relationships of urban metabolisms within such area, and one existing ontology describing the potential future buildable space as governed by Singapore land use planning regulations. As a demonstration, the framework is applied to selected plots within Singapore, for which two possible future metabolisms are simulated: electricity and drinking water. Data regarding the built environment and the allowable buildable space within such plots is retrieved and structured according to the three ontologies, and used to model future metabolic rates. Combining the description of future urban areas and their simulated potential metabolism, as demonstrated, could enable urban and systems planners to integrate quantifiable metrics about future urban districts and their resource use in planning processes, supporting impact assessments of planning proposals,

enhancing communication of knowledge and modelling efforts between different stakeholders, and ultimately supporting more robust decision-making.

Keywords: City planning, Semantic web technologies, Urban futures

P3

Urban Modelling for Singapore's Weather and Climate

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Rapid urbanisation and climate change are two intertwined challenges for cities. As a coastal city-sate located in deep tropics, Singapore, experiences unique weather and climate that are influenced by various factors including urbanisation, sea-level rise, and regional atmospheric patterns. In particular, urbanisation has been found to strongly affect local weather and climate in cities by increasing near-surface air temperature, reducing humidity, and enhancing convection. This makes cities like Singapore more vulnerable to meteorological hazards, such as the Urban Heat Island, flash flooding, and air pollution. Understanding the dynamics between urban developments and associated weather and climate in Singapore is crucial for sustainable planning and policy formulation. Since 2016, the Centre for Climate Research Singapore (CCRS) has started to develop an urban version of Singapore Meteorological Service's numerical weather prediction system (uSINGV) to investigate the impacts of urban developments on local weather and climate, based on the Unified Model from the UK Met Office. It uses high-resolution, urban models at 100 m grid scales, and various urbanisation-related datasets including land use land cover and urban morphology. With these features, uSINGV allows for a better representation of urban surface characteristics and demonstrated the capacity to begin resolving key physical processes such as turbulence and boundary layer structures. This was proven by comparing the model results with observational weather station data, radio sonde measurements, and satellite images. Given the promise of uSINGV, further developments to investigate extreme weather events and potential impacts of future longer-term climate projections and city development in Singapore with a focus on the next 50–100 years are in progress. These findings can help policymakers, urban planners, and scientists to develop evidence-based strategies for climate change mitigation and contribute to a more resilient and sustainable Singapore.

Keywords: Artificial intelligence, Public's perception, Text augmentation

P4

Physics Aware Digital Twins as Reliable, Responsible Tools to Predict and Manage Disruptions in Urban Complex Systems

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Intelligent modelling technologies such as digital twins can enhance community-centric planning by simulating urban environments and developing predictive scenarios in response to critical and uncertain situations, allowing aided or even automated real-time decision-making. While traditional data-based AI techniques can be considered to enable the process, they still entail a number of limitations, such as the need of large amount of very specific and difficult-to-access data, massive computing resources, and questionable, sometimes risky output decisions in a few specific situations, thus lacking ethical considerations in decision-making affecting humans. The Hybrid Artificial Intelligence (HAI) approach aims to address these gaps. It combines AI's strengths of collecting and analysing big data across systems on an accessible online platform, with the pairing of physics-informed and physic-augmented approaches to allow for updating the knowledge. Technically, a Hybrid Twin model of the ignorance (gap between knowledge-based prediction and the experimental observations) is constructed, and models are reduced by applying advanced parametric regressions techniques. This results in faster real-time diagnosis, prognosis and decision-making, using less data (frugality) yet with better accuracy in predictions, it remains almost explainable, and minimises the ecological footprint (sustainability). By enabling human-driven updating of knowledge and security certifications, it also enables a human centric approach where the privacy of citizens is respected. Through HAI, different technological functionalities can be elaborated and, subsequently, closely combined for constituting the complex system of systems emulating the city functioning within its environment. This is applied to a number of case-based solutions for critical urban systems, where environmental maps (wind, pollution, temperature etc.), digital energy footprint, and smart sensing of large critical civil and industrial infrastructures are assimilated to inform efficient maintenance, optimise energy distribution, and enhance crisis and emergency management. By accounting for multiple aspects of planning and evolving information in today's VUCA environment, these methodologies can become reliable, helpful tools to foster the planning of future urban system improvements.

Keywords: Artificial intelligence, Critical urban systems, Decision-making, Hybrid Twins, Human-centred AI, Hybrid Predictive intelligent modelling

P5

Non-asset-based Risk Models for Quantifying Future Climate Risk in Cities

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Floods affect more people than any other type of natural disaster, and the number of flooding events continues to rise. To safeguard lives and livelihoods, we need up-to-date insights into disaster situations and uninterrupted critical network infrastructure; however, the necessary data are often isolated in individual silos. Although tailored platform solutions exist to consolidate and assess flood related data, all of them are very limited in scope and not easily extensible due to proprietary data models. Moreover, these approaches lack the ability to disambiguate data and complex relationships across stakeholders and domains. Our work aims to bridge this gap. Using connected digital twins based on 'the World Avatar' dynamic knowledge graph, we create a semantically rich ecosystem of knowledge, data, and computational capabilities that connects several publicly available data feeds, including geospatial data (buildings, population, and roads), property sales data, real-time river levels, and weather observations. Enabled by a set of autonomous software agents which continuously ingests and operates on the latest real-world information, possible consequences of newly raised flood warnings automatically cascade through the dynamic knowledge graph and create timely insights into the number of people, buildings, and total building stock value at risk from flooding events. By integrating power, water, and telecoms networks, we can, furthermore, analyse potential flood-induced asset failures and how they may cascade across different utility networks, including direct and indirect asset outages. By using simulated flood maps (i.e., developed based on historical flooding events or climate change projections), we can also identify critical nodes to increase overall system resilience and foster decision making during several disaster management phases. The World Avatar thus creates a knowledge model based augmented reality for the development of holistic digital twins, supporting comprehensive cross-domain analyses to provide evidence-based planning insights for disaster preparation and response, but also advancing smart cities to influence the real world.

Keywords: Climate risk modelling, Equity, Sea level rise, Social vulnerability

P6

Designing for Diversity: Examining the Impact of Visual Features of Public Spaces in one-north, a High-Density District

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Urban high-density and heterogeneous living conditions can offer enriching experiences but also induce mental stress. Overexposure to diverse environmental stimuli can lead to social withdrawal and retreat to private spaces, which may lead to increased loneliness, isolation, and related mental and physical health problems in the society. It can also negatively impact interactions between cultural and social groups, leading to cultural tensions and segregation. Well-designed public

pedestrian networks and green spaces can serve as catalysts for community gathering and interaction among different user groups. Our study thus aims to embed considerations of social performance into urban planning by exploring the relationship between the visual features of public spaces and social integration in one-north, a model of high-density, sustainable urban development in Singapore. First, we analysed 5,800 street view images with the SegFormer model to capture visual features. Second, we added functional data from POIs and zoning plans. Lastly, we studied the travel patterns of 2,000 GPS users to gauge social integration, measured by heterophilous interactions, which emphasise those between individuals of varying socio-economic backgrounds. Users' socio-economic backgrounds were estimated by the median household income of their residential neighbourhoods. These features are synthesised in a regression model, offering insights into socio-spatial relationships in Singapore's One-north district. The regression analysis reveals a significant impact of visual features on social integration ($R^2 = 0.31$). Positive contributors to social integration include shade, greenery, and skylight, while roads and vehicles negatively affect it. The findings suggest that increased shade, greenery, and sufficient natural lighting in public spaces could enhance social integration among different socioeconomic groups. This could help reduce social withdrawal and address concerns related to gentrification. The implications of these findings could guide urban planning and design strategies, aiming to create more liveable and socially integrated urban spaces. This, in turn, could contribute to the mental well-being of urban residents.

Keywords: Computer vision, GeoAI, Social integration, Social interaction, Visual environment

P7

Cross-Domain Flood Risk Assessments for Smart Cities using Dynamic Knowledge Graphs

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Floods affect more people than any other type of natural disaster, and the number of flooding events continues to rise. To safeguard lives and livelihoods, we need up-to-date insights into disaster situations and uninterrupted critical network infrastructure; however, the necessary data are often isolated in individual silos. Although tailored platform solutions exist to consolidate and assess flood related data, all of them are very limited in scope and not easily extensible due to proprietary data models. Moreover, these approaches lack the ability to disambiguate data and complex relationships across stakeholders and domains. Our work aims to bridge this gap. Using connected digital twins based on 'the World Avatar' dynamic knowledge graph, we create a semantically rich ecosystem of knowledge, data, and computational capabilities that connects several publicly available data feeds, including geospatial data (buildings, population, and roads), property sales data, real-time river levels, and weather observations. Enabled by a set of autonomous software agents which continuously ingests and operates on the latest real-world information, possible consequences of newly raised flood warnings automatically cascade through the dynamic knowledge graph and create timely insights into the number of people, buildings, and total building stock value at risk from flooding

events. By integrating power, water, and telecoms networks, we can, furthermore, analyse potential flood-induced asset failures and how they may cascade across different utility networks, including direct and indirect asset outages. By using simulated flood maps (i.e., developed based on historical flooding events or climate change projections), we can also identify critical nodes to increase overall system resilience and foster decision making during several disaster management phases. The World Avatar thus creates a knowledge model based augmented reality for the development of holistic digital twins, supporting comprehensive cross-domain analyses to provide evidence-based planning insights for disaster preparation and response, but also advancing smart cities to influence the real world.

Keywords: Digital twin, Flood assessment, Interoperability, Knowledge graph, Smart city

P8

Global Streetscapes—A Worldwide, Geospatially Enriched Dataset of 7 Million Street-level Images over 677 Cities for Urban Science Research

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Street view imagery (SVI) has recently gained monumental recognition as a key data source for sensing our often complex and dynamic urban environments. The prominence of SVI is further propelled by the emergence of crowdsourced SVI (e.g., Mapillary, KartaView) which capture the urban environment from multiple viewpoints and conditions, across diverse spatial, temporal, and socioeconomical spectrums. However, the lack of information to describe the characteristics of these inherently heterogeneous images limits assessment of their quality and fitness of use in an automated way, much less for big data, potentially affecting experiment accuracy and hindering global-scale applications. To facilitate and advance the use of SVI in urban research, we introduce Global Streetscapes—a worldwide dataset of 7 million crowdsourced SVIs sampled from over 677 cities around the world, enriched with more than 200 metadata, geographical, temporal, contextual, perceptual, and semantic attributes. The enrichment data amounts to tens of gigabytes in size, while the 7 million images themselves amount to more than 3 terabytes. 10,000 of the images are manually tagged with nine contextual properties (e.g., weather, time of day, view direction, pedestrian/cyclist/vehicle perspective). Baseline deep learning models are then trained on these images (one model for each property), achieving accuracies ranging from 36.4% to over 98.3%, and are used to automatically label the remaining images. This open-source dataset could substantially facilitate the understanding of the properties of crowdsourced SVIs and the assessment of their fitness of use. Further, it could enable inclusive, global-scale studies to enhance our insights into the various urban environments worldwide and the geographical variations in their characteristics. The automated processes to construct this dataset make it easy to update it with new cities regularly. In addition, with the manual tags for a wide range of categories, the dataset also provides a realistic benchmark for evaluating future computer vision models for a plethora of urban research questions.

Keywords: Crowdsourced data, Data fusion, GeoAI, Machine learning, Segmentation, Street view imagery

P9

Impact of the Built Environment and Its Social Outcomes in the Singapore Context

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Social well-being and public health have been prominent issues in developing a liveable city, especially in densely populated Singapore. The relationship between the built environment and its social outcomes is a complex phenomenon influenced by various interconnected factors, making it a topic of significant research interest in urban planning and design. We thus investigated the relationship between urban physical and social forms in Singapore in terms of how people react to spatial planning, and its impact on their social capital and physical activity levels. We quantitatively assessed diverse physical features of the built environment (BE), including availability of amenities, public spaces, and transportation options, to understand their complex interplay and collective influence on social outcomes. Subsequently, we examined the relationships between spatial planning, social capital (SC), and physical activity (PA) levels, to gain insights into how the built environment impacts community well-being. Our results show a positive association between BE and SC. The BE variables (inclusivity and quality) have a significant relationship with SC variables of trust and attachment, but not social participation, moderated by factors such as length of residence and age. This underscores the potential for strategic urban planning to foster stronger community bonds and promote inclusive communities. On the other hand, the association between BE and PA levels within the local community is less apparent, probably due to multiple interacting factors. Different aspects of PA such as frequency and mode exhibit varied degrees of association with different BE features, hinting at different strategies that could be effective for enhancing public health and well-being. By unravelling the complex dynamics to reveal the nuanced relationship between the built environment and social outcomes in Singapore, the findings could help inform evidence-based urban planning of public spaces that enhance social capital and active lifestyles.

Keywords: Built environment, Physical activity, Social capital, Spatial planning, Urban space

P10

The Impact of COVID-19 Pandemic on the Fundamental Urban Mobility Theories using Transit Data from Singapore

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COVID-19 pandemic has reshaped the way people conduct their daily activities due to the temporary movement restrictions to curb the spread of the disease and the long-term flexible work arrangements adapted by many companies in the post-pandemic world. The changing activity patterns and resulting changes in mobility patterns have huge impact on various aspects of the

society, including the spatiotemporal changes in travel demand associated with various land use types, some of such changes are expected to be lasting as the 'new normal'. While numerous studies have studied the changes in mobility patterns, few has examined the changes through the fundamental mobility theories. In this study, we first revisit the well-established mobility laws in complexity science: gravity law, radiation law and visitation law at pre-pandemic, pandemic and endemic stages of the COVID-19 pandemic to check the invariance of the fundamental urban mobility laws. Transit Origin-Destination (O-D) data from Singapore is used to evaluate the fundamental human mobility models. Our results show that the three mobility models remained valid throughout the different stages of the pandemic, with visitation law outperforming the gravity model and the radiation law in model fitting. Despite the fact the fundamental mobility theories still hold, we do observed changes in the fitted parameters due to the pandemic. Our results show that land-use variable of gross floor area is a better predictor of transit flows in the gravity and radiation models, whereas in the visitation law use of population variable provides better predictions. Our study will help to further understand both the invariant features and emerged new features that influence the transit mobility patterns at a fundamental level, and the long-term impact of COVID-19 at a systemic level.

Keywords: Gravity model, Land use, Radiation model, Urban flows, Visitation law

P11

Towards a Heuristic for Demand Driven Adaptive Pressure for Airports a Global Perspective

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Active mobility, specifically walking and cycling, have been widely identified as key elements in promoting healthy lifestyles and creating liveable cities. As Singapore incorporates active mobility infrastructure like Park Connector Networks into its planning and policy goals, inter-user conflicts and spatial negotiation become inevitable. In particular, personal mobility devices (PMD) collision with pedestrians on shared paths have escalated safety concerns. Building up on William Whyte's work on improving public space design through observation and analysis, our study leverages computer vision technologies to automatically extract movements of pedestrians and PMD, for robust data collection and analytics. Our research aims to (i) deploy machine learning over long-duration video captures paired with spatiotemporal data visualisation techniques to gain data and insights on active mobility use patterns (ii) understand how different types of users behave and interact within these shared spaces and how the design of those spaces influences them. We deployed three CCTV cameras along Tampines Park Connector's shared walkway collecting a total of 169 hours of video footage over three consecutive days in July 2022.This data was then processed using state of the art object detection and tracking algorithms to identify over 20,000 unique instances of people, PMDs (bicycles, e-scooters), other objects (dogs, umbrellas, bags); and extract their movement patterns. Our findings show that most PMD users followed speed limits on shared paths, but a minority exhibited dangerous speeds. Focus should be given to minimise these Addressing this behaviour should be a top priority in planning solutions. Additionally, our findings highlight potential conflicts between pedestrians and PMD users on the cycling path, suggesting design and policy changes to minimise pedestrian presence on the cycling path. Furthermore, we show how design elements like overhead-cover and path design affect

usage patterns and analyse temporal and environmental factors on the volume, direction, and distribution of different user groups. This study concludes with a discussion on the advantages of computer vision technology methodology and recommendations for future research.

Keywords: Active mobility, Activity monitoring, Computer vision, Machine learning, Smart cities, Video analysis

P12

Self-Organised Criticality in a Model of Supply Chain Network

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Complex systems are characterised by non-linear behaviours, multiple interactions, and interdependencies, making them susceptible to a myriad of uncertainties. Self-Organised Criticality (SOC) is a phenomenon observed in complex systems when interactions between individual units of the system combine to give emergent properties at higher levels of organisation. Characterised by a power law distribution of event sizes, SOC thus assumes that the distribution of values is scale-invariant, where the shape remains the same regardless of the scale at which it is observed. We hypothesise that such a trait of SOC, which is makes it useful to study the distribution of disruption sizes in a supply chain. To explore this, we develop a generic-simple supply chain model with multiple agent interactions subject to cascading failures. We conduct numerical simulations to analyse the distribution of supply chain disruption sizes. Our model excels in illustrating the phenomena of 'avalanche' and 'scaling,' both commonly witnessed within SOC systems, under various simulation settings, strongly indicating a critical state. This compelling evidence substantiates the robustness of our model in replicating and encapsulating crucial dynamics observed within complex supply chain networks. These findings have provided a strong motivation to further explore the management of supply chain risks through the lens of Complexity Science, including extreme events that are deemed rare and unpredictable with prescriptive risk mitigation strategies. Moreover, we envision our model has provided the foundation to perform further research on other real-life complex systems.

Keywords: Complexity science, Power law, Self-organised criticality, Supply chain

P13

Emergent Spatial Distribution of Social Hotspots: Analysis of Three Planning Areas in Singapore

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Urban vibrancy shapes and is shaped by the spatial structure of social hotspots. However, few studies have sought to empirically quantify social hotspots and their emergent spatial order in urban communities. This limits the application of theories to understand urban vibrancy. Applying the concept of open complex systems, we examine the emergent spatial structure of social hotspots through the lens of the power law distribution. The hotspot size dispersion arises according to a power law as a result of self-organised functional and network centrality differentiation across hotspots in a community. We use point-of-interest (POI) data, GPS mobile phone data, and a spatial clustering algorithm to identify and size social hotspots in three planning areas in Singapore, namely, Queenstown, Jurong East, and Punggol. We also quantify the spatial distribution of street network density and public transportation services to reflect the planned built environment context in terms of accessibility and land-use intensity. In each planning area, the identified top social hotspots exhibit a power-law size dispersion. The dispersion appears largest in Queenstown (the most centrally situated in the city among the three planning areas studied) and smallest in Punggol (the least centrally situated), indicating different degrees of functional and centrality differentiation of hotspots in these planning areas. The size dispersion is influenced, but not fully determined, by the planned land-use context, indicating the important influence of different social and urban contexts on social hotspot formation in different communities. In particular, the social dynamics appear to amplify the influence of accessibility on hotspot size more strongly in Queenstown and Jurong East than in Punggol. These preliminary findings suggest the potential value of open-source GPS data for uncovering the influence of urban as well as planning contexts on social vibrancy phenomena. The data will enable further study of the scaling pattern of social hotspots in terms of their functional and network differentiation to provide further insights for urban policymakers, planners, and designers.

Keywords: Complexity, Complex adaptive emergent, People intelligence data, Spatial organisation, Systems social dynamics

P14

Pedestrian Movement Distribution Patterns in Multilevel Urban Environments

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As cities densify, urban planners and designers are increasingly utilising vertical space to accommodate growing populations and optimise land use. Elevated and underground spaces with programmes such as mixed-use complexes, indoor malls, and public transportation hubs, are integrated with the street network to form multilevel urban environments. Such environments offer multiple indoor and outdoor opportunities for pedestrian movement and interactions across different levels. With the increasing need to create vibrant and liveable cities, these intricate dynamics of pedestrian behaviour are unpredictable yet crucial to planning and design. This study focuses on the pedestrian movement distribution patterns of multilevel urban environments, specifically examining the influence of the spatial configurations on pedestrian flows, activity, and space utilisation. Using the case of Jurong Gateway in Singapore, it demonstrates the use of Spatial Network Analysis and video-based pedestrian mapping to model pedestrian behaviour in vertical indoor and outdoor spaces. The research takes place in three phases: Spatial Network Analysis, Pedestrian Mobility Mapping, and Socio-spatial Correlation. Spatial Network Analysis produces measures which are indicative of the accessibility, flows, or efficiency of the spatial network in the urban environment. In the second phase, the study maps pedestrian volumes, and the potential for occupancy in certain multilevel public spaces using sensors, video-based object tracking methods, and Machine Learning models. Lastly, the results are correlated and cross-validated using regression methods to identify potential key 'high-volume' and 'high-occupancy' spaces in the unmapped parts of the larger spatial network. The findings of this study contribute to the understanding of the association between vertical spatial configurations and dynamic pedestrian behaviour. The expected outcome of this Spatial Network Analysis-based approach is a multidisciplinary methodology to project pedestrian movement distribution patterns in similar vertical spaces. The research results inform evidence-based planning and design processes of vertical integrated developments in Singapore, and other high-density cities worldwide.

Keywords: Complexity, Computational urban design, Design space exploration, Multi-objective optimisation, Sensitivity analysis, Sustainable development

P15

The Roads One Must Walk Down: The Relationship between Commute and Depression

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As a vital aspect of individual's quality of life, mental health has been included as an important component of the U.N. Sustainable Development Goals. Given the substantial time working adults spend at work, travelling to work, and the increasing evidence of work stress, the effects of work on mental health have received much attention. This study focuses on a specific aspect of mental health: depression, and examines its relationship with commute patterns. Using survey data from 1,528 residents in Beijing, China, where depressive symptoms (CESD-10 scale), work stress occurrence, and self-reported work-to-home commute time was collected ,we find that every 10 additional minutes of commute time is associated with 1.1% higher probability of depression. We test for the mechanisms of the commute-depression link and find that commute is associated with depression as a direct stressor, rather than one that triggers higher work stress to increase depressive symptoms. When decomposing commute time into mode-specific time, we found that time on mopeds/motorcycles has the strongest association with depression – with an additional 1.9% higher probability per 10 additional minutes. Moreover, the commute-depression associations are stronger for older workers and blue-collar workers. Hence, policies that could reduce commute time, encourage work from home, improve job-housing balance or increase motorcyclists' safety to help promote mental health. The study contributes to the literature by examining the role stress plays in the journey to work – depression association, as well as a by-mode decomposition to examine mode-specific effects. Future research should keep testing the mechanisms that the role work stress plays in the commute-mental health nexus.

Keywords: Asian cities: Health; Planning; Sustainable mobility; Travel behaviour; Well-being

P16

Mapping Urban Green Space Networks with Visual Analysis

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As cities become denser, Urban Green Spaces (UGS) serve as important biodiversity habitats and social areas for city dwellers. The continuity of their networks addresses the ecological challenges of intensified land use and fragmented habitats. A disparity exists between macro-scale mapping of UGS and the on-the-ground experience at a smaller scale. Recent studies integrate techniques such as satellite imagery, drone photography, and lidar imagery with crowdsourced geospatial datasets and deep learning. However, visually assessing and mapping the richness of UGS at human-scale remains a challenge. Our research uses a case study of one-north, a sustainable innovation district in Singapore. We leverage computer vision for urban visual analysis to map street-level urban and greenery features onto the existing UGS green cover. We overlay vegetation and terrain features

from the semantic segmentation of street-level panoramic image sets on a gradient patch model of green cover in a 2km boundary of a lidar map, then use network analysis to assess the connectivity in the resulting mapping. The resulting mapping shows a variety of changes in the connectivity structure of the greenery patches. While the dominant edge connectivity of the main green region is reinforced while more evenly distributed, stronger node and edge corridors are now interconnected with neighbouring regions showing higher numbers and intensities of node and edge connectivity. This approach potentially assesses the impact of new planned visual structures on the UGS network. By combining the macro and street-level visual experience of green cover, our study gives insights into the impact of visual data on green space design and urban morphologies in dense environments. This enhances our understanding of UGS in addressing the complexities of urban planning and design. This approach empowers spatial planners and designers to adopt an urban science-driven approach for the planning of resilient, sustainable, and effective urban spaces.

Keywords: Computer vision, Geospatial data, Urban green space, Visual environment

P17

Enhancing Urban Resilience against Heat Exposure: Space use patterns through Spatial Network Analysis and Thermal Comfort Assessment

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Urban vibrancy is a multifaceted concept that is influenced by several factors such as spatial accessibility and people's comfort levels. Urban planners and designers are progressively pivoting towards evidence-based designs that augment both the vibrancy and liveability of urban areas, considering elements like spatial accessibility and thermal comfort levels. However, the challenge lies in striking a balance between these considerations, especially in multilevel urban environments in Singapore. In this study, we proposed a hybrid method combining Spatial Network Analysis and thermal comfort assessment to scrutinise space use patterns. We carried out field surveys to gauge the thermal environment and monitor occupancy in seating areas near Singapore's Westgate Mall. Using Spatial Network Analysis, we mapped spatial accessibility, i.e., betweenness. Meanwhile, occupancy details were mapped from video footage, and the thermal comfort index, Physiological Equivalent Temperature (PET) was estimated from collected weather data. A subsequent correlation analysis was conducted among these variables. Furthermore, a probabilistic model using Bayesian inference was proposed to estimate occupancy using both space accessibility and thermal comfort. Our findings revealed that occupancy had a strong correlation with PET in the early afternoon, with an R^2 of 0.71, surpassing its correlation with betweenness (R^2 of 0.66). Moreover, the probabilistic estimation of occupancy shows good accuracy, with an R^2 of 0.44 and a 90% confidence interval encompassing all the observed occupancy data. The study emphasises the importance of weighing both spatial accessibility and thermal comfort in urban planning, especially in the Urban Heat Island Effect context. By integrating our findings, urban planners and designers can craft strategies for cities that are more liveable, sustainable, and climate resilient.

Keywords: Resilient urban design, Space use pattern, Spatial network analysis, Thermal comfort

P18

A Digital Urban Climate Twin of Singapore to analyse Green Plan 2030 Scenarios

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Cities are committed to sustainable development to reach 2050 targets of the Paris Agreement. Sustainable development requires an integrated approach that takes the cities infrastructure, its heat emissions, the vegetation and land use, the behaviour of people and the prevailing climate into account. These complex interactions have to be understood, requiring computational tools to support the analysis. The Digital Urban Climate Twin (DUCT), developed by the Cooling Singapore 2.0 project facilitates the coupling of relevant models together with the integration of required input data. We demonstrate the capabilities of the DUCT by assessing a set of Green Plan 2030 measures for Singapore. Time-resolved heat emissions of buildings, traffic, industry, and power plants are modelled and further integrated as gridded anthropogenic heat emissions into a meso-scale climate model of Singapore. Vegetation and land use is represented in the form of local climate zones. In total 16 Local Climate zones are used for representing differences in urban and rural configurations in the Meso-scale climate model. A base-representation of the current situation of Singapore is first modelled and the contribution of different factors to the urban heat is evaluated. The analysis is conducted for a set of time periods in Singapore. Next, measures within the scope of the Green Plan's City in Nature, Energy Reset, Sustainable Living, and Green Economy pillars are translated into a set of scenarios using corresponding, adjustable variables such as electric vehicle share and vegetation cover, with the input data prepared. The impact of these scenarios on the urban heat for Singapore is then analysed, projecting that buildings and electric vehicle share can have a relatively large impact on UHI. This holistic analysis and visual interface can aid in deriving optimal urban climate adaptation solutions to improve outdoor thermal comfort, and the effects of potential future developments & policies on their effectiveness.

Keywords: Digital twin, Outdoor thermal comfort, Urban climate

P19

A Case-based Search Engine for Mapping Urban Patterns and Cases Integrating Street View Imagery

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Cities are considered complex and open environments with multidimensional aspects that influence each other in irreducible and unpredictable ways. The urban design process highly relies on individual understanding and implicit knowledge that is case-based and experience-based. Linking city science

and urban design is significant for progressing both sides. Both urban design and science can thus be enhanced by allowing individual knowledge as input to derive more generalizable evidence. Complex urban elements - the topics of science and design—need multi-source data and representations. However, we see a lack of digital modelling approaches for heterogeneous data integration, representation and interoperation. Therefore, we are working towards a methodology that integrates data streams, associates topical semantic urban elements, and enables a dialogue between users and machines, for mapping general urban patterns and specific cases. We present a case-based search engine for Nanjing that automatically collects urban semantic, spatial, and image data, extracts the geometry and image features, and enables easy case retrieval. Unsupervised learning and feature extraction techniques are applied to generate the general urban patterns, and the resulting patterns can be consulted by users using information retrieval techniques. We retrieved relevant cases using different combinations of geometry and imagery, illustrating both strong and weak relevance between urban patterns and cases. By enabling easy case retrieval, such a search engine could serve as an instrument for users to navigate among existing cases, and hence supports case-based reasoning related to urban design hypotheses about which characteristics make a particular case good (or bad), and would provide evidence to support or contradict case-based assumptions. This proposed framework can be expanded with additional data or combined with other urban search engines we developed. The model can help architects and urban designers with decision-making and supports the derivation of hidden rules in complex cities based on in-field, case-based experiences.

Keywords: Isovist analysis, Probabilistic modelling, Street view imagery, Self-organising map

P20

Understanding Active Mobility using Computer Vision and Data Visualisation

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Active mobility, specifically walking and cycling, have been widely identified as key elements in promoting healthy lifestyles and creating liveable cities. As Singapore incorporates active mobility infrastructure like Park Connector Networks into its planning and policy goals, inter-user conflicts and spatial negotiation become inevitable. In particular, personal mobility devices (PMD) collision with pedestrians on shared paths have escalated safety concerns. Building up on William Whyte's work on improving public space design through observation and analysis, our study leverages computer vision technologies to automatically extract movements of pedestrians and PMD, for robust data collection and analytics. Our research aims to (i) deploy machine learning over long-duration video captures paired with spatiotemporal data visualisation techniques to gain data and insights on active mobility use patterns (ii) understand how different types of users behave and interact within these shared spaces and how the design of those spaces influences them. We deployed three CCTV cameras along Tampines Park Connector's shared walkway collecting a total of 169 hours of video footage over three consecutive days in July 2022.This data was then processed using state of the art object detection and tracking algorithms to identify over 20,000 unique instances of people, PMDs (bicycles, e-scooters), other objects (dogs, umbrellas, bags); and extract their movement patterns. Our findings show that most PMD users followed speed limits on shared paths, but a minority exhibited dangerous speeds. Focus should be given to minimise these Addressing this behaviour should be a top priority in planning solutions. Additionally, our findings highlight potential conflicts between pedestrians and PMD users

on the cycling path, suggesting design and policy changes to minimise pedestrian presence on the cycling path. Furthermore, we show how design elements like overhead-cover and path design affect usage patterns and analyse temporal and environmental factors on the volume, direction, and distribution of different user groups. This study concludes with a discussion on the advantages of computer vision technology methodology and recommendations for future research.

Keywords: Active mobility, Activity monitoring, Computer vision, Machine learning, Smart cities, Video analysis

P21

Analysing Systemic Traffic Conditions in Singapore through Epidemic Spreading Models

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Urban traffic is a highly complex system. While there has been extensive studies on the microscopic modelling of traffic jams at the local level, incorporating these microscopic features, such network structure and traffic condition, and the associated theories at macroscopic, urban-scale studies are often lacking. Given how such microscopic details of urban traffic system may affect the evolution of congestion, new models are needed to enhance the predictive capacity of traffic management systems. One promising direction is based on percolation theory related to network spreading dynamics, like the SIR model (Susceptible-Infected-Recovery) used in epidemics modelling. In this study, we analyse the traffic data in Singapore, and aim to extract the empirical dynamics of traffic jams in the framework of epidemic spreading over road networks. We treat a traffic jam or relatively slow vehicle movement in a road segment as an 'infected' node, and a high-speed flow road segment as 'susceptible' node. By analysing the spatial-temporal data of traffic movement, we recover the empirical dynamical properties of the spreading of traffic jams at the system level. Our results suggest that the spreading patterns do not fit into the commonly used SIR model, which assumes 'recovered' road segments being unable to experience jams again, but rather a 2-type competing SI model, where congestions and free-flow traffic movement are two types of 'infections' competing on one network. The spreading and recovery parameters calibrated on Singapore data also shows that the existing traffic dynamics operate well below the 'percolation threshold' of global spreading, meaning no large area of traffic jam can emerge, which is consistent with the general perception of traffic conditions in Singapore. This study demonstrates the utility of the SI models, and. if combined with land usage and network analysis, such systemic approach could be used as a simplified framework to facilitate urban planning in better manage traffic at the system level.

Keywords: Complex network, Percolation theory, Phase transitions**,** SIR/SIS model, Urban traffic

P22

A Global Bottom-up Approach to Create Urban Digital Twins (UDT): Mitigating Greenhouse Gas (GHG) Emissions

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Several nations have taken a stance to reduce greenhouse gas (GHG) emissions in their industrial processes and operations. Furthermore, these nations have committed to achieving carbon neutrality goals within a short duration. However, accounting for emissions requires technical support in the form of tools and applications that can prove use cases for effective city management. Urban Digital Twins (UDTs) integrate multiple disciplines to improve city system efficiency. Nevertheless, UDTs that explore decarbonisation initiatives for cities are limited, as the applications restrict themselves to the building level and have minimum access to authoritative 3D data at the city scale. We propose a methodology to build a UDT platform using a bottom-up integrated 3D city energy dataset based on OpenStreetMap and local public data portals in Singapore. Local datasets are used to gather building type, completion year, and energy consumption data. A linear equation is used to calculate the building's operational GHG emissions based on energy modelling and the dataset. Each building is assigned a Singapore Region, Planning Area, and Subzone, this information allows city-scale analyses and data exploration. An interactive web map application with User Experience (UX) is developed for rapid heterogeneous data streaming. The UDT platform has a query system with three input scrollbars for quick access to the information—Planning Area, Built Year, and Building Typology. The UDT dashboard generates charts and visualisations based on GHG emissions calculation output. New scenarios such as low/high energy use and low GWP refrigerants in the future are created on top of the baseline (current energy use and technology). By using various interactive what-if scenarios for future scenarios, the UDT use case demonstration will help stakeholders develop GHG emission reduction and carbon-neutral strategies. The research provides a guideline to develop UDT applications around the world without or with limited authoritative open 3D datasets.

Keywords: Climate change, Energy modelling, Smart cities semantics, Urban analytics

P23

Can New Urban Rail Transit Lines Reduce Car Ownership? — Evidence from the Opening of the Circle Line in Singapore

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The existing empirical studies have presented conflicting arguments on whether investments in urban rail transit can restrict car ownership, and some of them face methodological challenges. In this research, we regard the opening of the fourth Mass Rapid Transit (MRT) Line in Singapore, the Circle Line (CCL), as a quasi-natural experiment to assess the treatment effect of rail transit on car ownership within a difference-in-differences modelling framework based on Household Interview Travel Surveys. We also employ a two-dimensional propensity score matching approach to creating matched samples with controlling for the spatial and temporal heterogeneity. We find that the CCL reduces the car ownership per household by 3.2 percentage points and 2.5 percentage points for those living within 500 m from the CCL stations with considering only individual characteristics and both individual and household characteristics, respectively. With matched samples, the treatment effect on car ownership level increases, suggesting that there could be gentrification process in station areas. Moreover, the CCL can significantly reduce the car ownership of households both living and working close to CCL stations than those only live close to CCL station or didn't report their fixed workplaces. Furthermore, the opening of the CCL shows a significant impact on households' decisions on whether to purchase their first car, but its impact on the number of cars given car ownership is insignificant. The research findings provide more robust estimations of the treatment effect and new evidence that supports the effectiveness of urban rail transit in restricting car ownership, which strengthens the justification of building more accessible MRT system. In addition, when designing new rail transit lines, the policy makers should attach importance to the role of MRT, individual and household factors, and heterogeneity issues to better restrict car dependency and achieve sustainable transportation.

Keywords: Car dependency, Difference-in-differences, Public transportation, Treatment effect, Two-dimensional propensity score matching

P24

Accelerating PV Adoption in Singapore: The Potential of Advanced Energy Communities

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Solar energy stands out as the most promising among the available renewable resources in Singapore. However, solar photovoltaic (PV) installations in Singapore are still far from sufficient due to limited land space, a low feed-in tariff, and significant investment costs. To overcome these challenges, the concept of the Advanced Energy Community (AEC) has garnered attention as an innovative business model that can potentially accelerate the PV adoption rate (i.e., fraction of energy demand met by local solar supply), through solutions like local energy sharing via microgrid, demand flexibility, the utilisation of public spaces, and the introduction of district cooling systems. While the economic and environmental benefits of AEC have already been extensively examined in literature, the potential of AEC to expedite the PV adoption rate in densely populated tropical urban centres, such as Singapore, remains inadequately evaluated. To address this gap, we develop an optimisation-based framework to assess the potential and drivers of the AEC model to accelerate PV adoption across Singapore. The simulation covers nine representative district areas, ranging from Housing and Development Board (HDB) residential areas, condominium complexes, central business districts (CBDs), industrial parks, university campus, to landed housing zones. The study's outcomes demonstrate that the incorporation of the AEC model can significantly reduce the Levelized Cost of Energy (LCOE) and therefore increase the PV adoption rate compared to the solar-leasing model and ownership model. Residential areas exhibit notably higher solar adoption rate by leveraging AECs compared to other district types because of the high PV generation potential and low energy demand. Among the various solutions incorporated by AEC, district cooling, utilisation of public space (e.g., carpark and corridor rooftops), and demand flexibility can substantially increase PV adoption rate. The results could inform the design of AECs in a high-density tropical city on various aspects, such as building mix, technological portfolio, and system operation.

Keywords: Advanced energy community, Distributed energy resources, Photovoltaic adoption

P25

Material Stock-service and Circularity Prospects of Buildings in Singapore

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The buildings and construction sector plays a vital role in socio-economic development, while being a primary consumer of resources. In Singapore, this sector is highly reliant on imports, and the city-

state is expected to double its building stock by year 2050. Estimates of city-scale building material stock and flow can contribute towards local resource circularity opportunities and decarbonisation. To examine this, we apply a bottom-up, retrospective material flow analysis to track concrete and steel stocks, flows and embodied carbon in Singapore buildings, from 2010 to 2020. The model operates on age-type specific gross floor area (m^2 of floor area) which are complemented by building-type specific material intensities (kg/m^2). Investigating seven building typologies, covering all public and private residential, commercial, and industrial buildings, we show that most inflows are directed to residential sector demand, while the largest outflow originated from the demolition of private industrial buildings. In 2020, 257 million tonnes of concrete and steel stocks were embodied in buildings. The cumulative material outflows for the next 10 years can meet around 37% of total annual material demanded for the past 10 years. As of 2020, embodied carbon in public residential buildings is the highest (93.04 $MtCO_2e$) among all building types, followed by private residential buildings at 64.67 $MtCO_2e$ and private industrial buildings at 45.42 $MtCO_2e$. Resource efficiency of residential and industrial buildings, in terms of material use per service index, has remained unchanged over the past decade, while that for commercial buildings has risen. Focusing on secondary resource utilisation and reuse can contribute to low carbon and circular built environment.

Keywords: Built environment, Circular economy, Embodied carbon, Material flow analysis, Sustainable cities

P26

Significant Carbon Mitigation Potential from Installed Rooftop Photovoltaics in Singapore: A GIS-integrated Life Cycle Assessment

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Solar farming has been increasingly being used for decarbonisation in cities. However, it is challenging to accurately quantify the life-cycle carbon mitigation potential of installed photovoltaic (PV) systems at a city-scale. This is because conventional methods relying on individual surveying are time-consuming and labour-intensive, while large-scale estimation confronts the data unavailability for installed PV size and location, the spatiotemporally heterogenous distribution of solar PV potential, and the complexity of carbon emission during the whole life cycle. To effectively support government decision-making for renewable energy transition, this study develops a deep learning-oriented Remote Sensing and Geographical Information System (GIS) integration model to estimate life-cycle carbon mitigation potential of all the installed rooftop PV systems. Specifically, the model is built by three interconnected modules: (i) an advanced semantic segmentation network is used to segment PV areas from satellite imagery, (ii) the segmented PV areas that quantify installed capacity, historical weather that determines land-surface solar irradiation, and three-dimensional building data for modelling shadow effects are combined to quantify the annual PV electricity generation capacity, and (iii) a life cycle assessment is adopted to estimate carbon mitigation potential of

rooftop PVs from manufacturing, transportation, installation and maintenance, and finally deconstruction. The proposed method can be generalised and used for global cities. As a case study in Singapore, the results show that, for the installed rooftop PVs, the carbon emission rate is considerably small, and the carbon reduction benefit is significantly large, which makes the carbon payback time equalling 1.51 years and the energy payback time equalling 1.29 years only. The net carbon reduction benefit was also estimated, suggesting that 4687774.5 tons CO2 emission could be reduced. This demonstrates a rapid offset of the carbon emission and a large reduce of energy consumption of rooftop PVs during the whole life cycle in Singapore.

Keywords: Building-integrated photovoltaics, Carbon mitigation, Geographical information science, Geospatial artificial intelligence, Life cycle assessment, Remote sensing

P27

Sidewalk the Talk: Translating Street View Imagery to Correct Perspectives to Enhance Bikeability and Walkability Studies

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The recent surge in the utilisation of street view imagery (SVI) and deep learning technologies has catalysed numerous studies evaluating active transportation infrastructure on a large scale. However, a significant limitation is that conventional SVI is captured from vehicles, which diverges from cyclists' and pedestrians' perceptions. Research has not yet quantified these biases nor suggested any methodologies for adjusting for these differences. We introduced mean intersection over the union of semantic segmentation as a partial loss function and utilised perspective images as input to better study these biases. Such a methodological enhancement provides a more accurate representation and understanding of the biases. Furthermore, we compared the effectiveness of Generative Adversarial Networks (GAN) models using Pix2Pix and CycleGAN architectures in correcting for these biases. CycleGAN offers a more general approach by supporting unpaired image datasets and allows bidirectional translations (from dataset A to B and vice versa), whereas Pix2Pix necessitates more curated paired-image datasets and permits only unidirectional translation (from dataset A to B). Our results reveal notable biases when comparing conventional SVI to cyclists' perspectives (R2: −0.84–0.10), and both CycleGAN and Pix2Pix models alone were able to reduce such biases (R2: −0.26–0.17). Moreover, the combination of CycleGAN model outputs and the LightGBM model demonstrated promise in diminishing these biases (R2: 0.55–0.69). As SVI ascends to mainstream prominence in evaluating the active transport and urban environment, this study provides an approach that rectifies perspective biases of pedestrians and cyclists, ensuring a balance of scalability and enhanced reliability in SVI analysis. This advancement paves the way for cost-effective active transport infrastructure assessments to recommend timely and precise urban planning policies that can amplify walkability and bikeability, thus nudging citizens towards greener, low-carbon transit options.

Keywords: Consortia, Green Intelligence, Internet of Trees, Microbiome, Restorative

P28

Biomimicry: Learning from Nature to Decarbonise the Built Environment through Effective Thermoregulation Strategies

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Our efforts to cool the human world are warming the planet. Cooling services release nearly 5 billion tonnes of carbon emissions, a whopping 10% of global greenhouse gas emissions. In Singapore, household and building air-conditioning constitutes 19% of Singapore's carbon emissions. With rising temperatures and cities getting denser and hotter, the demand for cooling in Singapore and beyond is only set to increase. Nature has solved for thermoregulation across a diversity of species that share our tropical climate. Many of these creative solutions are expressed via the organisms' skins, the largest interface in contact with the outside environment. To this end, bioSEA, an ecology and biomimicry design consultancy, has recently launched a design toolkit titled 'Biomimicry for tropical building skins. It has distilled best practices from more than 30 published global case studies and bio-materials that showcase the application of biomimicry for thermoregulation relevant for the tropical climate to be applied to the construction material used, design of wall panels or expanded to building scale. The case studies vary in their stage of development starting with conceptual studies to built projects or commercially available materials or products. The toolkit also features bioSEA's own designs inspired by the Elephant Skin, Desert Beetle and Termite Mounds that were synthesised into a six-step design process for readers to understand how to apply ideas of biomimicry to maximise passive thermoregulation capacity of the building – by improving ventilation, heat dissipation, humidity control, water capture, and limiting heat gain. Made possible with support from DesignSingapore Council's Good Design Research initiative, the toolkit aims to be a practical guide in applying biomimicry for effective thermoregulation in the tropical built environment and thereby, decarbonise through passive design approaches.

Keywords: Design toolkit, Nature's genius, Thermal comfort, Tropics

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SURE by Ramboll – Freeware for Sustainability Based Remediation Options Assessments

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The building sector currently accounts for 39% of global carbon emissions and dominates global material usage. As the global urban built environment is projected to grow by 60% by 2050, there is an urgent need to address the environmental impact of urban redevelopment precincts to align with the climate goals of the Paris Agreement and the UN Sustainable Development Goals. SURE is web-based freeware developed by Ramboll to compare the sustainability of remediation options. It is a multi-criteria assessment tool pre-loaded with over 70 indicators grouped under domains of environmental, social, and economic sustainability. SURE has been applied to over 50 remediation projects globally, including five projects in Australia and New Zealand (ANZ), where greenhouse

gases (GHG) emissions through redevelopment were projected as a key environmental sustainability indicator. In these ANZ case studies, GHG emissions for remediation options were projected by developing an indicative bill of quantities for each option and applying emissions factors sourced from the Australian Government National Greenhouse Accounts Factors database. GHG emissions for each remediation option were then scored and weighted based on the client's perception of the importance of GHG as a metric relative to other sustainability indicators. Using three urban redevelopment case studies, SURE demonstrated several key benefits compared to traditional assessments. These include improved stakeholder engagement and the ability to integrate a wider range of assessment metrics more efficiently. The SURE tool simplifies the evaluation of remedial options based on sustainability, enhances the consideration of relevant sustainability metrics, and supports stakeholder decision-making. Furthermore, SURE has the flexibility to adjust to the increasing focus on decarbonisation and is particularly relevant as a tool for decarbonising urban redevelopment, where many of the most challenging remediation solutions are required.

Keywords: Client-driven, Freeware, Sustainability-based remediation

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Adaptability of Buildings for Sustainable Built Environment: A Review

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The significant impact of the built environment on global carbon emissions is leading to an increased focus on building adaptability to enhance sustainability. This adaptability, which enables buildings to evolve with changing needs and conditions, is vital as cities rapidly expand. To counter premature obsolescence, attention must be given to the end-of-life treatment of buildings, emphasising reduced waste and emissions by incorporating flexibility into designs and structures from the early design stages. This research comprehensively examines building adaptability, defined as a building's ability to smoothly transition into new uses and purposes for its structure, eliminating the necessity for complete demolition. This research aimed to understand the factors contributing to adaptability and what has hindered its implementation so far. The significance of using adaptable building strategies lies in their potential to extend buildings' lifespans, reduce premature demolition, and promote the circular use of building materials. A comprehensive literature review, done on a global scale and in the scope of both residential and commercial buildings, highlighted the complex nature of the concept of adaptability in buildings, influenced by design, materials, processes, regulations, and user preferences. The review also revealed the state of knowledge in such flexibility, including the benefits, drivers, and barriers in the implementation of adaptable strategies in the construction of buildings. Additionally, considering a building in the form of different parts and layers with varying lifetimes can assist in achieving more adaptable designs in the future. By fostering circularity and minimising demolition, buildings that are designed to be adaptable align with sustainable urban development strategies to achieve environmentally conscious, resilient, and decarbonised cities. Ultimately, adaptability is not just an opportunity but an urgent necessity for a country with limited

resources, like Singapore, to decarbonise by minimising end-of-life waste through its building designs, construction processes and material selection.

Keywords: Design-for-disassembly, Modularity, Open-building, Prefabrication, Reconfigurable, Repurpose

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Interoperable Building and Solar Energy Simulations for Augmented Cities using Dynamic Knowledge Graphs

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In decarbonising cities, accurate granular data on current and projected energy requirements and renewable energy potential is required. However, access to these data is a key bottleneck. On one hand, such data may not exist as the digitisation and collection of these data is resource-intensive and dependent on political agendas. On the other hand, any available data remains fragmented and difficult to retrieve across organisations, technologies, and domains due to the heterogeneous data protocols involved. In this work, The World Avatar its capabilities to integrate and simulate cross-domain real-time data from documents and demonstrates technologies such as Building Information Modelling, geospatial software, and sensors to augment and support the city of Pirmasens, Germany along their renewable energy transition. The World Avatar employs a dynamic knowledge graph approach that integrates various software, tools, and data to augment reality with a rich interoperable digital representation of historical, current, and future knowledge. The key advantages of this approach are as follows: First, a rich interoperable knowledge base can calibrate and derive more accurate and precise city-scale simulation models with fewer assumptions. For example, building uses and geometry are considered for simulating energy consumption. Such simulations offer a cost-effective alternative to estimate building energy consumption for any application even if such data does not exist. Second, the World Avatar's knowledge, inclusive of simulation outputs, are accessible on platform-agnostic visualisation interfaces. When knowledge on their energy consumption, theoretical solar energy supply, installation costs, vendor and equipment datasheets are consolidated in one interface, such an approach enhances information transparency on consumers' estimated energy savings and surplus, which can empower consumer participation in local energy markets. Last, the interoperability achieved in the World Avatar is scalable, enabling the aggregation of granular cross-domain data up to the city and national scale to support more informed data-driven energy policies.

Keywords: Decarbonisation, Energy simulations, Interoperability, Knowledge graph, Smart city

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The City Energy Analyst (CEA) Toolkit Empowers Everyone in the Game of Decarbonising Cities

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Decarbonising cities is a game for everyone, including academic researchers, practitioners, government agencies, students and the general public. The City Energy Analyst (CEA) Tool engages and aims to empower a full spectrum of stakeholders in the game of decarbonising cities. To achieve this, CEA adopts a multi-interface strategy for different CEA users while maintaining its established core as a leading research-based, open-source urban building energy modelling platform developed in Zurich and Singapore. At the moment, CEA has three categories of interfaces. (1) For advanced users, CEA's extendable structure enables them to develop their plug-ins on top of the CEA core functionality. The plug-in developers can publish their work to share with the global CEA community. (2) For other professional users and university students, CEA offers a user-friendly dashboard on Windows and Macintosh operating systems. A web-based dashboard will roll out shortly after we complete the migration of CEA to the Cloud. (3) For everyone, we have created a web-based platform to illustrate CEA simulation results for laymen. Currently, Singaporean users can enter their home's postal code, floor number and window orientation, and then the platform will revert with customised vegetable-growing suggestions for the user's balcony and their potential environmental impacts in terms of reducing energy demand, carbon emission, water usage as well as the associated costs. Such information is dedicated to Singapore's "30 by 30" Goal, and soon we will include more CEA simulation results into this platform. To enhance the abovementioned three-interface strategy, we have hosted training programs and workshops that were open to both professionals and the public in Singapore, and soon we will be hosting more in-person and online CEA user meetings. As a result, we have seen CEA user groups in more than 50 countries worldwide across academia, government agencies, practices and beyond.

Keywords: Computational simulation, Global user community building, Open-source software, Sustainable urban design, Urban building energy modelling, Urban farming

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