Designing the Urban Forest:

Toward a visual-functional design decision support system for tree-scapes

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Abstract

The demands of urbanisation coupled with growing environmental climatic challenges of heat and flood make decisions about urban trees, their positioning, spacing and species a critical issue for achieving healthy cities in the future. Once considered a non-essential visual embellishment to urban streets, trees are increasingly seen as a crucial form of (green) infrastructure capable of addressing multiple human and environmental health problems. However, current street tree decision-making methods are spatially, visually and environmentally de-coupled, making them inadequate for synthesising spatial constraints, environmental dynamics and cultural historic community preferences. For landscape architects, who are often in the position of negotiating streetscape decisions, there are currently no methods to model, communicate, forecast, and synthesise the multiple criteria for streetscape performance.

The aim of my research is to develop and test a new tree-scape design approach that is simultaneously visual and functional, that responds to site conditions to inform decision-making about placement and species choice of trees in urban streets.

The *hypothesis* of this thesis is that emerging modelling technologies from gaming, animation and architectural sciences can be combined with techniques from geospatial analytics, algorithmic botany and urban forestry, to create the modelling framework for performance-based design decision support, that assists practicing landscape architects to coalesce divergent criteria of visual, spatial and functional aspects of tree-scape design.

To test this hypothesis, I use a three-part mixed-method. Firstly, I conduct a review of historical approaches to trees in cities, and a cross-disciplinary review of contemporary methods to model, analyse and visualise tree-scapes. Secondly, I use an iterative process toward development of a *tree-scape Design Decision Support System* (DDSS), bringing together emerging computational technologies from a range of disciplines to combine the criteria upon which tree decisions are made. I prototype the system using abstract micro-scaled 'petri-dish tests'. Thirdly, I test the DDSS using speculative design scenario experiments on three sites in Melbourne, Australia, each with specific environmental concerns: a coastal suburb with issues of *sea level rise and flooding*; a low-rise residential

precinct with poor tree coverage and issues of *heat vulnerability;* and an urban renewal precinct which faces both *heat vulnerability* and *flooding* issues.

The results of the applied testing of the DDSS on this range of speculative case studies demonstrate its capacity for use by designers to concurrently integrate hydrological flood-modelling scenarios, microclimatic moderation for active transport comfort, and visual impact of tree choices at both precinct and streetscape scales.

This thesis addresses the aim of the study by developing a design approach which can simultaneously express qualitative outcomes of tree choices and quantify key functional aspects of tree alternatives responding to evolving urban morphological, spatial and environmental conditions. It offers a novel method for simultaneously addressing *visual* implications of tree choices alongside quantification of *functional* benefits and a tool for negotiating street space with transport and engineering disciplines.

The thesis provides important insights and site-specific replicable methods for landscape architects to use for balancing subjective cultural preferences with environmental performance-based tree-scape design. It branches in the direction of adaptation to climate change and towards encouraging healthy, thriving and resilient communities.

Declaration

This thesis is an original work of my research and contains no material which has been accepted for the award of any other degree or diploma at any university or equivalent institution and that, to the best of my knowledge and belief, this thesis contains no material previously published or written by another person, except where due reference is made in the text of the thesis.

All figures and tables are produced by the author unless otherwise stated. All rendered images and maps are produced using the base platform unless otherwise noted.

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Publications during enrolment

Authored Books

White, M & Langenheim, N. (2020), *The Death of Urbanism - Transitions through five stages of grief*, Art Architecture Design Research [AADR] Spurbuch, Bamberg, Germany [in press as of 20-08-19].

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Awards and Exhibitions

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2016 (May-Nov) White, M., Langenheim, N., M., Kimm, G., "'Spatial Nearness' - Proximity and Accessibility", in X-Ray the City, Venice Biennale, Venice.

2016 (May-Nov) White, M., Langenheim, N., M., Kimm, G., Huang, X., Burry, M., "Cities… they're so hot right now, Hot in the city, hot in the city tonight…", in X-Ray the City, Venice Biennale, Venice.

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A portion of the work in Chapter 5: *Umbrella Cities* was published in a book chapter in *Planning Support Science for Smarter Urban Futures* in (2017).

A portion of the work in Chapter 04: *Research Method* was published in a journal article in the *International Journal of E-Planning Research* (2018).

Much of the work in Chapter 6: *Shady Cities* was published in the Urban Transitions Global Summit (2016) conference paper, and a journal article in *Sustainable Cities and Society* in 2019.

The thesis builds on initial concepts presented in a conference paper in International Urban Design Conference Designing Productive Cities (2014) and book a chapter in *Our common future in Urban Morphology* (2014).

Contents

Terms and Abbreviations

3ds Max	Autodesk™ 3ds Max™
Algorithmic botany	Botanical tree modelling generated with the assistance of mathematical algorithms
AutoCAD	Autodesk™ AutoCAD™
ENVI-met	ENVI-met™
Photoshop	Adobe™ Photoshop™
V-Ray	Chaos Group™ V-Ray GPU for 3ds Max version 3.6™
Xfrog	Xfrog™ Finite Recursive Object Generator
City Engine	ESRI City Engine™
Cinema 4D	Cinema 4D™
Grasshopper	Grasshopper™ Visual scripting plug-in for Rhino 3D™
Infraworks	Autodesk™ Infraworks™

Maya	Autodesk™ Maya™
Rhino 3D	McNeel™ Rhinoceros 3D™
SketchUp Pro	Trimble™ SketchUp Pro™
AURIN	Australian Urban Research Infrastructure Network
BIM	Building Information Modelling
BCCVL	Biodiversity and Climate Change Laboratory
CAD	Computer Aided Drafting or Computer Aided Design
CFD	Computational Fluid Dynamics
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DDSS	Design Decision Support System, see section 1.1.4 Defining key thesis terms (p. 30)
DEM	Digital Elevation Model
DELWP	Department of Environment Land Water Planning
EIA	Environmental Impact Assessment
GFA	Gross Floor Area
GPR	Green Plot Ratio
GPU	Graphics Processing Unit
GIS	Geographical Information System
GCCSA	Greater Capital City Statistical Area
HTC	Human Thermal Comfort
LAI	Leaf Area Index
LGA	Local Government Area
LIM	Landscape Information Modelling
PAI	Plant Area Index (also known as effective LAI)
POD	Pedestrian Oriented Development
PPD	Public Participatory Decision Making
PSS	Planning Support System
SSWMS	Surface Storm Water Management System

Streetscape	A streetscape is the collective design and appearance of buildings, footpaths, street furniture, gardens and landscape along a street.
SVF	Sky View Factor
TIM	Tree Information Modelling
TOD	Transport Oriented Development
Tree-scape	See section 1.1.4 Defining key thesis terms (p.29)
UHI	Urban Heat Island
Urban Forest	See section 1.1.4 Defining key thesis terms (p.29)
VIA	Visual Impact Assessment
WSUD	Water Sensitive Urban Design

Chapter 1: Introduction

[...] the Enlightenment view of the world stressed both order and nature. Within the concept of order can be seen the aesthetic values of visual clarity, harmony and symmetry, all of which result in a fresh sense of urban beauty [...] There was also a belief in a reciprocal relationship between nature and the human world, that the ways we design the world could help it achieve its full potential, while more contact with nature could make us more natural and less artificial' (Lawrence 2006).

1.1 Introduction

The broad scope of this research is to prototype a Decision Support System (DSS) for tree-scapes, that works across tree visual considerations, tree functional environmental benefits and the spatial constraints of urban streets. The point of developing a DSS that is simultaneously visual, spatial and functional is to coalesce the multiple divergent criteria upon which street tree decisions are made. The research is an investigation of evolving computational techniques for quantification, negotiation and communication of urban tree decisions. With this research I aim to address growing demands placed on industry to quantify the impact on human and environmental health of design choices, while also permitting creation of qualitative visualisation for use in public participatory decision-making (PPD) arenas.

To propose development of a DSS for tree-scapes, requires an understanding the contextual, spatial historic and environmental variables that impact tree-scape choices and how these are currently modelled. It is specifically a design DSS (DDSS), developed in a way that harnesses the emerging possibilities for design, that have become available through software and hardware developments in the computer-generated imagery (CGI), industry, particularly algorithmic (recursive 3-dimensional) tree modelling and daylight simulation, coupled with the growing quantity of spatial data evolving in the geospatial sciences. The DDSS differs from DSS developed in other disciplines in that it is must be flexible, able to be adapted to different software ecosystems currently in use in industry. In this chapter I outline the problem, state the aim of the thesis, discuss the scope of the research and provide an overview of the thesis structure.

1.1.1 The problem statement

Trees were once considered a non-essential, embellishment to urban streets. In contemporary cities, this consideration of trees is shifting towards their potential as a form of (green) infrastructure capable of addressing multiple human and environmental health problems. Considering trees as infrastructure has rendered the problem of tree-scape design too complex for the existing design approaches and current decision-making methods, as these are spatially, visually and environmentally de-coupled. The consideration of spatial constraints, environmental dynamics and cultural historic community preferences, requires communication techniques, modelling, and forecasting that can synthesise multiple criteria simultaneously.

City streets are changing

Currently cities globally are on the cusp of numerous transformations in transport, housing and the adaptation of infrastructure[1] to climatic change and increasing urbanisation[2] (Batty, 2013; Vojinovic & Abbott, 2012). It is on urban streetscapes where these transformations will be most visible. Taller, more compact building forms will impact streetscape light availability, new above ground storm water infrastructure will impact surface finishes and shifts in transport will impact street configurations. Making decisions about how these transformations will be achieved in contemporary streetscapes is critical to the success of our future cities.

Tree considerations are shifting

Street trees, when they became a norm, leading up the period associated with the Reformation Act of 1832, were employed primarily on visual terms. They were symbols of a publicly accessible garden, in contrast to the 16th century, inaccessible private walled pleasure gardens and *barco*[3] of the villas of the European aristocracy (Feng & Tan, 2017;

[1] Such as storm water management systems.
[2] Such as increasing storm intensity discussed further in Chapter 5.
[3] A *barco* was sometimes a feature of an area adjacent Italian Renaissance villa gardens that, while mostly left natural, had pathways planted with forest trees (in Italy these were sometimes open to the public). Where this Italian Renaissance garden fashion was taken up in Northern Europe (in conjunction with northern European forest management for hunting grounds), barco's remained predominantly

Lawrence, 2006). [Discussed further in section 2.2: *Rise of the Pretty City*]. However, in contemporary cities, this visual consideration of urban trees has shifted, to also include their multiple functional benefits for human and environmental health.

In terms of human health, urban trees have been shown to increase chances and distances of walking, thus increasing levels of physical activity (Sarkar et al., 2015), reduce exposure to ultra violet radiation, a leading cause of skin cancer (Parisi & Turnbull, 2014) improve pedestrian human thermal comfort (Sanusi et al., 2016), decrease heat related ambulance callouts (Graham et al., 2016), improve self-reported mental health status (van Dillen et al., 2012), decrease crime rates (Mullaney et al., 2015) and increase social cohesion[4] (Holtan et al., 2015). Tree functional contributions to environmental health, include capacity to reduce the speed and quantity of storm water (Xiao et al., 2000), filter pollutants from the air and stormwater runoff (Denman et al., 2006), provide habitat and food for animals (Livesley et al., 2016; McPherson et al., 1997) and sequester carbon (Nowak & Crane, 2002). These contemporary urban tree considerations, are epitomized by the rise of new terminology used to describe trees, in particular the terms, 'green infrastructure' and 'ecosystem services' (Benedict & McMahon, 2002; Costanza et al., 1998) [5] [6]. [These will be discussed further in section 2.4: *Rise of the Sustainable City 1975-and* beyond].

Tree-scape design decision-making is evolving

Contemporary tree-scape decision-making is a threefold problem. There is increasing *spatial* pressure on streetscapes arising from urbanisation processes, cultural and *visual* pressures arising from historic preferences, and increasing aspirations for the functional attributes of trees to help address growing *environmental* and human health problems. To harness the functional possibilities of trees, will require departures from traditional placement and species selections. This will at times result in tree-scapes that do not

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private until these villa garden extensions began to extend further into forest areas for (among other things) recreational purposes, and cities grew outwards towards the villas. The Villa, paths through the forests became structure for town roads (Lawrence, 2006, Chapters 1 & 2).

[4] Social capital has some contradictory definitions that are discussed by Holtan. Essentially, how close the neighbourhood ties in an area are or social cohesion.

[5] The term Green Infrastructure has been mutable over the last few decades but refers to a range of urban drainage systems that may or may not include trees. It is considered the broad, large scale principle of all water sensitive storm water management – See Fletcher 2015 SUDS, LID, BMPs, WSUD and more – The evolution and application of terminology surrounding urban drainage.

[6] Ecosystem services is an economic modelling approach to tree valuation which has led to increased funding and awareness of tree functional attributes and provides a method of quantification of tree benefits as a financial value.

conform to cultural or visual preferences and may require spatially explicit adjustment to transport and land use planning practices.

Many different disciplines are making these streetscape decisions using models that can privilege one, discipline specific criteria over another and produce forecasts for decision-making that conflict with the objectives of other disciplines. Currently, there is no way to model streetscape design decisions that simultaneously describe spatially explicit visual impact, functional benefit analysis and multiple disciplinary criteria. In addition, tree-scapes are public landscapes and as such, decisions about them are often made in Public Participatory Decision-making forums (PPD). While public participation in decision-making is a fundamental cornerstone of democracy (Arnstein, 1969), it can be difficult to negotiate the conflicts between improvement of environmental outcomes and community visual preference (Berry et al., 2019; Pierre et al., 2006). [This will be discussed further in section 3.3: *Modelling visual concerns*].

Figure 1: Pressure on space equals pressure on trees. The central Business District of Melbourne is reliant on street trees for provision of green space in certain areas (image colour range selection and adjustment using Adobe Photoshop™).

Visual streetscape decision-making: Despite the perceptual shift in the role of trees in cities towards their functional possibilities, tree cost benefit analysis still consistently shows that 'visual amenity' is the highest value tree contribution (Song et al., 2018)[7]. The impact of street design decisions on visual amenity is often a dominant concern in public

[7] As discussed by Song, amenity value was primarily quantified through effect of trees on property prices.

participation and consultation, and as such, streetscape designers, (often landscape architects) create decision-making aids for these forums that focus on expression of qualitative visual outcomes. However, the 2-dimensional production methods used to create these visualisations are often spatially ambiguous, and therefore not useful for analysis of environmental benefit, or for coordination with spatially explicit engineering concerns (Daily et al., 2009). [This is discussed further in section 3.3: *Modelling visual concerns*].

Spatial streetscape decision-making: There are increasingly complex spatial issues that impact tree inclusion in streets. Past decisions about urban form, land use, land administration boundaries, transport and discipline specific clearance regulations for services, have created streets with somewhat immutable and constrained spatial limitations. The decisions of these disciplines have direct and significant impact on tree possibilities. In these disciplines where trees are considered non-essential, 'expensive ornaments', the plasticity of trees can be taken advantage of and opportunities for trees can be overlooked through pruning for service clearances and reduction of available space (Jonnes, 2017) [Figure 1].[8] [These will be discussed further in section 3.4.4: *Ecosystem service modelling*].

Environmental decision-making: There are three barriers to inclusion of tree functional environmental benefits into streetscape decision-making. Firstly, Ecosystem service calculation, the most established method of quantifying tree benefits is a cost benefit analysis approach, visualised primarily through numeric, graph based financial units[9]. It can be poorly received in PPD forums due to its complexity and abstract output (Olander et al., 2017). Secondly, ecosystem service research has been poorly translated into policy (Laurans & Mermet, 2014; Sallis, Bull, et al., 2016) [10] and thirdly, in design situations, where scales change, objectives shift and contextual and spatial accuracy is needed, it has been difficult to apply as it has little interoperability with spatial or visual design modelling

[8] Compounded by private land ownership administrative systems such as the Cadastre adopted in Australia. In countries such as China and Singapore where government control of land is retained, this issue is less likely to occur. Urban consolidation is less piece meal.
[9] Economic modelling can suffer from assumptions of a 'rational agent' in decision-making models which are not often the case in PPD particularly where trees are involved (Millington et al., 2011).
[10] Sallis discusses the fact that research translation into policy-making / decision-making was too narrow and complex to be applicable to policy / design decision-making, due to the need to be able to test multiple possible outcomes.

methods (Grêt-Regamey et al., 2017; Liu & Jensen, 2018; Schägner et al., 2013; von Haaren et al., 2014)[11]. [These issues will be discussed further in section 3.4: *Modelling environmental concerns*].

1.1.2 A transdisciplinary research area

Streetscapes are both highly contested space and the arena where multiple complex adaptive systems unfold[12] (Furtado et al., 2015). Streetscapes are not only a cross disciplinary concern, they cross knowledge domains[13]; from the physical sciences (in the form of urban climatology), natural sciences (in the form of urban forestry) and the domain termed the 'sciences of the artificial' by Herbert Simon (the disciplines of design, land use planning and engineering[14]) (Collins et al., 2004; Lyall et al., 2011, p. 26; Simon, 1969) [refer Figure 2]. Each of these domains has their own research methods and processes. The methods used by designers, while being close to the design process of engineering, also need to incorporate aspects of scientific method. [This will be discussed further in section 1.1.6: *Research audience and motivation: Evidence based design*].

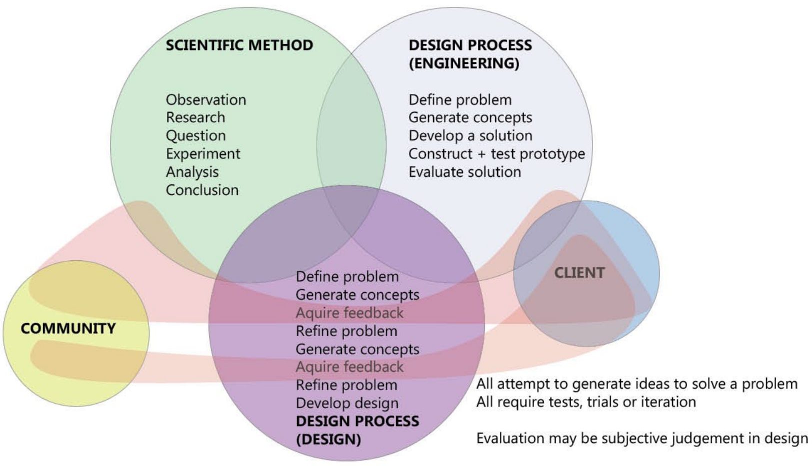

Figure 2: The intersection of scientific method, engineering and design processes, showing how feedback loops occur in the design process between disciplinary domains and non-disciplinary domains such as clients and the community.

> *Multidisciplinarity draws on knowledge from different disciplines but stays within their boundaries [additive]. Interdisciplinarity analyses, synthesizes and harmonizes links between disciplines into a coordinated and coherent whole*

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[11] Liu and Jensen discuss the need for stronger relationships between water sectors and urban design processes in the provision of green infrastructure for urban stormwater management.
[12] Complex adaptive systems describe interplays between a system and its environment.
[13] For some time 'people' and 'natural sciences' have been two separate domains of disciplinary knowledge (Lattuca, 2001, p. 13).
[14] Also computer science, medicine and education.

[interactive]. Transdisciplinarity integrates the natural, social and health sciences in a humanities context, and transcends their traditional boundaries [holistic] (Choi & Pak, 2006).

Choi and Pak[15] define the three terms in relation to health, services, education and policy disciplines, but their definitions are widely applicable to any research where the question bridges traditional discipline boundaries. The three terms describing cross disciplinary work are similarly defined in landscape ecology by Tress (2005), with the distinction that transdisciplinary research includes non-academic participants in the process (Schroth et al., 2011)[16]. Lattuca classifies research as trans or interdisciplinary if it aims to answer *questions that are applicable across disciplines*. For Lattuca trans or interdisciplinary research questions fall into one of two categories: Those that belong to both disciplines (*overlaps*) or those that belong to neither (*gaps*)[17] (2001, p. 82). The research question in this thesis; 'How do we improve streetscape decision-making?' is a question which is full of disciplinary *overlaps* (Huges et al., 2015; Lattuca, 2001).

The research for this thesis then required the sourcing of background from interdisciplinary and transdisciplinary research fields that have evolved over the past half century. These contemporary transdisciplines have evolved partially through societal change, partially through innovation, partially through digital transformation[18] and partially through a common connection to the need for design, analysis and simulation of urban spaces. These disciplines are; transport and land use planning, urban climatology, urban forestry, urban design, urban analytics and urban environmental engineering to name a few. [The specific components of these disciplines will be discussed further in *Chapter 3: Modelling for decision-making*]. I benefited greatly from systematic review papers in these transdisciplines that provided overviews of critical criteria. In particular (Grêt-Regamey et al., 2017; Kántor & Unger, 2011; Laurans et al., 2013; Song et al., 2018).

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[15] While there is a great deal of disagreement and lack of consistency in the definition of these terms between theorists; For instance, Lattuca defines transdisciplinarity as a type of interdisciplinary research. If using her definitions, the research in this thesis might more accurately fit into the category she defines as 'synthetic disciplinarity" (Lattuca 2001 p 82).
[16] Non-disciplinary participants being community stakeholders / citizens or industry professionals.
[17] Lattuca in this section is defining synthetic interdisciplinarity.
[18] Particularly the development of computer cartography or geographic information systems (GIS) (GIS Geography, 2015), and development of computer graphics (Marr, 1982).

1.1.3 Defining the disciplines

As with all interdisciplinary[19] and transdisciplinary research there are challenges in defining the boundary of the problem and selection of a finite set of disciplines, knowledge and methods that are to inform it, and how proposed solutions should be evaluated. [The selection of disciplines and evaluation methods will be discussed further in *Chapter 4: Research method*]. In this thesis, the particular transdisciplinary overlaps lie in the intersections between urban environments, the evolution of computational techniques for analysis and simulation and the growing understanding of the functional attributes of trees [refer Figure 3].

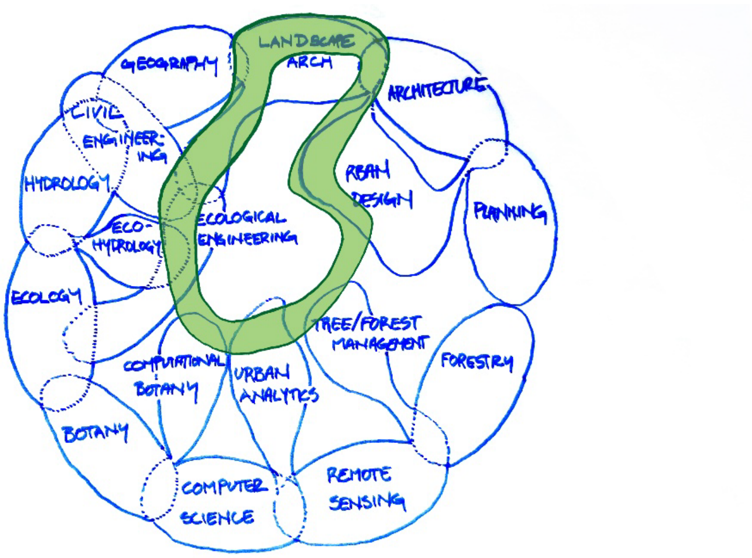

Figure 3: A transdiscipline that crosses other transdisciplinary research fields. This diagram shows some of the transdiscipline, specialisations that have arisen over the past half century from the intersections of traditional disciplines as they converge on computational techniques, increasing interest in urban form and a growing understanding of tree functions.

Sciences of the artificial: Design

Urban design: In the mid 1800's: Individuals from established disciplines such as civil engineering, geography and architecture, dealing with issues of public health management and waste-water disposal brought about by the industrial revolution and rapid urbanisation[20], managed the design of urban space. With the resolution of these infrastructural problems towards the end of the 19th century, the professions of landscape architecture, urban planning and urban design, arose as streetscape decision-makers.

[19] In some ways (and some researchers) do not consider the work of an individual to be interdisciplinary, and therefore transdisciplinary is more appropriate definition See Lattuca Chapter 1.
[20] Most notably Ildefons Cerdà in Barcelona, who trained as a civil engineer.

These professions were more focused on the visual, compositional aspects of city design than their infrastructure focused predecessors [discussed further in section 2.2: *Rise of the Pretty City*].

Sciences of the artificial: Visual computing

Visualisation has long been recognised as a communication tool, useful for decision-making as it transcends vocabulary barriers[21] (Kepes, 1995). From the late 1970's, the transdisciplinary field of visual computing[22] rapidly evolved. Many of the techniques developed in visual computing have been adapted and integrated into both architectural science and the gaming and animation industry, particularly the realistic, depiction of the behaviour of light, material optical properties and geometrically accurate algorithmic botanical tree modelling. The decision-making possibilities made possible through spatially explicit visual computer modelling techniques are used as the foundation of this research. [This is discussed further in section 3.3: *Modelling visual concerns*].

Sciences of the artificial: Transport and land use planning

Several built (human) urban systems such as land use, transport networks and housing are at work on streetscapes[23]. Recognition of the interrelated impact of these systems on each other led to early interdisciplinary research, for example, the relationship between land use, transport and population health (Hansen, 1959; Stevenson et al., 2016; van Dillen et al., 2012). Basic transport and land use planning and decision forecasting modelling, are touched on in this research as the application of the regulations developed in these fields have a formative effect on urban morphological structure and tree possibilities (Litman, 2009; Wegener Spiekermann, 2004). [These will be discussed further in section 2.3: *Rise of the Transit City 1890-1975*].

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[21] In particular see (Kepes, 1995).

[22] computer modelling and computer visualisation. Groß defines computer visualisation as a transdisciplinary field crossing three disciplines; computer graphics, human imaging and visual perception – together these are the field of visual computing.

[23] (Wegener Spiekermann, 2004) Wegener discusses nine subsystems at work in cities, networks, land use, workplaces, housing, employment, population, goods transport, travel and urban environment. The first eight of these fit into four 'rate of change' categories from the very slow to the very fast, but subsystem of 'environment' has may sub-systems and multiple temporal scales which are complex to categorise.

Physical science: Urban Climatology

The interactions between built form and environmental systems of weather patterns, led to the development of the interdisciplinary research field urban climatology in physical science (Chandler, 1965; Scholz, 2011). Urban Climatology[24] developed rapidly during the 1970's with the rising awareness of climate change and the relationship between climate and urban built form, leading to the definition of urban streetscapes as 'urban canyons' with their own particular volume of air or atmosphere (Nunez & Oke, 1977) [discussed further in section 2.4 *Rise of the Sustainable City 1975-and* beyond]. Urban Climatology outputs have been extended into planning and design decision-making through their occasional use in public forums and through the emerging field defined as environmental visualisation[25] (Bishop & Lange, 2005; Sheppard, 2012). This emerging field sits somewhere between, the practice known as *'environmental modelling'* (Robinson, 2011), and the practice of '*modelling the environment*' (Cantrell & Yates, 2012).

Natural science: Urban forestry and ecosystem service science

Urban forestry, defined as a specialised branch of forestry by Jorgensen in 1970, is a discipline concerned with the "*management of publicly and privately-owned lands in and adjacent to urban areas*" (Wenger 1984, pp887). In his original definition, Jorgensen stipulated that urban trees would be managed for their *'present and potential contributions to the physiological, sociological, and economic well-being of urban society'* (1970)[26], (Jorgensen in I. K. Brown, 2007). Urban trees have long fallen into this disciplinary grey area, between design and management professions, which has perhaps left them vulnerable to last minute or last stage consideration. In the last decade urban forestry has adopted GIS[27] systems for record keeping and urban forest structure analysis, for decision support of urban tree renewal strategies. In parallel to Jorgensen's call for urban forests to be managed for urban social benefit, ecosystem service science, a transdiscipline that

[24] The Chemist Luke Howard's published 'The Climate of London' 1833. He is attributed as the pioneer of urban climatic studies by Tony Chandler (Chandler, 1965; Howard, 1833).
[25] Ervin refers to this discipline as Landscape Modelling.
[26] Jorgensen includes an overall ameliorating effect of trees on their environment as well as their recreational and general amenity.
[27] Geographic Information Systems.

spans economic modelling, urban climatology and urban forestry arose[28], developing methods to calculate cost-benefit analysis of the supporting, regulating, provisioning and cultural value of trees[29] (Lele et al., 2013). Two particularly pressing areas have been the focus of ecosystem service science: Firstly the impact of trees on stormwater regulation responding to emerging urban drainage problems[30] and secondly the impact of trees on urban populations vulnerability to heat (Livesley et al., 2016).

1.1.4 Defining key thesis terms

As this research sits across multiple disciplines as discussed above, it is important to define the key terms used in the context of this thesis as these words can have multiple, and at times contrasting meanings in different disciplines.

Designing

In this thesis, the term *designing* refers to the activities undertaken by landscape architects working in industry from production of schematics all the way through to the delivery of spatial and materially explicit, construction documentation of projects. This is an important distinction to what might be considered design in a profession such as planning where construction documentation is not required. While the type of design undertaken by landscape architects can include public participation, consultation and integration of planning regulation, policy aspirations for sustainability and biodiversity in the early phases, these aspects are not always included in the scope of work, or, when they are included, they are an additional or optional hourly fee.

Urban Forest and Tree-scapes

Mirriam-Webster defines treescape as 'a landscape including many trees or groups of trees' (2019b). For the purposes of this thesis, I narrow this definition and use the term tree-scapes to refer to urban streets which include trees, their placement, spacing, and species choice. In this thesis the term *urban forest* is used to describe trees in the public

[28] The origin of the term is described by Lele as originating with Williams and Mathews 1970 '*Man's impact on the global environment: report of the study of critical environmental problems*' as 'environmental services' and was later defined as 'Ecosystem Services by Ehrlich and Mooney 1983. These articles preceded the MEA definition though the MEA definition (2005) is now the most widely accepted.
[29] And other urban vegetation.
[30] Urban drainage is another heavily diffused, multifaceted transdiscipline, spanning civil engineering, flood modelling, hydrology and the origin of the green infrastructure concept (Fletcher et al., 2015).

ream, specifically street trees and in some instances, trees in the private realm where they occur in front yard setbacks.

Visual-functional

In this thesis the term *visual-functional* is defined as follows:

V*isual* refers to the optical assessment of trees used to qualitatively analyse the visual impact, compositional and cultural preferences for tree-scapes.

Functional refers to how trees can impact heat vulnerability and flood adaptation which are usually calculated in ecosystem service science through either mathematical or empirical modelling and data.

In this thesis both *visual* and *functional* aspects of trees are calculated and assessed simultaneously using the same integrated model. I use the term *visual-functional* to describe this integrated approach.

Design decision support system (DDSS)

> *[...] it could be said that anything which provides rational, measurable and scientific data to help leaders make informed decisions is a DSS (River Logic, 2019).*

A key term used throughout the thesis, *design decision support system* (DDSS) is derived from 'decision support system' (DSS), a term initially associated with 'computer aided management tools (Sprague, 1980), which has since been adapted and integrated into many other disciplinary vocabularies. DSS have been coupled to geographic information systems, to become Spatial Decision Support Systems (SDSS) (Clarke, 1990), and have been developed to deal specifically with the needs of planners making strategic planning decisions to become Planning Support Systems (PSS) (Harris & Batty, 1993). The definition of DSS and subsequent discipline specific variations are still evolving (Geertman & Stillwell, 2009). Geertman and Stillwell (2004) summarise Harris and Batty's (1993) definition that a:

> *PSS forms the framework in which three sets of components are combined: The specification of the planning tasks and problems at hand, including the*

assembly of data; the system models and methods that inform the planning process through analysis, prediction and prescription; and the transformation of basic data into information which in turn provides the driving force for modelling and design (through a cyclic process).

They go on to note that Klosterman (1999) and Klosterman and Brail (2001) have described PSS as information technologies that are 'used specifically by planners to undertake their unique professional responsibilities' and that PSS synthesise the three components of traditional DSS—information, models, and visualization—and deliver them into the public realm (Geertman & Stillwell, 2004).

While various DSS, PSS and SDSS have been developed in academia over the past decade, their uptake by the planning industry has remained low (Geertman & Stillwell, 2009; Russo et al., 2017). This is potentially due to staff skilling requirements (requirement for learning interface and functionality), potentially due to lack of software maintenance beyond the production period (such as grant term / study period) (Lehman, 1980) and potentially due to lack of flexibility offered by the user interface for more complex or unforeseen tasks (Brownlow, 2020).

In response to the limitations and lack of DSS uptake experienced in the profession of planning and in recognition of the current state of software use and uptake in design offices which crosses multiple software platforms, I have not developed a single unified user interface or 'dashboard' for this *Design* Decision Support System. This is because A) the system is developed to be used by *designers* as opposed to planners, B) the system is designed to build upon and utilise existing extensive software and computer skill sets in use in this industry already, and C) it is also designed to be relatively simple to 'fix' as different elements of the system including the base platform and the various scripts and plugins are updated and modified at the very least annually. Notwithstanding, this DDSS could also be seen as a set of data driven workflows that could be further developed and 'skinned' with a single, unified graphic user interface or 'dashboard' to be more user friendly in the future. However, as noted by Brownlow dashboards can, in their aim to simplify data queries can quickly become redundant as they struggle answer every persons questions or when they disable the ability for people to 'take action' with the queries they make (2020).

1.1.5 Research aim

To develop and test a new tree-scape design approach that is simultaneously visual and functional, that responds to site conditions to inform decision-making about placement and species choice of trees in urban streets.

The key research question is:

Can environmental performance, spatial constraints and visual impact be integrated into a tree-scape design process?

In order to answer this question, the following sub-questions require answering:

- *What are the past and present decision drivers behind inclusion of trees in streets?*
- *What is the context of tree-scape design tool development (past and present)?*
- *What are the qualitative visual, quantitative spatial and the environmental modelling tools under development or available for streetscape decision-making?*
- *How do design and modelling approaches differ in different disciplines and sectors?*
- *Can we utilise growing availability and accuracy of spatial data sets in street-scape design decision-making?*
- *Can we combine and apply emerging modelling technologies in the entertainment industry (gaming and animation), digital procedural tree modelling, with computer aided design (CAD) and geographic information systems (GIS)?*

1.1.6 Research audience and motivation

> *[...] problem focused interdisciplinary research, addresses issues of social, technical and or policy relevance where discipline-related outputs are less central to the project design (Lyall et al., 2011, p. 17).*

Interdisciplinary research is considered by Lyall to fit into (and across) two distinct types: It can be either 'academically oriented' or real world 'problem focused', aimed at benefiting society beyond academia (Lyall et al., 2011). Design is often an application oriented knowledge field, and therefore design research often fits best into this 'problem focused' research type (van den Besselaar & Heimeriks, 2001).

As a landscape architect and consulting arborist with fifteen years of experience in landscape architectural practice, working on projects ranging in scale from the infrastructural (wind turbines and mine rehabilitation) requiring Visual Impact Assessment (VIA), to the residential scale design of private courtyards, I have gained an intimate knowledge of how tree-scape decisions are made in practice. On the one hand, decisions about streetscapes, these most important and challenging spaces, were made on intuitive, visual, and qualitative grounds in public consultation forums without accuracy (photoshop and coloured pencils were all most exclusively used here). On the other hand, technically accurate decisions[31] were at times unable to be implemented due to difficulties associated with balancing conflicting visual, spatial and environmental criteria that frequently occur in urban contexts. For a skilled landscape architectural practitioner with 'typical' CAD-literate technical skills, I know what is like to do a 'normal project' under 'normal circumstances' using these 'normal skills'. The lack of tools, workflows and decision support systems for people like me was a source of frustration and a motivation to see the spatially explicit evidence-based methods of VIA applied to these most important and high-use pieces of infrastructure.

The intended end-users of the DDSS I develop in this thesis are landscape architects and urban designers working in industry or government who, while historically tasked with the care of the visual quality of cities (Erickson, 2018) now face a growing need to implement evidence and performance-based decision-making, aiming to balance the growing number of often conflicting demands, technical, regulatory, ecological, and to quantify the functional outcomes of their design decisions.

Evidence and performance-based decision-making

> *Landscape architecture is at a stage similar to medicine when antibiotics were invented. Many people were dying every year from infections and the*

[31] Such as designs which addressed water sensitive design requirements.

new medicines provided instant relief. There are issues of similar import in the world today – global climate change, urban heat islands, mass migration to urban areas, loss of biological diversity – some of which are fatal to people and other organisms. Landscape architecture has a role to play in addressing these issues and many more. But our recommendations cannot be based on belief. They must be based on facts and knowledge (R. Brown & Corry, 2011).

Evidence-based decision-making (EBDM) is a term originating from medical science. It is a patient care decision-making method informed by three factors; patient choice, evidence found in scientific literature and practitioner expertise (Sackett et al., 1996). Brown and Corry make the analogy between medical EBDM and the decisions that face landscape architects today. While the 'medical practitioner' can be considered equivalent to the 'landscape practitioner', there are differences in the definition of 'the patient' and the scientific evidence. 'The patient' in EVDM in landscape architecture can vary in both scale and objectives and in many cases consist of three components with sometimes divergent definitions of the problem. The 'patient' can consist of a site, which has specific environmental conditions, or it can be a client who has financial objectives, or it could be a community group who may have cultural and visual preferences. The trifold, divergent needs of the patient(s) impact the relevance of the scientific evidence needed. And the needs of all three must be managed, moderated and evaluated against each other [refer Figure 4][32].

A subset of evidence-based[33] decision-making (in medicine and design) is performance-based decision-making (R. Brown & Corry, 2011; Brownson et al., 1999; Sackett et al., 1996). Performance-based decision-making requires modelling. Performance-based modelling for decision-making is often referred to as 'forecasting'[34] in transport

[32] It is also worth mentioning here that botany and medical science have been strongly related through western history with early botanic gardens being developed for the primary purpose of providing medicinal plants see (Beattie, 2008).
[33] Evidence-based decision-making in medicine is informed by three factors; patient choice, scientific literature review and practitioner expertise. Translating these three factors to design, patient equates to either society or client. However, Brown and Corry's call for Evidence-based landscape architectural research is more about methodical monitoring and reporting on the impact of built work on environmental conditions. Brown suggests the classic design school presentation boards should 'cite evidence'.
[34] In this research I use performance-based design and forecasting modelling interchangeably because in many ways they are just a disciplinary vocabulary distinction.

engineering and is heavily dependent on the definition of the problem and evaluation of the solution for which that forecasting is based.

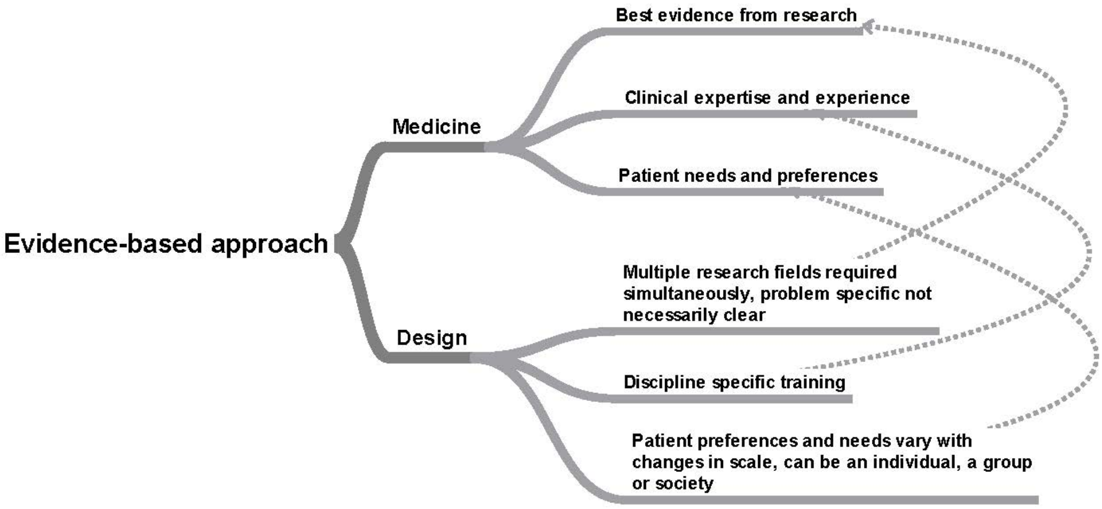

Figure 4: Diagram compares the three factors of evidence-based approaches in medical science and design.

1.1.7 Research design

I selected a mixed method approach of three components to complete this thesis: A formative research component (historic and model based); development of a Design Decision Support System (DDSS) and the testing of that DDSS in three ways. These three methods were selected first, to establish the historical context and contemporary tool development of street tree decision-making, second to develop ways for designers to utilise the growing quantity and quality of spatial data sets and evolving computing methods to improve tree-scape decision-making and third to test, refine and demonstrate the efficacy of the DDSS to changes of scale and shifting criteria in street and precinct scale design scenarios.

Component 01: Historic research

The historic component serves three purposes: It establishes the context and underpinning of current tree-scape selections. It establishes the direct and in-direct tree-scape decision makers in contemporary cities and it provides an overview of the evolution of tree-scape design, tool development and the criteria that drives them.

Component 02: DDSS development

The classic definition of a Decision Support System (DSS) as '*an architecture that accommodates "a system of systems" facilitating customisation and flexibility fit for a specific purpose*' (Geertman & Stillwell, 2009; Harris & Batty, 1993) [35], the second component of this research I develop a loosely coupled architecture of software, which is informed by, and draws from, multiple disciplines into a Design Decision Support System (DDSS). The system uses existing proprietary software commonly found in design offices coupled with plugins and scripts. It is designed to allow spatially explicit visualisation at multiple scales, from the individual streetscape to large scale precincts and allow quantification of a selection of environmental benefits. The method of this component is borrowed from software engineering methods, that combine aspects of 'Design thinking' and 'iterative' software development. In particular the process of 'prototype, test and refine' (Dingsøyr et al., 2012).

Component 03: Prototyping and design scenario testing

The third component has two parts. Firstly, the DDSS is tested on small scale, abstract digital design experiments or prototypes that I have called 'petri-dish' tests, in which variables are reduced and controlled. I then use these petri-dish tests to refine the DDSS for application to three precinct scale sites that have been selected for their specific environmental problems. The *Umbrella City* case study is a site that is impacted only by flood. The *Shady City* case study is a site that is impacted only by heat vulnerability and the *Synthesis City* case study is impacted by both heat vulnerability and flood simultaneously. Figure 5, shows the location of the sites in relation to each other. The sites (in red) are overlaid onto the boundaries of their local hydrological catchment and Local Government Area (LGA) boundaries.

[35] Harris and Batty were specifically defining Planning Decision Support Systems, and the problem of 'speculative data' which is an important proponent of planning and design work.

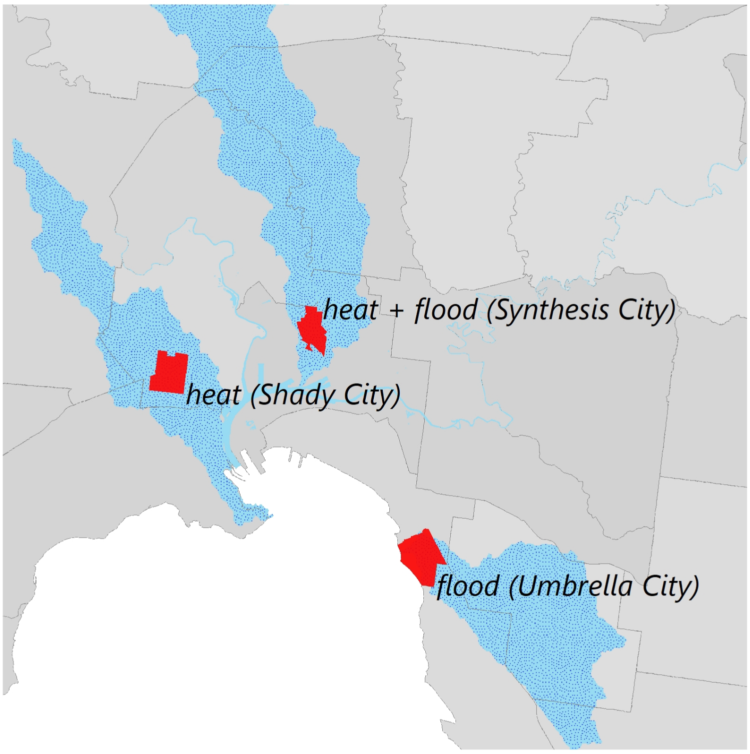

Figure 5: Three case study sites (coloured red), heat in isolation, flood in isolation and heat and flood simultaneously. Sites are shown over the hydrological catchment boundaries and LGA divisions, (map created in QGIS).

1.1.8 Research context

The interaction of urban form and climate on streetscapes

Streetscapes are then not only the conduits of transport and services infrastructure, but also conduits of a city's environmental condition, particularly storm water and heat (Batty, 2013). Streetscapes are where both these problems are most evident. Figure 6, shows a portion of flood modelling undertaken by Melbourne Water in 2016 of the Arden-Macaulay precinct and on the right a portion of thermal imagery taken for the City of Melbourne 2012.

Figure 6: (LEFT): Arden Macaulay precinct flood modelling (Source Melbourne Water 2016) and (RIGHT): Inner City of Melbourne thermal imagery (Source: City of Melbourne 2012).

This study was undertaken at Monash University in the Department of Architecture and was attached to the CRC for Water Sensitive Cities. The research is located in the inner and west Statistical Areas (SA) within the Greater Capital City Statistical Area (GCCSA) of the delta city of Melbourne, Australia, a city with one of the largest urban footprints in the world, facing substantial issues associated with climate adaptation.

Australia is well known for its environmental extremes of both heat and rainfall. This makes it an ideal context for a study into the relationship between climate, built form and urban tree decision-making (Bren, 2015, p. 20; Batty in Pettit et al., 2008, p. V). It is the driest continent with the lowest average streamflow, a precarious water budget and naturally high rainfall variability due to weather patterns including La Nina and El Nino (Eamus, 2006; Timbal et al., 2016). These existing climate variations are exacerbated by patterns evident in long term data of increasing intensity of rainfall events and decreasing annual inflow, particularly in the south-east of the Australian continent [refer Figure 7] (BOM, 2013) [discussed further in *Chapter 5: Umbrella City*]. Similarly, Australia is experiencing increased occurrence of extreme heat events [refer Figure 8] and has the highest rates of skin cancer in the world, an entirely preventable disease caused by Ultra Violet (UV) radiation exposure from the sun (Cancer Council Victoria, 2018) [refer Figure 9] [discussed further in Chapter 6: *Shady City*].

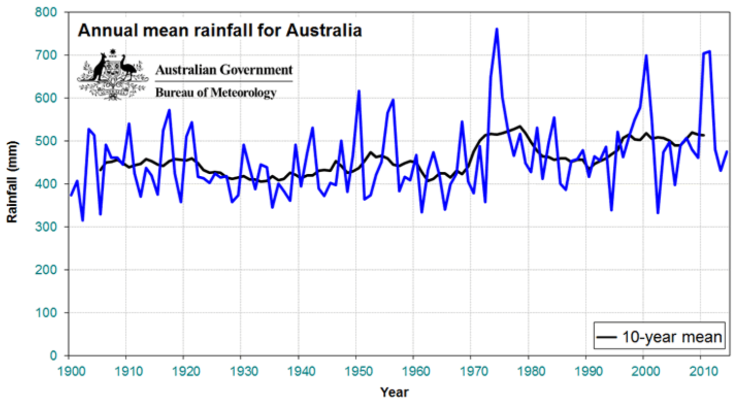

Figure 7: Increasing rainfall variability since 1970. The mean annual rainfall for Australia, patterns from 1900 to 2015. While rainfall variation has always been strong in Australia (BOM, 2015a).

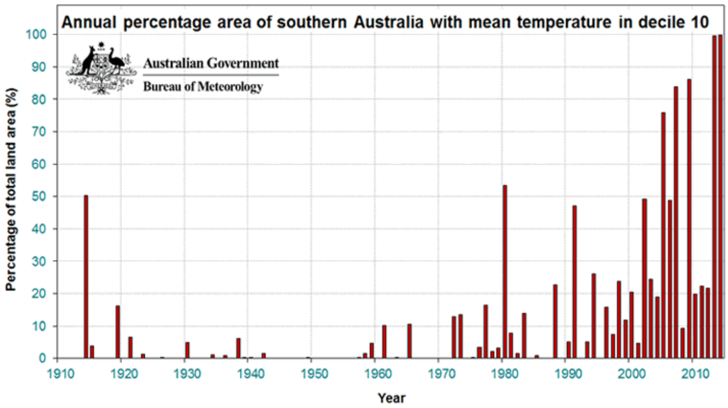

Figure 8: Increasing Australian heat Source: (BOM, 2015a).

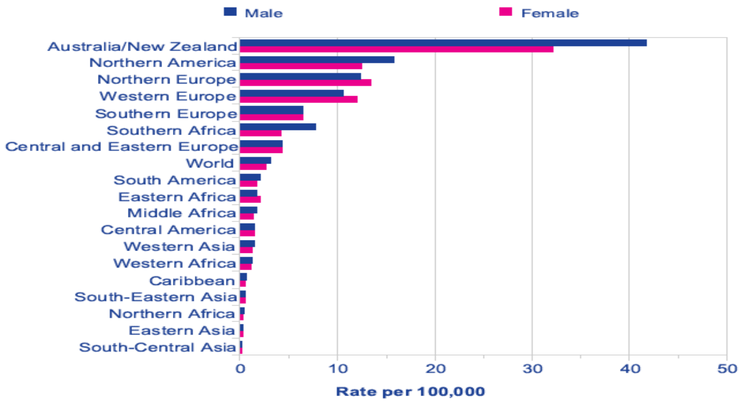

Figure 9: Global incidence of melanoma (Source: (WOC, 2014)).

1.2 Chapter outline

Chapter 01: Introduction

Chapter one states the problem, scope and aim of research and provides an overview of the thesis structure. It outlines the disciplinary fields, the method of the research and provides the chapter outline that follows.

Chapter 02: From Pretty City to Sustainable City

In chapter two, I outline three paradigm shifts in street design over the past two centuries from a primarily visual concern in the 19th century through to an environmental performance concern in the 21st century. I discuss how the drivers behind these three paradigm shifts evolved. In *Pretty City* (circa 1830 to 1890) I describe the use of trees in colonial city layouts. In *Transit City* (circa 1900s to1975) I describe the impact of mass transit on street design and in *Sustainable City* (circa 1975 and beyond) I describe the paradigm shift towards sustainability. The output of this chapter is presented in timelines, with some primary source analysis of historic maps of Melbourne and an analysis of the structure of Melbourne's street planting. The question associated with this chapter is:

What are the past and present decision drivers behind inclusion of trees in streets?

Chapter 03: Modelling for Decision-making

In this chapter I establish the grounds on which a selection of streetscape related disciplines model their decisions and what criteria they prioritize. I outline how designers' model to answer streetscape visual concerns, how environmental sciences model to answer tree environmental function concerns and how transport and land use planners' model to answer spatial concerns. In addition, I outline the definition of modelling, in particular, 3-dimensional, computational recursive tree modelling or algorithmic botany, as it relates to this thesis, and I outline what is needed to bring these concerns together in an equally considerable way. The questions I ask in this chapter are:

What is the context of tree-scape design tool development (past and present)?

What are the qualitative visual, quantitative spatial and the environmental modelling tools being developed or available for streetscape decision-making?

How do design and modelling approaches differ in different disciplines and sectors?

Chapter 04: Research Method

Drawing from the conclusion of chapter 03, I outline the framework of the DDSS which uses multipurpose software platforms commonly found in design offices boosted with middle ware consisting of both free scripts and commercially available plugins, integrated and informed by tree-scape modelling developments in other disciplines.

Chapter 05: Umbrella City

In Umbrella City I investigate the key challenges of tree-scape design for flood adaptation, particularly how hydrological tree species selection for green infrastructure and Surface Storm Water Management Systems (SSWMS) will have a substantial visual impact on streetscapes. I then use micro-scale digital design experiments (petri-dish tests) to isolate and test the DDSS for specific variables and processes, addressing the specific challenges of flood adaptation. The lessons from these digital design tests are then applied at precinct scale to a retro-fit low rise site that suffers from flooding.

Chapter 06: Shady City

In *Shady City* I investigate the key challenges of tree-scape design for shading active transport (day-time heat vulnerability) and how tree geometry, time of day and street orientation impact shade. I then use the micro-scale digital design experiments (petri-dish tests) to isolate and test the DDSS for specific variables and processes, addressing the specific challenges of shading active transport users. The lessons from these digital design tests are then applied at precinct scale to a retro-fit low rise site that experiences significant heat related issues.

Chapter 07: Synthesis City

In Synthesis City (a hot flooding city) I investigate the key challenges of tree-scape design for higher density sites, where both flooding and heat vulnerability are a problem, including how the interaction of trees and a 'street wall'[36] impact tree possibilities. I then use the micro-scale digital design experiments (petri-dish tests) to isolate and test the DDSS for specific variables and processes, addressing the specific challenges of an urban morphology with a street wall, shading active transport and selecting species for flood adaptation. The lessons from these digital design tests are then applied at precinct scale to an urban renewal site that experiences significant heat and flood related issues.

Chapter 08: Discussion and Conclusion

The DDSS I develop in this thesis looks to address the need for designers to quantify decision impact on human and environmental health of design decisions, using 'evidence-based' methods while still addressing and enabling Public Participatory Decision-making (PPD) in public space decision-making. This thesis looks to augment existing design approaches with the opportunities afforded through; better availably and quality of spatial data, better software and hardware and consolidation of research advances in urban

[36] Tall buildings on the property boundary.

ecosystem services. In the conclusion I discuss the implications of the work for industry, design education and further research.

1.2.2 Exclusions and limitations

There are of course many simplifications required in making a DDSS which has a holistic approach. Many of these important exclusions could be integrated into future research including:

Visual impact analysis: I did not attempt to gauge the quality of the images for visual decision-making or advocacy of design choices, beyond my own experience in this area. The imagery produced through this method, where the ability to very accurately control all variables could be very useful for perceptual studies in the future (Gobster et al., 2007; Kirkpatrick et al., 2012; Sommer & Summit, 1995; Ulrich, 1986; Zhao et al., 2017).

Visualisation science: I did not attempt to verify the level of photorealism of the images produced as the method used to produced visualisations is considered 'photorealistic'. In this thesis, visualisations are intended for use in making visual arguments for tree choices that may differ from existing preference (which need to be both abstract and compelling).

Risk management: A large part of urban tree management is risk. The outcomes of this thesis is a response to the need for larger growing species and greater quantities of trees needed for environmental performance, which do present increased risks for urban tree managers.

Human Thermal Comfort. In this study, human radian loading is limited to the provision of shade using the visible portion of the light spectrum.

Plant function structural modelling. Tree modelling is limited to structural accuracy only, no cellular interactions or growth dependencies.

Rainfall canopy storage: I do not use the model to calculate or quantify canopy storage capacities. The aim is to use the DDSS to assess visual outcomes of making functional water regulating tree choices. Rainfall interception quantification is an ongoing area of research where the type of tree modelling used in this thesis could be coupled in the future.

Quantification of transport mode selection: While higher numbers of street trees have been associated with increased levels of active transport selection and microscale path walkability traits (Ewing & Handy, 2009; Park et al., 2014), this study does not attempt to quantify how much impact trees have on transport mode selection.

Impact on biodiversity: There are potential relationships between biodiversity and urban form, and there are studies to show that use of native trees does increase some native animal habitat but there are also studies to show that a proportion of fauna show no particular preference when it comes to tree species (Kendal et al., 2014; Tratalos et al., 2007).

1.3 Summary

Contemporary cities have complex problems, spatial, environmental and social (Batty, 2013). Designers, assisting in or making direct tree-scape design decisions, need to meet the demand to quantify human and environmental health outcomes of these decisions, while still providing clear narrative of their visual impact. There is a clear need for new design processes which can be used to simultaneously illustrate both the quantitative / functional and the qualitative / visual impact. These processes can assist in making challenging, often unconventional tree decisions that will contribute to the comfort, environmental function and visual quality of our cities.

Representing trees in spatially explicit digital environments as 3-dimensional geometry, affords them the same spatial consideration as the geometrically determined regulations of other services, including vehicle traffic management, that have incrementally encroached on their growing space. By representing trees as geometry, a method for negotiating not only their aesthetic contribution but also their environmental function is simultaneously possible.

Chapter 2: From Pretty City to Sustainable City

> *It is very easy to compromise away a primary aesthetic gain […] in modern cities […] the dramatic unity of a single species planted in an allée or grove is forfeited by mixing diverse tree types that destroy visual harmony (Arnold, 1980).*

> *The primary purpose of street trees has changed […] from an aesthetic role of beautification and ornamentation to one that also includes the provision of services such as stormwater reduction, energy conservation and improved air quality (Seamans, 2013).*

2.1 Introduction

Current composition and placement of trees in urban streets are a legacy of past urban planning decisions and changing societal drivers brought about by catalytic events and advances in science and engineering. The purpose of chapter two is to establish the changing drivers behind tree-scape composition through three urban design paradigm shifts over the past two centuries and explore how, concerns from each paradigm still exert influence over contemporary street configuration. Firstly, in part 2.2: *Rise of the Pretty City* (circa1830 to 1900), I outline the European and American urban design drivers and the evolution of inclusion of trees in urban streets which influenced the town planning decisions of colonial settlements. Secondly, in part 2.3: *Rise of the Transit City* (circa1900 to 1975), I outline the paradigm shift in streetscape design associated with the evolution of personal motorised transport, and how this influenced planning decisions for most of the 20th century. And thirdly in part 2.4: *Rise of the Sustainable City* (circa1975 to 2050), I outline the environmental paradigm shift in contemporary streetscape design associated with the impact of human activity and urbanisation on the environment and human health. In this section I outline prominent contemporary problems of street design: Transport mode selection and heat stress, and streets and storm water flooding, which compel a need for substantial change in the way we design streets, and how we plan for trees in them. In this section I show how these issues have criteria that both align but also compete for literal and conceptual space.

Ultimately this chapter provides timelines of tree choices in Melbourne from 1835, a period associated with the aesthetics of urban reform, through to a projection of street tree planting, needed in Melbourne today for addressing the primary environmental concerns of flood and heat vulnerability. The rise and fall of these concerns are shown in Figure 10.

- **Pretty City** 1837- 1890, loosely aligns with the period commonly described as late British Colonialism (Beattie, 2008).
- **Transit City** 1890-1973, loosely aligns with the historic period commonly known as Modernism (Jencks, 2000, p. 77).
- **Sustainable City** 1973 and beyond, loosely aligns to the historic period commonly known as Postmodernism (Jencks, 2000, p. 77).

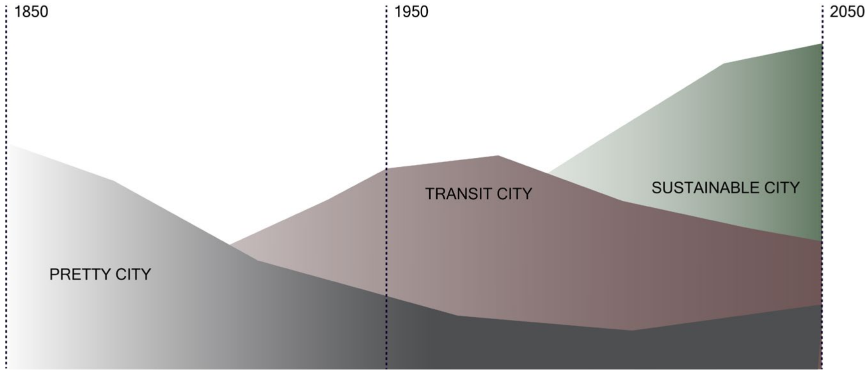

Figure 10: The evolution of streetscape decision drivers from 1850-2050, each still active.

2.2 Rise of the Pretty City

> *What distinguishes this period (1820- 1850) – more than anything else is not so much the growing acceptance of trees as elements of the urban environment but the increasing attempts to borrow and learn from other countries [...] (Lawrence pp177).*

It was during the Renaissance that tree lined streets began to appear on the outskirts of cities in Europe. Tree lined streets evolved into an urban norm with the immense physical expansion of cities and mass urbanisation of populations associated with the industrial revolution at the turn of the 18th century (Lawrence, 2006, p. 45). New urban design strategies formulated during this period arose in response to three drivers.

- The poor sanitation and living conditions of the rapidly expanding population of working-class citizens.
- The rising occurrence of infectious diseases such as Cholera in cities. Between 1830 – 40, both disease outbreak and poor hygiene conditions led to the development of Sanitation Movements[37] throughout Europe and a call for changes to the design of cities, which would decrease its spread.
- Changes in social structure resulting in the rise of a middle class of citizens with leisure time which was spent on travel.

Collectively, changes to the design of cities at this time are known as 'urban reform'. In many European cities, issues of urban reform largely centred around changes required to streets (Jones, 2006, p. 289).

2.2.1 Urban reform

> *Efforts to improve the physical conditions of cities took many forms […] changes in the physical condition of the street that would provide space for street trees: Wider and straighter with smooth and crowned pavement and drains beneath that connected to a system of sewers to remove both runoff and household waste, all bordered by raised sidewalks separated from the roadway by curb stones. And in an increasing number of places these routinely included trees along the sidewalks (Lawrence pp177).*

Two European cities had a particularly strong influence on the design of colonial settlements during the early 19th century. Both London and Paris, the two largest cities in Europe at the time were experiencing problems associated with rapid urbanisation and industrialisation. While other cities in Europe began including trees at this time, it is the

[37] The Sanitation Movement popularly if erroneously, believed the Miasma Theory of disease spread; that disease was spread by 'fedit air'. The beliefs of the sanitation Movement were antithetical to the findings of the Contagionists (See John Snow 1954 map of the outbreak of Cholera, traced to a water pump on Broad Street.

stories of London and Paris which can be considered to have the greatest impact on the design of planned settlements in Australia (Freestone, 2010).

Reform in London

London, at the time of the Industrial Revolution experienced rapid population growth and became the largest city in Europe (Rosen, 2004). Land in Britain at the time was largely owned and developed by the aristocracy, which saw a '*trend toward privatisation of the urban landscape that had become so prominent in the mid-eighteenth century become positively triumphant by the beginning of the nineteenth century*' (Lawrence, 2006, p. pp 146). This privatisation trend extended into the streetscapes of London until several Acts which slowly increased public authority and control were passed over an eighty-year period ushering in the British Age of Reform[38]. The initial Acts which enabled this transition, began with the Paving Acts of 1762 (*Westminster Paving Act*), the 1817 (*General Paving Act*) and the British *Reform Act* of 1832 (Johnston, 2015). With two further Acts, the *Municipal Corporations Act* of 1835 and the *Industrial Reform Act* of 1837, planners rather than landowners began to be able to plan public space for people, which opened up opportunities for street trees in London, until then, notably absent (Lawrence, 2006, p. pp149). Strength was added to the argument for urban trees, when in 1838 the *Sanitary Reform Act* and finally the 1848 *Public Health Act* was passed, largely a result of the emerging Sanitation Movements[39] report into the '*Sanitary Conditions of the Labouring Population of Great Britain*[40]' (Institute of Medicine, 1988; Johnston, 2015). Both the *Municipal Corporations Act* and the *Sanitary Reform Act* had extensive influence on the urban design decisions and development structure of colonial cities in Australia, particularly in relation to the width of streets and regular gridded layouts (Freestone, 2010, p. 22).

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[38] Disputably the Age of Reform is from 1832 – 1901. While reform in England was multifaceted and had many types, selected here are the act of reform which had most effect on streetscape design.

[39] It was Cholera, rather than social reform which is thought to be the primary driver behind changes to urban form, and is therefore plausible that Priestley's discovery in 1774 that plants could restore 'injured' air, otherwise known as the discovery of oxygen helped popularise inclusion of trees in streets (Kostof 2004).

[40] This report also led to the *Public Health Act* of 1848 which had extensive influence on provision of piped drainage systems in Australian Colonially settled cities such as Sydney (A. Wong, 1999).

Between 1817 and 1846, Paris, the second largest city in Europe, experienced a population increase of 48% and suffered from outbreaks of Cholera. Between 1833-1848, Claude-Philibert Barthelot, Comte de Rambuteau was made the prefect of the Department of the Seine, preceding the appointment of Barron von Haussman to the position by Napoleon III in 1853. Rambuteau, who's catch cry was '*water, air, shade'*, had a passion for trees, began the work of cutting wider boulevards[41] through Paris and the planting of the Champs-Elysees which would later form the foundation for the more ambitious reforms of Haussmann, Napoleon III and JeanCharles-Adolphe Alphand (Jones, 2006, p. 407; Lawrence, 2006, p. 193).

The designs of Alphand, Haussman's chief engineer, for the Boulevards of Paris, integrated trees with engineering concerns and stipulated a minimum distance between trees and buildings (nominally 5m) and street casement widths of 26 and 36m [refer Figure 11]. These street widths and positioning of trees at a generous distance from building façades allowed taller building development and wider footpaths than the widths of 20 and 30m specified by Sir Robert Hoddle in the layout of Melbourne's streets. Melbourne's boulevard designs with street casements of 20 and 30m meant narrower foot paths and trees located much closer to buildings than in the Paris boulevards. These initial dimensional decisions have had far reaching implications for the quality of the streetscape under conditions of increasing density.

Urban reform was both functionally engineering driven, involving the paving of streets and the implementation of waste-water drainage systems and sewers, as much as it was (medical) science driven, with origins in enlightenment philosophy stemming from finding of the scientific revolution of the16th and 17th centuries. However, urban reform also had a closely intertwined aesthetic component. The French origin concept of '*urban embellissement*'[42], popularised through the writings of Voltaire[43] reached a peak in 1823.

[41] Boulevard, a wide street typically lined with trees
[42] Urban embellishment.
[43] Voltaire the French Enlightenment writer (1694-1778), *'combined humanitarian, hygienic and utilitarian considerations with a concern for urban beauty'* (Jones, 2006, p. 289).

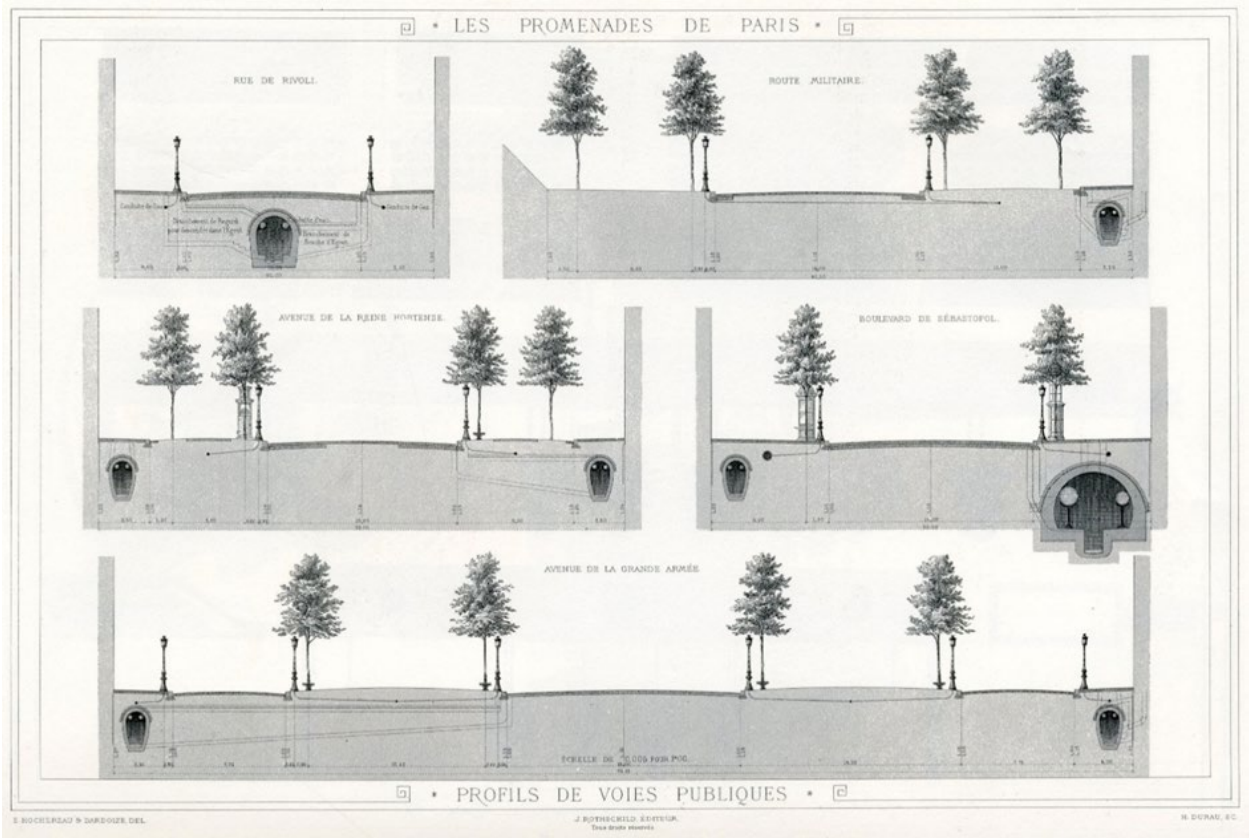

Figure 11: The designs of Les Promenades de Paris, by Adolphe Alphand 1873, showing the integration of underground engineering infrastructure and minimum distances of trees from building façades (Source: Bibliotheque Nationale de France. http://gallica.bnf.fr/ark:/12148/bpt6k310316c Public domain).

This concept of '*urban embellissement*' is considered the precursor to the professions of urban design and urban planning (Jones, 2006, pp. 289–284; Kostof, 1999). The close link between scientific and aesthetic drivers behind global movements for urban reform would continue throughout the 19th century, exemplified by the American Medical Association's Committee on Public Hygiene 1849, calling for *"public squares, tastefully ornamented and planted with trees.....as one of the most powerful correctives to vitiated air [...]"* (AMA 1849 in Lawrence, 2006, p. 208).

2.2.2 Urban reform and the visual function of trees

In '*City Trees*' (2006), Lawrence outlines three visual functions of urban trees in Europe and America from the 16th to the 20th centuries: These are: '*The display of power*, particularly of an individual; '*aesthetics*', brought about through changes in recreation and social structure; and '*national preference*', brought about by differences in national identity, development history and qualities unique to place such as the indigenous vegetation of America and Australia.

The display of power

Lawrence discusses the examples of use of trees by both Louis 14th and Napoleon III as the display of an individual's power to plant trees. Rows of trees (or allées) were planted by Louis the 14th in captured towns in the 16th century. Similarly, the boulevard incisions made by Napoleon III into the core of Paris in 1855 can in many ways be considered an expression, not so much as a gift of a garden to the populace[44] but a display of order and power. In both cases use of a single species at regular spacings were used[45].

Aesthetics and recreation

Societal changes brought about by reform and industrialisation, also resulted in increasing recreational time and a subsequent rise of a middle class. Particularly popular recreation activities of the time were the game of Pall Mall and carriage riding. Both activities were accompanied by long straight rows of trees, which became symbolic of this newly found recreation, and which, when the game was no longer in favour, became pedestrian promenades (Lawrence, 2006, p. 33). This period also coincided with increased travel as a form of recreation. This resulted in increase in influence from foreign sources in particular the French Formal style of urban design which was almost universally applied throughout the world by the end of the 19th century (Lawrence, 2006). '*by 1780 there was hardly a town that did not have some sort of green promenade, and the larger cities typically had several*' (Lawrence, 2006).

European national preferences

Lawrence draws a distinction between the tree preferences of the European cities of France, England and the Netherlands and nascent north American cities. During the late 18th century, many European towns were affected by mass population increases, and expanded beyond their initial Mediaeval cores. Towns began to encompass the gardens of the aristocracy located on their outskirts which often included privately owned but popular, and publicly accessible forest walks ('*barcos*' Italian *bosques*' in French or '*walks*' in Britain) (Lawrence, 2006). In the case of Paris, this physical expansion encompassed the

[44] In contrast to the generously wide streets, little public space or parks were inserted into Paris through this process (Jones 2006).

[45] It is worth noting here that it is this sort of planting which Ian Mcharg in his book *Design with Nature* 1969 was particularly against as it represented human dominance over natural systems (Herrington, 2010).

garden of the Tuileries Palace and the '*Grand Cours*', laid out by André Le Nôtre in 1667[46], which was to become the foundation of Paris' most famous future tree lined boulevard; the Champs Elysees. In contrast, English cities where the Palladian and picturesque[47] styles[48] were in fashion, and urban development was predominantly controlled by private interests, street trees were avoided, even frowned upon (Johnston, 2017).

North American national preferences

In American cities, trees were planted by residents according to personal preference outside individual homes and were the responsibility of these individuals rather than a municipal or governing body (Lawrence 2006). During American Independence (1776), this street tree planting style shifted towards use of native American species, identifying America's unique vegetation as it's distinguishing asset (Dümpelmann, 2019, p. 28). This shift is sometimes considered the rise of an ecological aesthetic[49], reflected in the work of subsequent American landscape architects such as Frederick Law Olmstead[50], in his plans for Central Park 1857 and later in the work of Ian McHarg in the 1960's and '70's, in particular his project known as 'The Woodlands Texas' (Yang et al., 2013).

2.2.3 The impact of Urban reform on colonial streets

European urban reform movements influenced the planning of new colonially settled cities in America, Canada and Australia. Towns laid out at this time were routinely gridded and included space for trees on wide 'healthy' streets (Freestone, 2010). Melbourne, Australia, colonised by the British in 1837 is an example of one of these gridded town plans and is the context for this study.

Between 1824-31 The British Army Officer, Sir Ralph Darling, was appointed as the governor of New South Wales. Governor Darling along with members of the board of Inquiry, Surveyor General Thomas Mitchell and William Duramesq were responsible for the

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[46] André Le Nôtre is considered both the first Landscape Architect from his work on the gardens of Vaux-le-Vicomte for Louis the 14th and the founder of the French Formal Style.
[47] William Gilpin 1724-1804, originated the idea of the picturesque as informal, naturalistic even rugged mountain scenery. He then developed the idea of the picturesque as a set of rules for depicting nature, which were later developed and applied to landscape architecture by Richard Payne Knight and Uvedale Price.
[48] Palladian Style, (Architecture) derived from the work of Venetian Architect Andrea Palladio (1508 – 1580), interpretation of classical architecture, strong symmetry, formal, perspective.
[49] Also known as the 'ecological approach' to design.
[50] Olmstead was not a purist about native vegetation, but selected plants based on their visual 'effect' (Wilson, 1994).

development of regulations to guide planned settlements in Australia (Freestone, 2010, p. pp97). Freestone describes the conversation between the members responsible for the production of the Darling Regulations of 1829 which were intended to '*ensure a uniform approach to town layout for both convenience and aesthetics'*. The main debate was over the width of streets. Mitchel proposed '*narrow streets to alleviate heat, dust and winds'* based on a Spanish model but Duramesq and Darling's preference was for '*wide streets to admit air and breezes'*. The discussion Freestone describes could be reframed as decision based on either climate or aesthetic considerations, though suggests that prevalence of the Miasma[51] theory at the time would have rendered 'wide streets as healthy streets' lending a health weighting to Darling's argument.

Governor Burke took over from Darling in 1831-37. In 1837, under instruction from Burke, the Surveyor Robert Hoddle laid out the gridiron plan for the central business district (CBD) of Melbourne. To compromise between the regulations established by the previous NSW governor Darling, calling for '*wide tree lined streets'* and the stipulations of the current governor Burke calling for rear access ways, Hoddle elected to cut small 10m wide streets between the larger blocks reducing the Darling stipulated allotment sizes rather than the width of the 30m major streets (Lewis, 1999). While Hoddle's CBD grid is unique, Hoddle's adaptions of the Darling regulations, the grid structure and street casements widths are repeated throughout the cities suburban areas of Melbourne (Freestone, 2010, p. 60).

The street tree plantings of Ferdinand von Mueller

In 1864 Daniel Bunce described Melbourne as having *'lovely avenues which meet the eye in whatever direction the Metropolis is approached'* (Daniel Bunce in Spencer, 1986). In 1855 Melbourne experienced a population explosion, due to gold rush wealth, known as the Marvellous Melbourne period. At that time, the Botanic Gardens was the scientific centre of Melbourne preceding the establishment of the University. It was at this pivotal time that German botanist and pharmacist Baron Sir Ferdinand Jacob Heinrich von Mueller was appointed as scientist in charge of the Botanic Gardens. While Von Mueller's primary task

[51] (Beattie, 2008) suggests that the miasma theory 'cast a long, if ironically unseen, shadow on constitutions and colonisation'.

was the taxonomic classification of Australia's unique vegetation, he was also charged with design and layout of the gardens and several adjacent streets such as St Kilda Rd between the Botanic Gardens proper and the crossing of the Yarra River into Swanston Street. Von Mueller's preferred streetscape species predominantly consisted of very large evergreen trees. Avenues of *Eucalyptus globulus* which grow to a height of 60m, *Brachychiton acerifolia (up to 35m)*, *Pinus radiata (up to 30m)*, *Araucaria heterophylla (up to 65m)*, *Cupressus sp*. and *Cedrus sp*. are some of his streetscape species selections [refer Figure 12 and Figure 14], alongside other large North American species which had only just been discovered by colonial botanists (Spencer, 1986).

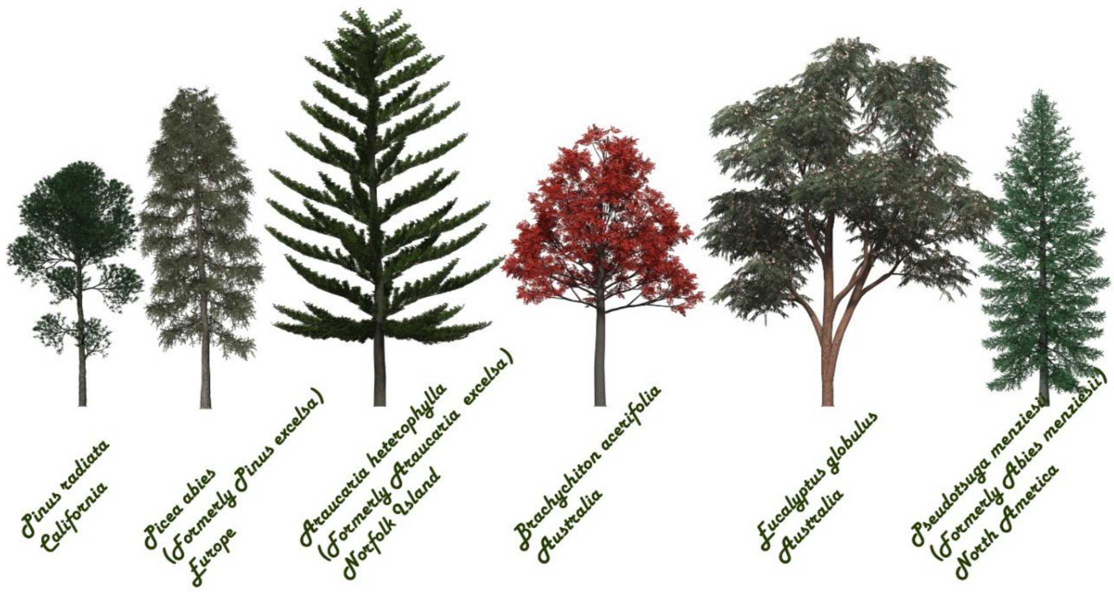

Figure 12: Shows a selection of species used by Mueller in Melbourne streetscapes between 1850-1880 (predominantly large evergreen species) (Data source Spencer 1986).

Though these plantings were initially met with approval from other eminent horticulturalists at the time, a generation later, deciduous species began to be the preference such as the *Platanus x acerifolia*, (London Plane), a range of Elm sp. and the *Populus alba* (Silver Poplar) (Spencer, 1986) [refer Figure 13]. By 1890, the end of the Marvellous Melbourne period, Melbourne had grown into a substantial city brimming with civic pride, culminating in the preparation of the city to host the International Exhibition of 1890.

Figure 13: Collins Street circa 1900 with plantings of London Plane, many of which are still in place today, though close to the end of their useful life expectancy. The street structure was designed to include trees. Collins Street was originally designed, primarily as a walking environment (Source https://www.victorianplaces.com.au/node/65584).

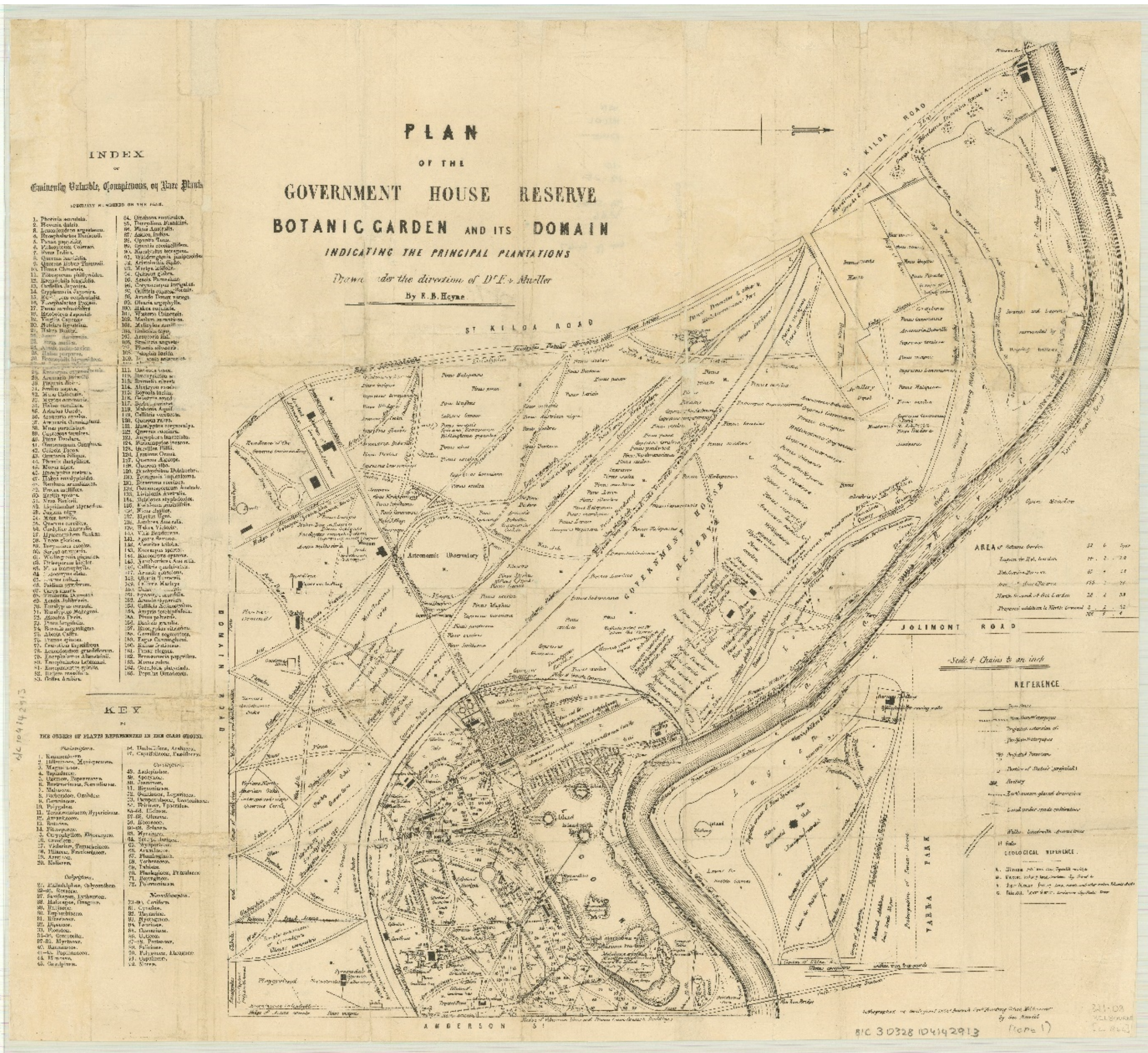

Figure 14: 1864 von Mueller's plan for the Botanic Gardens including St Kilda Rd - with Eucalyptus globulus and Pinus laricio (now Pinus nigra) planted alternately along the street (Source: Royal Botanic Gardens library Melbourne).

2.2.4 Scientific discoveries

Through this pre-antibiotics era, when belief in the Miasma theory of disease spread was widely accepted, there were a number of scientific discoveries which are likely to have influenced popular thought, particularly in relation to human health, urban design and trees (Beattie, 2008)[52]. The streetscape design stipulations of the Sanitation Movement, who were heavily invested in the Miasma theory and the spread of disease through 'bad air', may have been influenced by Joseph Priestley's accidental discovery of photosynthesis, (that plants release oxygen and thereby '*restore injured air*'[53] (1772), which later allowed Julius Robert Mayer in 1840 to develop the first law of thermodynamics or that 'plants convert light into energy'.

This era is also known as the 'Golden Age of Plant Hunters' (Musgrave et al., 1999)[54]. Plant discovery was enthusiastic during this period particularly with the newly invented 'Wardian Case' (1842), an early terrarium which could be used to transport living plant specimens across the globe. Plant hunting was a pursuit of the director of the Botanic Gardens, Ferdinand von Mueller, who's early large evergreen species choices for the streetscapes of Melbourne may simply have been a case of availability (or lack of) (Musgrave et al., 1999).

Scientific discoveries in the representation of space were also underway during this period. In 1826, Joseph Niece, invented photography which was adapted into a spatially accurate map reproduction method used in the British Ordinance survey of 1855. Later still, this method was developed into a spatially explicit mapping method in its own right with the first aerial photogrammetry tested by Aimé Laussedat in 1858 using kites (*Encyclopaedia Britannica*, 1998). These representational discoveries can be considered the first stages of spatially explicit raster data collection, allowing a far more rapid and easily reproduced method of spatial survey.

[52] This relationship is discussed by Beattie particularly in relation to the fears and worries associated with Cholera and the impact of the Miasma theory on colonial thought.
[53] Priestley, termed this process dephlogisticated air.
[54] Generally considered to be circa 1770-1860.

2.2.5 Composed cities

Towards the end of this period, urban planning (which was closer to the practice of urban design at this time) had begun to be formalised as a discipline, increasingly focused on compositional aspects of urban form as described by Erickson (2018). In England, this was most notably manifested in the '*Garden City'* ideas of Ebenezer Howard 1898[55], which, in Australia, evolved into a native flora and fauna movement through the 1920s - 30s (Byrne et al., 2014) circa 1890 – 1900, in North America the overtly compositional '*City Beautiful Movement'* evolved, with the central premise being that more beautiful cities would lead to more responsible citizens (Wilson, 1994).

Also at this time (1889), Camillo Sitte, penned the '*City Planning According to Artistic Principles* (1889)[56], criticising plan based design and asking that streets be seen as 'rooms' or enclosures where individual buildings were not as important as the overall structure of a city. Sitte's[57] formalist approach was reflected in the later writings of urban streetscape theorists such as Allan Jacobs and Henry Arnold (1980; 1993).

Also at this time in Vienna the Gestalt School of psychology began to form, with the precursor work of Christian von Ehrenfels[58] 1890 essay on '*On Gestalt Qualities'* (B. Smith, 1988). The principles of Gestalt attempted to explain the ways humans perceive objects in space based on similarity proximity and continuity (as a compositional whole) (Craighead & Nemeroff, 2004). These 'laws or principles of Gestalt are still widely used in visual perception studies of trees and streetscapes, data visualisation, software and web site user interface design. In particular the Gestalt laws of 'symmetry' and 'closure' (where streets are seen as outdoor rooms) have been identified as urban design qualities which can be achieved on streetscapes using trees, and in doing so, improve the perception of those streets (Ewing & Clemente, 2013) [59]. The formalist ideas that developed from these early writings of Sitte and the Gestalt school are somewhat divergent to the ideas which began

[55] This ideology was more about sub-urban self-contained green belt development and uncharacteristically for the time, did not have a staunch visual compositional recommendation.
[56] Not translated into English until 1945.
[57] Sitte's work is considered 'formalist' and is reflected in the work of writers such as Allan Jacobs (Great Streets).
[58] Ehrenfels is an unfortunate founder due to some pretty distasteful beliefs. Max Wertheimer is considered more officially the founder of Gestalt.
[59] The qualities are imageability, enclosure, human scale, complexity and transparency.

to be explored in response to sustainability challenges that are discussed in section 2.4. *Rise of the Sustainable City 1975-and* beyond.

2.2.6 Conclusion

> *Echoed in other cities, the 'socio-spatial patterns, transport networks and essential services, which were laid down in those years ... are easily recognised even today' (Freestone, 2010, p. 212).*

What we inherit from the *Pretty City* period is a stylistic preference for how trees are integrated into streets which adhere to aesthetic principles of symmetry, enclosure and cultural tradition. In streets with a low or mid-rise housing morphology, this tree arrangement works well. Deciduous trees allow light into buildings in winter and block heat in summer, and replicable, symmetrical street structures or streetscape skeletons[60] (Harvey et al., 2015) provide clarity for car-based transport modes as they decrease visual clutter [61]. Visual ideas of 'street enclosure' ratios which originated with Sitte, such as guidelines about the most aesthetically pleasing street height to width, are still commonly applied to urban design frameworks today despite difficulties in quantifying the actual value of this arrangement (Park et al., 2014).

What we also inherit from this period is a concept known in planning disciplines as 'Neighbourhood Character', which can be considered a localised version of what Lawrence identified as 'National identity' (DELP 2018). It has both aesthetic and heritage components. Neighbourhood Character manifests in tree-scape design decision-making through local municipal authority, 'preferred tree species lists' which in part, are species known to thrive in the area but also in part an expression of the character or identity of that municipality.

The City of Melbourne still bears the path dependency and historic neighbourhood character of colonial urban design decisions. On its wide street casements, designed to include trees the initial, symmetrical, 'horticultural fashion of the day species selections are

[60] Harvey et al. Define the streetscape skeleton as the massing of buildings and street trees.
[61] This is also sometimes referred to visual complexity, which, with higher rates, can improve pedestrian perceptions of streetscapes, though this is a bit contentious and highly individually preferential.

still apparent. In the figure below I analysed the current structure of the street tree planting of the city of Melbourne [refer Figure 15]. Streets depicted in red on this plan are still planted with symmetrically placed rows of deciduous London Planes, and in Pink are the symmetrical rows of deciduous Dutch Elms. Recently developed or renewed parts of the City (shown in green) are planted with native species such Spotted Gum.

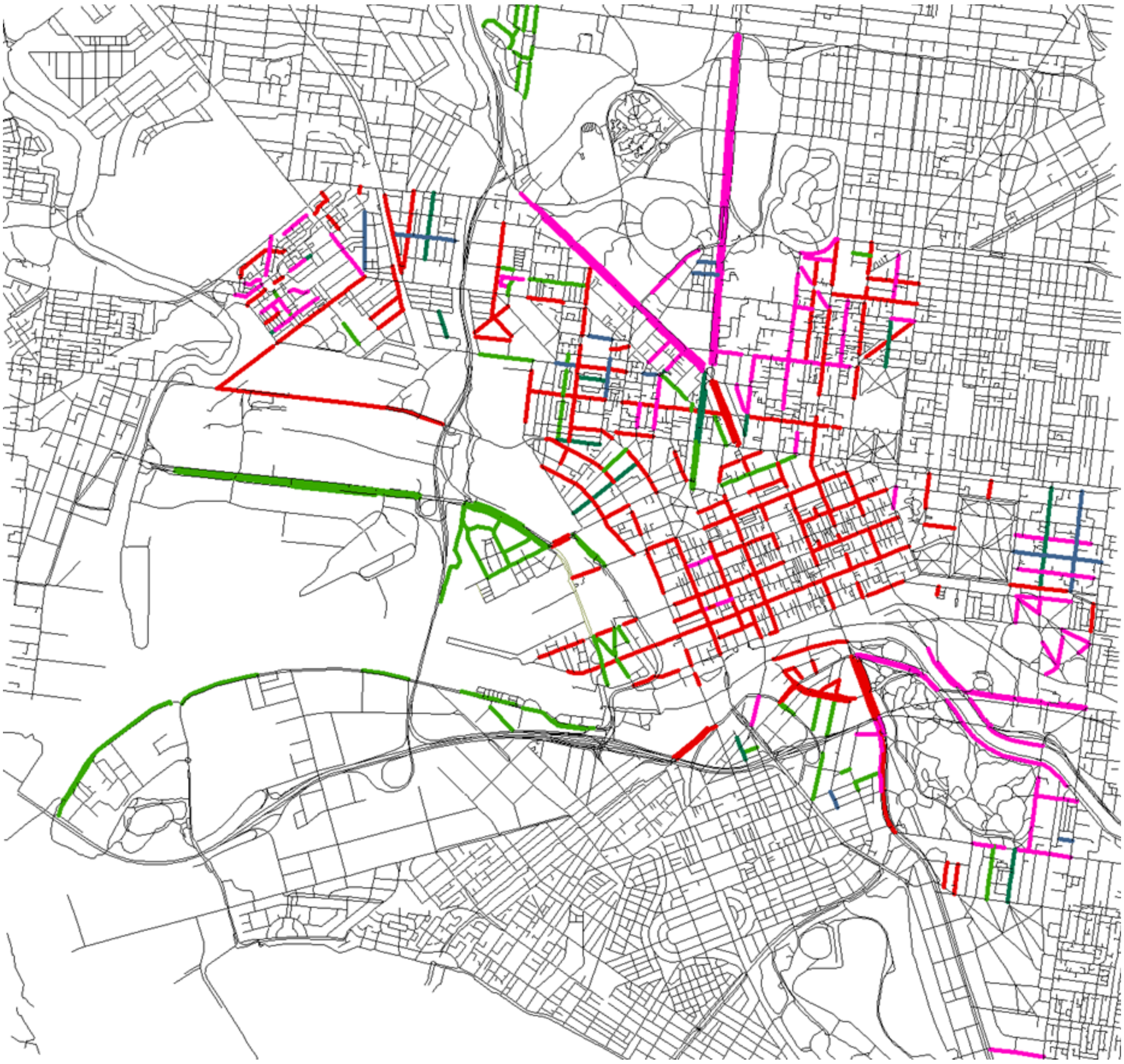

Figure 15: Structure of City of Melbourne's streetscapes showing prevalence of historic symmetrical planting structure of deciduous avenue trees still existent today (Platanus sp (in red), Ulmus sp. (in pink) and native species (in green) (QGIS).

In the timeline shown in Figure 16, I have brought together all of these events, movements, discoveries and ideas so that they can be seen in relation to each other. In particular how the development of Melbourne and the growth in civic pride in the period known as Marvellous Melbourne (associated with the wealth from the gold rush), would have contrasted to the sense of urban decay as Europe continued to suffer from outbreaks of Cholera and contrasted again with events which were taking place in America, related to slightly earlier colonisation and a growing sense of self.

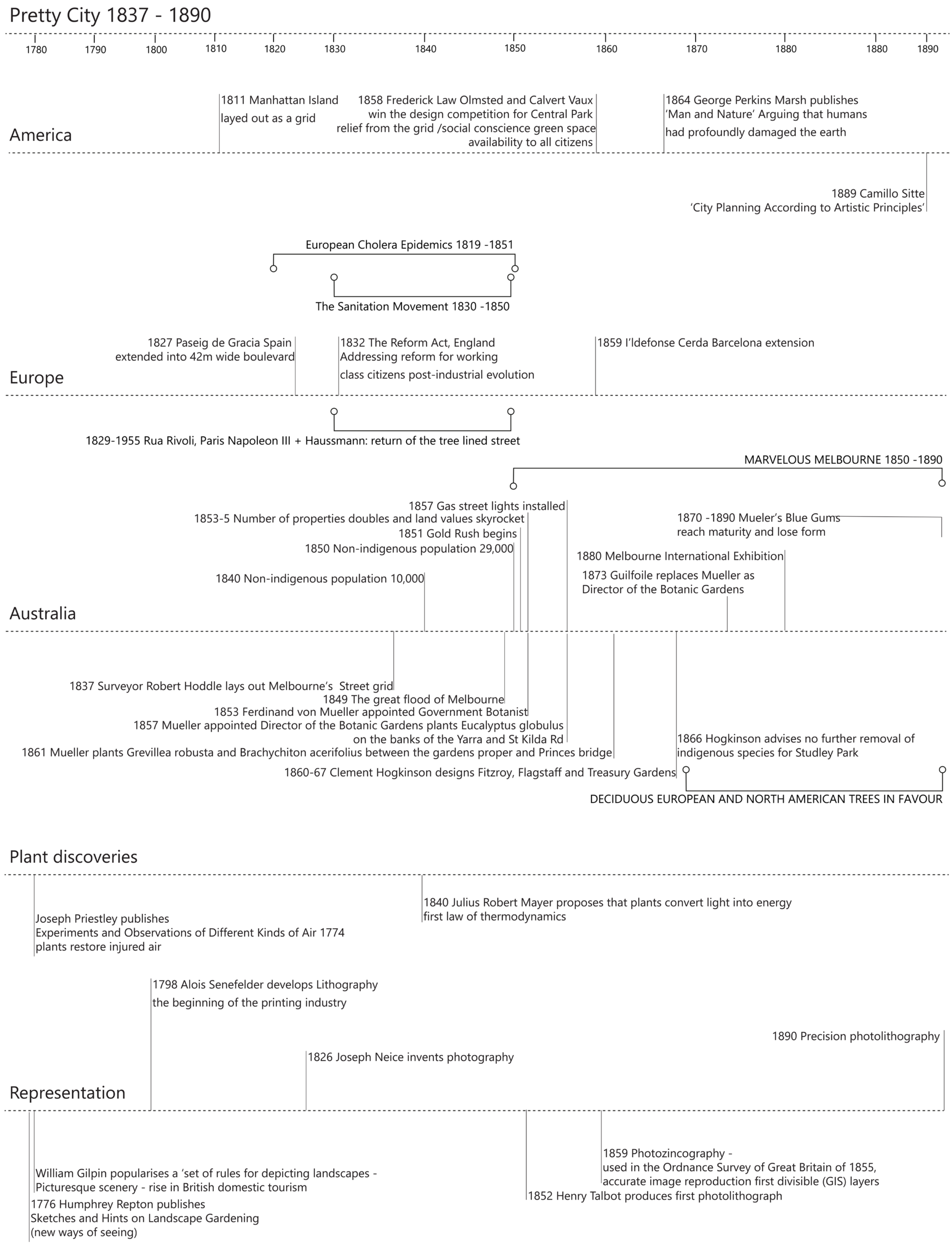

Figure 16: Timeline of events, movements, ideas and discoveries between 1770 to 1900. When all of these events, movements, discoveries and ideas are compared to one another it is possible to see how the Evolution of Melbourne and particularly the growth in civic pride in the period known as Marvellous Melbourne (associated with the wealth from the gold rush) would have contrasted to the sense of urban decay in Europe as it continued to suffer from outbreaks of Cholera.

2.3 Rise of the Transit City 1890-1975

> *Streets comprise more than 80% of public space in cities, but they often fail to provide their surrounding communities with a space where people can safely walk, bicycle, drive, take transit, and socialize. (NACTO, 2013).*

> *One of the greatest influences on the structure of streets in the past 100 years is traffic engineering (Mees, 2003).*

Generously proportioned city grids provided a robust structure, to accommodate the extreme societal and infrastructural change which have occurred over the past two hundred years; from provision of services such as gas, electricity, sewerage and telecommunication through to mass individual car ownership and urbanization. However, many of these changes have only been possible through incremental encroachment on space originally intended for street trees. Sometimes the encroachment has resulted in complete removal of trees and at other times the plasticity of tree growth has been taken advantage of, resulting in street trees with poor form and function (Moore, 2009).

2.3.1 Streets and private transport

Initially, with the introduction of the personal motor vehicle at the beginning of the 20th century, cars and pedestrians were considered to have equal rights on roads. However, increasing prioritisation of vehicle comfort over pedestrian safety, induced the demand for car travel, smooth road surfaces and constraint of pedestrian spaces (Mees, 2003). By 1910, automotive interest groups in America were lobbying for the right of way for cars on roads, relegating pedestrians to specific points of crossing (P. D. Norton, 2008) [62]. With cars as the dominant form of transport, gridded colonial cities which were unconstrained by mediaeval walkable cores, exponentially expanded outward based on the premise of continued growth in car ownership and use until the 1970's (Davison, 2004). This development pattern, applied to Melbourne's street development strategy is known as the

[62] In cities such as Detroit, this led to many child deaths. Children were struck by cars in front of their houses (no playgrounds existed at the time). No speed limits, no stop signs (Loomis, 2015).

American urban sprawl model (Davison, 2004; Freestone, 2010; Victoria & Auditor-General, 2017).

2.3.2 The Infrastructure of Melbourne's streets

It was not only the development of personal vehicle transport which shaped Melbourne's streetscapes between 1900 to 1970. In 1891 the Melbourne Metropolitan Board of Works[63] was formed and the responsibility for urban street tree planting became integrated with road and services design and was no longer in the hands of the government botanist (Dingle & Rasmussen, 1991). Trees became unnamed crosses on streetscape plans, primarily drawn to ensure they did not conflict with underground service [refer Figure 17].

In 1880, construction of an electricity supply was initiated, which brought with it a pole and line system, followed five years later by the beginnings of a tramways system and associated overhead catenary. five years subsequent to the tramway the sewer and storm water system began construction, which brought with it, the now heritage registered blue stone curb and gutter, still extant in Melbourne's streets. This drainage and sewer system has had a profound legacy on both environmental conditions such as stream health and the spatial capacities of the street. For instance, the heritage registered bluestone curb and gutter make bike paths adjacent to footpaths unachievable despite their safety advantages (Department of Transport QLD 2015) [refer Figure 18].

[63] Formation of Metropolitan Board of Works Organisations were an outcome of the British Municipal Corporations Act of 1837.

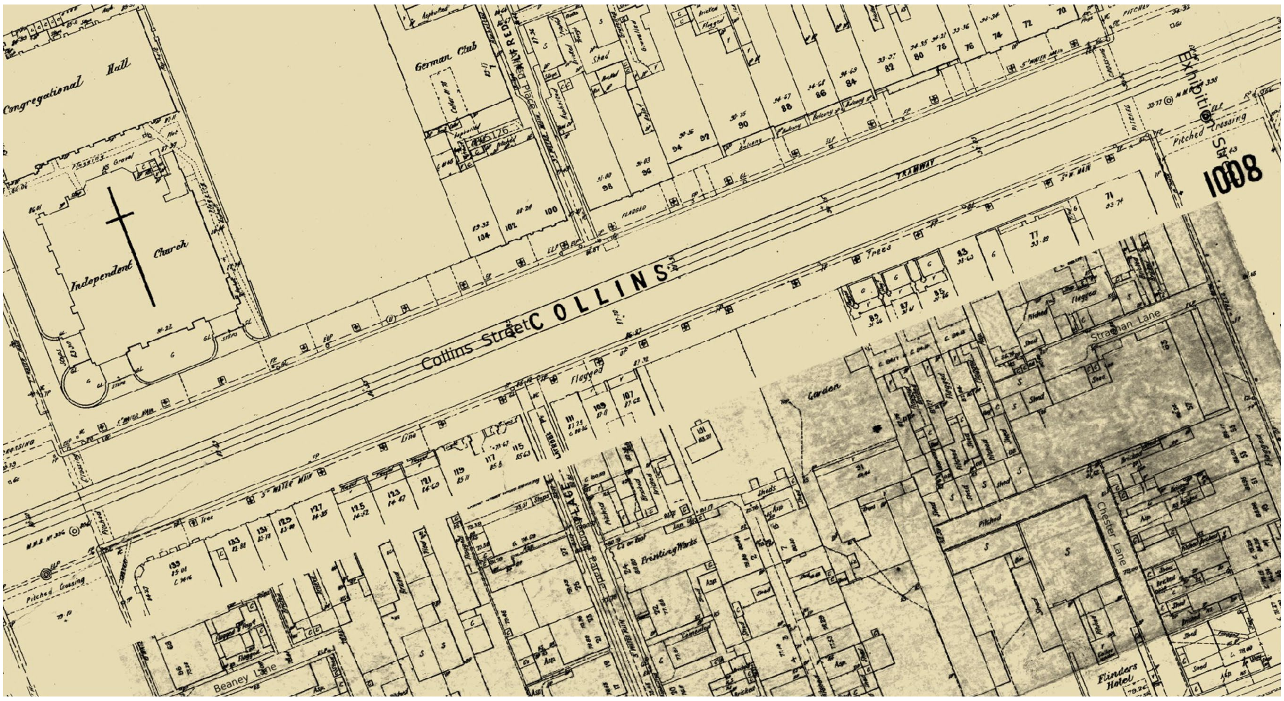

Figure 17: Melbourne Metropolitan Board of Works plan for 1890. Shows trees as crosses on the Northern side of Collins street (Source: http://maps.melbourne.vic.gov.au/).

Figure 18: Heritage registered bluestone curb and channel C1890 restrict the possibilities for safe cycle paths adjacent footpaths (Source http://www.evergreencivil.com.au/hampton_street_brighton.html).

2.3.3 Suburban sprawl

The Darling regulated grid, like, the Manhattan Island grid in New York (Martin & March 1972), was repeated through suburban Melbourne giving rise to replicable streets throughout the state nominally 10, 20 and 30m casements despite differential traffic flow and low-rise suburban development morphology (Freestone, 2010; March, 1975). In suburban Melbourne, it is common to find that these streets still contain permeable median strips, or grass verges, other-wise known as nature strips which may originally have been a provision for livestock (Butler-Bowdon & Couchman, 2008). Today, these nature strips house both street trees and most of the above and underground services. Nature strips can be dug up at any time for repair works to underground services making their purpose and value to residents ambiguous. This neither one nor the other state of nature strips led the architect and social commentator Robin Boyd to declare nature strips '*a mockery of the communal garden*' (Boyd, 1960).

2.3.4 Designing for the driver experience

In 1956, Melbourne was selected to host the Olympic games. Preparation for this international event resulted in intense development of the inner city and, like the preparation for the International Exhibition of 1889 before it, catalysed a movement to define Australia's' and particularly Melbourne's identity (Byrne et al., 2014). Concurrent with the preparation works for the Olympic Games the Society for Growing Australian Native Plants was formed, a nationwide movement with the aim of '*promotion of [...] native plants for garden, park and farm*' (Hockings, 2015). Further urban development followed after the Olympics with the office of housing towers constructed in the 1960's.

An unusual streetscape planting palette emerged in Melbourne during this time of increasing densification and intensification, high levels of car ownership, and a growing national identity featuring the unique Australian flora and fauna (Spencer, 1986). Selections for street tree species had been steadily decreasing in size over the past century so, despite the rising interest in Australian native species there was no increase in the use of the iconic, but often very large Eucalypts in streets (Spencer, 1986). Instead, plantings of smaller native species interspersed with smaller European and Asian species began to appear all over the city and suburbs, in particular the ubiquitous *Prunus blireana* and *Melaleuca stypheloides* combination (Spencer, 1986; Yau, 1982) [refer Figure 19]. Widespread car ownership also saw spaces such as medians and nature strips increasingly dedicated to on street parking [refer Figure 20]. Figure 21, shows this increasingly diminutive species section in comparison to the early large evergreen choices of Mueller.

Figure 19: Remnant planting of Prunus blireana and Melaleuca stypheloides on George Street Fitzroy, Victoria (source: Google maps).

Figure 20: Typical car parking in a city street, Melbourne 1957 (Source: https://www.victorianplaces.com.au/node/65203).

1850 1900 1950

Figure 21: Street tree planting changes from the initial large growing species selected by Mueller.

2.3.5 The view from the road

Just as carriage riding which developed into a recreational past time in the 16th century Italian Renaissance, which brought with it tree lined boulevards, the advent of the era of personal motorised transit had an impact on the way street design was conceived. Merriman discusses how this manifested in the work of Landscape architects in post-World War II in Britain in relation to the design of road infrastructure (2006). He suggests that the focus of landscape architects shifted away from pedestrian experience and preferences such as 'visual complexity[64]' and towards 'simplicity, rhythm, visual clarity and driver speed during this period. What this equates to is that the focus of design was on the perspective of the driver experience (Lynch et al., 1964; Merriman, 2006)[65] [refer Figure 22]. This privileging of the driver perspective is often still apparent in streetscape visualisations created by designers today, which use the centre of the road the as the axis of movement. The perspective of these visualisations allows the viewer to imagine themselves driving a car with a symmetrical row of trees on either side. A contemporary example of this type of visualisation can be seen in section 3.3: *Modelling visual concerns* [refer Figure 37]. The view from the road and the privileging of driver experience, over that of the pedestrian was not only demonstrated by the perspective point of the visualisations of designers

[64] (Ewing & Dumbaugh, 2009; King & Chellman, 2014) discuss visual complexity and the pedestrian experience.
[65] The view from the Road was a study of driver experience, taken from multiple car trips. [Link to the short movie made by Appleyard] https://www.youtube.com/watch?v=xP3maTrQZXE.

during this era, but also by the regulations of traffic engineering. Regulations governing highway design to maximise driver safety at high speed, started to be applied to road design at this time, known as the principles of 'forgiving design' [refer 3.5.1: *Transport planning*].

Towards the end of the 1960's, new studies were defining differences between road and freeway design such as Oscar Newman's 1972 '*Defensible Space Theory*'[66] and Don Appleyard's *Liveable Streets* (Appleyard et al., 1982). These studies called for reduction of traffic volume and speed on residential neighbourhoods due to the negative impact of traffic on social cohesion[67].

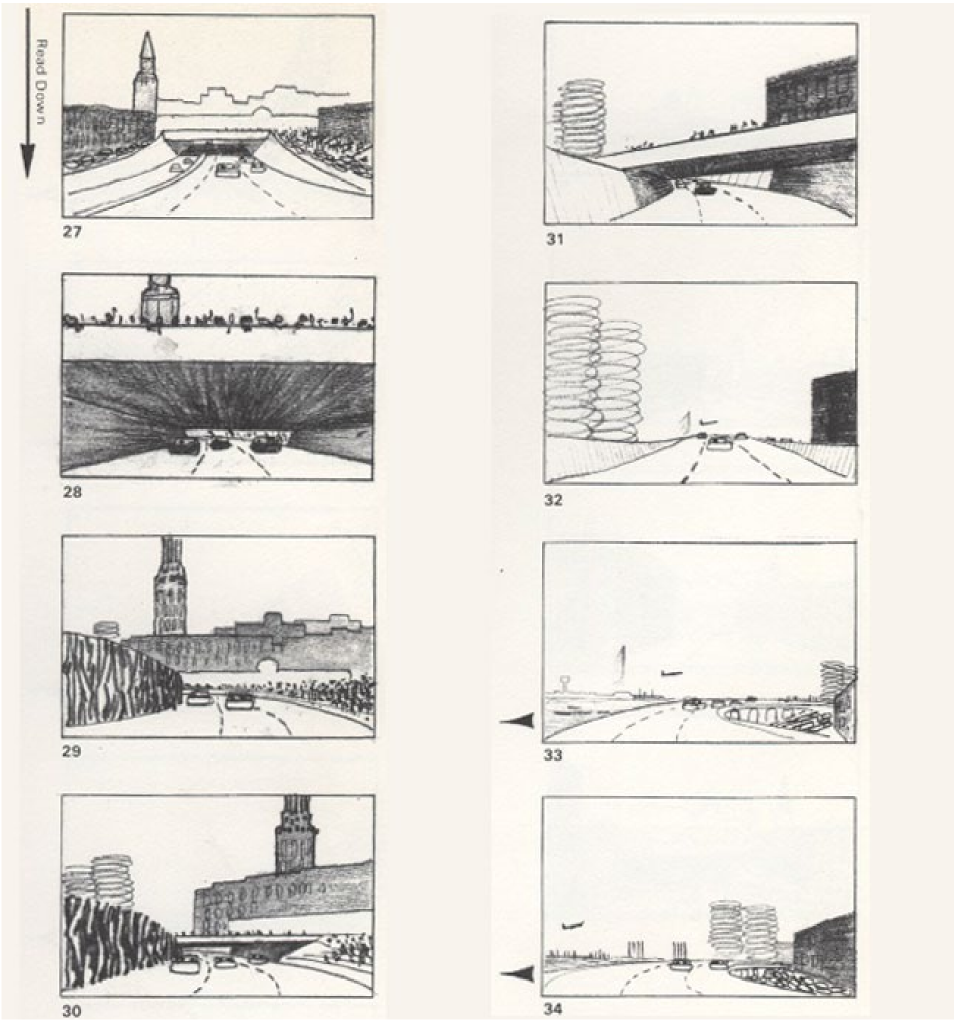

Figure 22: Shows diagrams from the 1964 study 'The View from the Road' by Kevin Lynch and Don Appleyard described the driver experience of freeways (source: (Lynch et al., 1964).

[66]Newman's study lead to the Crime Prevention through Urban Design movement and worked with the fact that fast moving traffic is perceived as unsafe.

[67]Appleyard's study was a pairwise comparison of higher traffic volumes). study of the reduction of social interaction on streets corresponding to increasing traffic volumes.

2.3.6 Scientific discovery

Alongside the 1970's beginnings of the understanding of the negative impact motorised transport on streetscape environments, and with the advent of the 1973 oil crisis, a new societal innovation was about to transform the ways in which design was undertaken, be it the design of vehicles or the design of the streets on which they were driven. This was the era of the release of Atari's first commercial video game PONG (1972), the release of the first satellite imagery from the American satellite CORONA program (1959) and the launch of the first operational Geographical Information System (GIS) program by the US department of Forest and Rural Development (1960) [discussed further in section 3.2.3: *Two spatial paradigms for modelling*].

During this period of innovation in computer visualisation, came a new understanding of the possibilities of a mathematical and architectural description of tree growth, form and architecture (algorithmic botany). In particular the L-systems of Aristid Lyndemayer developed in 1968 (Prusinkiewicz & Lindenmayer, 1990), the recursive branching structures developed by Hisao Honda (1971) and the architectural structural analysis of trees by Hallé, Olderman and Tomlinson (1978) [discussed further in section: 3.3.5*: Modelling the visual properties of light and trees*] These innovations in the understanding and representation, brought with them, spatially explicit, data rich visualisation possibilities for design decision-making.

2.3.7 Conclusion

By looking at these events, movements, innovations and theories in relation to each other on a timeline [refer Figure 23], it is possible to see how, during the Transit City era, urban theory shifted away from the turn of the 19^{th} century concerns, for a composed or beautiful city, towards transport infrastructure and driver comfort. Trees remained a visual embellishment to streets during this era, but the experience of the driver became the primary consideration. Through the 1950's and 60's, the size of trees selected for streets were reduced as smaller species posed less risk to drivers and were more easily pruned for other service infrastructure such as overhead powerlines.

However, towards the end of this era, growing awareness of social, human and environmental problems associated with motorised transport start to herald a shift towards a new design decision paradigm. In European cities, such as Utrecht, the traffic related deaths provided impetus for change and the re-investment in cycle infrastructure (Bliss, 2019). In America, Environmental Impact Assessment began to be mandated for freeway development proposals (Mees, 2003) and recognition of the damage caused by polluted storm water runoff into waterways led to requirements to rethink urban drainage strategies (Walsh et al., 2005). Together these issues, (alongside many others) led to the rise of concern for a *Sustainable City*, which I will discussed next.

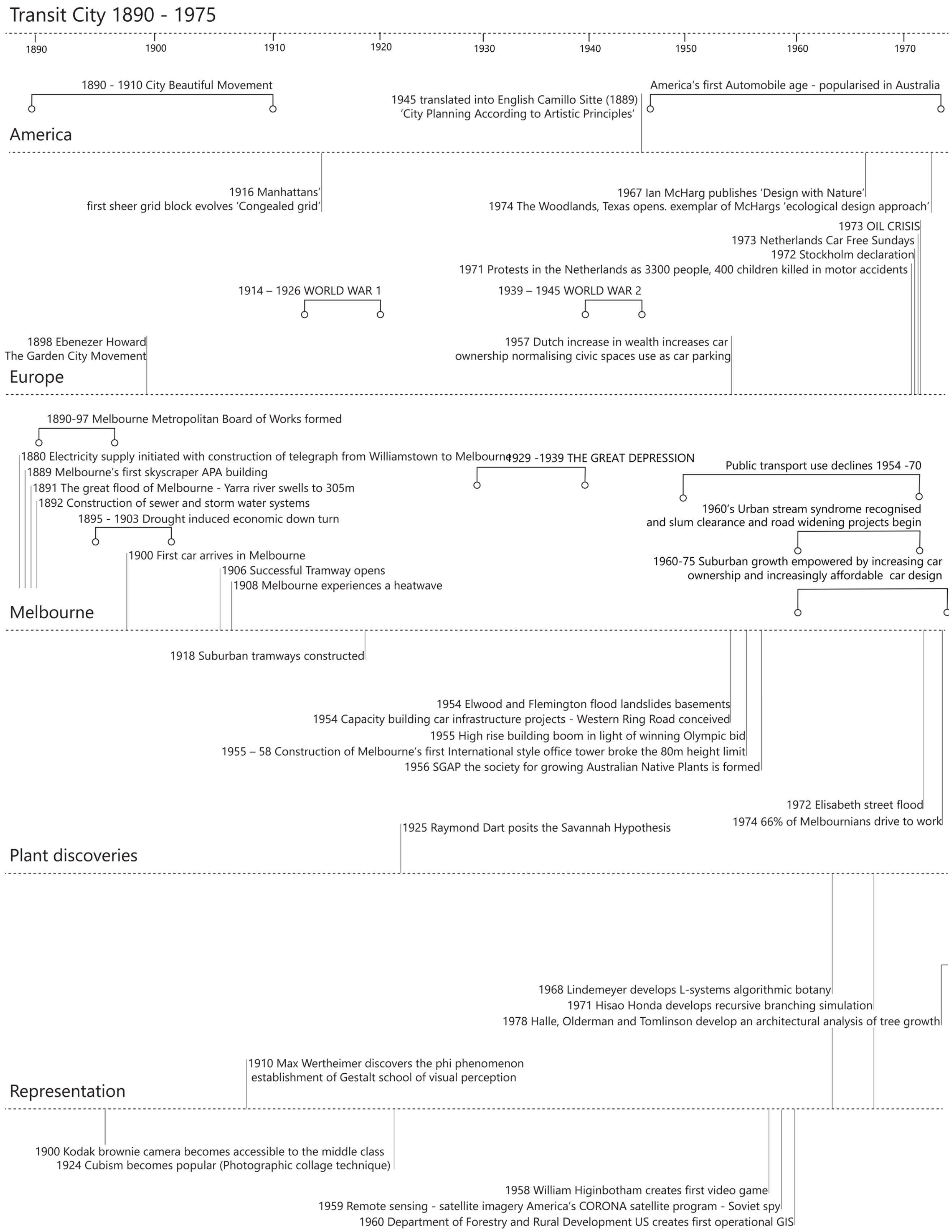

Figure 23: Timeline of events, movements and innovations between 1900 -1975, showing the shift from compositional, aesthetic city design concerns, towards transport and infrastructure concerns, and finally towards the end of this period, towards environmental concerns.

2.4 Rise of the Sustainable City 1975-and beyond

> *The local scale (neighbourhood, streetscape, precinct) is the most likely scale at which climate change adaptation strategies will be implemented by local government authorities, focusing on streetscapes in suburbs with vulnerable populations […] (Block et al., 2012).*

Globally, one of the first issues associated with high car use was a road casualty epidemic. In the 1960's, in reaction to this epidemic some European cities, particularly those of medieval pre-car structural origin such as Utrecht began to revise their road infrastructure to promote cycling (Bliss, 2019). The response to the transport accident epidemic in the younger, less constrained gridded cities of colonial origin in the US and Australia was much slower. These cities continued to expand their road infrastructure well into the 21th century with car ownership per capita continuing to rise until well into the 21st century.[68] (Charting Transport, 2017; Davison, 2004; Litman, 2016).

The generously proportioned gridded structure of colonial city streets, *designed* to include trees, was, (at the expense of that tree space) flexible enough to accommodate the rise of mass motorized transport and other infrastructure innovations such as, gas and electricity supply, telecommunications and disposal of wastewater. Now new challenges needed accommodation in this two-hundred-year-old street structure. That of rapidly urbanizing populations and a rising number of anthropogenically derived environmental problems (Newman & Jennings, 2008). Of the many environmental problems which began to arise during the 1970's; global warming; deforestation; over population; limits to non-renewable energy sources; ozone depletion and pollution of scarce water resources, two have a very direct relationship to urban trees.

2.4.1 New challenges

The first of these challenges which relate to urban trees is the 'Urban Stream Syndrome[69], a phenomenon where pollutants carried by fast moving piped urban storm water runoff

[68] In Australian capital cities car ownership per capita has slowed and is even declining in Melbourne in recent years.

[69] The Urban Stream Syndrome was recognised as a direct result of the speed of storm water reaching waterways. Particulates and pollutants did not have time to be filtered before stormwater reached streams and rivers. This resulted in decreasing biodiversity and stream health.

enter and damage waterways. Unintended, negative environmental consequences of the piped underground infrastructure of water supply, disposal and drainage of cities, a primary engineering achievement of the past two centuries, began to be exposed and interest in the capacity of trees to slow storm water and compartmentalise pollutants arose (Ladson et al., 2004; Walsh et al., 2005; T. Wong, 2013) [70] [71].

The second of these urban tree related challenges; is the theory of anthropogenic global warming, which describes the phenomena of increases in the earth's average temperature, in part caused by carbon emissions from motorised transport. Increases in the average temperature of the earth, results in increasing occurrence of high-pressure systems which trap heat beneath them, causing, among other things heat waves. The human cost of heat waves are increasing numbers of heat related deaths, including the 70,000 deaths associated with the European heat wave of 2003 (WHO, 2019).

2.4.2 New approaches

Between the 1973 oil crisis and the 1979 first World Climate Conference the concept of Sustainable Development began to rise as a household concern, heralding a socio-political paradigm shift towards sustainability (Girling & Kellett, 2005). Alternative urban design approaches evolved during this time, arguably beginning with New Urbanism. The New Urbanism approach called for more compact walkable development models, aiming to reduce car use (Duany et al., 2014). Concurrent with New Urbanism, but with a focus on working with natural systems, particularly waterways came the 'Landscape Urbanism approach[72] (Ellis, 2015)[73]. While the fundamental driver of both approaches is sustainability, the differences between them was a response to different priorities. Landscape Urbanism was more concerned with environmental repair (Gray, 2006), while New Urbanism was more concerned with compact transit-oriented development and pedestrian accessibility (Congress for the New Urbanism & Talen, 1999).

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[70] Which later extended to storm water moderation as increased storm intensity began to overwhelm existing piped storm water systems.
[71] At source control (Department of Environment 2004).
[72] The Landscape Urbanism movement (attributed originally to Ludwig Hilberseimer 1956 See (Waldheim, 2016, Chapter 7) for in depth discussion.
[73] Subsets of Landscape Urbanism include Green Urbanism (Girling 2005; Beatley 2011), Ecological Urbanism (Mostafavi and Hill). The debate between these schools of thought is heated and often loaded, it is not my intent to delve into their theoretical differences in this thesis.

2.4.3 The Landscape Urbanism approach to water systems

By the turn of the 21st century urban environmental concerns[74] (in particular the Urban Stream Syndrome) led to the consideration of urban vegetation as a form of green infrastructure with functions that could positively contribute towards environmental performance goals (Bélanger, 2009; Benedict & McMahon, 2002). Recognition of the Urban Stream Syndrome also resulted in a paradigm shift in stormwater management practices, infrastructure design and theory, away from the 'rapid as possible transfer' of storm water to receiving water ways, to the complete reversal, 'as slow as possible transfer[75], with preference for managing storm water where it falls in 'daylighted' or integrated, decentralised surface based storm water systems (SSWMS) (Walsh et al., 2005; T. Wong, 2013). Trees are critical in these systems as their canopies can reduce the speed and quantity of storm water and their root systems remove water from retention and detention systems [refer Figure 24][76].

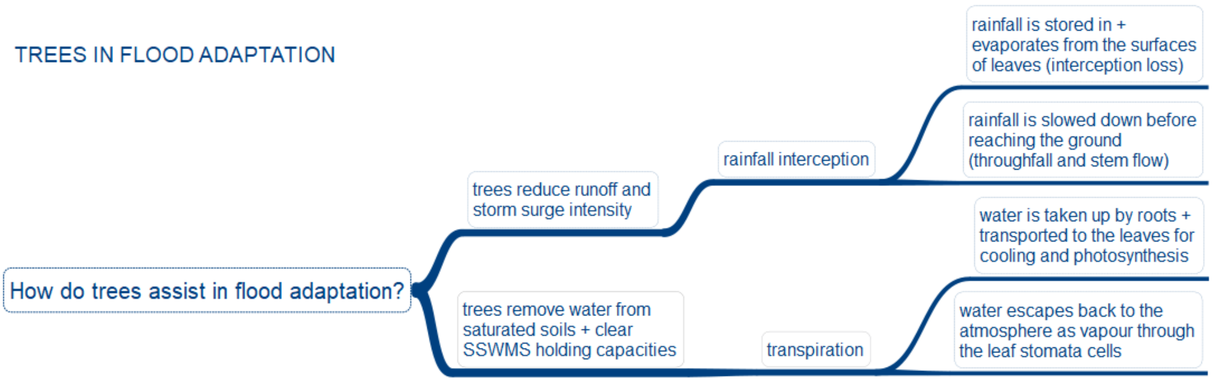

Figure 24: Diagram showing dominant mechanisms of trees used in flood adaptation.

SSWMS[77] work with the natural system of topography and the structure of the unit known as a hydrological catchment (Bren, 2015; Eamus, 2006). When the Australian and American land management systems were implemented in the 19th century, the impact of discounting hydrological boundaries were not well understood. Political boundaries formed along the edges of waterways, in direct opposition to the natural system of water

[74] Ecological performance, carbon emission, ++, heat related mortalities, obesity, anxiety associated with decreasing selection of active transport modes, UV exposure particularly children, traffic signal wait times, reduction of particulate exposure PM10's and PM 2.5s.
[75] Slowing the speed of storm water allows pollutants and particulates to be filtered out of storm water before it reaches waterways.
[76] SSWMS consider overland flow paths, integrated water cycles, bioretention and biofiltration. Bio filtration systems contain plants as opposed to infiltration systems which are unplanted. Biofiltration systems do not retain water, bioretention systems can however retain a body of water.
[77] Examples of strategies for this are global: Suds (Low Impact Development (LIDS) North America and New Zealand., Water Sensitive Urban Design (WSUD) Australia, and Sponge City, China as discussed by Fletcher 2015.

flow in hydrological catchments as they were established on the grounds of '*neighbourhoods of people who interacted with each other on a day to day basis*'(Williamson et al., 2010) [refer Figure 25]. Interactions with people in neighbourhoods on opposite sides of waterways was hindered by lack of water crossings (Lokman, 2017; Williamson et al., 2010).

Recognition of the natural systems of waterways and catchments formed a fundamental driver for Landscape Urbanists. They integrated (SSWMS) into their designs, which improved urban water way quality outcomes, but also required at times an uncompact use of space. This led to criticism of the Landscape Urbanism design approach as it appeared to encourage continued suburban sprawl[78] (Duany et al., 2014). I look at the key challenges of integrating SSWMS into tree-scape design in Chapter 5: Umbrella City.

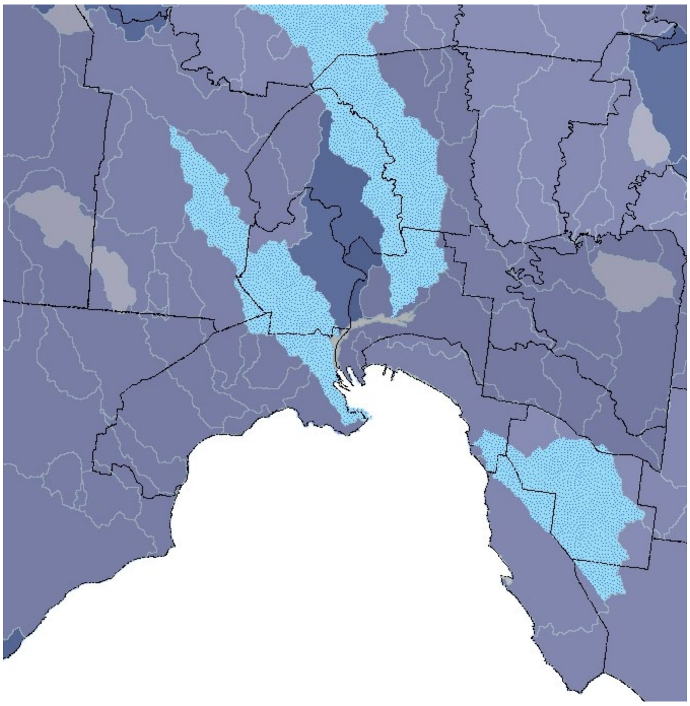

Figure 25: Map shows the disjuncture between inner Melbourne's hydrological catchments (different shades of blue) (source: Bureau of Meteorology Geofabric) and the municipal boundaries (source: Australian Bureau of Statistics).

2.4.4 New Urbanism approach to carbon emission reduction

The New Urbanist response to arising environmental problems in contrast, focused on reducing carbon emissions from motorised transportation, through compact urban growth

[78] Dispersed development with room for natural water systems reduced capacity for compact development This was in fact the case with McHarg' Woodside development which was 'designed with nature' (ecological design approach) but which later became an enclave for high income earners.

within close proximity to public transport in their designs[79], aiming to promote walking over car use (Duany et al., 2014).

The New Urbanist concept for compact growth is based on the concept of *pedestrian accessibility* to public transport aligning with the principles of *Transit-Oriented Development* (TOD) (Newman & Kenworthy, 1989). The primary premise of TOD being that density should be concentrated in areas which are a ten-minute walk from public transport nodes [refer Figure 26] [discussed further in Chapter six: *Shady City*, in relation to active transport modes].

Figure 26: Aerial photograph of transit oriented development in Arlington (source: Creative commons 2.0 licence [https://en.wikipedia.org/wiki/Transit-oriented_development)](https://en.wikipedia.org/wiki/Transit-oriented_development)

New Urbanists down played the inclusion of nature in cities as a sustainability criterion because of the negative impact it's inclusion would have on the efficiency of urban transport systems and TOD (Weller, 2008). However, pedestrian accessibility was not their only criterion. New Urbanism also stipulated visual rules pertaining to building height limitations and 'zero lotted' development (also known as a street wall, where buildings

[79] This is sometimes referred to as walkability. However, walkability is a metric, usually an index, used to describe how walkable an area is. While many approaches to measuring walkability have been proposed, the best known is that of the three D's (Cervero & Kockelman, 1997). Density, being the measure of number of people per hectare, Diversity being the measure of mix of land use types and Design being the measure of the quality of the built environment and its suitability for walking (Cervero & Kockelman, 1997). While density and diversity are relatively easy to measure and when calculated together with a distance (denoted as R to avoid confusion), they can be considered a measure of accessibility or city compactness.

have no front setback, based on a European city ideal (Alexander et al., 1977, p. pp.593; Ewing & Clemente, 2013, p. pp 11). These visual rules did not necessarily translate well into US and Australian cities with their development histories entwined with personal motor vehicle ownership, wide colonial road widths and extreme climatic conditions (Fishman, 1982; Jenks et al., 2004).

In Australian cities, the application of the visual rules of New Urbanism resulted in conflict with TOD concepts which would, if faithfully applied, result in towers near transport. Instead, the New Urbanist visual rules resulted in a consistent building height [refer Figure 27] which has had far reaching urban environmental and social repercussions, including conflation of housing affordability issues (Daley et al., 2018; Jenks et al., 2004) and increasing site coverage ratios (to maximise yield). This in turn, led to reduced permeable to impermeable surface coverage ratios, exacerbating overland flow and reducing urban communities access to green space (Beatley, 2011).

Figure 27: Birdport Road Poundbury England showing an ideal New Urbanism form. (Source Google street view).

Depending on the specific structure, (street orientation, street widths, building heights), constrained building heights worsen pedestrian environments as they leave footpaths solar exposed in summer and overshadowed in winter. Trees are critical for moderating the impact of height controlled mid-rise development as they can be used to improve poor thermal conditions for active transport users [refer Figure 28] [discussed further in 3.4.1:

Modelling tree heat moderation]. New Urbanist design guidelines are stipulated for the case study site in Chapter 7: *Synthesis City* and are discussed further in that chapter.

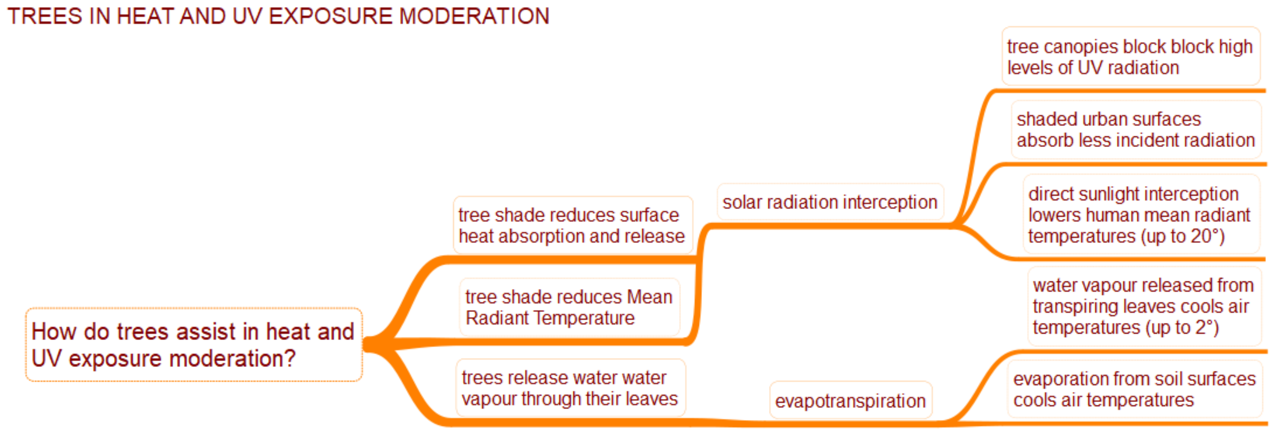

Figure 28: Shows the main mechanisms by which trees moderate heat.

2.4.5 The view from the footpath

Two competing issues are apparent in the differences between New Urbanism and Landscape Urbanism as they grappled with two competing aspirations, achieving 'urban consolidation' and improving 'urban environmental conditions'. Approaches which descend from Landscape Urbanism include the Green Streets movement[80], in which the 'daylighting' of storm water strategies is the priority. While the descendants of New Urbanism include Smart Growth, Multimodal and Complete streets movements. Smart Growth, still calls for compact development but abandons the New Urbanist height limitations, and multimodal (complete streets) priorities accommodation of all forms of transport (particularly increasing cycleways) (NACTO, 2013). There are still several difficulties involved in resolving the priorities of these movements. They both require a reconsideration of the spatial footprint currently allotted to car parking and traffic flow, both look for spatial opportunities offered by changes to transport modes such as vehicle automation. Achieving the objectives of both requires careful balance, as this streetscape space is limited[81] [refer Figure 29].

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[80] A subset of Green streets is Creek Streets http://www.streetcreeks.org/#about emulate natural hydrological and ecological systems in urban environments, using a distributed, de-centralized network of curb side channels and water-cleaning bioswales that treat the "first flush" of polluted surface runoff, and allow the remaining cleaner water to rainfall continue downhill.

[81] Green Infrastructure', stemming from a variety of sources and without an entirely accepted definition but attributed to the American Greenways movement focusing on quality of entire natural systems (Firehock & Walker, 2015).

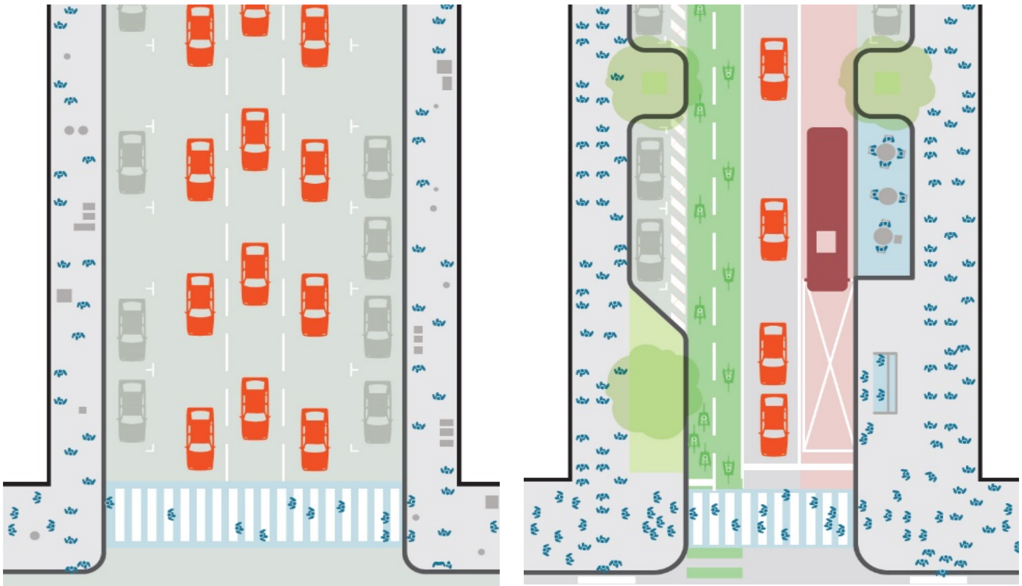

Figure 29: Shows (LEFT) the transformation of an existing 20m wide street into a (RIGHT) Multimodal street. Parking lanes are subsumed by cycling and planting, traffic lanes are reduced to a single stream of one-way traffic. The left diagram suggest that the existing street does not have trees (not often the case). The RIGHT diagram then suggests that space originally inhabited by trees will be required for multimodal transport requirements. (Source: NACTO Global street design guide).

2.4.6 Conclusion Sustainable City

Growing awareness of environmental and human health issues associated with vehicle prioritisation began to shift streetscape decisions towards designs which both promote active and sustainable transport choices and towards supporting natural drainage systems. When these spatially competitive issues are looked together, urban storm water management (WSUD[82] in Australia) and transport-oriented-development (or TOD), in light of world events, it is quite reasonable to see how either issue could be prioritised [refer Figure 30]. Both issues are as pertinent to the development of cities today (if not more so) as they were in the 1960’s. With the requirement to accommodate both multimodal transport and water sensitive design on spatially constrained streets a clear need spatially explicit modelling and decision-making methods become evident.

[82] Water Sensitive Urban Design.

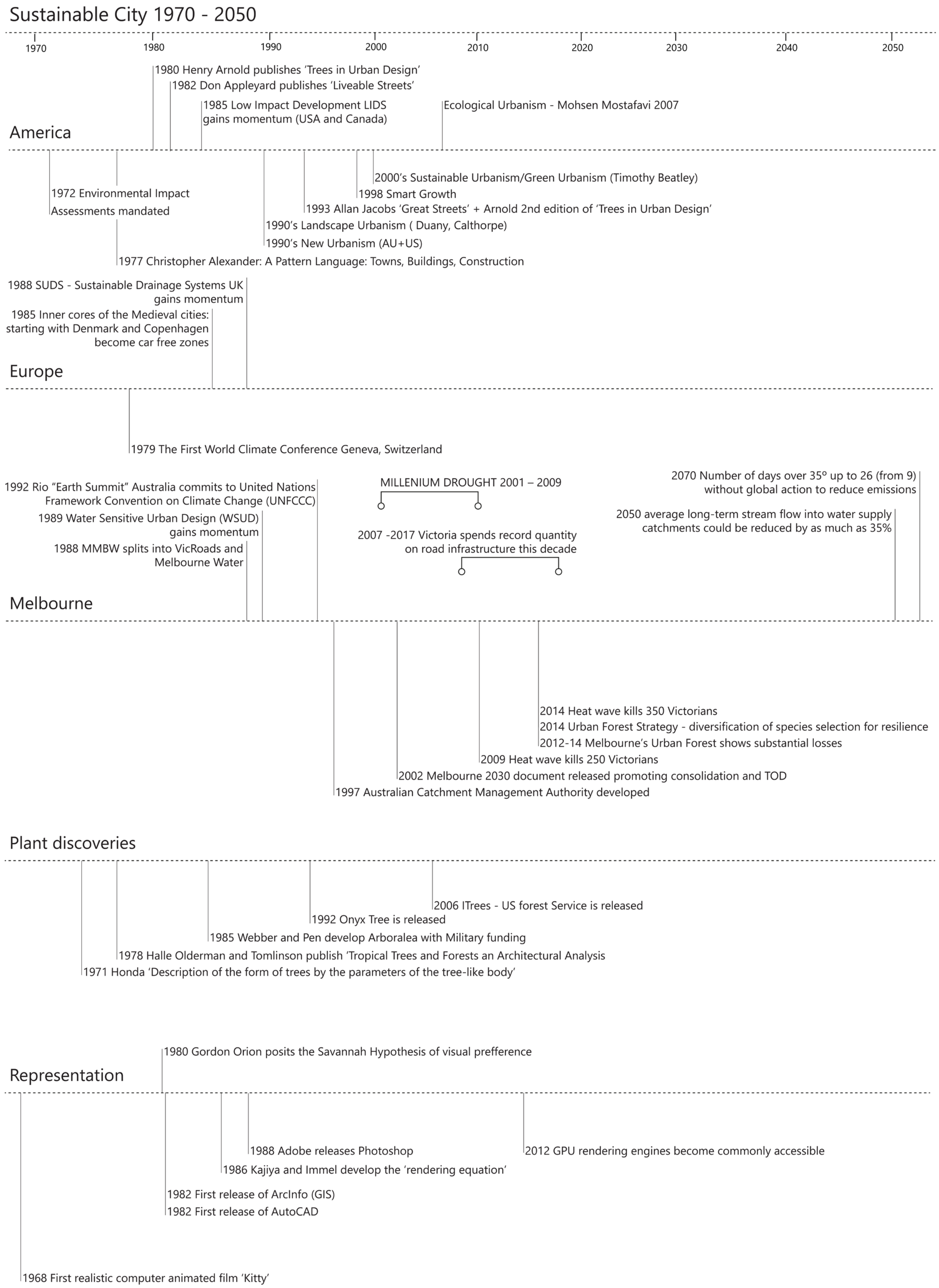

Figure 30: Timeline showing the evolution of urban storm water issues (Water Sensitive Urban Design) and Transport Oriented Development (TOD) and how these two issues were taken up by New Urbanism and Landscape Urbanism

2.5 Conclusion

In chapter two I asked the question*: What are the past and present decision drivers behind inclusion of trees in streets?*

The drivers behind tree inclusion on urban streets have had three major shifts over the past two-hundred years. Initial colonial period tree-scape decisions were visually driven, coupled to new ideas which arose with industrialisation, rapidly urbanising populations and urban health. The turn of the 20^{th} century saw decisions which repurposed space designed for trees on generously proportioned colonial city streets, driven by innovations in transport, services and storm water management. And in the late 20^{th} century, rising awareness of anthropogenically induced environmental problems saw the drivers of tree-scape decisions shift towards their function as a form of green infrastructure. Figure 31, is a visualisation of these changes in tree species selections as they have evolved over the past two centuries in Melbourne, beginning with the large evergreen species selected by Mueller in the 1850's to the increasingly diminutive species selected through the transit oriented era. In this last era, we once again may need to increase selection of large evergreen species for moderating environmental problems, particularly storm water speed and quality which will be discussed further in the next chapter.

Figure 31: Shows the changes in streetscape planting over two centuries in Melbourne, projecting a return to large evergreen species in the future to meet sustainability goals and function as green infrastructure.

Each of the decision drivers associated with these three paradigm shifts is still at play in streetscapes. Visual, aesthetic amenity concerns still drive tree decisions in public participation and consultation forums. Transport and land use demands still put streetscape space under pressure and growing environmental issues require substantial changes to the configuration of streets. Current aspirations to increase tree canopy cover to fulfil functional environmental requirements are widespread as is road reclamation (reducing the quantity of road surface dedicated to vehicles), but achieving consensus about how and where tree canopy cover will be located and how this will work within the limited space of streets is a complex negotiation between multiple stakeholders and street design disciplines. Decision-making methods for streetscape designs and development of 3-dimensional processes and modelling which can communicate both functional and visual aspects of design scenarios are needed, and these methods need to include and consider trees as 3-dimensional infrastructure.

Chapter 3: Modelling for decision-making

> *To model is to test and proclaim one's understanding of the real system, or the object of the model. In the landscape, the systems and elements range all the way from the branching structure of trees to the physics and waves of rainbows, and even the human dynamics of crowd behaviour. Landscape modellers are thus, heavily dependent upon other sciences and research endeavours to fill in knowledge about the fundamental landscape elements and their behaviour [...]. How to know what knowledge from these disciplines is relevant, find it and keep it current, translate it into model form and incorporate it intelligently into models, is a daunting challenge. (Ervin, 2001)*

3.1 Introduction

In the previous chapter I outlined the changes between past and present decision drivers for including trees in streets. I demonstrated how the problem of streetscape design has become more complex over the past two hundred years, as streets are becoming an increasingly constrained spatial envelope in which multiple complex and adaptive systems must unfold (Furtado et al., 2015). In this chapter I investigate the ways in which uncertainty in streetscape systems is addressed by multiple disciplines through modelling. I investigate the visual, spatial and environmental criteria and modelling techniques utilised by designers, environmental scientists and transport planning disciplines. As this is a transdisciplinary review each of these areas is covered as a broad-based overview.

Visual, spatial and environmental performance of streetscape designs are difficult to comparatively measure or analyse as there is no holistic system which links across the diverse range of concerns. This means that different disciplines are often working in isolation from one another which causes two problems: First, one discipline may put forward an 'impossible to achieve' design, untested against the criteria of other disciplines; and second, the criteria of one discipline can be ignored or considered irrelevant by another discipline (Flourentzou, 2012).

The outcome of this chapter suggests that a visual-functional approach to design using a Design Decision Support System (DDSS) which can integrate spatial, visual and environmental concerns, could provide a more structured and informed process for decision-making with multiple criteria. While such a visual-functional approach would not answer all questions, it would allow a simplified but holistic systems overview (Bishop & Lange, 2005). To achieve this holistic overview, complexity trade-offs are required, which will be discussed in this chapter and in Chapter 4: *Research method*(Larsen et al., 2016; Niño-Ruiz et al., 2017).

3.1.1 Aim

The aim of this chapter is two-fold: Firstly, to establish the grounds on which different disciplines model streetscapes and what criteria they prioritize in those models. And secondly to establish the way spatially explicit visualisation created from the growing quantity, quality and veracity of spatial data can be coupled with new modelling techniques to inform streetscape decision-making.

This aim has three associated questions:

What is the context of tree-scape design decision support development (past and present)?

What are the qualitative visual, quantitative spatial and environmental modelling systems available for streetscape decision-making?

How do design and modelling approaches and attendant hierarchies of priorities differ in different disciplines?

In section 3.2 of this chapter I discuss the definition of modelling and visualisation and how advances in computing over the past few decades have changed these definitions. This section clarifies the type of modelling and visualisation described in this thesis and used in the modelling framework of the Visual-Functional, Design Decision Support System developed in chapter four.

In section 3.3 of this chapter I discuss the evolution of modelling for visual concerns and how different types of modelling and visualisation have evolved to address the requirements of *Public Participation in Decision-making* (PPD), considered best practice in design and planning (Marks, 2004). This section also discusses the evolution of spatially explicit visualisation in planning from its origins in *Visual Impact Assessment* (VIA).

In section 3.4 of this chapter I discuss the evolution of modelling for environmental concerns in environmental sciences, dealing predominantly with analysis and simulation of environmental conditions such as heat and tree storm water regulation. I also discuss the visual output of these types of modelling such as thermal heat maps and hydrographs.

In section 3.5 of this chapter I discuss the evolution of modelling the spatial concerns of transport and land use planning and how the regulation-based policies and modelling techniques used by these disciplines have impacted possibilities for tree inclusion in streets.

In section 3.6 of this chapter I discuss what is needed for landscape architecture and tree-scape design decision-making to moderate between environmental concerns, creation of visual aids for public participation and spatial negotiation with the regulations of transport and land use planners.

3.2 Modelling, visualisation and decision-making

> *Models permit abstraction based on logical formation using a convenient language expressed in a shorthand notation, thus enabling one to better visualise the main elements of a problem while at the same time satisfying communication, decreasing ambiguity, and improving the chance of agreement on the results." (Li et al., 2004; Saaty & Alexander, 1981).*

All disciplines involved in predicting the impact of probabilistic problems, decisions or phenomena on existing systems, use forms of forecast modelling. Disciplines involved in streetscape decision-making are no exception, as they are charged with making decisions or assisting decision-makers with choices about streetscape infrastructure today which may have far reaching consequences for the streetscape of tomorrow. Forecasting models for streetscapes are undertaken for a range of reasons but the three which are most relevant to this thesis are:

- the impact of responding to climatic extremes on public tree decisions.
- the impact of increasing population density on streetscape structure.
- the impact of transport transformation on tree-scape possibilities.

Ideally the forecasting models of multiple disciplines could be applied concurrently to streetscape decision-making. However, the models employed by each discipline can be complex, include multiple divergently weighted assumptions and criteria, require detailed input data or be overly abstract, making the usefulness of their outputs in multi-disciplinary environments or public participatory decision-making (PPD) limited (Flourentzou, 2012; Laurans & Mermet, 2014). In addition, the techniques and software platforms used by each discipline can have poor interoperability.

While several mathematical models to deal with complex systems have been developed to aid decision-makers such as the Analytical Hierarchy Process (AHP) of Saaty and Alexander[83], the inherently spatial nature of streetscape decision-making, the somewhat subjective and changeable nature of visual preferences and the lack of agreement on criteria prioritisation between disciplines involved, make their application cumbersome. Of all the systems which are at work on streetscapes, the spatial envelope is the system with the least capacity for change. This constrained spatial envelope must therefore be the starting point for decision making, within which all other criteria must be met or moderated [refer Figure 32]. Streetscape decision-making is therefore defined less a mathematical and more a spatial multi-criteria problem (Sheppard & Meitner, 2005)[84].

[83] Saaty and Alexander developed the Analytical Hierarchy Process and the Analytical Network Process, pairwise comparison measurement theories devised to aid decision makers make trade-offs between multiple competing aspects or criteria of a decision. The priority value scales are derived by experts in these processes (Saaty, 2008).

[84] Sheppard describes this same problem in relation to moderation and conflict between Sustainable Forest Management and Public Participation in forest management visual impact.

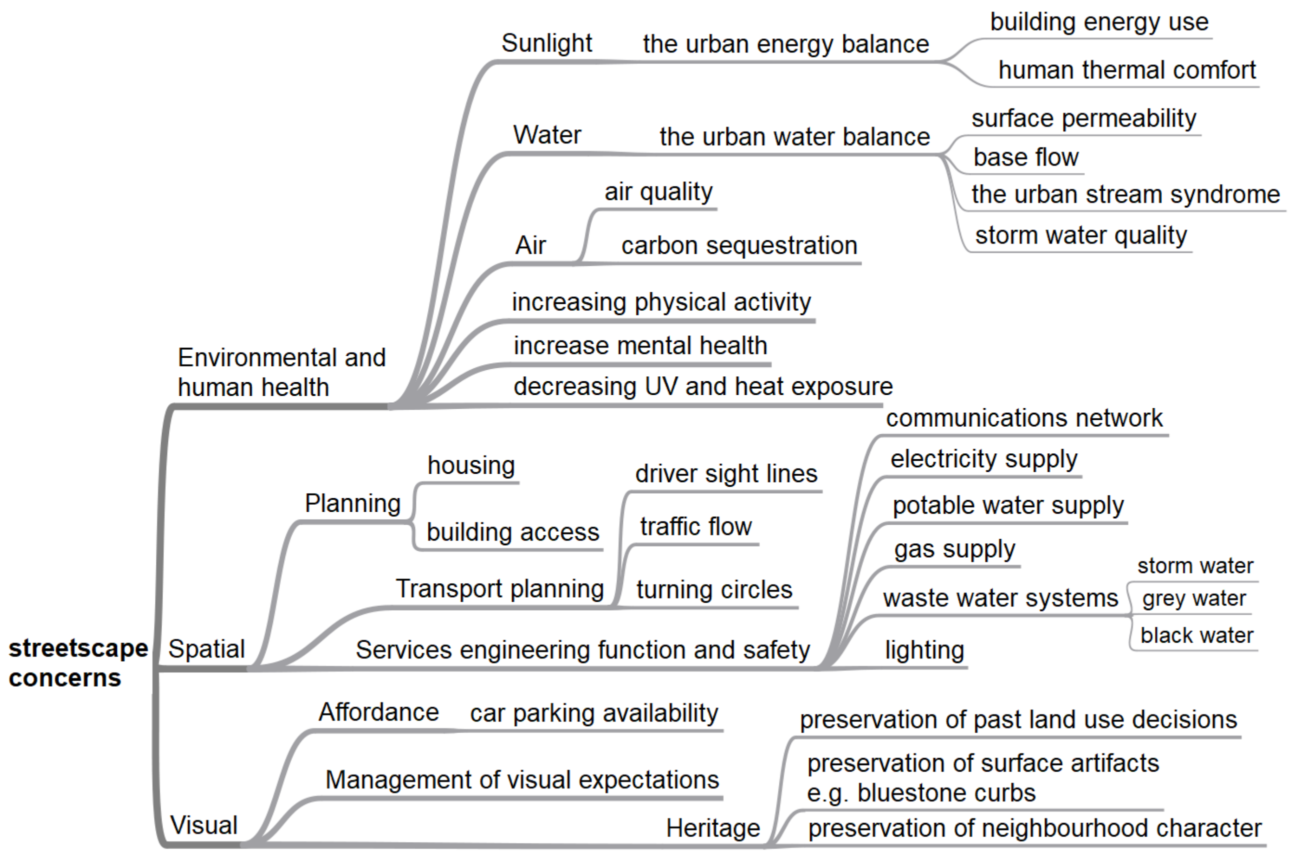

Figure 32: Shows some (not all) of the multiple conflicting criteria which must be balanced on streetscapes.

3.2.1 On the definition of modelling

Disciplinary definitions of what a model is vary. In art, 2-dimensional paintings and drawings that create an illusion of 3-dimensionality are considered modelling[85] (Philadelphia Museum of Art, 2019), a set of building plans was once, (pre computing) also considered a model, while in mathematics, a model describes a system using mathematical language (Merriam-Webster, 2019). It helps to define what is meant by 'modelling in the field of design, 'post computing' as it often simultaneously conforms to both the artistic and the mathematical definition. If we look at the 1981 'pre computing' definition of models offered by Saaty and Alexander we are given three broad categories of model; conceptual, physical or mathematical (Li et al., 2004, p. 5; Saaty & Alexander, 1981).

Conceptual models were defined by Saaty and Alexander, as unsystematic, abstract models. They are often studied in cognitive psychology, and in that discipline, they are

[85] Chiaroscuro modelling was a shading technique developed during the Renaissance which use the contrast between light and dark to achieve a perception of volume. Also, volumetric lighting, in atmospheric optics / meteorological optics known as crepuscular rays / god rays.

considered an internal thought processing model[86]. Saaty and Alexanders' definition of conceptual modelling has also been applied to the activities of designers such as sketching in the early phases of projects as discussed by Lawson and Goel (1995; 2006).

Physical models were defined as analogue scaled down versions or representations of spaces or systems. For example, traditional 3-dimensional physical models made from card or timber and 2-dimensional imagery which create an illusion of space. This type of physical model is frequently used for design presentation (Li et al., 2004). Physical models are a scaled representation of sites, meaning that for precincts or large sites, object such as trees must be heavily abstracted (Muhar, 2001) [refer Figure 33].

Figure 33: Physical urban planning concept model by design office OMA of a design scheme for Melun-Sénart, 1987, shows the use of nails to represent trees (source: https://www.flickr.com/photos/bcmng/albums/72157630026757656).

Mathematical models were defined by Saaty and Alexander as '*allowing simulation or analysis of a system in a quantifiable way, beyond what can be gained from a physical model alone*', though a physical model can be used as an input into a mathematical

[86] Related to the computational theory of the mind (well beyond the scope of this thesis) Lawson 2006.

model[87] (1981). Mathematical modelling for design decision-making has been a developing practice since the early 1960's, extensively using physical models as an input (March, 1975). Mathematical models also include 'biophysical models of plant growth such as those included in the urban forest management model and decision support system i-Tree (USDA, 2006), from which visualisations can be generated in the form of 2-dimensional maps. These visualisations provide a unique way of seeing quantitative tree data but they do not allow for visualisation of qualitative information [refer Figure 34].

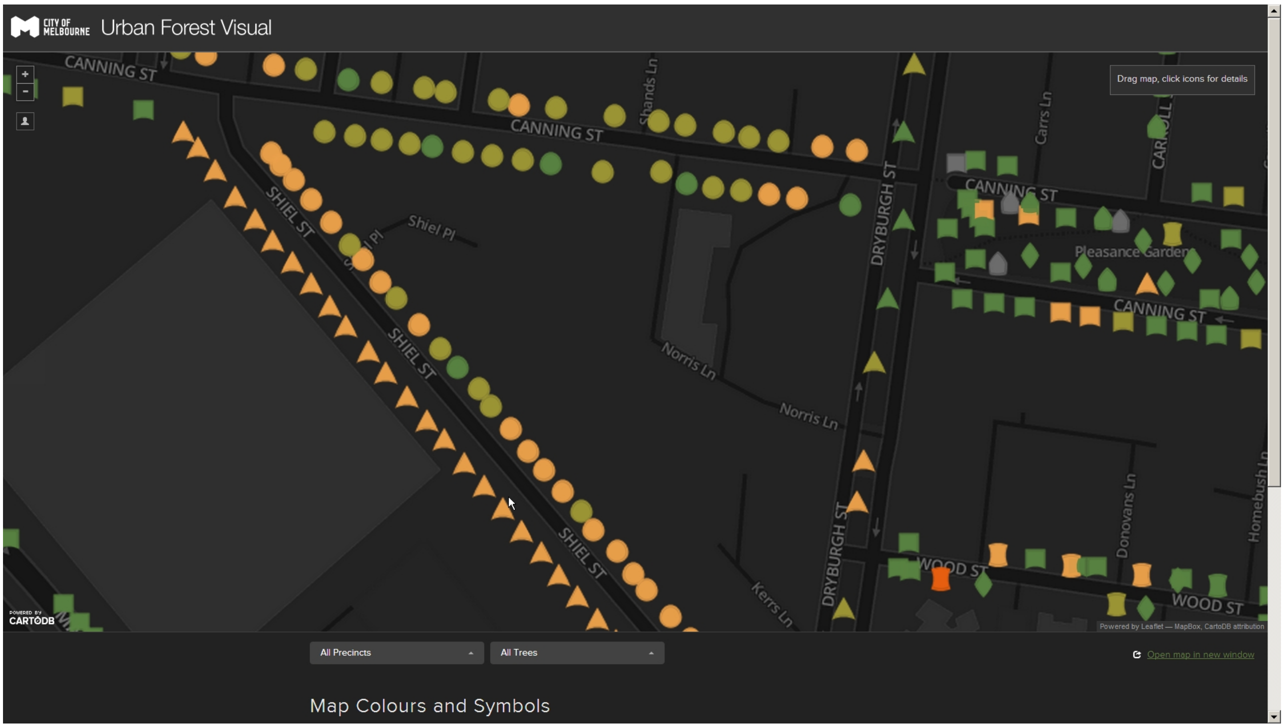

Figure 34: The Urban Forest Visual. Interactive data visualisation map of tree health assessment / audit of the City of Melbourne (Source: OOM Creative 2012 http://www.oomcreative.com/project/oom-melbourne-urban-forest-visual.html).

Digital-physical models for performance-based design

While Saaty and Alexander's definitions of modelling are still robust, the advent of computing has brought with it, hybrid models. One of these is the digital-physical model. Digital models of space under Saaty and Alexander's classifications still fall under the physical category. However, digital-physical models, blur the distinction between physical and mathematical modelling (Li et al., 2004) [88]. Todays' digital-physical models are created in software packages which allow the physical site to be used as an input for a variety of system analysis and simulation of both qualitative and visual as well as those with a

[87] Criteria for the usefulness of mathematical models was by Myer (accuracy, descriptive realism, precision, robustness, generality, fruitfulness).
[88] Li et al. discusses Digital Elevation Models (DEM) as actually being a mathematical model rather than a physical model.

quantitative and environmental [89] nature. Digital site models are not constrained to a single scale as is the case for traditional physical models but are constructed at 1 to 1 scale. In architecture, this digital-physical modelling is increasingly employed in 'performance-based' design as discussed by Rivka Oxman. Oxman's definition of performance-based modelling, design geometry (in his case; the building) is modified through performance simulation procedures to inform *form generation* (2008).

3.2.2 On the definition of visualisation

Computing has had an equally profound impact on the definition of the word 'visualisation', attributed to Bruce McCormick, a data scientist, who in 1988, redefined visualisation as 'a *type of modelling undertaken in a CAD environment*' (Bishop & Lange, 2005; McCormick, 1988).

> *This was a new use of the word [Visualisation]. Earlier dictionary definitions were restricted to the process of forming a mental image or envisioning something. The more recent usage involves the process of interpreting something in more visual terms or, more particularly, putting into visible form (McCormick 1987 in Bishop and Lange 2005).*

Like modelling, the contemporary definition of visualisation has different meanings across disciplines. The term can be confusing, as many disciplines put their work into 'visual form'. A visualisation can be an open-ended 2-dimensional abstract sketch such as those used by designers in PPD forums with the objective of enabling community discussion, but it can also be a graphical output of a microclimate simulation or a graph or map (MacEachren, 1995). The definition of 3-dimensional, spatially explicit visualisation is quite specific: These visualisations are constructed from accurate spatial data in one of two software environments which utilise one of two spatial paradigms: cartesian space or geospatial space (Schroth et al., 2011).

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[89] Oxman defines performance-based models in architecture as the exploitation of building performance simulation for the modification of geometrical form towards optimisation of a design.

3.2.3 Two spatial paradigms for modelling

GIS[90] software, first launched with the name ArcInfo™ in 1982, was designed primarily for analysis of geospatial environmental data. This was the same release year as Autodesk's vector based cartesian drawing program, AutoCAD™. Neither program had a graphical user interface, both were controlled through the command line and 'undo' was limited to a single step. These very complex and very new computing environments served to escalate an already heated divide in landscape architecture courses in America, centred around design method. On one side; Ian McHarg's, *'Design with Nature'* map overlay method[91] with its focus on *spatial environmental data analysis* lent itself to GIS (Herrington, 2010)[92]. This method was adopted in the *Geodesign* school of thought and by disciplines such as urban climatology and environmental science (Steinitz, 2012). However, McHarg's overlay method of design was criticised as being somewhat tyrannical and antithetical to the creative *form generation* focused schools of thought (Treib, 1999). Form generation was more easily explored using cartesian (CAD platforms) because of their capacity for integration with construction and engineering practices. At the time, neither software platforms were particularly useful for the visualisation of qualitative aspects of design[93].

3.3 Modelling visual concerns

In this section I describe the evolution of modelling and visualisation for qualitative design decision-making. Design disciplines use visualisation as a method of forecasting visual outcomes and enabling stakeholders, to make decisions about those outcomes (Reiber, 1994). Visualisation is an efficient method of communication as the visual cortex, the largest system in the human brain is dedicated to processing images and can do this task efficiently (Gattegno, 1969). Visualisations have the capacity to communicate complex systems while negating issues of language barriers and reliance on discipline specific

[90] Geographic Information System.
[91] The map overlay method was first described by Jacqueline Tyrwhitt in 1950, but later championed by McHarg.
[92] In particular, see Mark Trieb. This division of schools of thought revolve around the influence of Ian McHarg and his map overlay design method. The critique of his method is discussed by Herrington in depth, suggesting that, McHarg's emphasis transformed a generation of landscape architects from being designers into analysts, thereby disabling creative design.
[93] Other methods were used for the qualitative aspects of design. Though in 2011, in efforts to combine mapping with visualisation ESRI purchased a gaming engine add on: City Engine ™.

vocabulary (Gibson, 1979; Kepes, 1995; Klosterman & Pettit, 2005; Pettit et al., 2008; Tufte, 1997).

In design, the most efficient methods of producing visualisations are 2-dimensional. This is an important factor considering the very small percentage of a project budget that public participation or consultation processes represent and how frequently iteration is required (often). However, the use of 2-dimensional visualisations for design decision-making has three major issues. Firstly, the perspective from which the visualisation is captured or projected can create bias by privileging a single standpoint and manipulating the perspective of the viewer to best advantage (Gibson, 1979; Gill, 2013; Marr, 1982). In streetscape design, this privileged standpoint is often taken from the centre of the road, which shows a symmetrical driver experience rather than that of a pedestrian [as discussed in 2.3.5: *The view from the road*]. Secondly 2-dimensional visualisations have poor spatial accuracy making them unsuitable for coordination of decision outcomes with other disciplines (Flourentzou, 2012; Paar, 2006), and lastly, critical assumptions and omissions can be made using the 2-dimensional visualisation methods of ‘plan’, ‘section’ and ‘perspective’. Ideal scenarios which are rarely achievable in real world conditions such as a length of street having a constant condition of uninterrupted tree canopy can be depicted, like the two-kilometre long avenue of Linden trees of the George Garden Hannover [refer Figure 35].

Figure 35: Ideal, continuous canopy cover, George Garden, Hannover, Germany Linden trees on the two-kilometre-long Herrenhausen Avenue, planted in the 1840's (Source: https://de.wikipedia.org/wiki/Georgengarten_(Hannover)).

3.3.1 Design visualisation modelling

Public participation (PPD) is increasingly mandated in public space decision-making by acts such as the Rio Declaration on Environment and Development (Antrim, 1992), the European Landscape Convention (COE, 2000) and more recently in the United Nations, 2030 Agenda for Sustainable Development (Berry et al., 2019; Gill et al., 2013; Lange & Hehl-Lange, 2011). PPD is often undertake in the early phases[94] of a street design project. Public participatory decision-making is different from public consultation. In PPD, the aim is to give citizens agency in decisions while in public consultation there is no such requirement as these forums can be used to inform or at times placate citizens[95]. In each of these forums the role of the designer can be quite different and requires quite different visualisations. In community consultation, the designer is often acting as an *educator or advocate* for design decisions which have already been made and it is hoped that the community will agree with. In this role designers produce visualisations which are realistic

[94] Also known as 'sketch design' and 'design development'.
[95] In Arnstein's ladder of public participation, 'consultation' falls under the middle rungs of 'Degrees of Tokenism', flanked by 'placation' below and 'informing' above. While PPD is in the upper rung, aiming for 'citizen control' or at least 'delegated power'.

in nature, forecasting and or advocating the visual outcomes of design decisions [refer Figure 36 right]. In PPD, the designer must act as a *facilitator*. In this role, designers produce a different style of visualisation, one which is sketch based and abstract enough to *'appear open for comment'* (MacEachren, 1995; White & Langenheim, 2018) [refer Figure 36 left]. Both these types of visualisation can be considered 'conceptual models' (artistic definition).

The 2-dimensional Photoshop collage technique shown on the right in Figure 36, was pervasively adopted in landscape architecture at the turn of the 21st century. Initially this photorealistic representational method, lifted landscape architecture out of the manual sketch territory, but over the ensuing decade it also served to stagnate landscape representation. It delayed forays into landscape modelling techniques which can enable more process based analysis of design scenarios (Amoroso, 2016; Cantrell & Holzman, 2015; Weller, 2015).

Figure 36: (LEFT) shows a sketch-based image which is abstract enough to be open for comment (source: https://yoursay.bayside.vic.gov.au/sandringham-village-masterplan), (RIGHT) shows an image which might be produced to gain advocacy for a design (source: OCULUS landscape architecture and urban design Melbourne).

In the past (pre 1990), 2-dimensional visualisations were entirely adequate for the two tasks required of designers in these public decision-making and consultation forums: Either to *advocate* for a design or to *educate/facilitate* actual public participation in decision-making[96]. Both types of visualisation were primarily required for communicating qualitative visual impact and application of artistic principles[97] [98] to streetscapes, which were the dominant concerns of the time (Arnold, 1980). However, this 2-dimensional

[96] This related to Arnstein's 'Ladder of Public Participation (Arnstein, 1969).
[97] Gestalt principles which are still used in graphic design and game creation, in particular 'The law of past experiences', 'the law of symmetry' and the 'law of enclosure', are all also applicable to streetscape design.
[98] These might now be termed cultural ecosystem services.

visualisation production technique is inadequate for complex contemporary urban design concerns. They exacerbate the perception of urban trees as qualitative, non-essential decorative embellishments to streets (Lawrence 2006), and are inadequate for simulating or communicating complex environmental function, spatial constraints and systems (Ervin, 2001). Figure 37, shows a typical 2-dimensional representation of a streetscape. Tree shadows appear to come from two separate sun locations, making the road surface feel invitingly shady from the perspective of a person driving.

3.3.2 Design construction modelling

At the conclusion of PPD or public consultation, designers shift into more mathematical modelling and visualisation methods to enable construction of projects. In these later phases, designers create measured (quantitative) drawings in entirely different software platforms to the previous ‘sketch design’ and ‘design development’ phases of the project [refer Figure 38]. For construction documentation, spatial, vector based cartesian platforms such as AutoCAD are used, in which highly accurate measured construction drawings can be created and coordinated with the drawings of spatially focused engineering disciplines. However, this shift in both software platform and type of visualisation is not without problems. Qualitative aspects of the design are jettisoned during this process as they are essentially ‘irrelevant’ to the task of co-ordinating more ‘measured’ concerns such as project construction budget and materials.

Figure 37: Libby Gallageher, Cool Streets 2017 - visualisation of street shade using 2-dimensional Photoshop method - appears to shade the street from two sun positions (Source [https://www.coolstreets.com.au/the-cool-streets-method).](https://www.coolstreets.com.au/the-cool-streets-method)

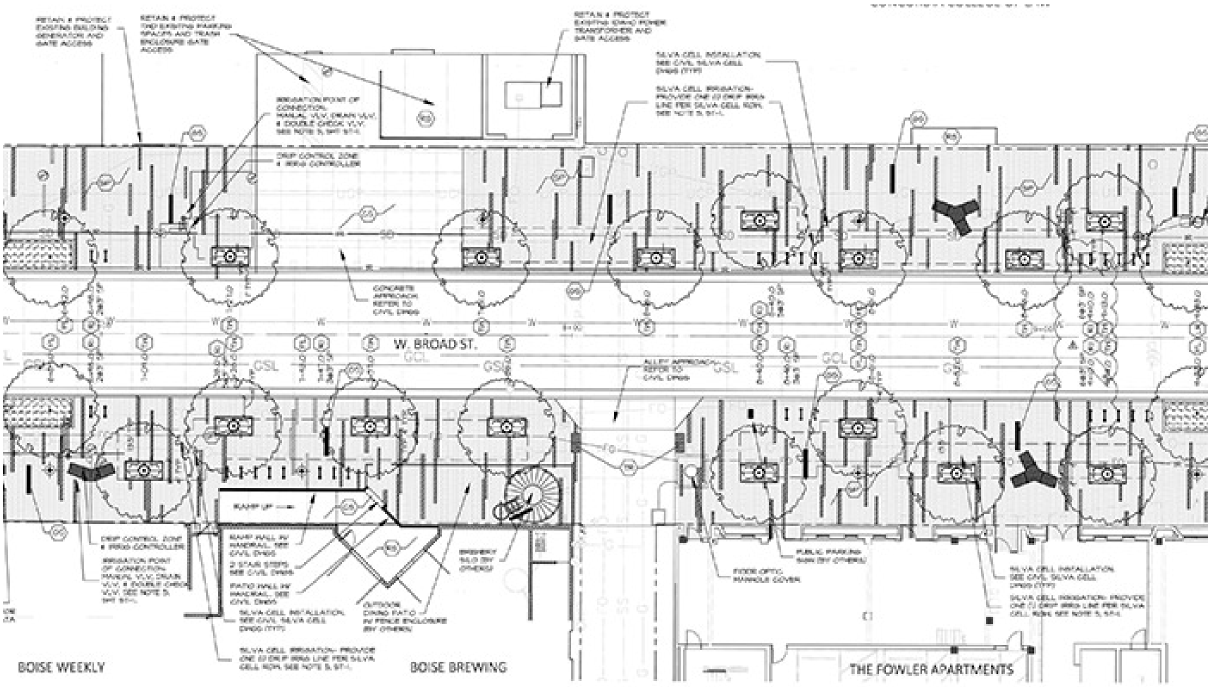

Figure 38: Streetscape construction documentation drawing (Source [https://jensenbelts.com/landscape-architecture/landscape-design-process/).](https://jensenbelts.com/landscape-architecture/landscape-design-process/)

3.3.3 Shifting design modelling methods

At the turn of the 21st century, design offices were chiefly using manual production methods for visualisation in both the early and late stages of design, but in the past two decades, they have transitioned to using proprietary[99] digital tools for this work. These commercial software packages and associated hardware are a substantial financial investment for landscape practices (Paar, 2006). At a minimum, a graphically oriented, raster-based program such as Adobe Photoshop ™ is needed for the early (qualitative) phases of sketch design and design development and a vector-based cartesian program such as AutoCAD ™ is required for the (quantitative) documentation and construction phases. This shift in visualisation production methods is often associated with a loss of decision outcomes from earlier stages in the project (Flourentzou, 2012). During this transition, street trees can be lost to the requirements of vehicle turning circles, while others are lost to provision of driveways and spacing between trees can be increased to save on tree pit costs.

3.3.4 3-dimesional design modelling

3-dimensional design modelling has been developing over the past two decades in three areas:

- Construction modelling or Building Information Modelling (BIM) driven by the need for coordination with engineering disciplines, is focused on construction, costs, quantity surveying (Landscape Institute, 2016).
- Data driven/ spatially explicit 3-dimesional visualisation modelling driven by the need for visual accuracy for Visual Impact Assessment studies (VIA) (Lange, 2001; Pettit et al., 2008) and
- Visually realistic modelling for advocacy, driven by the need for public acceptance of large-scale private development projects (Bishop & Lange, 2005; Groulx & Lewis, 2019).

Building Information Modelling (BIM)

BIM modelling arose from the need to be able to automate calculation of construction costs and co-ordinate the work of multi-consultant teams working on large scale buildings. It is an attempt to bypass the issue of error prone manual detail cross referencing. What BIM platforms attempt to do is attribute and populate data attached to linework in a

[99] Gloulx (2019) notes that despite the availability of low cost or opensource environmental modelling options uptake or use of these software packages is still low.

geometric model. These models 'live link' (automating the coordination) with the drawings of engineering disciplines, highlight any spatial clashes between these drawings and output quantity survey data. ArchiCAD™ (released 1982) is widely considered the first true BIM product on the market as it was the first to enable creation of both 2-dimensional and 3-dimensional geometry (P. Smith, 2014). Nearly all construction documentation packages now offer this capacity, as the industry transitions to automated coordination (Lien, 2016).

Visual Impact Assessment (VIA)

In the 1960's the environmental movement was strong in the US. Environmental lobby groups helped to formalise policy for attaching Environmental Impact Assessments (EIA) to proposed infrastructure developments[100] (a practice later adopted in Australia) (Mees, 2003). Visual Impact assessment (VIA) developed as a subset of EIA, particularly pertinent to forest stand dynamics (timber management plans) and large-scale infrastructure projects such as wind turbines (Smardon, 2016). VIA required realistic or defensible unbiased visualisation of change over time (Bishop & Lange, 2005; Ford et al., 2014; Gobster, 1999; Smardon, 2016). VIA required spatial data which at the time of its inception was scarce or expensive, the use of nascent software[101], substantial commitment of staff time, a specialised skill set and expensive hardware (Paar, 2006). Initial tree visualisations needed to be computationally efficient for VIA. Trees were usually represented as two intersecting planes with a tree photograph mapped to each plane, known as 'billboard trees' (Pettit et al., 2008) [refer Figure 40]. Billboard tree models can be suitable for large macro scale visualisations but there are issues with their use at meso and micro scales. Often edges of the intersecting planes are apparent, they are not useful for testing spatial implications such as accurate shading, they are usually brought in from a coupled library which lack editing capacity and yet are not abstract enough for creation of 'open for comment' visualisations needed for public participation forums[102] (Bishop & Lange, 2005; Ervin, 2001; Gill et al., 2013; Irvin & Stansbury, 2004; Malamed, 2011; Paar, 2006). In the initial years, VIA modelling was undertaken in GIS environments [refer Figure 39], and only

[100] In particular rampant freeway building which was occurring at this time.
[101] Such as the first Geographic Information System was released in 1982, developed by the landscape architect Jack Dangermond.
[102] The photographic level of plant detail can be unproductive for facilitating discussion.

in 2011 with ESRI's purchase of the 'game engine[103] 'City Engine™ was it possible to use more realistic, 3-dimensional trees in this form of visualisation[104]. VIA techniques are still reserved for large scale projects due to the workload and skill levels they require to produce. Both the GIS skills and the data formats which are at the base of VIA create a transferability barrier into and for users of cartesian construction platforms (designers). Despite the spatial accuracy advantage these models offer over 2-dimensional sketch and collage methods their outputs are essentially decoupled at the transfer to the construction phase.

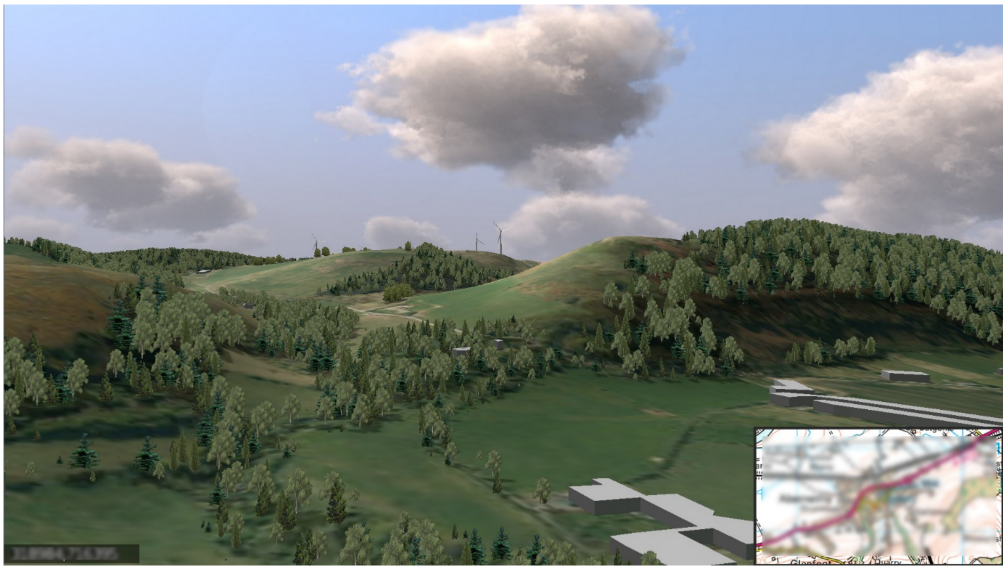

Figure 39: Billboard trees used over 3-dimesional map created in GIS environment and displayed in a game engine environment (Source: StackExchange 2013).

[103] Game engines are used to display 2-dimensional or 3-dimensional graphics, play animations and sounds, detect collisions between objects and move objects in ways that simulate the laws of physics while managing memory usage.

[104] Prior to ESRI's purchase of City Engine, Stock et al. developed a manual conversion process for GIS data to inform 3D models and visualise them using the Opensource Torque game engine developed by GarageGames. These models could be coupled to the proprietary visualisation tool 3D Nature's Virtual Nature Studio and a library of tree 'assets. The system was known as SIEVE (2008, 2011).

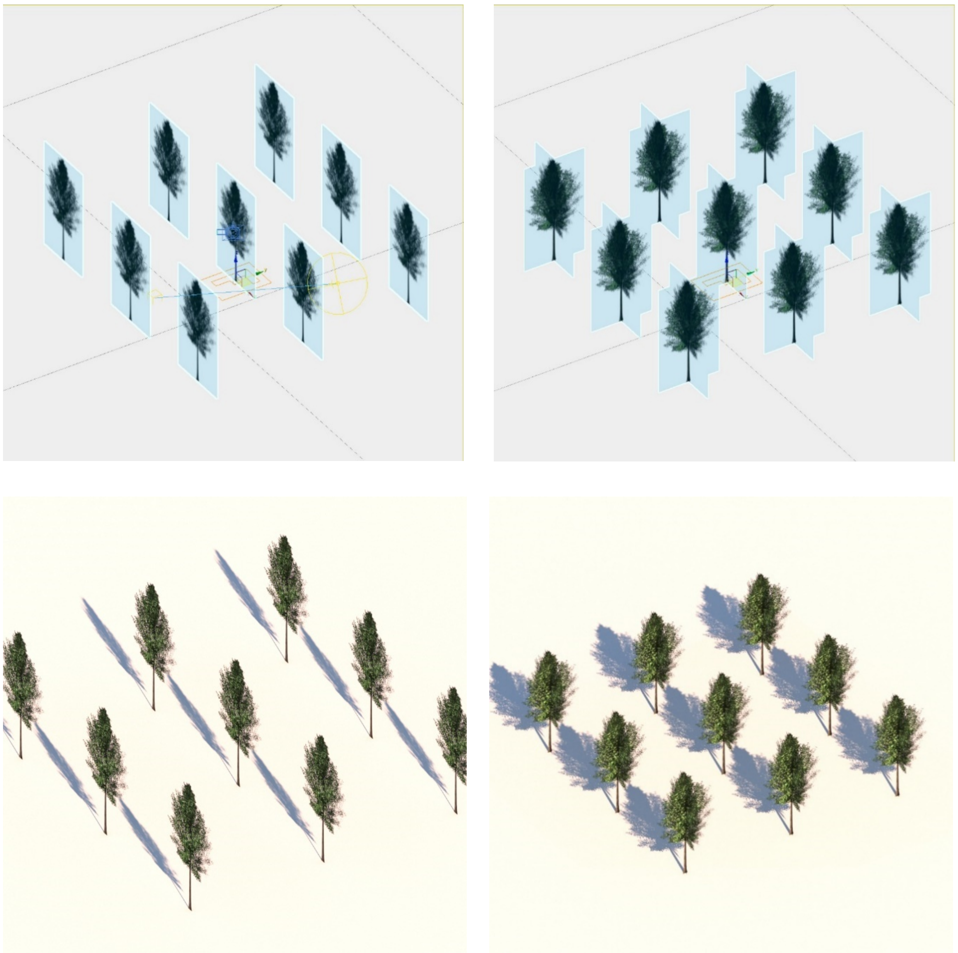

Figure 40: TOP Billboard trees, are composed of two intersecting rectangular planes each with an image of a tree mapped to it. BOTTOM Billboard trees are not accurate enough for analysis of spatial implications such as shading.

3-dimensional visualisation (Advocacy imagery)

From the early years of development, the techniques and software used in Computer Generated Imagery (CGI) for film television and gaming, have been of interest to design professions for production of realistic visualisations. This technology has the capacity to photo realistically depict, the properties of light and its interaction with materials in a geometric environment (Akenine-Mo¨ller et al., 2018, Chapter 1). Many of the same equations and algorithms developed for lighting engineering and environmental science are incorporated into these spatially accurate platforms. However, the association they have with 'fantasy' and virtual or imaginary world building and because liberties can be taken with the truth where desired, this type of visualisation is often only used in design offices for image generation with an objective of gaining public acceptance or advocacy (Groulx & Lewis, 2019)[105]. We don't necessarily associate the graphics of the movie Avatar (Cameron, 2009) [refer Figure 41] with the possibilities of construction or environmental

[105] Perhaps akin to Arnstein's lowest rung of the public participation ladder, 'manipulation'.

simulation but it is entirely feasible. Recently, it was argued by Guznenkov and Zhurbenko, that due to the high level of complexity required to construct geometrically accurate visual models in these platforms, that computer graphics should become a new 'transdiscipline, spaning 'Descriptive Geometry' and 'Engineering Graphics' in its own right (2018). It is this mixture of extreme accuracy coupled with the possibilities of strategic liberties which make these platforms ideal for testing spatially explicit scenarios which do not as yet exist.

3.3.5 Modelling the visual properties of light and trees

Figure 41: Trees from the movie Avatar created using Autodesk's Maya™ released December 2009 (source: https://james-camerons-avatar.fandom.com/wiki/Hometree?file=Pandora8.jpg).

Modelling visible light

In computer-generated imagery (CGI) the accurate depiction of the behaviour of the visible light spectrum and how it is perceived by the human eye (photometry) is a critical area of research. Luminous flux and luminous intensity or 'visible light', (luminance and illuminance) is a psychophysical phenomenon of the perceived brightness of light to the human eye, measured in Lux. Lux measurements have a luminosity function which weights each wavelength according to the human eye perception, weighting those in the visible part of the light spectrum highest and disregarding those in the invisible portion (Groß, 1994).

The same daylight simulation techniques, common to both CGI and lighting engineering are based on ray and path tracing equations developed by Turner Witted in the 1980s[106] (1980) and realistic simulation of light reflection, refraction and absorption qualities of materials (including albedo). Ray Tracing uses three points to project a ray from, and projects calculations to the screen using calculations of how the human eye will understand it to represent shadowing and reflection from neighbouring surfaces (Groß, 1994) [refer Figure 42]. Ray tracing was improved in the late 1980's by James Kajiya's development of the 'rendering equation' which combined ray tracing with radiosity borrowed from thermal imaging engineering (1986). With the integration of the radiosity equation, ray tracing rendering was able to take Global Illumination[107] into account (Immel et al., 1986).

Ray tracing accuracy has been progressively improved by inclusion of photon mapping and sub surface scattering (dealing with the translucence of objects or light absorption, reflectance and transmittance) and integration of 'path tracing' (H. W. Jensen, 1969)[108] a decade later which can be used to generate images indistinguishable from photographs. While these rendering techniques were initially too computationally expensive for desktop machines, by 2008, NVIDA[109] was producing graphics cards which could help the computational load of computing accurate visible light through use of CUDA[110] core technology (use of GPU[111] for calculation). This is now commonly available in graphics intensive hardware laptops(Haines & Akenine-Möller, 2019).[112]

[106] The recursive ray tracing rendering algorithm.
[107] Global Illumination – how light bounces off surfaces and onto other surfaces.
[108] Lafortune and Purcell.
[109] NVIDIA is a graphics card company.
[110] Stands for Compute Unified Device Architecture, a programming language that can make use of the Graphics Processing Unit
[111] GPU Graphics Processing Unit
[112] These are often referred to as Gaming laptops as the powerful graphics card is also good for fast visual refresh rates.

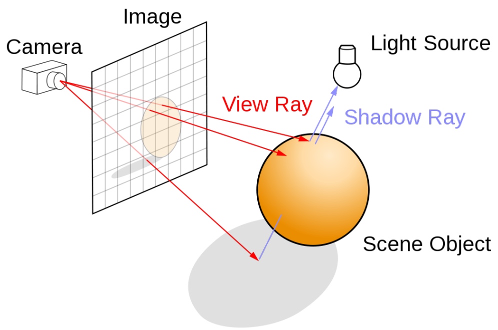

Figure 42: Shows how Ray tracing uses a 'view ray' and a light source ray to create a realistic image of an object onto a computer screen (source: https://commons.wikimedia.org/wiki/File:Ray_trace_diagram.svg).

Algorithmic tree modelling

The 3-dimensional digital modelling of geometrically accurate trees is another area which has developed rapidly over the past half century in an array of disciplines including the CGI gaming industry, but also in defence, hydrology catchment management and agroforestry (Prusinkiewicz & Lindenmayer, 1990; Weber & Penn, 1995)[113]. The study of the geometry of plant branching structure extends as far back (or further) as the work of Leonardo da Vinci in the 15th century [refer Figure 43] (Prusinkiewicz & Lindenmayer, 1990). The study of the arrangement of leaves along a stem is a little younger, dating back to the 18th century with the work of Charles Bonnet, who discovered that leaves often conform to the Fibonacci sequence of numbers resulting in leaves more or less arranged at 137.5 degree angles around a branch (known as phyllotactic spirals) (Deussen & Lintermann, 2005). This arrangement maximises leaf surface area to sun exposure and avoids production of redundant leaves [refer Figure 44][114]. In the late1960's several researchers began developing computer programs to simulate branching structures and phyllotaxy, using two main approaches; rule based and procedure based (Deussen & Lintermann, 2005, p. 3).

[113]In the defence industry, structurally accurate trees are important for assessing troop ground visibility and also for flight training simulation. These are discussed further by (Rebollo et al., 2014)
[114] Note: This is image does not illustrate Bonnets phyllotaxy drawings as well as some of his others.

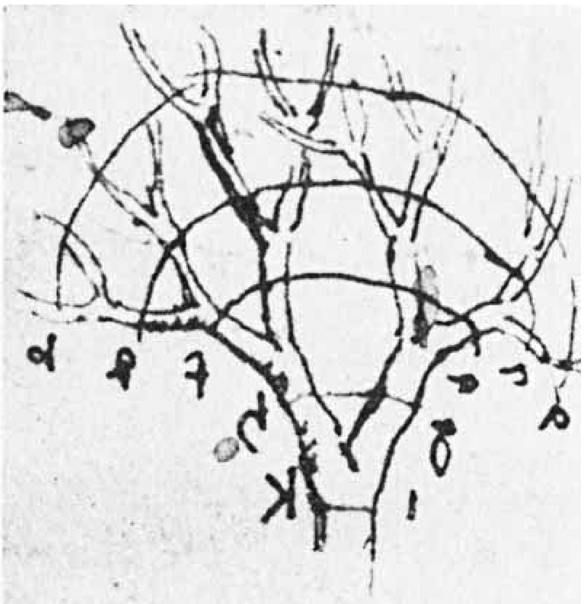

Figure 43: Shows the diagram of the hypothesis of Leonardo da Vinci that total branch thickness along each arc equals trunk thickness (Richter & Leonardo, 2017 plate 27).

Figure 44: Charles Bonnet mathematical description of leaf arrangement conforming to the Fibonacci sequence (Source: (Bonnet, 1754 plate 111)).

While there was considerable disagreement over which approach was better for generating branching structures, the rule based L-systems of Aristid Lindeymayer [refer Figure 45 left)[115] or the procedural recursive methods developed by Honda in 1971 [refer Figure 45 right], it was the eventual combination of the two approaches by Oliver Deussen and Bernd Lintermann in their software package X Window Finite Recursive Object

[115] 1968 Lindemayer introduced L-systems as a theoretic mathematical framework for describing branching where a line (stem) re-writes a (parallel) scaled versions of itself, scaled, displaced(to the stem end) and angled (Prusinkiewicz & Lindenmayer, 1990, Chapter 1).

Generator or Xfrog™[116] which became the most widely adopted method. While the use of geometrically accurate tree models may differ between disciplines, since the development of Xfrog many other plant generator programs have been developed which combine these rule based and the recursive procedural branching methods. In some cases this structural modelling also includes cellular interactions and biological modelling, collectively known as algorithmic botany (Deussen & Lintermann, 2005; 1971; Prusinkiewicz & Lindenmayer, 1990; Runions et al., 2007).

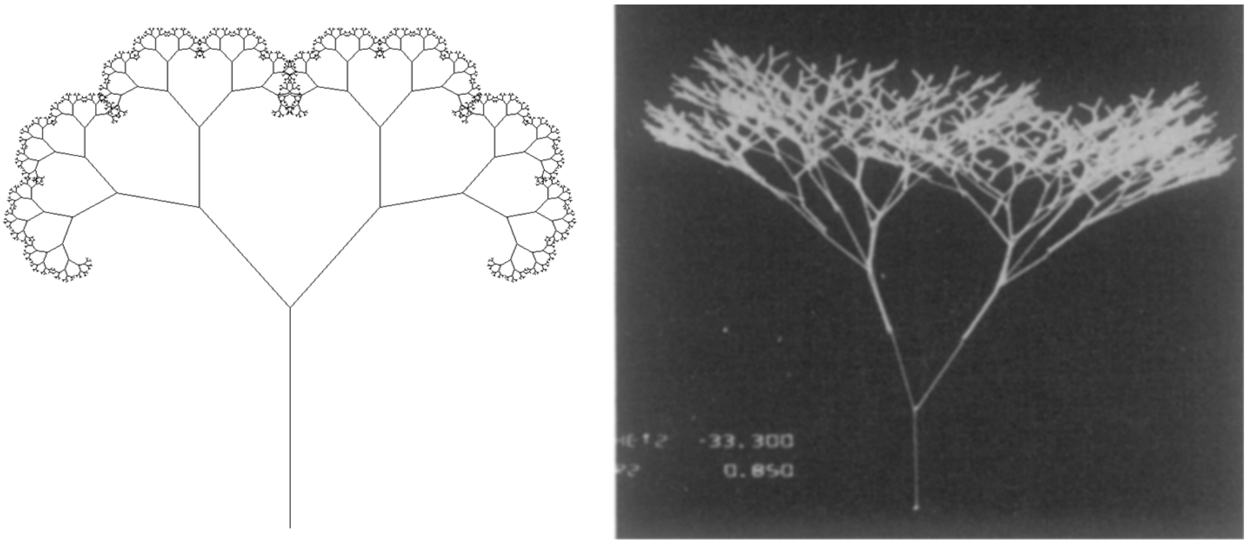

Figure 45: (LEFT) 2-dimensional recursive branch modelling L-system of Lindeymayer and Prusinkiewicz (RIGHT) 3-dimensionial recursive branching of Honda (source Honda 1971).

With the ability to 3-dimensionally model simple branching structures coupled with development of algorithms to distribute leaf geometry according to the rules of phyllotaxy, the first semi-realistic 3-dimensional tree-geometry models were made possible[117]. There were, however, limitations to computational hardware to render these objects, limiting their use in design[118]. In design, 3-dimensional trees, for the most part were abstracted to a 'lollipop' form or semi lollipop form [refer Figure 46].

[116] There were other examples but Xfrog is the most widely known

[117] Later improved through achievements of Blumenthal and Oppenheimer using curves instead of straight lines (Prusinkiewicz & Lindenmayer, 1990, p. 53) and incorporation of algorithms to enable creation of the tree architectural forms described by Hallé, Olderman and Tomlinson (Halle et al., 1978).

[118] I first tried using tree models in the late 1990's. Only one or two trees could be included in a scene before the machine would crash out.

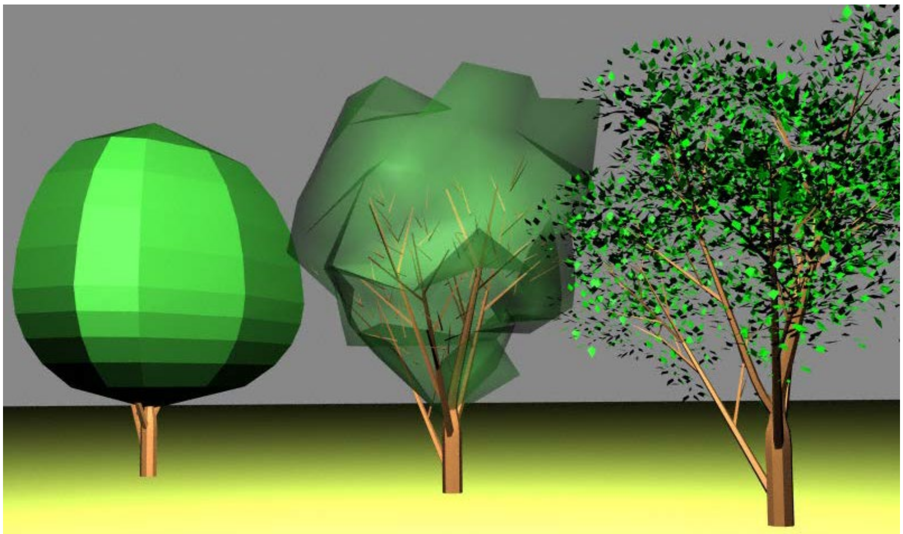

Figure 46: (LEFT) lollipop tree, MIDDLE semi-lollipop tree and (RIGHT) simple 3-dimensional tree with leaves.

Proxy-object modelling

Each of visually, structurally, geometrically realistic three-dimensional tree can contain millions of polygons, and until very recently, they have been computationally expensive to use extensively in landscape scenes (Rebollo et al., 2014). With the advances in computer hardware and development of 'proxy-object' and Level of Detail (LoD), modelling' which harnesses the recent advances in use of the Graphics Processing Unit for computation, partial or selective representations of complex geometry can be stored in efficient ways until required for rendering. Figure 47, shows an example of a 'proxy-object' tree model which is stored as a point-cloud (efficient because points have no polygon dimensions to calculate). These methods allow many thousands of trees to be used in a scene before the site model becomes too computationally expensive for the scene to be rendered/ visualised or adjusted (Rebollo et al., 2014; White & Langenheim, 2014b) [refer Figure 47].

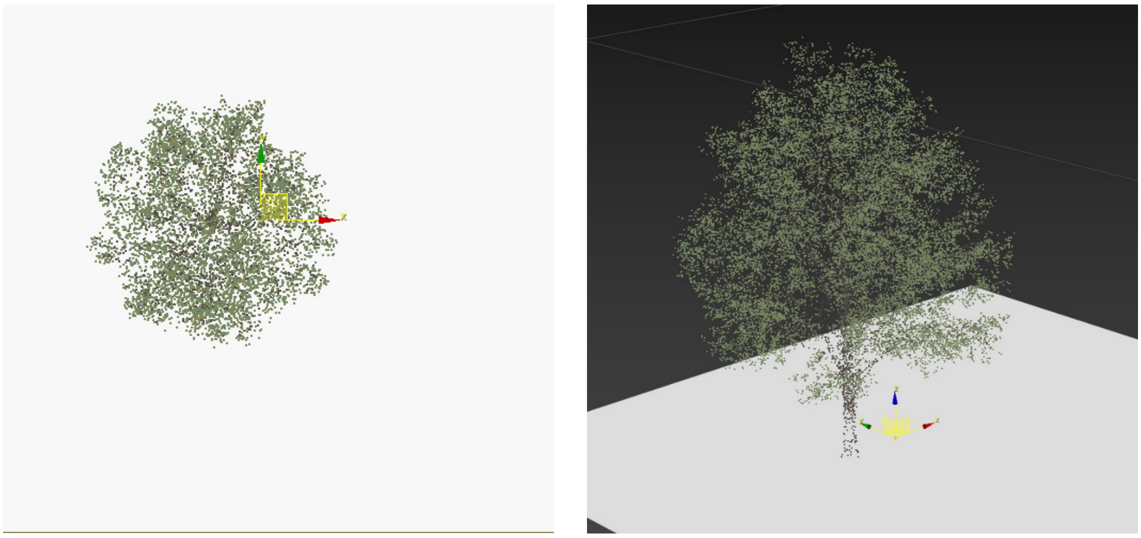

Figure 47: Shows plan and elevation of a point-cloud representation of a 3-dimensional geometric tree for computational efficiency.

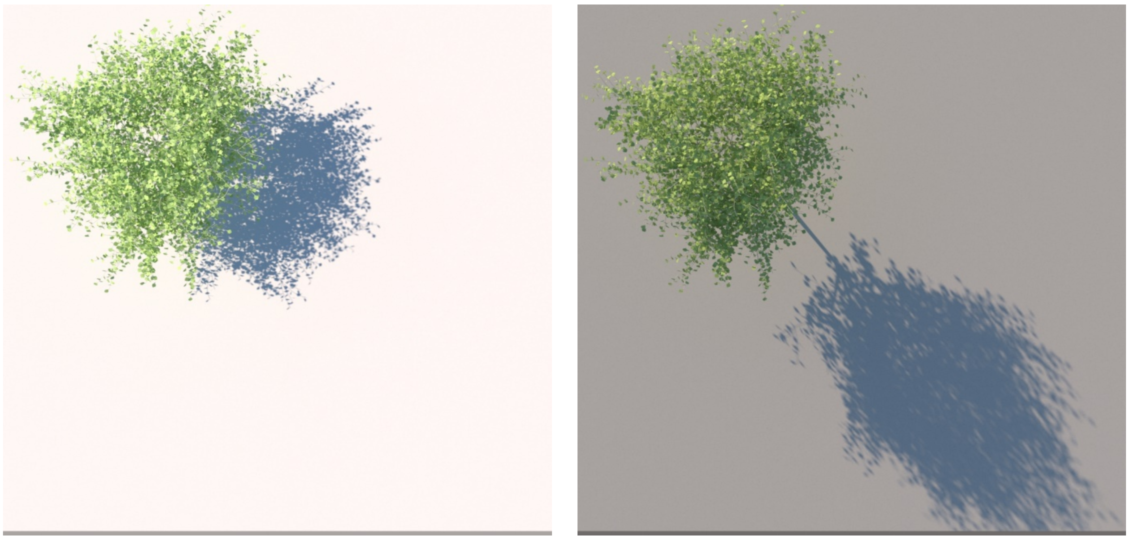

Figure 48: 3-dimensional tree model rendering with shadow cast from accurate sun position. The effect of Global Illumination shows the increase in shadow 'blur as shade is cast from the top of the tree).

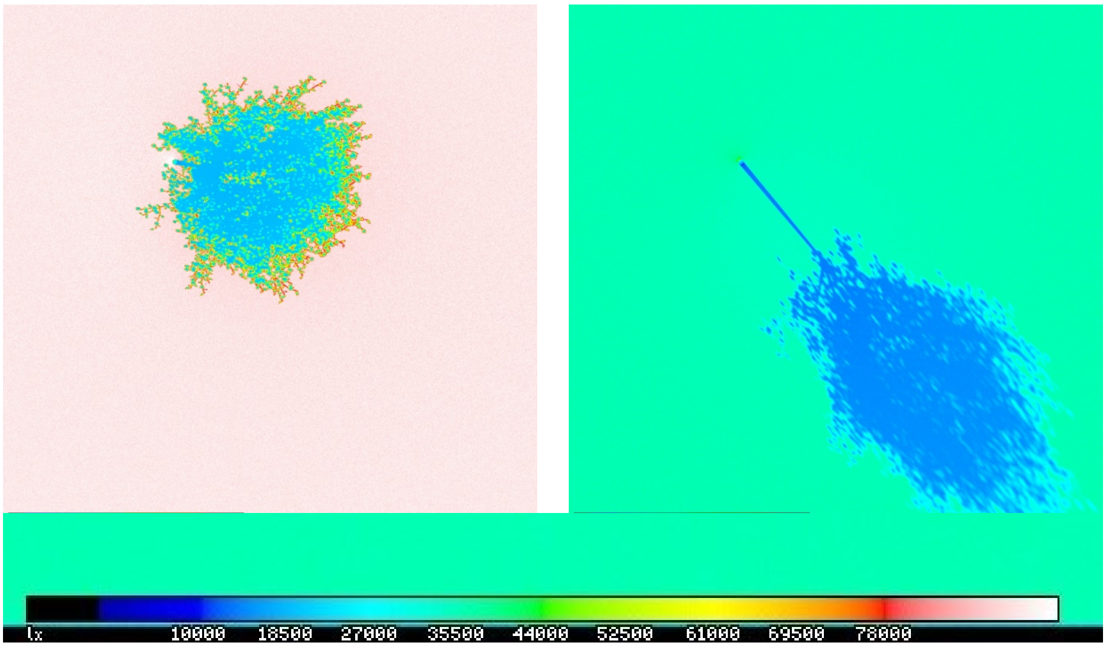

Figure 49: 3-dimensional tree model combined with lighting analysis.

Recently, 3-dimensional tree models combined with ray tracing and accurate optical properties of light behaviour were validated in an outdoor lighting engineering studies by Sadeghi and Mistrick and were shown to have high accuracy for environmental simulation (within 6%) particularly if optical properties of leaf transparency were included) (Sadeghi & Mistrick, 2018) [refer Figure 48 and Figure 49].

3.4 Modelling environmental concerns

The modelling of functional human and environmental services and disservices of street trees are complex and calculation methods are still evolving (Pataki et al., 2011). The disciplines of urban climatology, urban forestry, ecosystem service science and urban hydrology are concerned with modelling these issues and ways to incorporate the findings into decision-making[119]. In this section I will describe the evolution of a limited selection of approaches for quantifying the impact of urban trees on heat and flood moderation. In addition, I describe how these benefits are visualised and how those visualisations could be, or are, used in streetscape decision-making.

Microclimate simulation models are used to analyse interactions between the geometric and thermal properties of buildings, trees and environmental phenomena (Dorer et al., 2013) [120]. Hydrological simulation models are used to forecast the impact of urban surface properties (such as land and canopy cover) on run-off speed and quality of storm water (Szota et al., 2018). Ecosystem service scientists then use the outputs of micro-climate and hydrological modelling to calculate the services[121] of trees and the benefits they provide in biophysical or monetary units. While the cost-benefit approach of ecosystem services has been instrumental in bridging the outputs of microclimate modelling with financial decision-making sectors, the approach has been more difficult to integrate into public participation forums (Bolund & Hunhammar, 1999; Dwyer et al., 1991; Feng & Tan, 2017; Lele et al., 2013; McPherson et al., 1997). [Discussed further in section 3.4.4: *Ecosystem service modelling*]. The functional benefits offered by trees are an ecosystem service

[119] There are several other valuable models such as (Grêt-Regamey et al., 2017; Olander et al., 2017; Rosenthal et al., 2015; Vogt et al., 2017) which aim to increase consideration of tree functional attributes in public participatory decision-making environments, however as they are not associated with a specific type of visualisation I have not included them in this discussion.
[120] Predominantly first undertaken to understand the impact of urban material choices on energy consumption (sustainability issue).
[121] These services are divided into four categories; provisioning, regulating, supporting and cultural.

however, the DDSS I develop is not (at this point) intended for forecasting tree benefits in financial units.

Urban climatologist often use the computational fluid model ENVI-met™(Bruse, 2004) to visualise their outputs to help inform urban tree decision-making [refer Figure 50]. However, while the results of these microclimatic simulations are spatially explicit, the voxel-based outputs of ENVI-met™[122] are quite visually abstract (which is to be expected as this is not their primary purpose). The voxel-based model construction methods required in ENVI-met do not integrate with the existing modelling methods of design or engineering disciplines[123] (Naboni et al., 2017). More recently, urban climatology models for assessing tree impact on heat issues such as Human Thermal Comfort and the Urban Heat Island effect which have better interoperability with design software have been trialled, a selection of which are discussed in the next section.

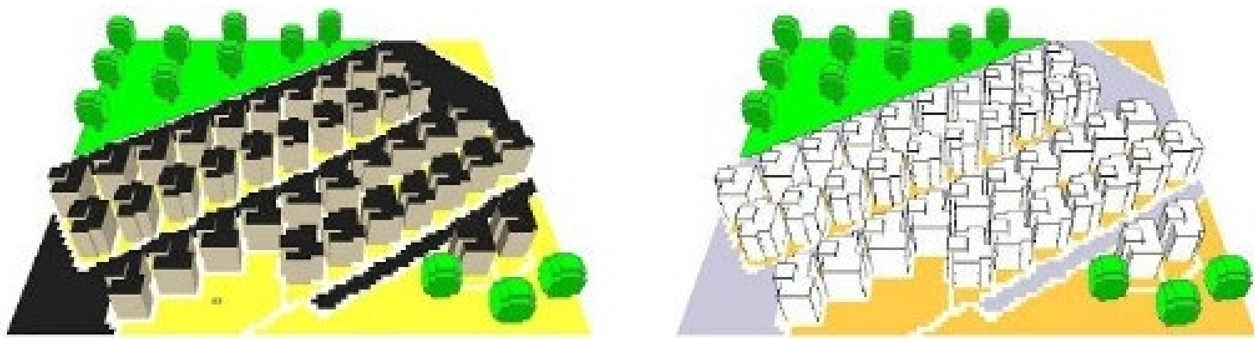

Figure 50: Voxel-based tree modelling from ENVI-met (Source: https://www.hindawi.com/journals/amete/2014/547974/fig10/)

3.4.1 Modelling tree heat moderation

Modelling the interaction between urban form and microclimatic conditions of urban streets has been an growing research area for well over a century, beginning with the seminal work of Luke Howard, *the Climate of London* (1833). It became an increasingly significant occupation during the 1970's with the work of Nunez and Timothy Oke on the energy balance of urban Canyons (1977). In current urban microclimate modelling the interaction of street trees and light (solar radiation) are focused on two major issues. These are the Urban Heat Island effect (UHI), a measurement of the difference between night and

[122] A voxel is akin to a 3-dimensional pixel with 'smart surfaces' which can give feedback of effect of given stimuli.
[123] Difficulties have been experienced in attempts to operationalize the Ecosystem Service approach.

daytime air temperatures between urban and peri-urban development and the other is outdoor Human Thermal Comfort (HTC), the measurement of moderating effects of trees on the comfort of pedestrians during the daytime.

Human thermal comfort modelling (day-time thermal comfort of pedestrians)

The measurement of HTC is typically an index of human radiation loading that a person experiences under specific climatic or activity conditions. Models[124] initially developed to forecast the impact of building morphology on indoor HTC, in the past few years, have been shifting their focus to include outdoor conditions and the integration of the impact of both buildings and vegetation, particularly trees on HTC levels (Coccolo et al., 2018; Sanusi et al., 2016). In most models designed to predict HTC, six factors are taken into consideration: humidity, air temperature, air velocity, incident solar radiation (radiant temperature) and how these impact the heat balance of the human body or physiological equivalent temperature (PET)[125] (Kántor & Unger, 2011). Of these factors, tree shade, is considered to provide the greatest reduction in mean radiant temperature, achieved through tree '*ability to block incoming shortwave radiation* (sunshine), particularly in the absence of a breeze/airflow (I. Lee et al., 2018). There are several models which have been developed for simulation of outdoor HTC which include consideration of the more complex factors which impact mean radiant temperature. These were recently reviewed by Naboni, who also highlighted the issues of including these complexities into early stages of design decision-making as tools are quite specialised for use in urban climatology analysis (Naboni et al., 2017)[126]. Figure 51, shows an example of how trees are considered in the Ladybug / Honeybee plugin for Rhino 3D model for heat analysis. While this is a quick analysis method (does not require computational fluid dynamic as in the case of ENVI-met), the output is still visually abstract. A more sophisticated model for visualising and calculating HTC which integrates with CitySim was more recently developed by

[124] HTC can be simulated in a variety of platforms developed over the last decade including CitySim (Robinson et al. 2009), ENVI-met (Bruse 2004) and Ladybug and Honeybee plugins for Rhino 3D ™ (Roudsari et al. 2013).
[125] Considers the human body a type of engine.
[126] With the Ladybug Honeybee option, the most attractive to the design profession as Rhino and Grasshopper are common platforms for design professions, (outputs kilowatt hours or temperature for a given hour).

Coccolo [refer Figure 52] (Coccolo et al., 2018). However, the trees in her model are still too visually abstract, to be suitable for public consultation forums.

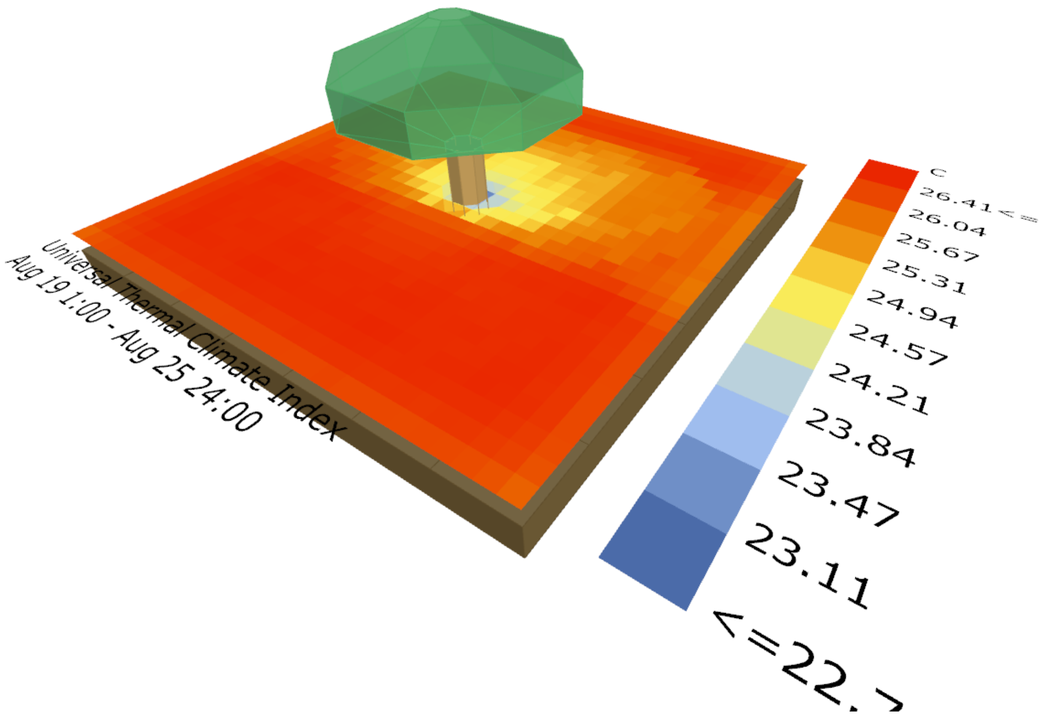

Figure 51: trees in Ladybird Honeybee simulation (Source: https://www.grasshopper3d.com/group/ladybug/forum/topics/outdoor-comfort-and-tree-transparency?page=1&commentId=2985220%3AComment%3A1607193&x=1#2985220Comment1607193)

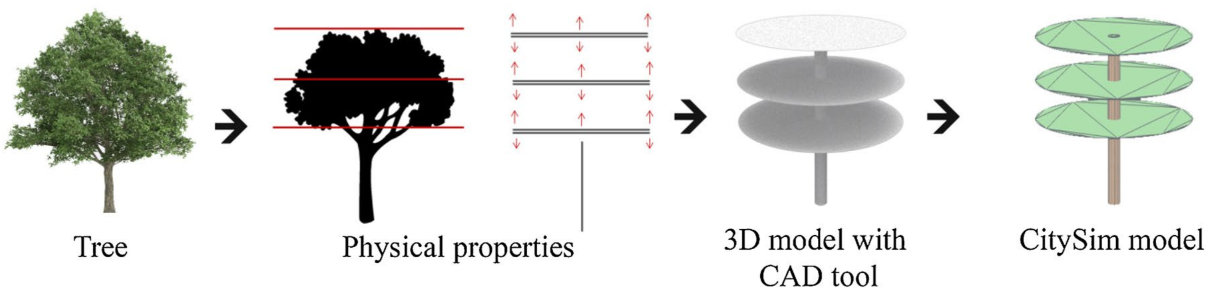

Figure 52: Coccolo tree models integrated with CitySim longwave emissivity, shortwave absorptivity and reflectance). By the proposed methodology, the Leaf Area Index (LAI), or ratio of total leaf area to the plan area of the canopy, is defined by superimposing the surfaces of leaves at different heights by considering their geometrical properties (height, diameter of foliage and leave width) and their physical properties (Leaf Area Index).

Urban Heat Island modelling (day/night air temperature differences)

The other primary heat consideration of urban climatologists is The Urban Heat Island (UHI). A regional scale measurement of the difference between day and night surface or air temperatures between urban areas and their rural counterparts. When solar energy that was absorbed by building materials during the day, is released as longwave radiation at night, in conditions where street canyons are narrow, this energy is trapped and warms the air resulting in higher night-time air temperatures in urban areas (Matzarakis et al., 2007). Development patterns which have a low 'sky view factor'[127] or deep canyon urban morphology, tend exacerbate differences between night-time urban and rural air temperatures [refer Figure 53], but these same conditions also deliver lower day-time temperatures. As inclusion of trees in these streets further reduces sky view factor, there is the possibility that trees in these conditions exacerbate the problem of UHI, causing a conflict in tree decision-making for daytime, night-time heat moderation.

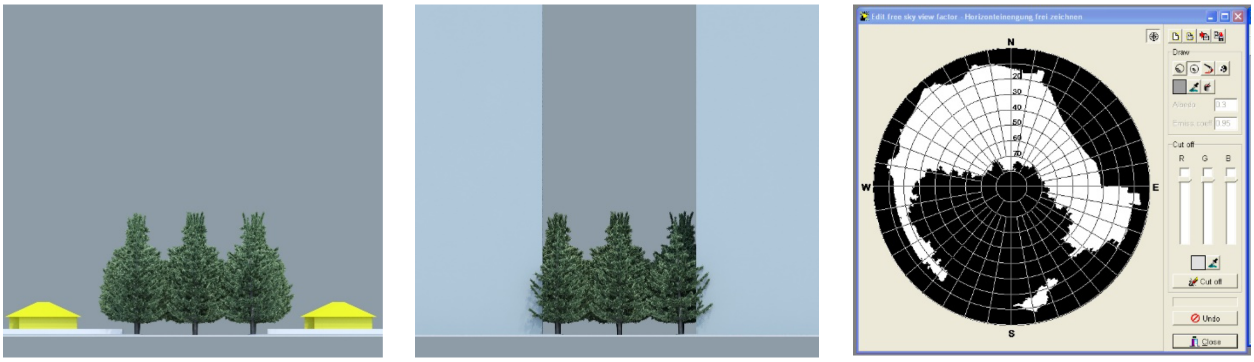

Figure 53: (LEFT) A shallow street canyon has a high sky-view factor and allows warm air to escape in the evening, (MIDDLE) A deep canyon has a low sky-view factor and traps escaping long-wave radiation (RIGHT) sky view factor is reduced by trees (calculated using Rayman).

Conflicting criteria for UHI, HTC and UV moderation

Higher night-time temperatures impact energy use for cooling while higher daytime temperatures can cause heat stress, impact citizen transport mode selection and are associated with greater risk of exposure to harmful levels of UV light. While it has been suggested by several researchers that increasing the spacing between trees would better allow night-time longwave radiation to escape urban canyons (Dimoudi & Nikolopoulou, 2003; B. Norton et al., 2015; Spronken-Smith & Oke, 1999), using this strategy would also have a negative visual impact to the continuity of trees (streetscape skeleton or enclosure effect)[128], cause a reduction in daytime HTC and increase the risk of Ultra Violet radiation exposure[129]. Decision-support systems have been put forward by researches to help decision-makers balance between these two primary urban heat issues, such as the tool

[127] Sky View factor is a measurement of how much sky is visible from a point on the ground looking directly upward. It can be either simulated in software such as RayMan (Matzarakis et al., 2010) or measured from digital hemispherical photos of existing conditions.
[128] A continuous canopy is consistently associated with enclosure, which has a positive correlation with perceptions of safety (Harvey ae. 2015).
[129] Exposure to UV radiation often occurs through the 'bouncing of UV light reflecting from solar exposed ground surfaces (particularly surfaces with high albedo) for example, the sand on beaches, reflects to the underside of beach umbrellas. While urban pavements do not generally have high albedo values (asphalt has a 5-10%), UV radiation which reaches ground surfaces is reflected from it.

developed by Ruiz et al. (2017). Ruiz, developed a tool for application by urban planners when making streetscape decisions to balance between the possibly divergent requirements for moderating UHI and HTC. Ruiz compared differences between daytime HTC and night-time UHI in the arid city of Mendoza (low wind hot summers cold winters) Western Argentina in nineteen tree lined (forested) urban streets with different height to width ratios. While the climate of Argentina is quite specific, the findings of Ruiz' study corresponded well with other studies in different climatic conditions. These findings were:

- That trees increase thermal comfort by 60 to 70%.
- That daytime thermal comfort increases with lower sky view. Taller building morphology on narrower streets are more thermally comfortable on hot days than low morphology on wide streets.
- But in contrast, better night-time heat dissipation was achieved in streetscape conditions of low height to width ratios and no trees.

These outcomes suggest that in some climatic contexts, planting less trees is required for moderating UHI but more trees are required for moderating HTC. Ruiz modelling approach for assessing tree impact on heat uses tree geometric variables as the main input. These are:

- Tree height (tree magnitude)
- Tree canopy width + spacing between trees (Trees per meter and number of trees).
- Tree canopy characteristics (look up table for tree canopy permeability) [130]

Ruiz model highlights the need for better understanding of tree impact on UHI before it can be used as a factor on which to base tree decisions. Particularly in light of work from other researchers who found that that tree canopy cover had little influence on long wave energy release at night (Chatzidimitriou & Axarli, 2017), and that tree canopy radiation interception, reduced pavement solar exposure during the day, thereby reducing the quantity of longwave radiation released from those surfaces at night (Tan et al., 2017)[131]. Ruiz model also highlights the importance of geometric properties of trees in modelling

[130] Riuz does not expand on the measure of permeability other than referencing Cantón et al. (1994) and Tak & cs et al. (2016). In general, this is usually described as leaf Area Index (LAI)
[131] Albeit in very different climatic conditions.

their impact on urban heat issues. Tree direct solar interception is looked at in more detail in Chapter 6: *Shady City* and Chapter 7: *Synthesis City*.

3.4.2 Modelling urban flood mitigation

Modelling the functional capacity for trees to regulate storm water for both flood mitigation and improvement of urban stream quality has been another diffused disciplinary area of research crossing urban forestry, civil engineering and urban climatology. The water storage capacity of tree canopies and the permeable surfaces they grow in, help to slow the speed of storm water, thus reducing overland flow and allow particulate matter to settle where it falls rather than being transported to receiving waterways. Urban flood scenarios and their interaction with types of vegetation or functional tree choices are not something that is commonly used as part of the decision-making visualisations for public participatory forums. The outputs of modelling these interactions are predominantly hydrographs (which show the storm water rate of discharge over time) or other forms of graph which are not connected to the visual impact that these hydrological choices represent. Figure 54, shows the graph output which can be output from the i-Trees Hydro module showing the impact of tree choices on the reduction of storm-water volume[132]. The capacity for trees to impact storm water speed are dealt with in models in two primary ways:

- As a roughness co-efficient[133] (vegetated ground cover is considered rough and therefore slows storm water).
- As a canopy interception rate base on leaf and tree architectural characteristics (Xiao et al., 2000).

Tree selection based on their canopy traits for interception and maximisation of vegetated ground would have a profound visual impact on streets.

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[132] Note i-Trees hydro is being developed to output a number of other important data and is being developed to compare more than one land cover scenario but it is still a US based model.
[133] See Manning's equation (*Manning's Equation*, 2006).

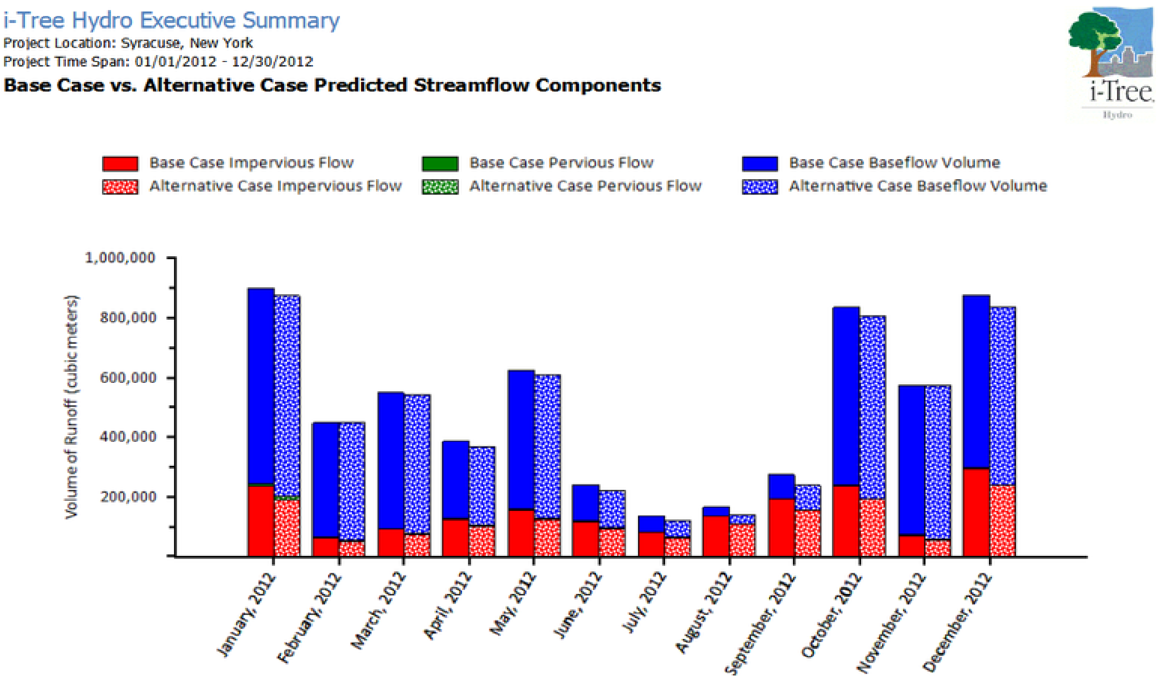

Figure 54: Shows a graph-based representation of impact on storm-water quantity achieved through tree-cover. This is an example of the visualisation which comes from modelling flood scenarios, still primarily concerned with storm water speed and the impact of that speed on water quality rather than the visual impact on streetscapes.

3.4.3 Integrated heat and flood attenuation models

The most recent development for quantifying tree functions in urban microclimate and hydrology simulation models, have been integrated into packaged plugins for Geographic Information System platforms (GIS) such as the open source QGIS. The most comprehensive example of an integrated model is the Urban Multi-scale Environmental Predictor model (UMEP) that integrates multiple tools such as the 'Solar Long Wave Environmental Irradiance Geometry' model SOLWEIG and the evaporation-interception model for urban areas SUEWS which can be used to calculate the impact of green infrastructure on runoff (Lindberg et al., 2008, 2018). These combined tools are a useful approach as many of the data sets required are common to each.

The primary tree data input for the SUEWS component are:

- Area covered by trees
- Type of trees either deciduous or evergreen[134] and

[134] It is interesting to note that the Open Street Map (OSM) project which allows contribution of spatial data by citizens asks for this distinction between evergreen and deciduous species be given when tree data is entered. OSM data is increasing used over standard municipal data-sets for streetscape analyses as more comprehensive pedestrian data is available from that source.

- Leaf or Plant Area Index (LAI or PAI) (leaf/plant surface area projected up from $1m^2$ surface area) or Leaf or Plant Area Density (LAD or PAD) [refer Figure 55].

The primary input tree data of hydrological models, unlike the solar radiation models which concentrate on tree geometric properties, focus on species attributes and traits such as branching architecture, size, type (deciduous or evergreen) and canopy density.

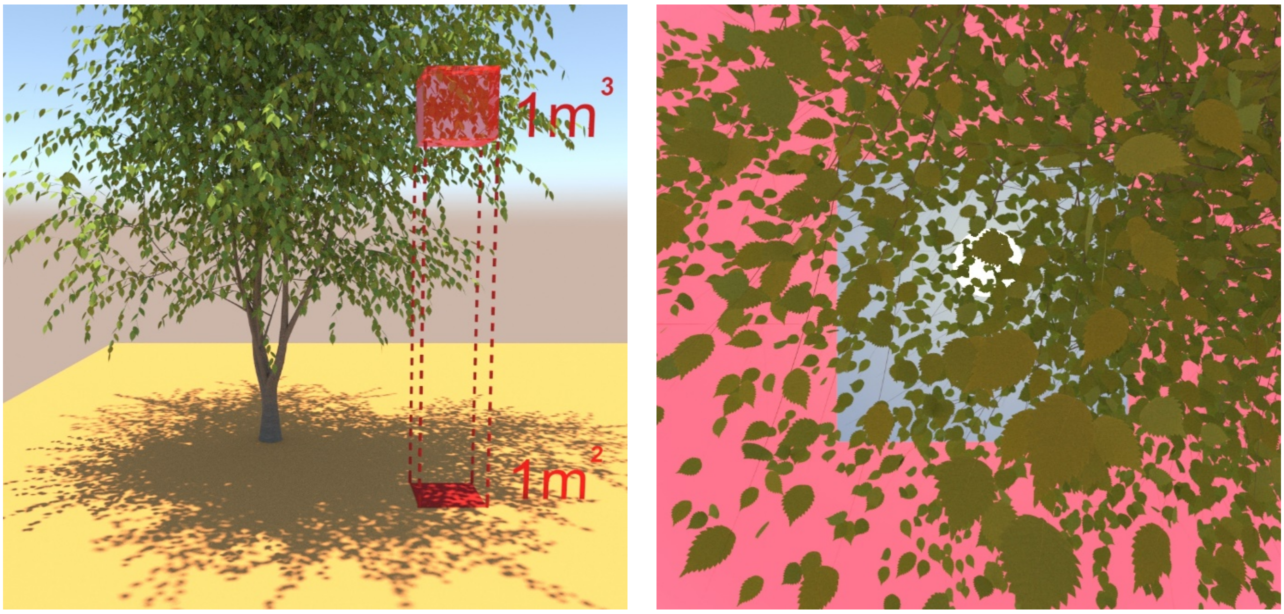

Figure 55: (LEFT) shows how 3-dimensional tree models generated in CGI software could be used to simulate trees of a specific LAD / PAD and (RIGHT) shows how a camera view can be used beneath a modelled tree to simulate LAI/PAI measurement imagery.

3.4.4 Ecosystem service modelling

Multiple attempts have also been made to integrate ecosystem services (or functional tree benefits)[135] into decision-making with the community such as that of Hilde and Paterson (2014) and that of Daily et al. (2009). Hilde and Paterson coupled the 'Scenario planner software platform: *Envision Tomorrow* (Fregonese Associates, 2014) with the ecosystem service calculator i-Trees (USDA, 2006), and Daily et al. developed the inVEST tool with outputs including decision-making maps, trade off curves and balance sheets. Both tools aimed to improve community environmental understanding (and thereby increase integration of environmental considerations into decision-making) (Daily et al., 2009). However, both Song (2018) and Grêt-Regamey (2017), in their systematic review of these tools and their outputs, found there were substantial problems. In the following section I

[135] Most of the literature in this area is focused on the ecosystem service approach or is framed in relation to ecosystem services. In the context of this thesis the term can be seen as 'loosely referring to functional benefits provided by trees' rather than specifically referring to financial quantification.

will discuss the four key problems identified by Grêt-Regamey in light of the findings of the previous section and chapter 2.

01. integration of the concerns of other disciplines was lacking.

As I identified in section 3.3: *Modelling visual concerns*, there are a number of non-disciplinary stakeholders involved in streetscape decision-making who's (often primarily visual) concerns, need to be brought together with environmental performance goals of environmental science disciplines and the safety regulations of service infrastructure, transport and land use planning disciplines; discuss in the next section [3.5: *Modelling spatial concerns (trees, transport and land use planning)*]. It is often landscape architects who must bring the decisions of these varied disciplinary and non-disciplinary groups together into a cohesive plan of action.

02. respect to the political / organisational decision-making processes was lacking.

As discussed in section 2.4.5: *The view from the footpath,* there have been recent shifts in transport priorities towards pedestrian accessibility which represent opportunities for streetscape infrastructure re-design and renewal. Despite this transport paradigm shift, opportunity for changes in streetscape configuration can still be missed through lack of consultation, communication or coordination between organisational decision-making processes (Huges et al., 2015; Jaluzot et al., 2014). In addition, renewal projects happen at multiple scales (micro to macro), and sometimes in response to 'adhoc' or emergency damage repair, rather than on planned timelines. In section 3.5: *Modelling spatial concerns (trees, transport and land use planning*), I will discuss how land use and transport planning decisions and regulations impact tree inclusion on streets and how these aspects need to be included in tree decision-making processes.

03. tools were overly focused on ecosystem services at the expense of other services.

Currently decisions about street trees are not commonly based on the relatively new concern of quantifying their capacity to meet environmental performance goals (Bodnaruk et al., 2017). As I discussed in section: 3.3.1: *Design visualisation modelling*, in the early stages of design, in public decision-making or consultation forums, the primary concerns of the community are not usually centred on the cost-benefit or even the functional benefit of trees but on other less quantifiable, qualitative visual, historic or cultural concerns. Like other economic models, the ecosystem services cost benefit analysis approach can suffer from the problem of 'assuming a rational agent' which may not be a fair assumption in these forums (Millington et al., 2011). In addition, road assets and other services which are housed in streetscapes are a high cost construction and maintenance item for municipal authorities, which are not simple or inexpensive to reconfigure (Vogt et al., 2017).

> *04. tools did not work with spatially explicit constraints.*

Street design situations are inherently spatial as are the regulations of services provided within streetscape pavements. As I discussed in section 3.3.2: *Design construction modelling,* in the later stages of design, landscape architects are often required to bring together these spatially explicit clearance regulations with the qualitative concerns of the community. It is during this process, where the many conflicting and competing systems which must be accommodated in streetscapes are brought together, that spatially inexplicit criteria or decision outcomes may be ignored or de-prioritised [discussed further in the next section].

3.5 Modelling spatial concerns (trees, transport and land use planning)

> *'Transport planning is undergoing a paradigm shift, a change in the way problems are defined and solutions evaluated […]. The old paradigm assumed that transportation refers simply to mobility (physical travel) and evaluated transport system performance based primarily on vehicle traffic conditions. The new paradigm recognizes that the ultimate goal of most transport is accessibility (people's ability to reach services and activities), and considers a wider range of impacts, objectives and options' (Litman, 2016).*

Land use and infrastructure networks (transport, communications, drainage, utilities) are considered to be some of the most permanent, stable systems of the physical structure of cities (Wegener Spiekermann, 2004). Once in place, this physical, often centuries old infrastructure, designed in response to outdated objectives, must be adapted to accommodate other systems which change at much faster rates; for example; population density, car ownership, travel modes and goods transport [refer Figure 56].

In this section I discuss the evolution of spatial modelling concerns in the transport and land use planning sectors. Both sectors work with the spatial, geometric constraints of streetscapes. Problems are 'solved' in these disciplines through the development of written regulations, to govern the form of new building works. Many of these regulations are developed in response to a hierarchy of criteria which reflect the data available at the time. Sometimes these regulations become entrenched and continue to be applied well after new data shows a need for revision of those objectives.

Since the mid 1980's, there has been increasing recognition of the bi-directional relationship between land use and transport systems which has led to development of integrated models (of transport and land use) and a continuous re-evaluation of their objectives, criteria and purpose.

Figure 56: System adjustment low density to high density, changes transport mode systems. The subspaces created by trees planted in the footpath at a time when vehicle movement or parking was prioritised.

3.5.1 Transport planning

Transport planning has had two primary objectives since its' inception in the mid-20th century. The first objective was streetscape safety, through *minimisation of fatalities* and collisions. The second objective was to *minimise congestion or disruptions to traffic flow* (Derobertis et al., 2014). In the 1960's with the development of the Transport Safety Movement and the National Safety council in America, these two objectives appeared to align. Traffic accident fatality data and the outcomes of tests performed on the 'General Motors Proving Ground[136]' by Ken Stonex (1961) showed that most traffic accident fatalities occurred when drivers ran off the road and collided with objects such as trees. The data from the Proving Ground tests also showed that most cars that ran off the road came to a stop within 30ft (9.1m). This stopping distance was to become an entrenched clearance zone applied not only to highways but also to roads and streets, as part of a movement to reduce traffic accident fatalities. This movement was known as the application of the 'forgiving design' philosophy, aiming to see a second line of defence for drivers who made accidental mistakes (Nader, 1965). In addition, wider, more 'forgiving' lane widths were adopted into official standards which aided traffic planners to also meet their second objective; minimisation of congestion and traffic flow disruption. However, the application of the forgiving design philosophy to streets had at least five unforeseen and unfortunate consequences.

- 01: Streets with wide clearances and few visibility obstacles (no trees) were perceived by drivers as safe and they adjusted their behaviour accordingly; increasing dangerous driving and speed (Ewing & Dumbaugh, 2009; Naderi et al., 2008).
- 02: This driver behavioural adjustment increased the danger to active transport users such as cyclists and pedestrians[137].

[136] The GM proving ground was a 'crash proof highway testing course designed by Stonex.
[137] Traffic deaths are rising in America – where a twenty-five year high of 40,000 road death fatalities occurred (6,000 of which were pedestrians). However, it is pedestrian deaths which are increasing the most rapidly as a percentage.

- 03: Roads which privileged driver safety and convenience privileged vehicular modes of transport spawning an age of *induced demand* for both roads and cars[138] (Derobertis et al., 2014; Litman, 2009)[139].
- 04: Data collection practices favoured vehicle transport criteria, and were therefore informed by road and traffic concerns rather than walk-quality concerns (Litman, 2009).
- 05: Streetscape elements such as trees, which improve the walk-quality for pedestrians and the environmental function of streets, were considered obstacles to meeting the objectives of crash and congestion minimisation and were removed from streets. Figure 57, shows an example of vehicle prioritisation where pedestrians and tree pits are both located in a very narrow footpath.

Today the issues associated with the 'forgiving design' philosophy have been recognised, propelling a paradigm shift in the objectives criteria and methods of transport planning (Litman, 2016). As discussed by Litman '*the way problems are defined and solutions evaluated in transport planning can be surmised within the shift in prioritisation from mobility* (a term driven by the objective of congestion minimisation) *to accessibility*' (a measure of popular destinations such as shops, schools and parks within a walking distance (800m) from home) (Litman, 2009). The shift in transport planning objectives recalibrated modelling approaches away from the conventional (at the time) 'linear series' model which assumed that slower transport modes would be *replaced* by faster modes in the future towards inclusive modes where Walk + Bike + Train + Bus + Car + Airplane all simultaneously considered, giving rise to 'multimodal' transport planning (NACTO, 2013).

[138] Also known as 'generated traffic' when it is cheap and convenient to use a particular mode because road capacity allows it.
[139] This led to a transformation in understanding of traffic flow and its modelling. Traffic flow was once considered as akin to a fluid but is now more generally seen as a substance more like a gas which expands to fit whatever container it is given and hence increasing road capacity can have little impact on traffic flow (Litman 2009).

Figure 57: A street in Kingsville, Victoria showing recent (resident requested) removal of tree from between the parking bays and re-located into the already narrow footpath, reducing walking space.

3.5.2 Modelling pedestrian access

While walkable access to popular destinations has been actively promoted by urban designers for several decades [refer 2.4.5: *The view from the footpath*], early consideration of accessible walking catchments (or Pedsheds) were generally drawn on plans as a simple circle of 800m radius or ten minutes walking at 1.33s/per minute [refer Figure 58]. Today, agent-based tools exist for assessing the impact of street network interruptions such as freeways, water ways and traffic light wait times (White et al., 2017) [refer Figure 59]. Agent based modelling is also used in gaming and animation to simulate crowds of moving objects, such as people or animals with particular behaviours such as a walking speed and or collision avoidance. The potential for combining an agent based pedestrian accessibility with shade provision will be explored in Chapter 6: *Shady City* alongside re-organisation of transport data to simulate pedestrian conditions.

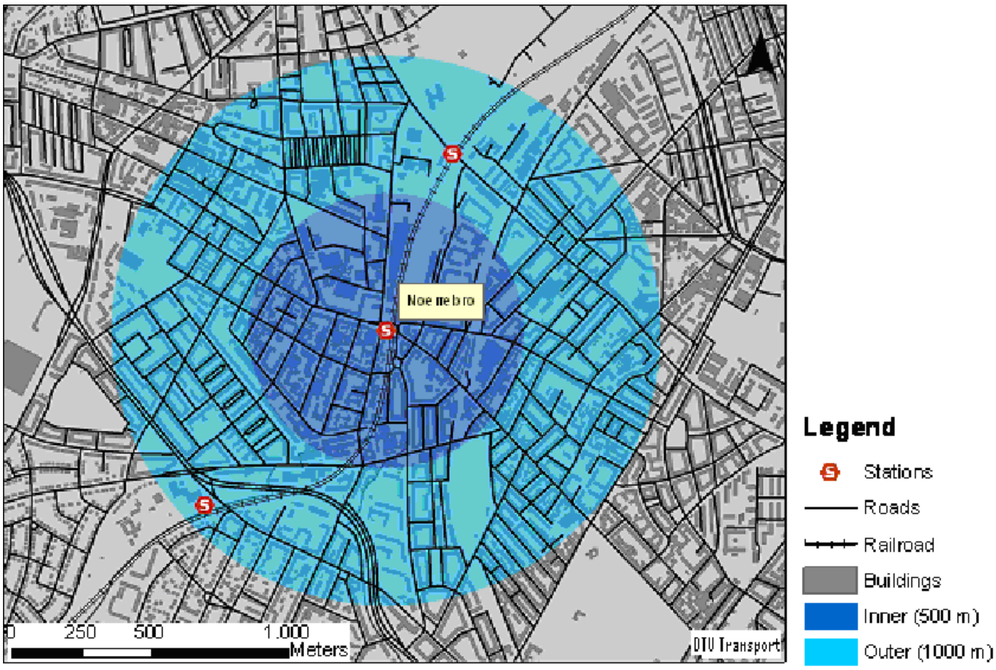

Figure 58: Circular catchment area of Noerrebro Station in Copenhagen. (Source: (Elkj & Landex, 2009).

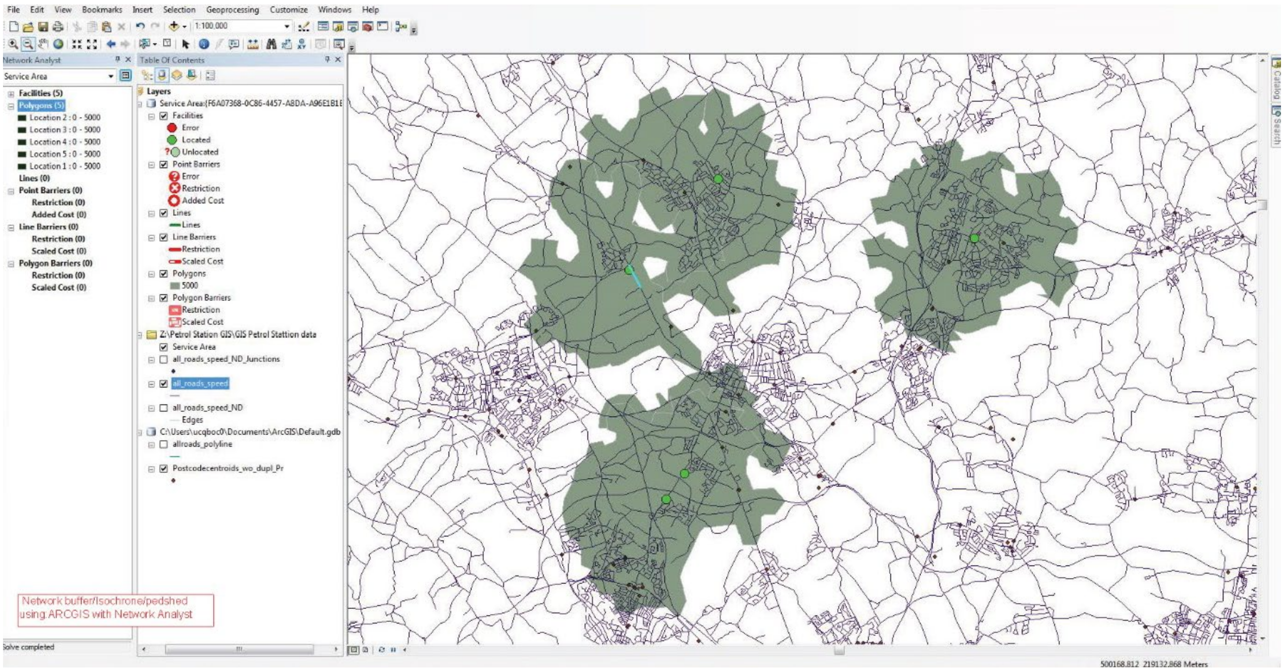

Figure 59: Pedshed catchment analysis ESRI Network Analyst.

Visibility triangles

Other streetscape design features which are often legacy infrastructure of the 'forgiving (to vehicle drivers) design' are elements such as 'visibility triangles'. These are an imaginary cone emanating from the driver's eye height representing their line of sight or the edges of their peripheral vision, and the safe stopping distance the driver requires at a given speed at an uncontrolled intersection (no traffic lights, stop or give way signs). Traditionally, trees are not allowed in these visibility cones as an added safety measure even on controlled streets (NACTO, 2013). With recent revision to the safety regulation of urban intersections which suggest making them more compact, bringing pedestrian crossing activities into the focal area of the driver, and restricting car parking (known as intersection daylighting)[140] substantial increases in footpath space for pedestrians may be available, but these spaces, if left without trees may also be zones of pedestrian and cyclist solar exposure [refer Figure 60].

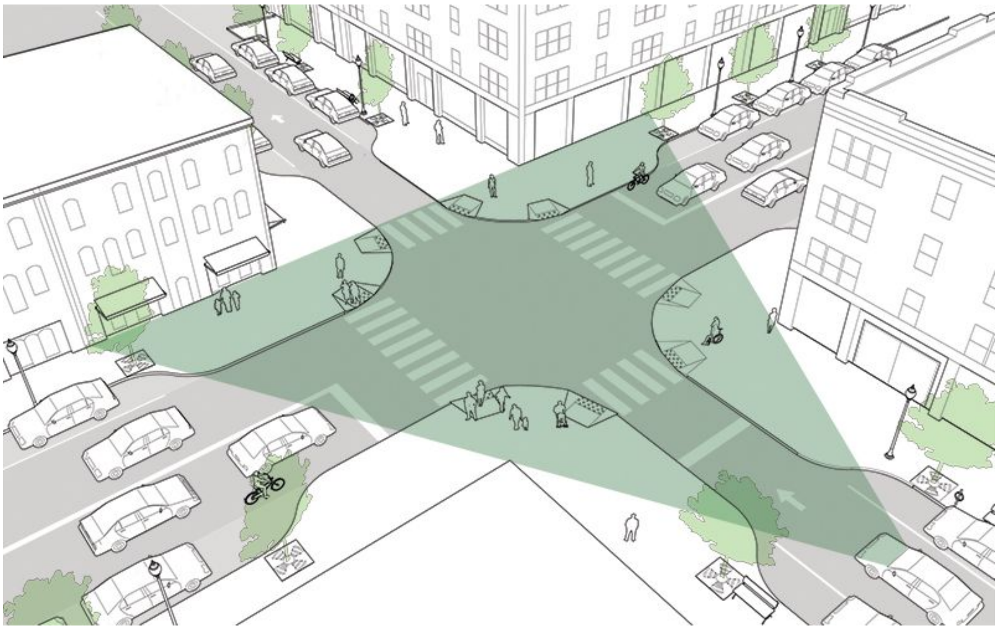

Figure 60: From the NACTO Street Design Guide 2013 showing new regulations for more compact intersections: The intersection has been 'daylighted' (no parking in proximity to the intersection), pedestrian activity is within the focal zone of drivers and curb radii have been tightened. Trees are however still excluded from the zone – though this is now considered a third line of defence, not a mandatory regulation. (Source: NACTO Global Street Design Guide).

3.5.3 Land use planning

The link between land use planning and transport planning is well recognised, with researchers in the walkability area (Stevenson et al., 2016). Land use planning, like transport planning, has spatial concerns which are often translated into regulations, and can become entrenched and sometimes strict in ways which disable more environmentally conscious design. Land use planning has suffered from the same prioritization issues as transport planning. Two of the most pressing issues which land use planners must negotiate in public consultation forums are: 01) The negotiation of new higher density development in existing residential areas. Land use planners must negotiate building height with residents who are fearful of losing light amenity, often resulting in building height restrictions. 02) Reduction of pressure on on-street parking availability due to

[140] The concept of 'intersection daylighting', like storm water system 'daylighting' is important here. Daylighting is where parked cars are removed for a distance at intersections, allowing intersection narrowing.

increased density. Often, the planning response to this issue is stipulation of onsite parking for new developments. The unintended consequences of these building height limitations and parking provision have had far reaching environmental and social impacts as well as restricting possibilities for trees:

- 01 In high density: Restricting building heights has reduced housing supply and therefore housing affordability (Daley et al., 2018).
- 02 In high density: Restricted building heights and high land costs has forced development types which maximise floor area (less permeable site surfaces) that exacerbate urban flooding issues.
- 03 In low and moderate density: Regulations for the provision of off-street parking with driveway access have been shown to increased car ownership, decrease selection of active transport, exacerbate car dependant sprawl development patterns and are a leading cause of child fatality (Australian Government, 2014; Marsden, 2006; Partrick et al., 1998; Shoup, 1997). In addition, large areas of public and private land can be dedicated to driveways, restricting room for trees [refer Figure 61].
- 04 In areas that have narrow lot frontages, land use planning regulations such as clearances between driveways and street trees, implemented with the intention of protecting tree root zones can further restrict tree possibilities. Driveways in this development morphology can be so closely spaced that clearances sometimes overlap [refer Figure 62].

Figure 61: Off street parking policies increase car use, decrease site permeability, reduce pedestrian safety and reduce opportunities for tree planting.

Figure 62: Clearances of three metres between trees and driveways (in red) are sometimes specified and are designed to protect tree roots from damage (City of Moreland, 2014). However, in areas with very narrow frontages, this clearance can further limit tree opportunities.

3.6 What is needed in landscape architecture for tree-scape design?

Ability to consider multiple criteria simultaneously

In the past five years substantial progress has been made in the capabilities of hardware and software for handling the modelling and rendering of complex forms such as trees and natural phenomena which previously required high end computers, (not the usual desk top machine found in design offices). With changes to software and hardware highly accurate and flexible landscape modelling can now be performed on a reasonably standard laptop, though both current skill levels and perceptions of this type of modelling as only useful for advocacy type visualisation may be a challenge to overcome (Gill, 2013; White & Langenheim, 2014a).

Mathematical and conceptual modelling

Figure 63, shows a diagram of how different types of modelling are perceived and how it might be possible to bring these together into one system to aid design decision-making. CGI industry modelling tools, while they are visually focused, also integrate highly accurate mathematical modelling in the form of physics-based lighting, geographic sun positioning, accurate 3-dimensional geometric tree modelling and even simple agent-based accessibility making it an ideal mathematical *and* conceptual modelling tool. However, as this technology is predominantly developed for the purpose of constructing compelling narrative imagery, (which is how it is currently utilised in the design industry) it will require some adjustments, add-ons and plugins to enable it to harness the growing quantity of geospatial analysis available through GIS, to become a visual-functional approach.

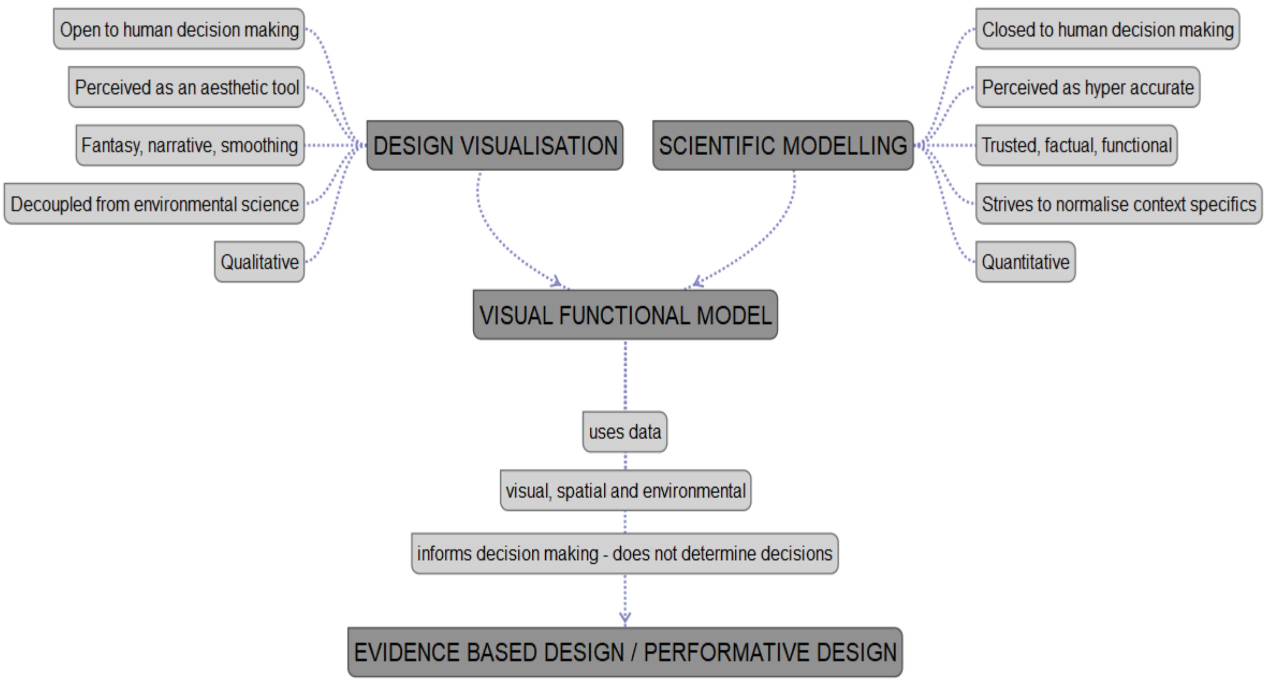

Figure 63: Shows an idea of the perceptions of mathematical modelling and visualisation modelling. Bringing these together may allow for both quantitative and qualitative outputs simultaneously.

Design modelling tools against requirements

A part of the motivation for thesis study, as discussed in section 1.1.6: *Research audience and motivation,* the idea is to build upon existing knowledge, skills and software that is nascently in use in the design industry, so that it can be integrated into design practice. To select the existing software environment in which to base the system discussed in the following chapter, I summarised the key design & Visualisation tools as of 2017[141] [refer Table 1] (White & Langenheim, 2018).

[141] Note, this is not an exhaustive list of possibilities, and all of these platforms are actively and aggressively developed (due to competition between them). This list therefore, out of date as soon as it is completed. However, it does provide a snap-shot of tools, required capabilities and required add-ons from which to select.

Table 1: Table showing analysis of common design modelling software for urban designers suitable for rapid, procedural urban scaled/precinct tree modelling with material and daylight analysis capabilities.

Software	Common in LA/UD practice	Inbuilt physical daylight	Inbuilt physical shaders	Inbuilt Parametric /procedural modelling	Inbuilt proxy object rendering	In app tree modelling via plugins	Inbuilt Daylighting analysis
Rhino 3D (McNeal)	Y	N (Y with additional plugins)	N (Y with additional plugins)	Y (with grasshopper plugin)	N (Y with additional plugins)	N	Y (with grasshopper plugin)
Maya (Autodesk)	N	Y (Mental Ray)	Y (Mental Ray)	Y	Y	Y (Xfrog)	N
SketchUp Pro (Trimble)	Y	N (Y with additional plugins)	N (Y with additional plugins)	N	N (Y with additional plugins)	N	N (Y with additional plugins)
Infraworks (Autodesk)	N (becoming common)	N	N	Y	N	N	N
3ds Max (Autodesk)	Y	Y (Mental Ray)	Y (Mental Ray)	Y	Y	Y (Speed tree, GrowFX)	Y
Cinema 4D (Maxon)	N	Y	Y	Y	Y	Y (Xfrog)	N
City Engine (ESRI)	N	N	N	Y	N	N	N
Blender	N	Y (with Cycles)	Y (with Cycles)	Y	N	N	N

3.7 Conclusion

In Chapter 3, I asked the questions: *What is the context of tree-scape design tool development (past and present)? What are the qualitative visual, quantitative spatial and the environmental modelling tools under development or available for streetscape decision-*

making? How do design and modelling approaches and hierarchy of priorities differ in different disciplines?

The answer to the first of these questions is that the context of tree-scape design tool development is multidisciplinary. It involves landscape architects, land use and transport planners, urban climatologists, urban foresters and ecosystem service scientists among others. Each of these disciplines is developing complex models in rapidly evolving software environments.

The answer to the second of these three questions is that there are qualitative visual modelling tools developing in the design disciplines, quantitative microclimate and hydrological analysis tools being developed in science disciplines and quantitative spatial tools being developed in engineering / transport and land use planning disciplines which impact tree decisions. While there are some coupled models under development, these do not include visual impact assessment capability and do not work across transport accessibility concerns and tree functional benefits.

The answer to the third question is that: Priorities in the design sector, while they are shifting towards functional concerns, are still based on the need to quickly and iteratively forecast and communicate clear visual impact of design decisions in public participation forums. Priorities in environmental sciences are the functions of trees in moderating environmental conditions and in engineering, the priority for tree inclusion (or exclusion) revolve around transport safety.

To respond to all the issues outlined in this chapter in an integrated way, a visual-functional Design Decision Support System which can represent both quantitative and qualitative impact of decisions is needed. There are aspects of the technology developed in the CGI industry which could address the need to simulate functional environmental impact and qualitative visual impact in a spatially explicit environment.

Chapter 4: Research method

[…] develop research methods that are explicitly designed to meet the needs of decision-makers. These needs often include the development or application of research tools and methods that are not overly complex, that reflect the capacity (e.g., expertise, funding, etc.) available to decision-makers, and that address the specific informational needs of each decision-context (e.g., provide results at necessary levels of certainty and precision) (Olander et al., 2017).

4.1 Introduction

In chapter 2, I outlined the drivers behind urban tree decisions in colonial cities over the past two-hundred years. [refer 2.5: *Conclusion*] In chapter 3, I outlined the disciplines involved in tree-scape decision-making, the criteria applied, the objectives, the modelling methods and computer platforms used to forecast the outcomes of tree-scape design decisions [refer 3.7 *Conclusion*]. In this chapter, I will describe the research method developed and applied in this thesis, outline the development of a visual-functional modelling framework for a streetscape Design Decision Support System (DDSS) and give an overview of the selection criteria used to identify appropriate case studies on which to test the DDSS.

4.1.1 The research gap

The study of tree decision drivers, disciplinary criteria, objectives and modelling approaches to making urban tree-based decisions exposes a research gap: That the visual-functional benefits of trees need to be equally visible and comparable in the decision-making process, and preferably in a spatially explicit format**.** This is an important research gap for designers in industry or government, who are often in the role of negotiating streetscape decisions with the community while simultaneously striving to improve design decision outcomes to address environmental challenges. To address this research gap, I ask the key question of this thesis:

Can environmental performance, spatial constraints and visual impact be integrated into a tree-scape design process?

4.1.2 Hypothesis

That: *emerging modelling technologies from gaming, animation and architectural sciences can be combined with techniques from geospatial analytics, algorithmic botany and urban forestry, to create a performance-based design-decision-support system, which assists practicing landscape architects to coalesce divergent criteria of visual, spatial and functional aspects of tree-scape design*[142].

4.1.3 Selection of the research method

To test this hypothesis, I selected a three-part mixed methods approach. The first method I used was 'formative research': Where I drew from a wide range of sources and disciplinary perspectives including academic literature, multi-platform software comparison and data analysis and processing techniques to inform the purpose and goals of a DDSS for tree-scapes. The second method I used, took facets of software development (iterative, or agile and Software Development Life Cycle Method) (Dingsøyr et al., 2012) to inform the construction of the DDSS. And the third method I used, draws from education science (A. L. Brown, 1992; Collins et al., 2004) and landscape ecology (Felson & Pickett, 2005) and is known as 'design experiments'. I selected this method to test the application of the first and second parts of the research to 'case-study' sites in the form of speculative design scenario experiments.

4.2 Mixed methods

4.2.1 Formative research

To understand the multi-disciplinary environment of streetscape design and the emerging technologies streetscape decision-makers are using to forecast street design outcomes, I used a broad literature review coupled with software investigation. The literature review, touched on major aspirations for, urban tree environmental performance goals, current

[142] I have chosen to use the term 'hypothesis' here instead of 'research question' though the method of testing the hypothesis, is a mixed 'design method' including both qualitative and quantitative approaches and is therefore not strictly the scientific method.

trends in transport and land use planning, and streetscape design decision-making processes from early stage public participation and consultation through to late stage construction documentation.

I then reviewed current and emerging modelling techniques and software used in the design industry, environmental science, services engineering and the CGI industry. These formative investigations were filtered by the requirement to know how different disciplines make tree-scape decisions and what level of simplification of discipline specific criteria would allow the development of an integrated tool to use for simultaneous assessment of functional and visual street tree impact.

4.2.2 DDSS development

Based on the outcomes of this formative research and in response to the problem described by Russo (Russo et al., 2017)[143], I selected existing software components, already either commonly, or in nascent use in the design industry, coupled with suitable plugins, scripts, data acquisition and processing methods to form a loosely-coupled architecture of software components[144] as a design decision support system. The selection of components was filtered by industry current practice, building and extending existing skill bases, interoperability, availability, flexibility and capacity to accommodate insights from disciplines other than design specifically, tree function in flood adaptation and heat moderation for active transport users. While there are advantages and disadvantages to levels of coupling within a framework, from loose to fully integrated, loose coupling allows for the greatest flexibility[145].

4.2.3 Test part 01: Petri-dish

To then test the applicability of the DDSS to streetscape urban tree design decision-making, I used a two-part process. In the first part I used micro-scale abstract (predominantly digital-physical models of single streetscape intersections), to isolate

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[143] The uptake of DSS in other fields as they already use a set of existing software.

[144] Levels of coupling is a term borrowed from software development describing 'the degree to which software components are dependent upon each other'. Components can be loosely coupled, tightly coupled or integrated (Rouse, 2011).

[145] On the one hand disparate software programs, even when open source, if they involve onerous import and export functions for design iteration they are predominantly ignored or underutilised by a time constrained industry. On the other hand, integrated software platforms for landscape design are often not powerful enough or flexible enough to perform multi-scalar analysis or, where they are powerful enough, prohibitively expensive for a budget constrained industry.

specific variables and prototype the application of the DDSS. I have called these micro-scale digital design experiments, petri-dish tests. Each petri-dish combines and applies the emerging modelling techniques, plugins and data sets relevant to the key challenges outlined in each chapter.

4.2.4 Test part 02: Case studies as speculative design scenarios

To then test the applicability of the DDSS to meso or precinct scale urban tree design decision-making, I applied the outcomes of the petri-dish tests to sites in Melbourne facing key challenges where selection of trees for their functional attributes could improve environmental or human health performance of the site. The specific challenges I chose to address are tree choices for flood adaptation and tree choices for shading active transport paths given their status as providing the highest cost-benefit after visual / amenity value (Song et al., 2018).

Each case study provides a mechanism for exploring complex urban variables of built form, land use, transport and trees impact on an emerging environmental condition in either isolation or in combination.

In Chapter 5: *Umbrella City*, I test the DDSS application to a precinct which suffers from flooding. The site was selected as it is a suburban coastal morphology at the base of a hydrological catchment. This site allowed testing the integration of future flood modelling scenarios of the site undertaken by the CRCWSUD researchers with tree species visual impact assessment and management implications.

In Chapter 6: *Shady City*, I test the DDSS application to a precinct where active transport users are vulnerable to solar exposure. The site was selected as it is an inland, suburban morphology with low tree canopy cover which was assessed as having a heat vulnerability index of 8/10 (Loughnan et al., 2013). This site allows testing of tree planting scenarios to improve shading in streets around a school zone walking catchment and quantification of time spent in shade on the journey home from school.

In Chapter 7: *Synthesis City (hot flooding city)*, I test the application of the DDSS to a precinct which suffers from both periodic flooding and solar exposure. The site was selected as it suffers from both conditions simultaneously and it is an urban renewal precinct where the proposed development morphology is for a (zero lot) street wall, equal canyon 1H x 1W street width to building height ratio. This site allows testing of street tree planting and buildings interactively and brings together the considerations for flood and solar exposure.

4.3 Modelling framework inputs

4.3.1 Flood modelling data

In this thesis, I incorporate external flood modelling data from researchers in the CRC WSUD and Melbourne Water Corporation. These projected flood conditions are input into the model framework as georeferenced maps. As discussed in 3.4.2 *Modelling urban flood mitigation*, tree functional considerations in storm water regulation are species specific traits such as canopy interception capacity. Plant species with tolerances to, and mechanisms in storm water regulation I selected from academic literature.

4.3.2 Sunlight shading and overshadowing data

As discussed in 3.3.5, tree functional considerations in heat moderation / protection from solar exposure are geometric in nature. I therefore developed the DDSS in this part to output geometric crown-form and canopy dimensions as a guide for species selection. Tree street overshadowing is also an optical problem (photometry rather than radiosity). I therefore elected to input light parameters into the DDSS using a photometric sun system[146] (day, time, season and geolocation adjustable) in conjunction with an optical Ray tracing rendering method to allow accurate, seasonally adjusted shadow impact assessment [147]. The V-ray sunlight is based on International Illumination Engineering (IES) physically based sky rendering parameters and can replicate optical properties of light

[146] The geolocated sun system 'gives the correct angle and movement of the sun over the earth at a given location' (Autodesk Inc. 2019).
[147] The sun positioning system was originally part of the daylight system included in the MentalRay™ rendering engine and has the capacity for input EPW weather files. However, due to recent advances in calculation of light bounces and changes in the relationship between Autodesk and NVIDIA, the development of the MentalRay render engine has been discontinued. To alleviate this issue, I used the sunlight system of the render engine Chaos Group V-Ray GPU for 3ds Max version 3.6™ plugin to calculate light interception. Its positioning is then linked to and controlled by the legacy MentalRay™ sun positioning system.

(luminance and illuminance) and shade when used in conjunction with realistic materials and Global Illumination parameters[148].

4.3.3 Transport modelling data

As discussed in section 3.5.1: *Transport planning*, the application of transport regulations and clearances have an impact on tree possibilities, and road data collection favours vehicle transport concerns. I use two transport data sets to generate footpaths, cycle tracks and tree line alignments, recalibrating that vehicular data to inform more pedestrian oriented concerns. Street casement geometry is taken from the Vicmap Property Simplified data set owned and maintained by the Victorian state DELP[149] and street centre line data is taken from the PSMA[150] available through the Australian Urban Infrastructure Research Network (AURIN). I also used the online agent-based pedestrian access modelling tool PedestrianCatch.com and it's prototype shade analysis version developed by (White et al., 2017).

4.3.4 Urban morphology modelling (existing and proposed)

Existing building footprint data from Lidar and photogrammetry data between 2009 and 2016, for inner Melbourne, kept by Melbourne Water Corporation was made publicly available in 2016 through the AURIN portal. I used these footprints in areas where they were available, though there are several known limitations and inaccuracies of this data as it has been autogenerated. There are many instances where edges of the pixels in the raster photogrammetry data are confused with building edges, resulting in linework which is inaccurate and computationally expensive when made into 3-dimensional objects (many more polygons than actually required). I used several methods to attempt to clean this data including using the 'spline cleaner' plugin http://www.splinedynamics.com/spline-cleaner/ . However, for the purpose of testing my hypotheses, the level of accuracy was suitable.

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148 The indirect illumination which occurs when light is bounced off other surfaces).
149 Department of Environment, Land, Water and Planning.
150 Public Sector Mapping Agency.

4.3.5 Existing tree data

Over the past decade, local government authorities have been transitioning their urban forest records to GIS based methods. This has opened up a range of possibilities for both tree data visualisation (such as the Urban Forest Visual) [refer Figure 34], and integration of tree data with other streetscape concerns. I used street tree inventory data for each of the three case study sites available through http://www.opentrees.org/, or from the local council directly. Figure 64, shows the system inputs as described above, how these are brought together and what the outputs will be. This diagram is an extension to the diagram in (White & Langenheim, 2018).

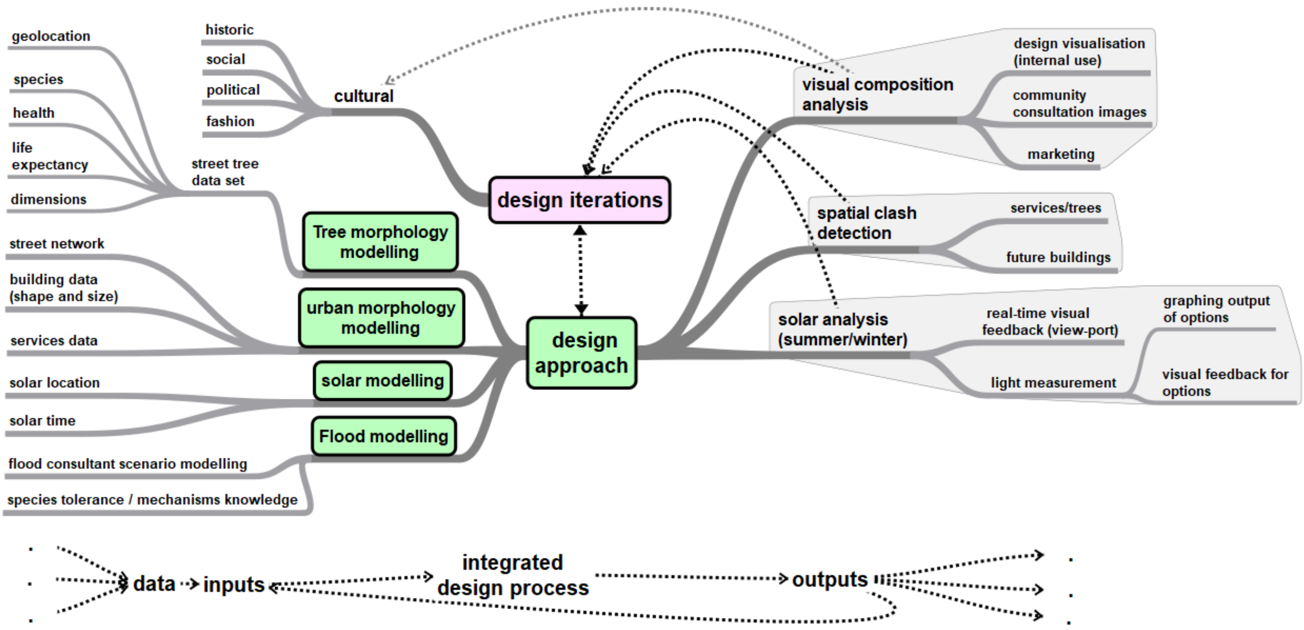


Figure 64: Shows inputs for the system (with cultural inputs included separately arising from community consultation and participatory decision-making). These are gathered into an integrated design process (completed using the DDSS) to output visual decision-making aids, assess spatial constraints and assess shading options and requirements.

4.4 The DDSS framework

As established in section 3.6: *What is needed in landscape architecture for tree-scape design?*, the framework for the DDSS needs to achieve the following:

- enable use of many multiples of 3-dimensional geometric tree models.
- enable analysis simulation of precinct scale models.
- enable analysis of design scenarios.

4.4.1 The base platform

As summarised in section: 3.6: *Design modelling tools against requirements*, there are a variety of potential base platforms suitable for this research. I selected Autodesks' 3ds Max (version 2019/20) as the central software as it met the key criteria in Table 1. 3ds Max is a procedural, combined modelling and rendering software package which is highly customisable through the addition of plugins and scripts. It is commonly used in architecture, landscape architecture and urban design practices though generally only for visualisation and advocacy image creation purposes[151]. It has the capacity to 'live link' with spatial engineering software such as Autodesk's Civil CAD or AutoCAD, and GIS based data can be imported either through scripted plugins, or manually via a package such as AutoCAD. 3ds Max also has inbuilt animation capabilities allowing for demonstration of change over time, physically accurate material shaders allowing different levels of material (leaf) reflectivity and emissivity using the well-integrated, ray tracing rendering plugin V-Ray and physically accurate cameras. The programs basis in gaming and entertainment translates to a strong focus on photorealistic capabilities. 3ds Max has built in digital-physical cameras which can be callibrated to physical camera.

4.4.2 Algorithmic trees

The key to making spatial constraints, environmental functions and visual impact of trees concurrently considerable is the use of recursive 3-dimensional algorithmic tree geometry modelling. This can be achieved in two ways. Tree models can be included in scenes either as 'assets' from externally generated library of tree models or they can be procedurally 'grown'. I have used both types of tree modelling in this thesis.

Tree model libraries

The most comprehensive, editable and photorealistic library at the time of this thesis was available from Xfrog[152] (version 3.5) (Deussen & Lintermann, 2005). I selected the Xfrog Oceania libraries as these contain tree models for species native to (or at least visually

[151] Personal comment From Dermot Egan from Tract.
[152] The Xfrog reseller claims that all of their tree models were created by specially trained botanists

similar to) native species of the context sites[153]. Models are provided both in native .xfr and .max format. Native .xfr format models can be edited with the stand alone Xfrog software platform and then imported into the base platform as a mesh object or the .max meshes can be directly imported if no structural editing of the tree form is required. Once imported into the base platform simple pruning such as adjustment to the number of leaves, leaf visibility or changes to leaf and bark textures and scaling are still possible.

Procedural tree modelling

Where the Xfrog tree models were not suitable, I procedurally 'grew' trees from scratch. These 'hand'-made trees allow far greater flexibility and control than using library asset trees, though they also incur a greater time commitment to create. In this research I used the inexpensive third-party plugin GrowFX (version 1.9.6) by Exlevel a procedural tree plugin for 3ds Max to create a number of 'hand'-made trees. This plugin was selected over the Xfrog stand-alone software as it is directly operable from within the base platform, meaning that tree editing remains dynamic[154].

Proxy-object modelling

For the placement of the trees within the precinct models, I selected the scripted procedural plugin ForestPro (Version 6.2.1) from iToo™ which allows thousands of high-polygon trees to be distributed as 'proxy-objects' in Autodesk's 3ds Max™. The large detailed tree models, constructed from (at times) millions of polygons, are temporarily replaced by computationally 'cheap' point clouds in the viewport display mode until full rendering is required. Tree placement is managed by this same plugin, with procedural distribution either by vector street centre lines (derived from the PSMA data) or by raster (flooding or overshadowing maps). Using this plugin, any form of geometric object can be distributed in the scene, with multiple controls, in what is known as a 'scatter'. Figure 65, shows street centre lines (in pink), being used as a 'driver line' to offset rows of geometric

[153] Note: Reflecting the multitude of unique forms Australian native plants can take, the Xfrog Oceania libraries have up to twelve model variations for each species. This is in contrast, to their tree libraries for other parts of the world typically only contain three variations based on plant maturity. (young semi-mature and mature).

[154] Note: While tree library models are suitable for many purposes. It is the procedurally grown trees which will in the future provide the most accurate integration with the needs of the science discipline sectors.

objects onto either side of a street intersection. The objects can be replaced with other objects at any time, an or, spacing and offsets can be adjusted.

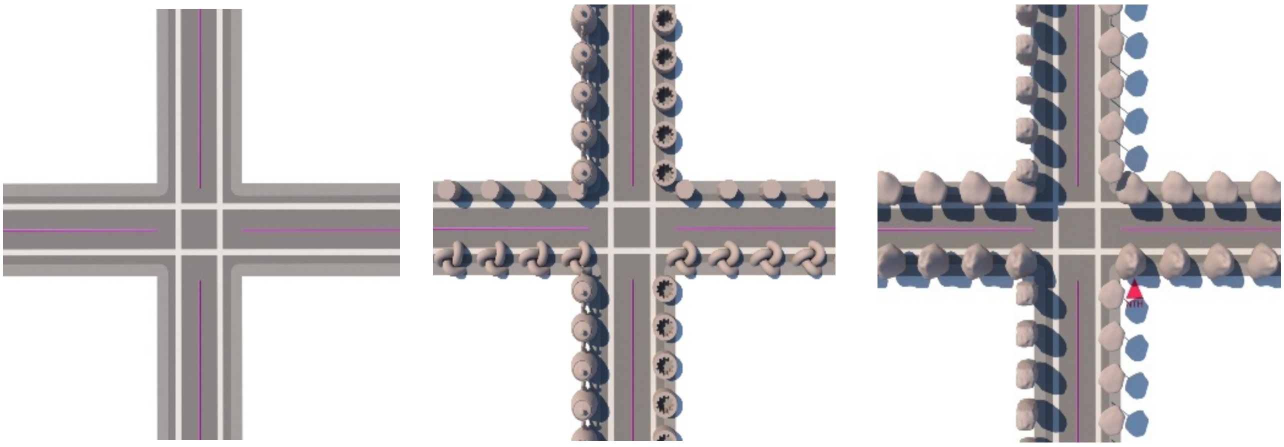


Figure 65: (LEFT) shows the process of using street centre lines (in pink). (CENTRE) geometric objects are placed by specifying an offset from the centre line, which can be adjusted at any time. (RIGHT) The 'geometric objects can be supplanted with other geometry (such as trees). Transforms such as scale and spacing between objects is also perpetually adjustable.

QGIS and ArcGIS

For data processing and transfer of geospatial data from AURIN to a format that can be imported into the base platform, it must go through either QGIS (a free open source Geographic Information System, or it can be taken through ESRI's ArcGIS. Data was projected from geodetic coordinates to cartesian coordinates and exported as .dwg format (GDA94 to MGA zone 55). Vector, point and polygon data was compiled in Autodesk's AutoCAD, and assigned a spatial transposition point. (A reference zero point which makes it easier to work in the base platform). The DDSS framework is described in the diagram in Figure 66.

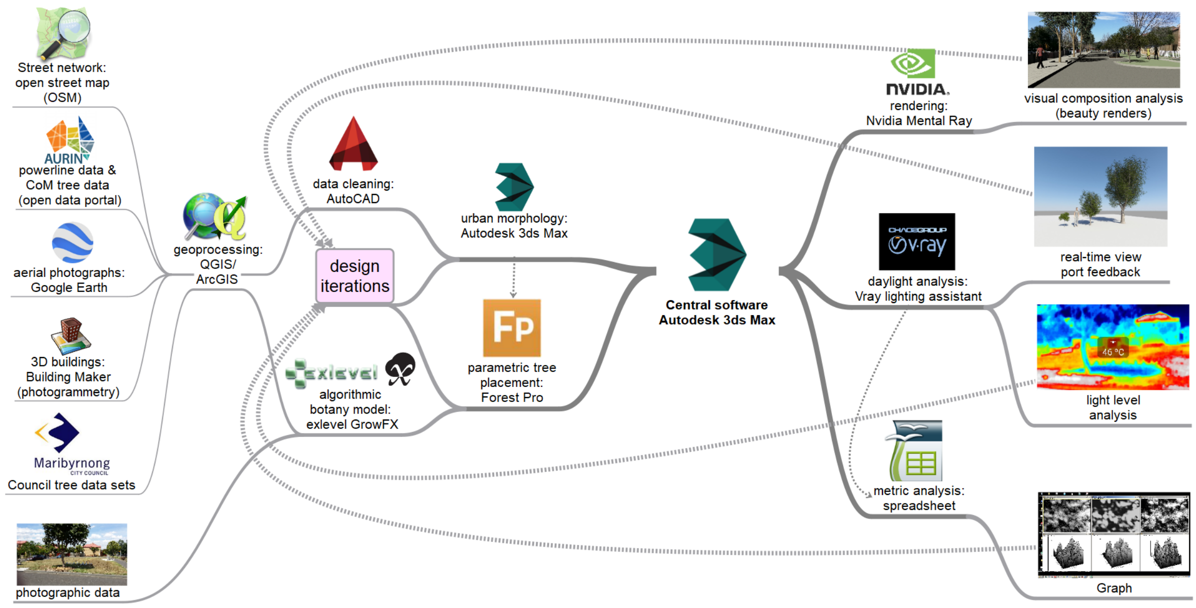


Figure 66: This diagram shows the technical make-up of the proposed decision support system with data sources, geoprocessing and modelling software used to feed into the central model, as well as the analysis technology for assessing the user's different designs.

4.5 Criteria for case study site selection

To test the applicability of the DDSS in a real-world situation I selected three sites for case studies. The context of the study was inner Melbourne and inner west statistical area 4: It was important to select the sites for testing of flood and heat in isolation and for them to have similar development patterns but contrasting environmental problems. The third site, where the DDSS was to be tested on an urban renewal condition needed to have both environmental conditions present as well as suitability for urban renewal. Each of the sites selected is quite typical of each of these conditions.

4.5.1 Two sites with limited variation of form and one urban renewal

There are recognisable, state-wide and GCCSA[155] patterns across the state of Victoria in heat, rainfall and canopy cover. To the east of Victoria, rainfall levels are both higher and more consistent throughout the year, while in the west, drier periods occur during hotter months. Surface temperatures increase in a south to north direction, a few degrees cooler along the coast. While there is only 100mm difference in rainfall and a 2°C surface temperature difference between the two suburban single environmental condition sites

[155] Greater Capital City Statistical Area

there are substantial differences in the public tree canopy cover between the two. The recent Greater Statistical Area of Melbourne benchmarking of Melbourne's canopy cover [Figure 67] show that the west to east rainfall gradient is particularly well correlated with canopy cover percentages (B. Jacobs et al., 2014)[156] [refer Figure 68]. The LGA in which the *Umbrella City* case-study site to the east of Melbourne was found to have a canopy cover 16.2% while the canopy cover of the *Shady City* case-study site in the west has less than half that (7.4%) canopy cover. Similarly the heat vulnerability of these sites follows a similar pattern, with the *Shady City* site assessed as having a heat vulnerability of eight (out of ten) and the *Umbrella City* site assessed as having two (out of 10) (Loughnan et al., 2013).

The third site is an ex-industrial urban renewal precinct within the inner city which faces issues of both heat and flood simultaneously coupled with pressure for the streetscape provide a large proportion of the public open space. This site provides an opportunity to synthesise the lessons from the two suburban sites along with the implications of deeper canyon types. Figure 69, shows the three sites overlaid with the 2100, 100-year flood event levels.

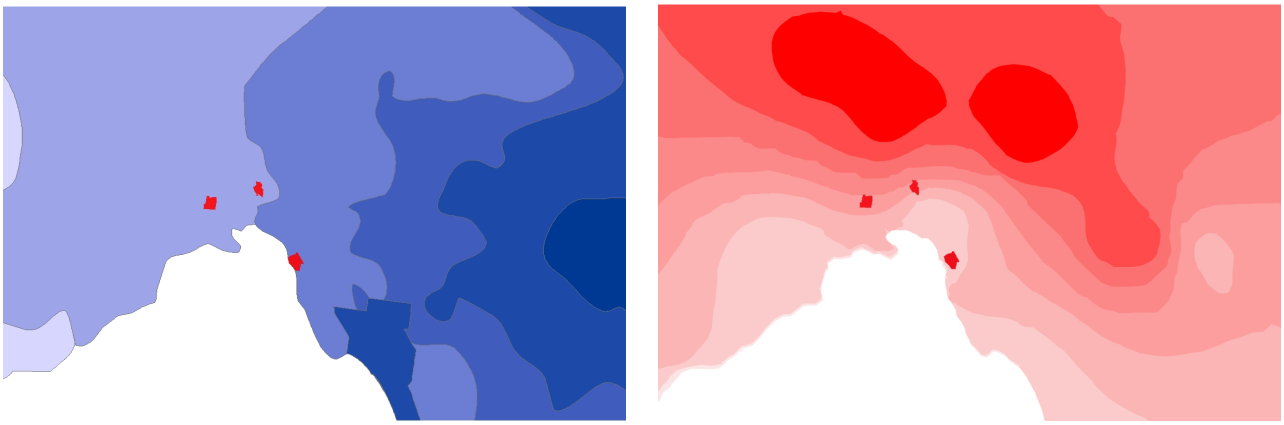


Figure 67: (LEFT) shows the pattern of annual rainfall increasing from east to west (range from 400mm annual rainfall in the west (pale blue) to 1100mm in the east (dark blue)) (adapted from (Melbourne Water Corporation, 2010) (RIGHT): Shows the pattern of surface heat increasing from the coast at 30 ° to 36° moving north, adapted from BOM 2018 surface temperature analysis December 26th 2018 range between 29°(pale red) and 36° (dark red) [*https://twitter.com/bom_vic/status/1078107182955220992*](https://twitter.com/bom_vic/status/1078107182955220992) *METAR data December 27th 2018 (created using QGIS).*

[156] While annual rainfall and seasonal consistency are likely to play a role in this inequity of canopy cover in Melbourne, built factors are also a consideration. The west of Melbourne is traditionally working class, with an industrial history (Morrow 2012). This land administration history results in smaller block sizes, which in turn mean higher plot ratios (building to site area ratios), alongside street and power infrastructure which caters for larger trucks and high voltage power lines with high voltage clearance requirements, that require greater amounts of tree canopy pruning. Both rainfall rates and the land use patterns that have resulted from Melbourne's west, industrial history are likely to play a role in the findings of high western suburb heat vulnerability indexes (Loughnan et al., 2013).

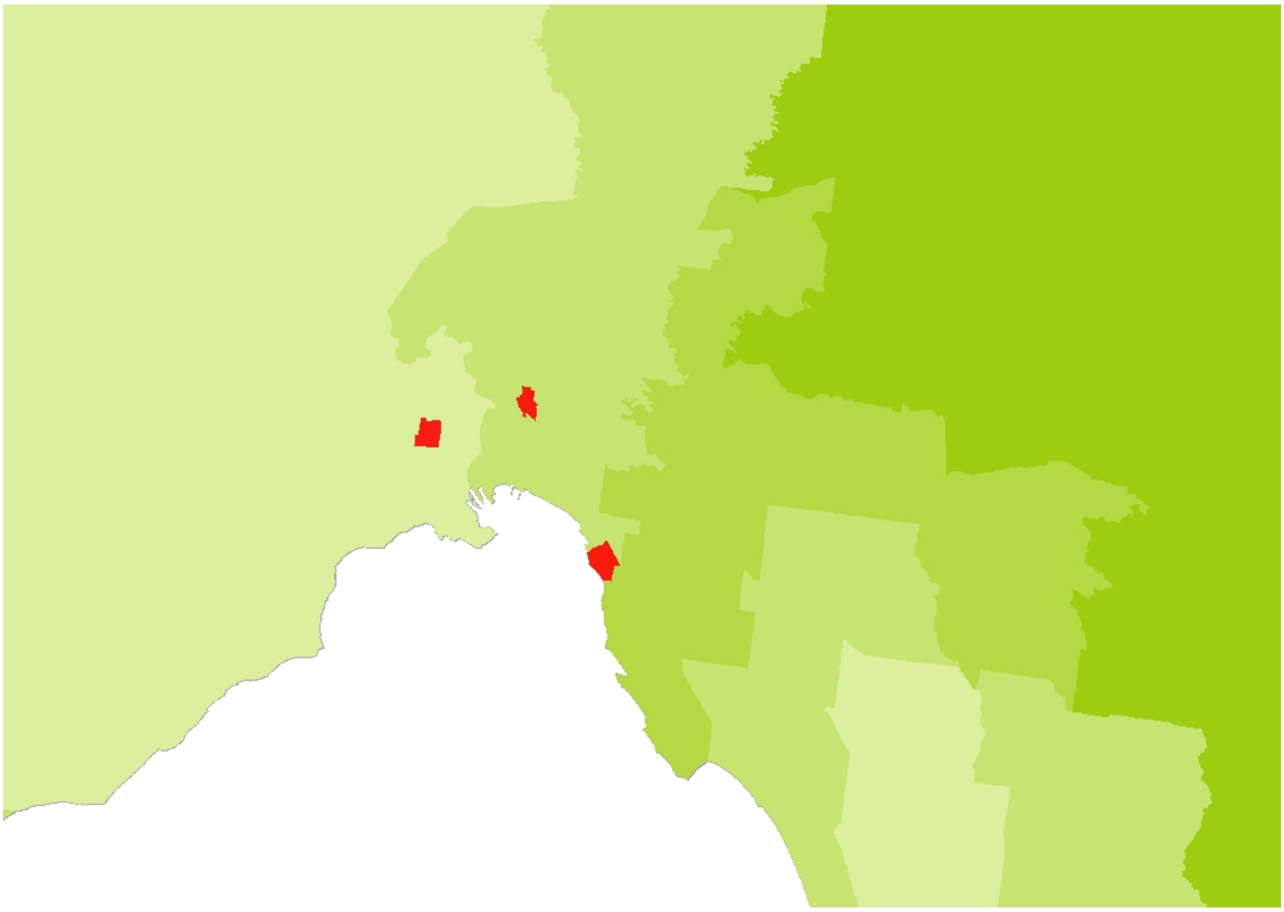


Figure 68: Canopy cover Adapted from the 2014 canopy cover by LGA mapping for Melbourne by the Institute for Sustainable Futures University of Sydney (Jacobs et al., 2014). 0-9% (pale green) to (50% in dark green) (created using QGIS).

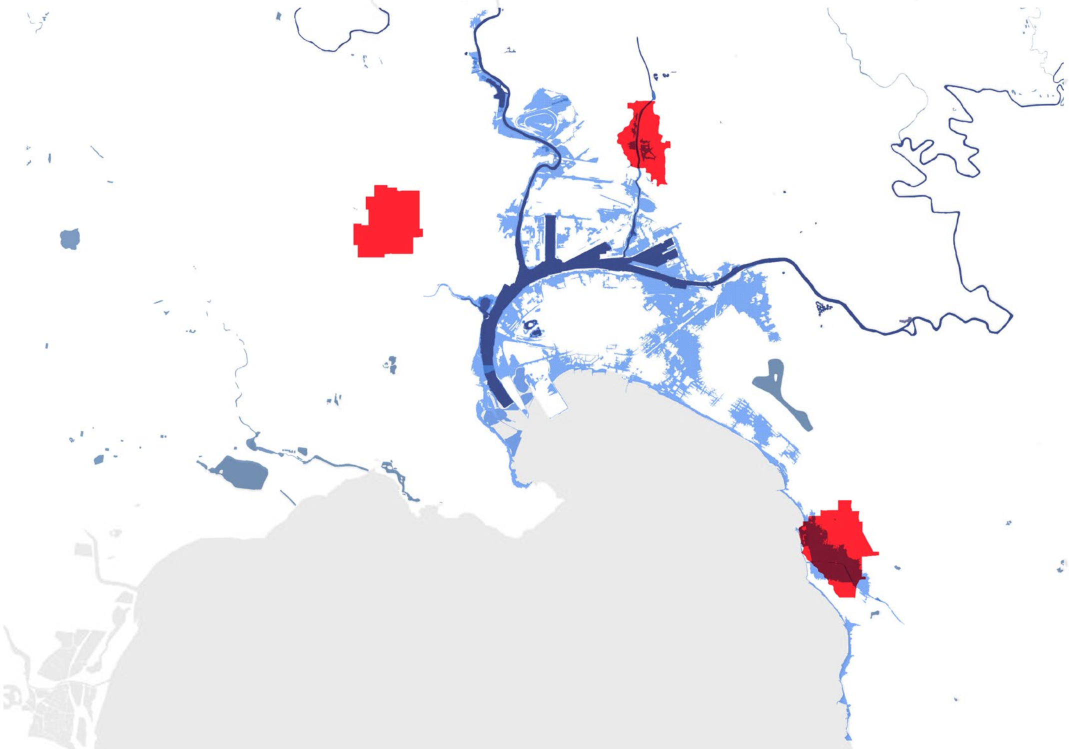


Figure 69: Sites overlaid with the Melbourne Water 2100 flood level for 100-year events given a predicted sea level rise of 0.8m by 2100, (created using QGIS).

4.6 Conclusion

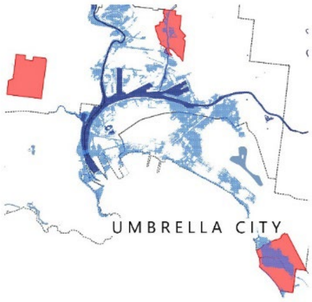
Toward a Design Decision Support System: Drawing from modelling methods used by a range of streetscape design disciplines, I have developed a flexible and adaptable modelling framework which is spatially explicit, useful for communicating traditional qualitative visual outcomes and adaptable to simulation of certain aspects of ecosystem service provision. In this framework trees are integrated as geometric objects within 3-dimensional micro and meso scale models. While there are a range of applications which have the potential for inclusion of 3-dimensional trees to some extent, balancing my personal skill level with the base platform capacity for scale range, temporal investigation (using animation bar), integration with spatial cartesian platforms, and the availability and utility of Forest Pack scattering tool for multiple complex geometry, I found this suite of software to be the most appropriate. Notwithstanding – the software selection is less important than the overall approach, which can be replicated using entirely alternative platforms if the utility exists within them.

The objectives of the DDSS are as follows:

- Permit adjustable tree decision-making responding to shifting objectives.
- Allow tree decisions to couple into infrastructure renewal opportunities.
- Allow quantification of footpath shade provision outcomes of tree species and placement selections and communicates those outcomes visually.
- Allow production of traditional qualitative visual outcomes of the same decisions for discussion with the community.
- Allow communication of spatial implications of tree decisions with engineering sectors.

In the next three chapters the ability for the DDSS to meet these objectives will be tested.

Chapter 5: Umbrella City



Various researchers have already noted impacts on coastal and island environments and most coastal communities are cognizant of the ongoing discussion about a threefold threat: sea level rise, the associated loss of soil storage capacity and more intense storms overwhelming the current "stormwater" infrastructure. (Huber et al., 2017).

Local governments are often referred to as being "on the front line" of climate change adaptation (Adams-Schoen, 2015).

5.1 Introduction

In the previous chapter I outlined a modelling framework for tree-scape design decision support suitable for production of qualitative visual impact imagery alongside quantitative environmental and spatial implication testing. In this and the following two chapters, I develop and test that modelling framework, adapting it to site specific performance criteria. In this case; the adaptation of streetscapes to increased occurrence of flooding and the visual and tree-scape management impact these adaptations will have. Both coastal and storm-water flooding are occurring with increasing frequency in Australia, and while there are various ways buildings can be adapted for flood, trees must still be planted in the ground.

Flood risk mitigation and adaptation are pressing issues faced by local councils seeking to implement resilience planning (Adams-Schoen, 2015). Surface-based storm water management systems (SSWMS) or Green Infrastructure[157] is increasingly proposed as a measure for this issue on streetscapes[158]. Tree species used in SSWMS have mechanisms and tolerances which are critical for these systems to operate successfully. Species may

[157] See Fletcher 2015 for term disambiguation of Green Infrastructure. Here it is used in alignment with the term recognised by the EPA 2012 https://www.epa.gov/green-infrastructure/what-green-infrastructure. They are also commonly known as 'at-source storm water control measures.

[158] It is the green infrastructure or at-source storm water control measures that have the greatest impact on reducing peak flows (Burns et al., 2015). Tree species selection alone (not incorporated into GI) will have little impact on flooding during rainfall events over fifteen minute durations.

need to be flood and or salt tolerant[159], have constant transpiration, high rainfall storage capacity or the ability to access ground water (Mitchell et al., 2014; Szota et al., 2018). However, some of the visual attributes of these species with specific flood mitigating mechanisms have been correlated with negative visual community preferences. Their use on streetscapes may therefore be met with resistance in PPD forums particularly when the species are historically unfamiliar to the local community[160] (Edwards et al., 2012), [refer 2.2: *Rise of the Pretty City*]. In addition, these species may have unfamiliar or nuanced maintenance requirements which require adjustment of current tree management practice.

The aim of this chapter is to investigate the possibilities of applying the visual-functional DDSS modelling framework to work with flood forecast data and tree species selection, aiding streetscape flood adaptation.

Key Question: *Can environmental performance, spatial constraints and visual impact be integrated into a tree-scape design process?*

Sub Question 01: *Can we utilise growing availability and accuracy of spatial data sets in street-scape design decision-making?*

Sub Question 02: *Can we combine and apply emerging modelling technologies in the entertainment industry (gaming and animation), digital procedural tree modelling, with computer aided design (CAD) and geographic information systems (GIS)?*

In section 5.2 of this chapter I investigate the key challenges of tree decisions for both storm water and coastal flood adaptation through catchment elevation dependent (SSWMS). Trees that are included in these systems need to tolerate niche conditions or have specific mechanisms related to their interaction with water. These specific tree species can often have unique visual qualities and maintenance challenges and as such, their use

[159] Predicted change in temperature range associated with climate change and associated amplification of moisture deficit and heat stress, show increased risk of pest vulnerability, see Mitchel 2014 and Allen 2010

[160] This is known as place attachment but also equates to the Gestalt principle of 'the law of past experiences'.

on streetscapes need to be judiciously negotiated not only with local community groups but also tree management sectors across multiple municipalities (COM, 2014a)[161].

In section 5.3 of this chapter I develop a series of abstract digital-physical modelling prototypes I have called petri-dish tests [refer section 4.2]. In the petri-dish tests of this chapter, I isolate the specific factors and variables involved in making functional (in this case hydrological) tree species selections and the visual impact of their use on streetscapes. The petri dish tests in this chapter respond to the broad scale implications of whole of catchment flood adaptation and differences between tree function in storm and coastal flooding. I discuss the results of these petri-dish tests in relation to their application of the DDSS framework to the specific localised conditions of the case study site.

In section 5.4 of this chapter I apply the DDSS framework to the Umbrella City case study site, the coastal and storm water flood affected suburb of Elwood, Victoria. With a predicted sea level rise of .8m by 2100, Elwood is increasingly at risk from both storm water overland flow and tidal storm surge[162] (Melbourne Water Corporation, 2012). In this case study future flood modelling undertaken by the CRC for Water Sensitive Cities for the suburb, under different sea level rise scenarios is integrated with emerging spatial data of surface water catchments from the Bureau of Meteorology[163] and used to inform spatially explicit future tree species selection.

5.2 Part 1: Key challenges

The flooding of a catchment[164] is governed by above ground factors of catchment size, shape, soil type and permeability, land cover, elevation, slope severity and location in relation to coast, as well as underground factors; such as the design of storm water pipe systems and the properties of underground water flows. Flood severity is, at its simplest level, an equation of these physical attributes of a catchment and the duration and

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[161] Whole of Catchment water management approach has been argued for in Australia for many years – see CRC for Catchment Hydrology see Ladson 2004 Improving stream health by reducing the connection between impervious surfaces and waterways.
[162] Storm surge is restricted to coastal areas, where waves and tides exceed normal high-tide limits because of winds and rainfall.
[163] GeoFabric V3 (based on the 1 second DEM).
[164] Also known as a watershed.

intensity of storm events (Bren, 2015). Stormwater runoff is not common in natural, heavily vegetated catchments with high levels of permeable surfaces as rainfall is either intercepted by tree canopies *before* reaching the ground, or infiltrates into the ground where it falls (source point). However, in urbanized catchments, vegetation cover is low and non-porous surfaces are dominant. In these conditions, a large quantity of rainfall reaches the ground and flows overland from upper elevations towards receiving water bodies[165] which results in flood problems for low-lying (lower catchment) areas. In addition, when these low-lying areas are coastal, their risk of flood can be exacerbated by storm surge or tidal flooding[166]. For example, the case study site for this chapter, positioned at the lowest elevation of the Elster Creek catchment, suffers from both storm water and storm surge flood.

Figure 70: This aerial image, the vegetation of Elwood has been selected using a threshold process. It shows the street trees of Elwood, between Dickens street and the Elster Canal (which regularly floods) has trees with larger canopies than those in surrounding areas. Image produced using colour range pixel selection and adjustment in Adobe Photoshop.

[165] Receiving water body is the creek, river, stream at the base of the catchment.
[166] There can be positive outcomes for trees in low lying areas, in that trees can be larger, healthier and more abundant than trees at higher elevations due to the availability of water (Bren, 2015).

5.2.1 Stormwater flood and water infrastructure

Major rainfall events are sometimes called one-in-one-hundred-year events. This term refers to the average exceedance probability (AEP)[167] [168]of a storm event occurring, of a specific *duration* with high enough *intensity* to deliver a specific quantity of rainfall at a point location. AEPs were used to calculate the required capacity of underground pipe system infrastructure to accommodate overland flow, but over the past half century AEPs have changed in Australia with the growing intensity of rainfall events also showing patterns of decreasing duration (BOM, 2018b)[169]. These more extreme storm events overwhelm underground drainage systems more frequently, resulting in more frequent flooding. In some areas where this is a recurring problem such as Brisbane Australia, housing (where it is possible) is being adapted to avoid inundation [Figure 71][170]. Changes in AEP's are increasing the urgency for implementation of surface-based storm water systems (SSWMS)[171] to reduce the increasing pressure on underground pipe systems unable to handle the intensity of contemporary flood events. These tree species need to function in reducing flood intensity as well as tolerate extreme conditions such as prolonged inundation and salinity. [Refer 2.4.3]

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[167] The term one-in-one-hundred-year event is considered misleading. Firstly, the AEP is a measure of rainfall rather than a measure of site's propensity for flooding. Low-lying sites are often subject to flooding due to overland flow rather than rainfall and hence will flood far more often than the AEP suggests. Secondly rainfall duration varies from a few minutes to multiple days while the calculation of the AEP is based on only one specific intensity rate, therefore, even sites which do not receive overland flow can flood more often than the AEP suggests. When multiple areas are averaged together, and any duration is considered the probability of flooding becomes much higher than suggested by the term one in one-hundred years.

[168] There is also the ARI or the average recurrence interval which is defined by the Bureau of Meteorology as the average or expected value of the periods between exceedances of a given rainfall total accumulated over a given duration – assuming periods between events are random.

[169] Increasing occurrence of short duration / high intensity floods lead to flash flooding https://www.csiro.au/en/Research/OandA/Areas/Assessing-our-climate/State-of-the-Climate-2018/Australias-changing-climate

[170] However, change is slow and in some case new housing is still being constructed as slab-on ground in flood prone areas due to community expectations and desires and lack of knowledge (Bird et al., 2013).

[171] Storm Water Management can be considered an interchangeable term for urban drainage see (Fletcher et al., 2015), which refers to subset of mechanisms within regionally developed terms around urban storm water. Surface-based systems refer to above-ground systems rather than piped systems.

Figure 71: House raised to avoid flood level in Rockhampton Queensland from http://www.elakiri.com/forum/showthread.php?p=9214757

5.2.2 Tree species selection for stormwater flooding

Tree species selection criteria for SSWMS are specific to the demands of the system and the context specific environmental conditions. Trees have two main mechanisms which can be used in storm water management. **Rainfall interception** is an above ground mechanism, which reduces runoff speed and quantity by interrupting rainfall before it reaches the ground (Baptista et al., 2018; Xiao et al., 2000) and high tree **water-use** strategies[172], which remove water from bio-filtration systems through transpiration, freeing up water holding capacity for further storm events (Szota et al., 2018). While these two mechanisms are important *during* storm events, there is a third issue to consider in selection of trees for SSWMS. In locations where drought is more common than flood or rainfall is inconsistent, the most desirable species will be both **flood *and* drought tolerant**. This is a rare naturally occurring attribute (Niinemets & Valladares, 2006).

[172] Transpiration rates, and root water uptake.

Higher quantities of rainfall interception can be achieved by increasing the size of trees (Xiao & McPherson, 2002), using trees with denser canopies (more leaf and branch surface area per cubic meter)[173] (Baptista et al., 2018) and trees with foliage characteristics such as surface roughness, leaf and stem stiffness and leaf orientations which hold water and encourage re-interception, (Xiao & McPherson, 2016).

There is not a simple relationship between tree size and rainfall interception capacity, but it does follow that greater overall canopy cover will be capable of intercepting more rainfall. However, large trees have been found to have both negative and positive, context sensitive preference correlation. Tree size was positively corelated to visual preference in the pan European study by Edwards relating to trees in parks (2012). In contrast a hypothetical tree size scenario study by Andrew found that 79% of UK home owners would remove trees they considered too large (2014). Similarly an Australian study by Kirkpatrick found that 60% of the stated reason for tree removal on private property was tree size (2012), and Williams found that tree size preference was negatively correlated in a study using images of trees in a streetscape context (Williams, 2002). These three studies suggest that the context of proximity of large trees to property (such as streetscapes) where size presents personal risk may be a negative visual preference factor[174].

Canopy density has been found to have a profound impact on canopy interception. In the study by Baptista comparing controlled specimens of *Ulmus procera* (Dutch Elm), *Platanus × acerifolia* (London Plane*), and Corymbia maculata* (Spotted Gum), she found that the Dutch Elm specimen, despite its smaller projected canopy dimension and total surface area than the specimen of London Plane, intercepted more water due to its greater canopy density[175]. While Dutch Elms were a popular street tree in Melbourne from the late 19th C., found to have a higher visual preference in the study by Williams (2002), it is no longer planted in Melbourne due to risks associated with Dutch Elm Beetle (Neumann & Minko, 1985).

[173] LIA and or PAI.
[174] Williams also found in her study of Melbourne street tree preferences that larger trees were negatively corelated.
[175] Measured through area index – i.e. fewer sky view gaps when photographed from below.

Several studies have shown that species with the highest rainfall interception capacity are conifers (Asadian & Weiler, 2009; Xiao & McPherson, 2016). However in forest preference literature, conifers are consistently negatively correlated (Edwards et al., 2012; Gerstenberg & Hofmann, 2016; F. S. Jensen & Koch, 2000; Schraml & Volz, 2009). In addition, large and coniferous trees present tree management issues as they pose a greater safety risk in terms of branch failure, pest and disease attack and generation of leaf and cone litter (T. W. Wong et al., 1988).

Drought avoiders, visual preference and tree management

Evergreen trees with higher or constant transpiration rates which do not reduce their water use in winter months are useful for removing water from storm water management systems (Szota et al., 2018). However, these species are often known as 'drought avoiders' in that they need additional water resources during dry periods as they cannot change their strategy of high transpiration. Current streetscape tree selection and management in Australia favours 'drought tolerant' species as the condition of drought is more frequent than that of flood. Drought tolerant species reduce their transpiration to very low levels for weeks or months at a time[176]. This is a good survival mechanism, but it also reduces the rate of transpiration, which reduces the rate of water removal from retention systems.

'Drought avoiders' can have traits which make them challenging for use in urban streetscapes. Some develop mechanisms for accessing oxygen whilst inundated, such as knee roots and pneumatophores, for example *Avicennia sp* and *Taxodium distichum, others* develop shallow root systems, or drop limbs and leaves to reduce energy use during times of stress. An extreme example of the shallow root system and limb drop strategy is the River Red Gum (*Eucalyptus cammaldulensis*) the root system of which, gives way in strong rapids, allowing the fallen trunk to regenerate as a harp tree (Colloff, 2014) [refer Figure 72]. In urban tree management many of these mechanisms present both high risk and difficulties for establishment and maintenance of suitable conditions.

[176] There is another group that drops their leaves - they can be thought of as drought escapers. London Plane tree is an escaper, dropping leaves to rapidly reduce water use, because it cannot reduce transpiration rates physiologically.

Other species avoid environmental extremes such as drought by developing a fast life cycle such as *Acacia sp*.[177]. These fast life cycle species are not a popular choice for urban tree management as individual specimen longevity is an important component in the cost benefit of street trees (McPherson et al., 1994).


Figure 72: (LEFT) Eucalyptus cammaldulensis has a weak root system which gives way under rapid water movement and (RIGHT) Avicennia sp. develops 'knee roots' or pneumatophores in order to access oxygen during inundation with salt water.

5.2.3 Coastal flood and sea level rise

Sea level rise is already increasing the frequency of tidal inundation in coastal cities worldwide. Ft. Lauderdale, Florida for example is expected to have increased occurrence of street flooding under king tide conditions from 24 to 120 times per year over the next decade (Brooks + Scarpa, 2019; Huber et al., 2017). A rising sea level has three major implications for street tree selection in coastal sites. The first being tidal inundation, the second being tidal influence on the depth of ground water effecting a loss of soil storage capacity and the third being a rise in the salinity of water tables where aquifers are unconfined (Winter & Judson, 1998). Salt-affected sites are a niche environment in which only highly specialised plants can grow.

[177] These species survive through seed dispersal rather than individual specimen longevity. Many Australian native species have developed this mechanism in response to drought stress.

Figure 73: Salty Urbanism Brooks and Scarpa, Ft Lauderdale sea level rise adaptation strategy 2017. Streetscape king tide inundation.

5.2.4 Tree species selection for coastal, salt affected flood

Tree species with a tolerance to salt-affected coastal flooding growing conditions are few (Marcar et al., 1995). Over the past two decades more frequent coastal flooding problems have led to an interest in two plant specialisations; ground water dependant species (phreatophytes) and plants adapted to tolerate salt; (halophytes and euhalophytes) (Landmeyer, 2012) [178]. The latter are adapted to tolerating varying levels and exposures to salinity, often through specific growth habits or mechanisms which make them challenging to maintain in urban environments, for example succulence, laterally extensive shallow root systems or a high leaf turn over (Koyro, 2008). Phreatophytes are species that are genetically programmed to either access groundwater (obligative) or have the option to access ground water (facultative)[179]. They have a low geographic coverage in Australia (2%) but likely occurred in greater abundance prior to European settlement (BOM, 2018a) [180]. Few phreatophytes are suitable as street tree plantings, with the exception of some Australian *Banksia sp*. though there is a high degree of variation between genus tolerance to water availability (Groom et al., 2001)[181]. Between 1966 and 1996 long term species

[178] Tolerating repeated but not constant exposure to saline root conditions.
[179] or the capillary fringe: wetter area above the groundwater upper boundary.
[180] Inflow dependent communities mapped as likely to occur in the case study area (Elwood) by BOM in their Groundwater Dependent Ecosystems Atlas.
[181] Facultative phreatophytes have both deep roots and surface roots while obligate phreatophytes must have access to ground water, Banksia sp. were found to vary in sensitivity to ground water levels.

composition structure monitoring of four vegetation transects through Banksia woodland over the Gnangara Groundwater Mound[182] in Western Australia was undertaken. The results of the study showed a decrease in abundance of drought sensitive *Banskia littoralis* in response to lowered watertable heights and their replacement by the more drought tolerant *B. menziesii*, *B. attenuata* and *B. prionotes* (Groom et al., 2001). This was attributed to the latter species facultative use of groundwater in times of drought.

The appearance or visual characteristics of halophytes and phreatophytes, adapted to niche saline and water table conditions are 'unconventional' in terms of formal tree-scape norms in common use in Melbourne. To use them in streetscapes would be in visual keeping with the 'ecological design approach', which has been met with mixed response in forest preference literature when compared to 'conventional design (Yang et al., 2013) [refer 2.4.3 for discussion of ecological and conventional design approaches].

5.3 Part 2: 'Petri-dish' tests responding to key challenges

In the following section I describe a series of abstract digital-physical design experiments or prototypes which I have called petri-dish, in which specific factors of visual and environmental impact of tree decisions are tested in isolation. The petri-dishes allow me to test the application of the DDSS on specific visual-functional phenomena for flood adaptation and accordingly adjust the process to the constraints of the precinct scale case study site. As established in the previous section, tree decisions for flood are context specific, relating to elevation within the catchment and proximity to the coast. As such, the petri-dish tests in this chapter first investigate the DDSS application at the broad scale 'whole of catchment' (macro) scale and the individual streetscape (micro) scale in order to refine the application method to the localised (meso scale) conditions of the case study site.

In this chapter the petri-dish tests investigate the ways in which the suppression or occurrence of 3-dimensional tree models can be controlled on a digital site model. Two types of digital site topography model are tested (vector derived) and a raster-based

[182] The mound lies over a shallow unconfined aquifer.

(image/map derived) [refer section 3.3.3]. The results of the petri-dish test lead to selection or rejection of specific methods for the case study site.

Note: While these flood adaptation 'petri-dishes' reference specific plant species, those species should only be considered as indicative; based on the current evidence from literature.

5.3.1 Interceptors and high water-users visual impact study

On streetscapes, the use of either high-water use adapted species ('ecological' aesthetic) or the high-rainfall interception species (conifer aesthetic) would be a strong visual departure from the traditional plantings discussed in section 2.2.2. In the following petri-dish I test the DDSS capacity to respond to the key challenge of negotiating the visual impact of selecting street trees for their functional mechanisms in flood adaptation with residents. This petri-dish is at the micro streetscape scale, looking at species selection in relation to site elevation within the catchment. In this case; the use of **high-rainfall interception** species (conifers) in the upper catchment and **high-water use** species ('ecological' aesthetic) in the lower catchment.

Upper catchment conifer species were selected from tree rainfall interception studies (Kermavnar & Vilhar, 2017; Thomas, 2016; Xiao & McPherson, 2016)183. Lower catchment salt and inundation tolerant species were selected from Marcar, 'Trees for Saltland' (1999). Recursive 3-dimensional tree geometry models fitting the visual description of these species were then selected from the Xfrog 'Oceania' and 'Conifer' libraries [refer section 4.4: Tree model libraries]. While it was relatively simple to fit the selected conifer species to a geometric tree library model, fitting the lower catchment high-water use species were more difficult. Species such as this, with their specific visual qualities are not often used in advocacy imagery, film and television and as such, in no case was there an exact tree geometry model to fit from the Oceania library for any of these species. Visually similar models were matched as closely as possible to the species selection from Macar [Table 3].

[183] In the study by Xiao, conifers had the highest surface water storage capacity.

Table 2: High rainfall interception species for upper catchment sites

Species selected from Xiao et al.	*Picea pungens*	*Picea engelmannii*	*Pinus ponderosa*
billboard			
Xfrog model	OC07_var 9 *Casuarina equisetifolia*	OC22_var 2 *Acacia harpophylla*	OC49 var 7 *Eucalyptus dumosa*

Table 3: Salt tolerant high-water use species for lower catchment sites matched to Xfrog model variation (visually similar).

Species selected from Macar	*Casuarina glauca*	*Acacia ampliceps*	*Melaleuca halmaturorum*	*Melaleuca ericifolia*	*Eucalyptus occidentalis*	*Banksia attenuata or menziesii or*
billboard						
Xfrog model species	OC07_var 9 *Casuarina equisetifolia*	OC22_var 2 *Acacia harpophylla*	OC49 var 7 *Eucalyptus dumosa*	OC57_var 9 *Melaleuca alternifolia*	OC47 var 3 *Corymbia calophylla*	OC26 var 6 *Banksia serrata*
Special tolerances	Swamp She-oak moderate salinity tolerance	Salt Wattle (native to WA)	Moderate salinity tolerance, prolonged inundation	Moderate salinity tolerance, prefers swampy sites	Moderate salinity tolerance, prefers swampy sites	B. attenuata occurs in WA B. menziesii or prionotes (orange flowers).

Upper and lower catchment street intersection models

To represent indicative tree decisions which would be required to adapt streetscapes to function towards storm water moderation, I constructed a 3-dimensional digital model of a street intersection in the DDSS base platform. These were constructed of a simple flat plane and extruded linework to represent footpaths and kerbs with abstract indicative 3-dimensional house models [refer 4.4]. In the lower catchment intersection model, housing was raised up to clear the flood level as in the image of Rockhampton housing in Queensland [refer Figure 71]. Each street segment had a centre line which was used as the tree model distribution driver. In this circumstance I made two copies of the intersection model, one for each of the conditions of upper and lower catchment, however it would also have been possible to use a single intersection model and just change parameters for each condition.

Using negative and positive offsets of the street centre line, I distributed the 3-dimensional tree models of the high-water use species along the streetscape footpaths in the lower catchment intersection and high-interception species along the footpaths in the upper catchment model [refer Figure 75].

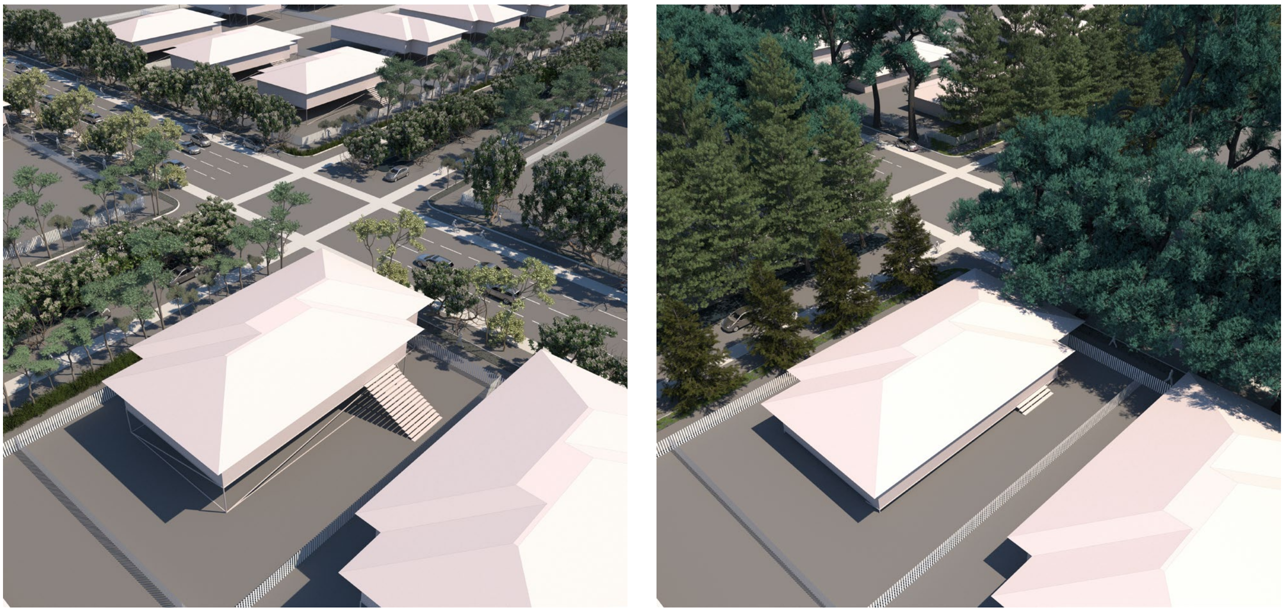

Figure 74: (LEFT) Shows a typical lower catchment streetscape intersection with high water-use species. (RIGHT) shows a typical upper catchment streetscape intersection with high rainfall interception species.

Visualising the key challenge for lower catchments

If the streetscapes of upper and lower catchments were adapted to flooding in this way, they would have quite different issues. While flooding in lower catchment sites may be reduced through planting of upper catchment sites with Conifer species, lower catchments may still flood due to coastal inundation. To show the visual impact of this possibility, flooding streetscape level renders were taken of the lower catchment intersection, with flood simulation using a simple plane with reflective material with noise[184] mapping and an index of refraction of 1.33 Figure 75, Figure 76, Figure 77].

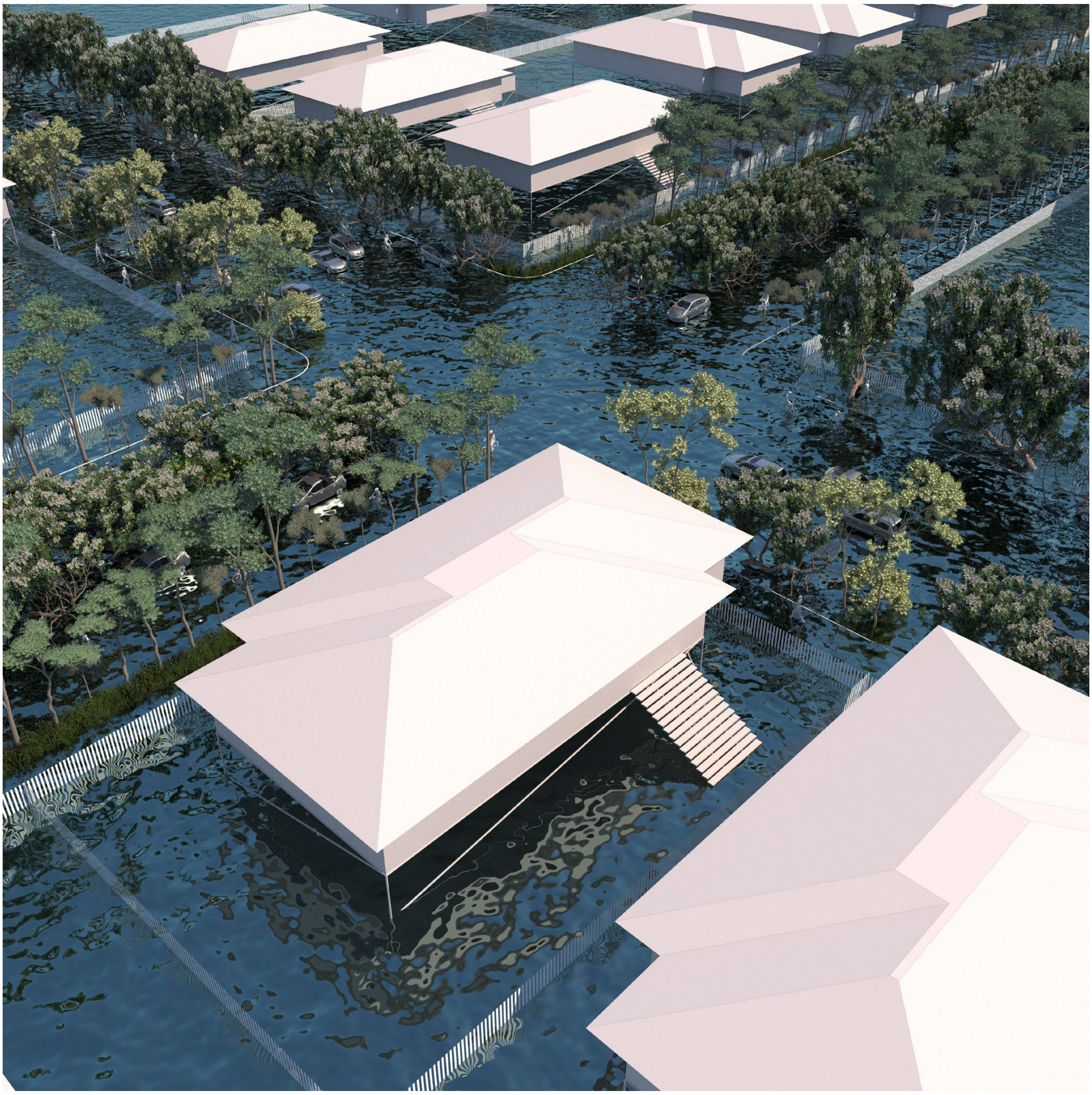

Figure 75: (LEFT) Lower catchment streetscape intersection using high water-use species not in flood (RIGHT) in flood.

[184] Noise mapping is a procedural texturing system, developed by Ken Perlin which simulates natural complexity (used extensively in the CGI industry).

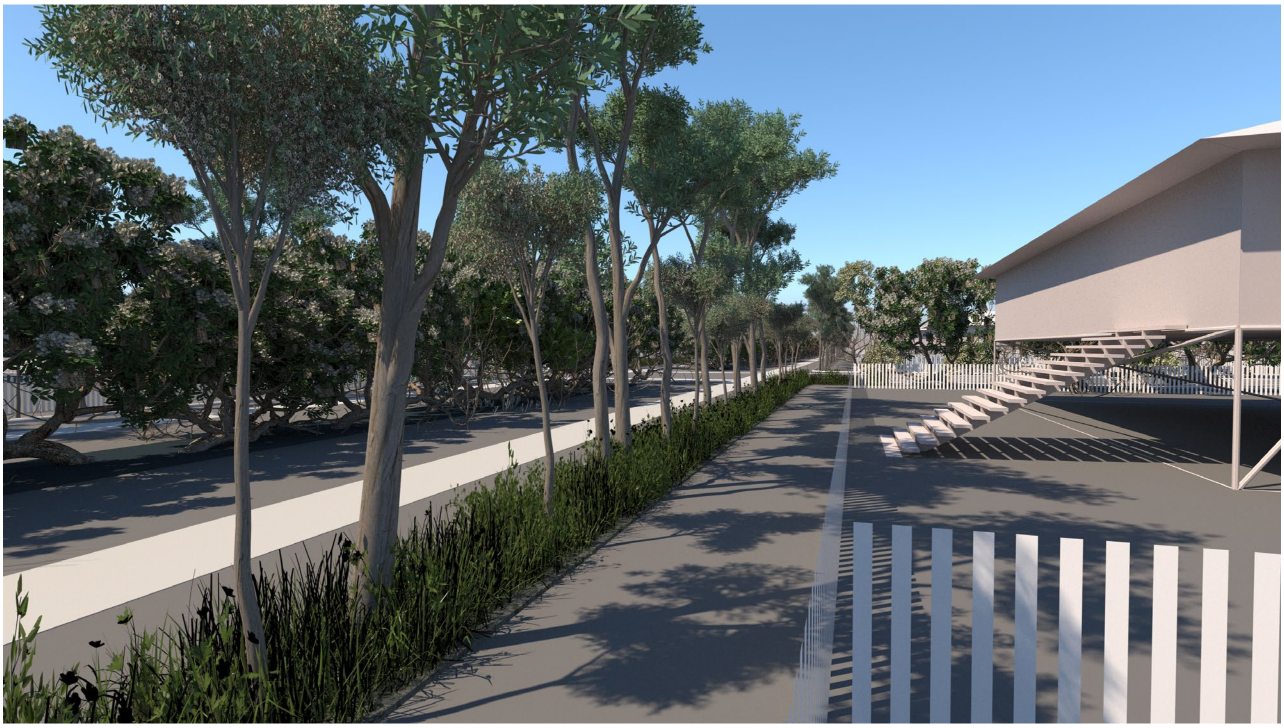

Figure 76: Intersection model of lower catchment streetscape using functional species selection. Housing has been elevated to accommodate periodic flooding.

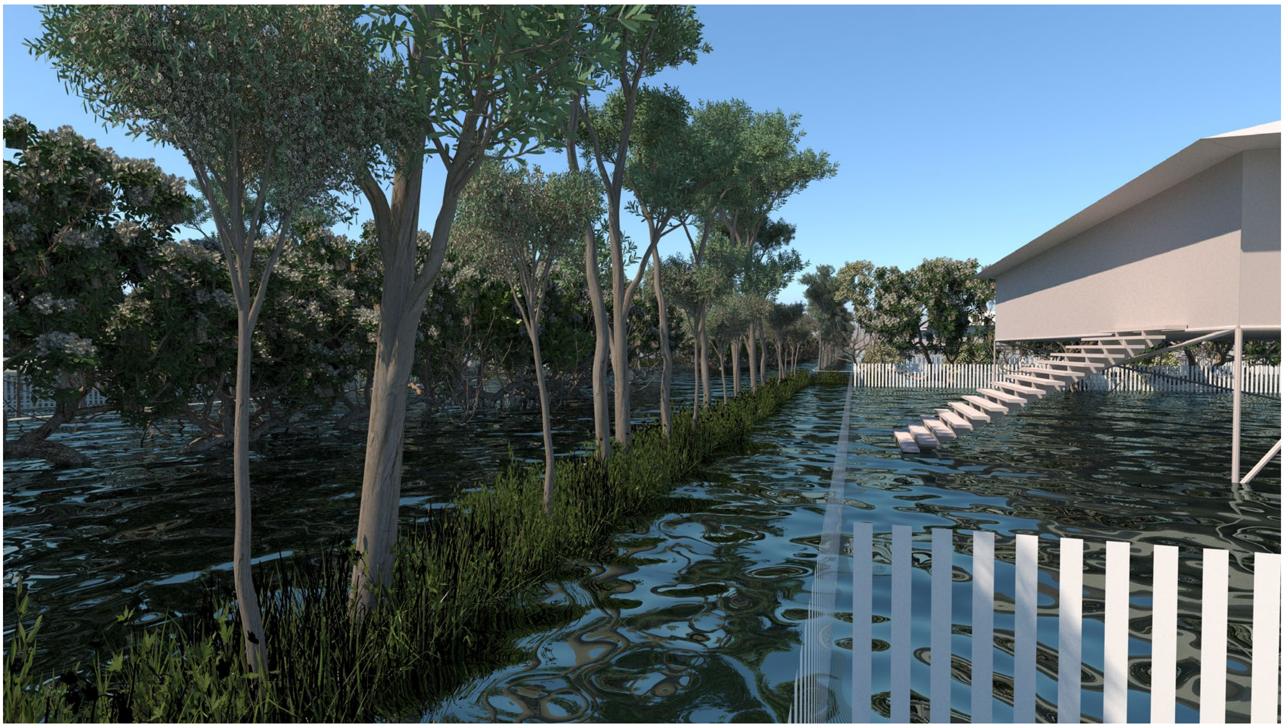

Figure 77: Lower catchment visualisation to show impact of in-flood scenario.

Visualising the key challenge for upper catchments

While functional planting in upper catchments can assist in moderating lower catchment flooding, residents in upper catchments can be quite removed from the flooding realities for their low-lying neighbours. Increasing the planting of high rainfall interception species in upper catchments then presents a different problem; that of streetscape overshadowing in winter. To visualise the light impact of this tree choice, I set the sun positioning system in the base platform to a mid-winter day, in an overview and a streetscape level [refer Figure 78].

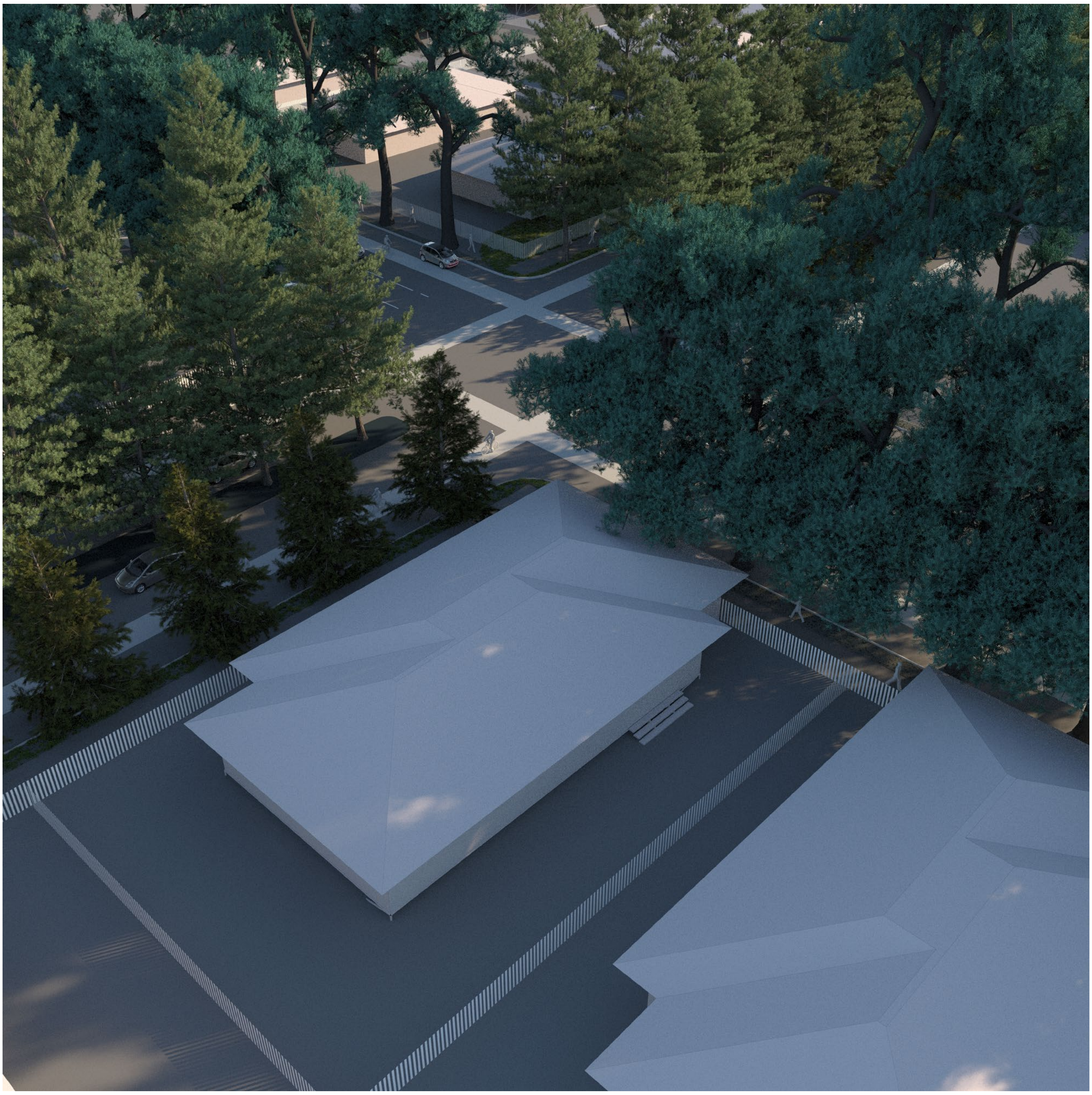

Figure 78: upper catchment streetscape intersection using high interceptor species in winter.

Figure 79: Intersection model of upper catchment streetscape using functional species selection (conifers). Above in summer and below in winter (showing winter overshadowing impact).

Outcomes

Using the DDSS, I was able to output visualisations of a realistic quality showing the qualitative visual impact of functional tree choices for water regulation at a streetscape scale. This form of visualisation could be used as decision-making aids in PPD. The renders reveal some of the conflicting criteria such as winter light levels (deep overshadowing) and rainfall interception, which might impact tree functional choices for flood moderation. The use of commercially available tree libraries for this task was relatively efficient once models had been selected, though there were limits to accuracy and editability. This petri-dish also required detailed geometry for footpaths, curbs and medians. These were simple to generate on a flat plane but can be more difficult to replicate over a site topographic model. In this petri dish the intersections were not site specific and as such have limited capacity for assessing specifics of numbers of trees needed or site-specific impacts relating to variables such as street orientation or building setback. In the next petri-dish test I will use elevation data to inform tree species placement.

5.3.2 Interceptors and high water-users elevation study

This 'petri-dish' test responds to the key challenge of elevation dependent tree mechanisms required in SSWMS. In this petri-dish I use elevation and localised sub-catchment pooling data gathered from an abstract digital topography model to drive species range. Digital topography models can be generated from contour or spot level elevation data which are then joined by a mesh of triangles. This mesh is known as a Triangulated Irregular Network (TIN)[185]. I constructed a vector based, abstract digital topographic site model (TIN) in the base platform, using contour lines with elevation value which were draped with a terrain object and converted to a 'quad mesh' (regular gridded quadrilateral surface) using the free plugin 'Va-Mesh-Conform'[186]. Alternative methods of terrain creation if contour data is not available, is displacement of a plane object using a texture map, or terrains can be digitally sculpted to desired requirements [187]. To analyse the areas where water would pool on this site mesh, I used a particle system (currently in beta testing) to analyse the flow of rainfall. The particles are programmed with a gravitational force which makes them flow over the surface and pool where the surface is concave. After the simulation of the rainfall event, I selected the concave surfaces on which pooling occurred and set these to a different material from the rest of the mesh [Figure 80].

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[185] While TIN mesh files are the most accurate, these meshes can be difficult to edit. Where editing is required TIN meshes can be retopologized using a quadrilateral mesh. For a description of retopology see https://www.quora.com/What-is-retopology-and-how-do-you-do-it-with-ZBrush.

[186] https://www.scriptspot.com/3ds-max/mcg/va-mesh-conform.

[187] Digital sculpting is a term use in the animation industry to describe the adjustment of a mesh object. The process is similar to painting however the 'brush' action deforms the mesh according to given settings.

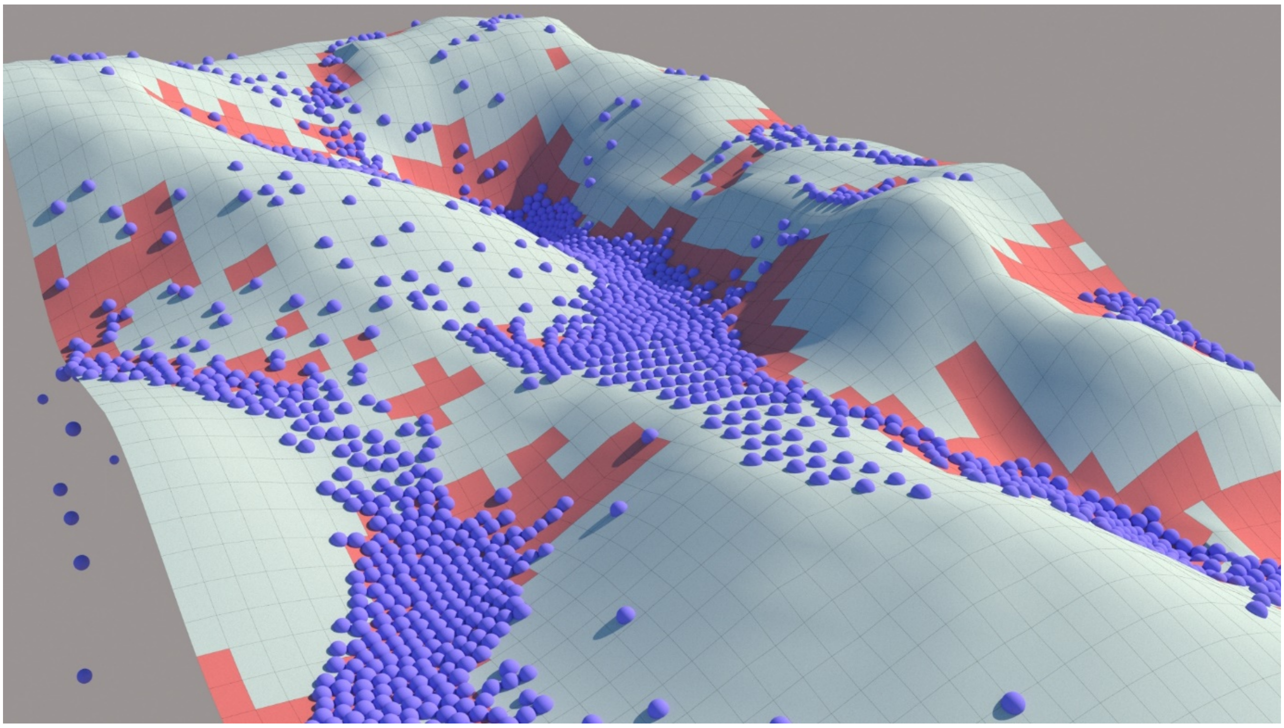


Figure 80: Sub-catchment analysis performed using a TyFlow flow of particles (purple) programmed with a gravity force. The particles collect in depressions on the surface which would act as localised sub-catchments (shown in red). In some circumstances these areas will need high water-use species, regardless of elevation within the catchment to clear capacity in SSWMS.

Altitude and sub-catchment-controlled plant communities

Using the same 3-dimensional tree geometry models as in 5.3.1, I created two communities of plants. One consisting of the high rainfall interceptors (the conifers) and the other consisting of high water-users (the salinity adapted Australian natives). Firstly, the high-water users were proxy-object scattered (applied) over the entire mesh, adhering to only the selection of sub-catchment polygons [refer Figure 82]. In a separate proxy-object scattering, the high-water use plant community was also applied to the mesh with an altitude limitation [refer Figure 82]. Both the sub-catchment scatter and the altitude control scatter of tree models were brought together with overlaps controlled through the surface exclusion function of the scattering plugin [refer Figure 83]. Finally, I applied a proxy-object scatter of the conifer plant community altitude limited to only occur in higher elevations [refer Figure 84].

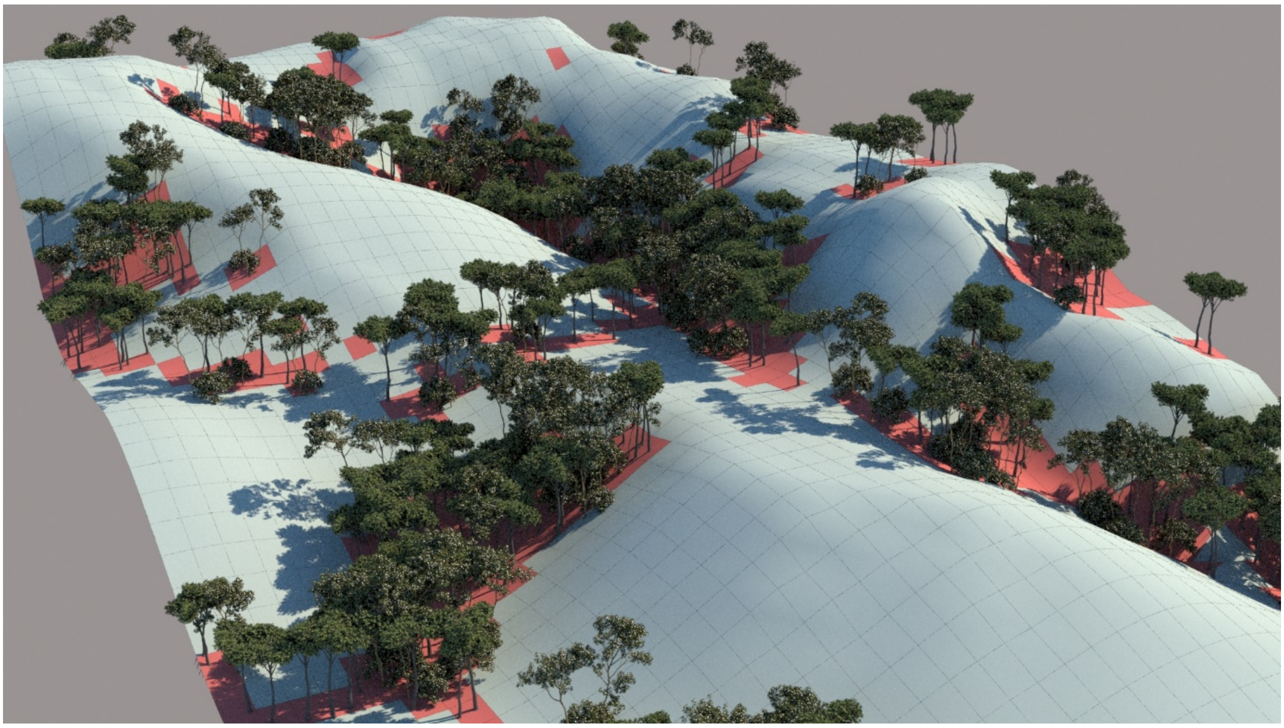


Figure 81: High water-use species occurrence controlled by selection of concave polygons of the mesh where water pooling occurred (shown in red) using the particle test above.

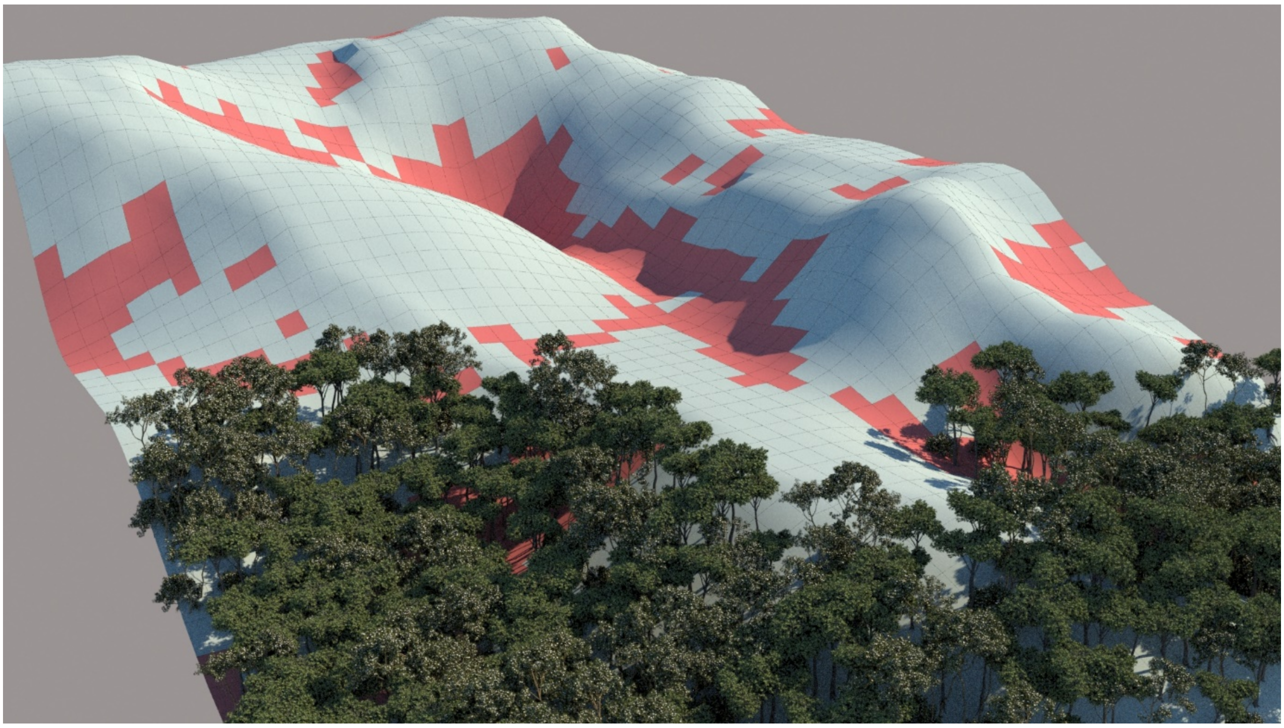


Figure 82: High water-use species occurrence controlled by elevation limitation.

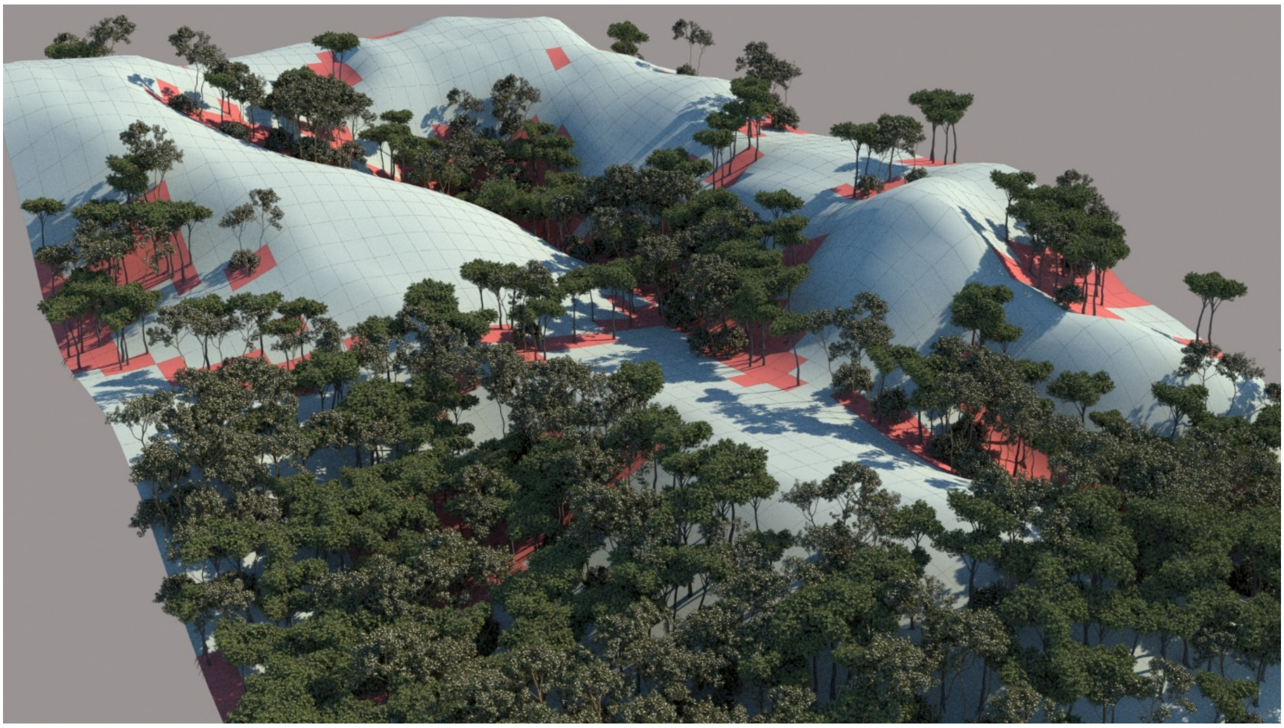


Figure 83: High water-users occurrence controlled by both altitude and concave areas.

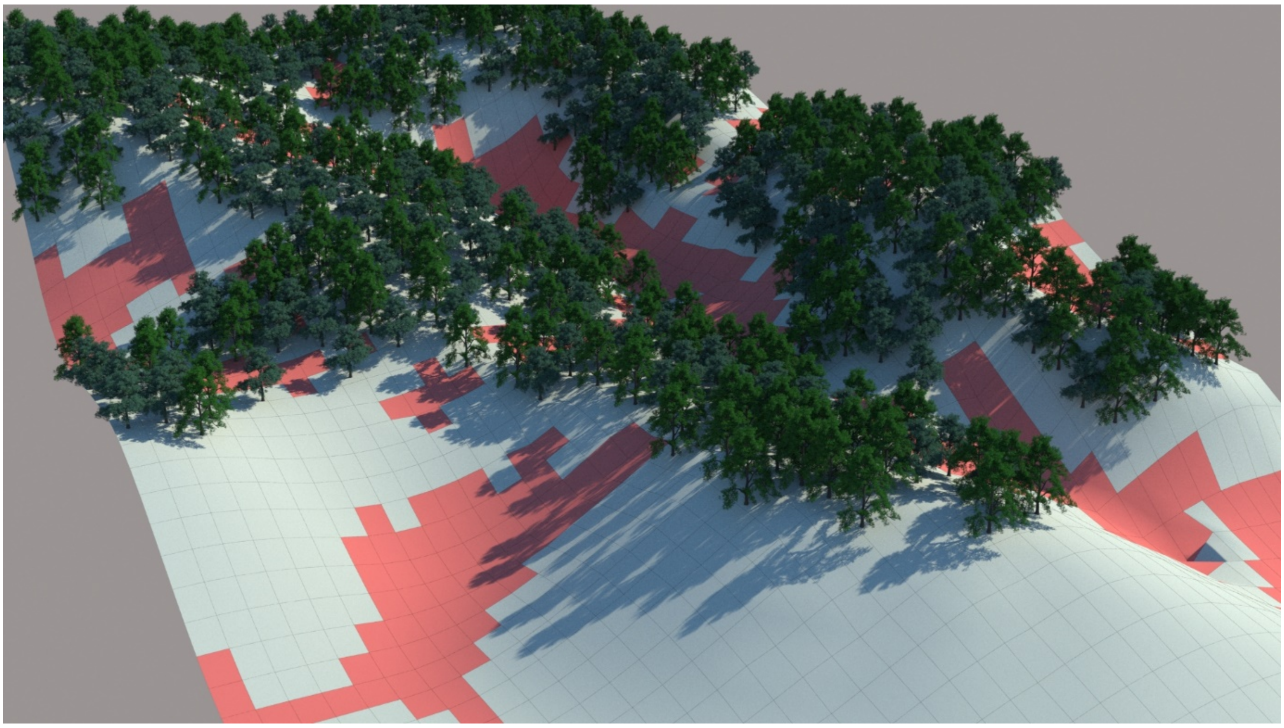


Figure 84: High rainfall interception plant community, occurrence altitude and concave slope controlled.

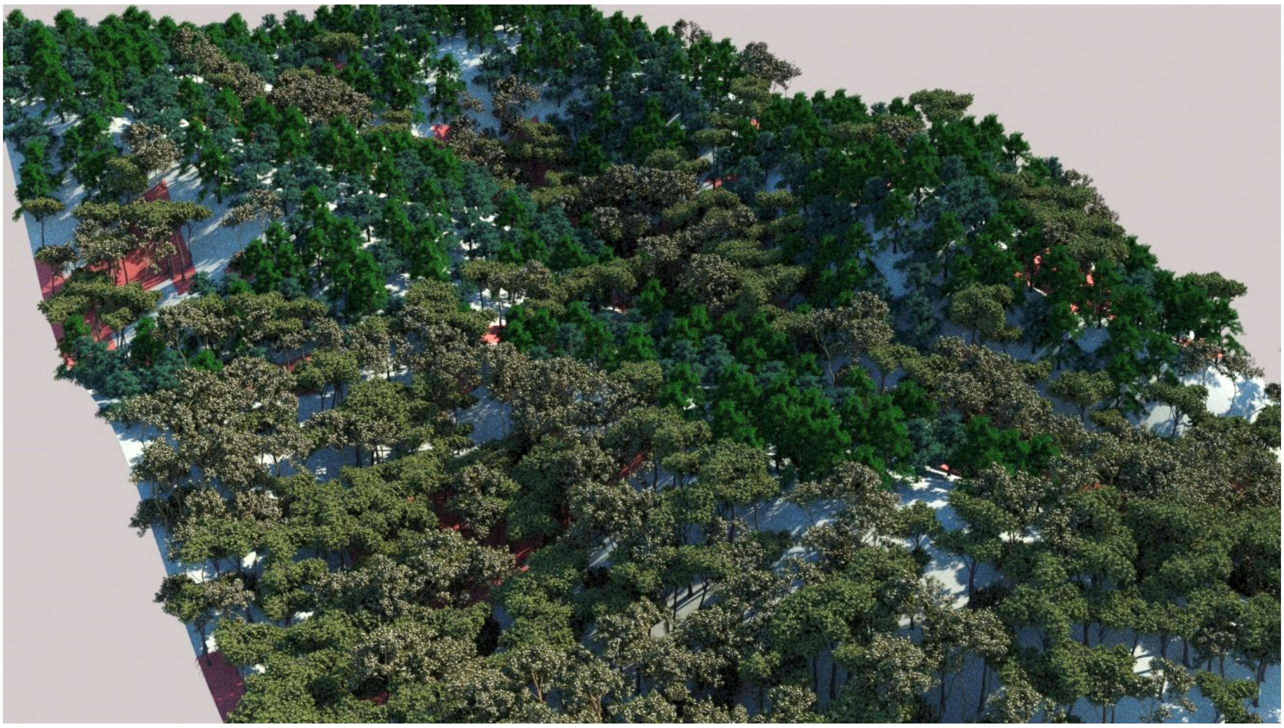


Figure 85: All three plant community scatters.

Outcomes

The vector TIN based method was highly successful and flexible for controlling the site-specific occurrence of plant communities on a site with intense slope and altitude variation. However, on sites where there is less variation in these values it may not be appropriate. Highly detailed TINs are required for micro scale grading and drainage for built systems and structures such as roads, kerbs and house lots but they are computationally expensive due to the high number of polygons required to accurately describe the topology of a terrain surface (Li et al., 2004). Coupled with the high polygon count of tree geometry models this method may currently be too computationally expensive and may need to be reserved for 'whole of catchment' considerations rather than more detailed site-specific applications or meso and microscale impact assessment. In the next petri-dish I investigate a less computationally expensive method for representing topographic form; the raster-based (image) Digital Elevation Model or DEM.

5.3.3 Trees and flood: DEM approach to species selection

This 'petri-dish' responds to the key challenge of integrating multiple possible flood scenarios into tree-scape decision-making for flood adaptation. The alternative approach to using a TIN mesh to drive species distritribution is to use the pixel intensity based method used in raster-based Digital Elevation Modelling (DEM). DEMS are grey scale images, of which each pixel has a single Digital Number (DN) denoting pixel brightness. This DN can be translated into a measurement of height (2.5 dimensional), the brighter the pixel the higher the altitiude. This system allows a much more computationally efficient storage method for large and complex sites. A grey scale image such as the gradient ramp in Figure 86 below, can be used in much the same way as a DEM representation of elevation through its single (DN) which represents light intensity. Any binary condition can then be represented.

In Figure 86 below, pixel DN values are used to drive both the density and scale of the geometry objects within this scattering of tree models. This is done using the 'density by map' effect within the proxy-object scattering plugin to the base platform. The default setting takes higher brightnes levels as higher density. However – both effects need to be inverted to represent the phenomena of healther and more densly distributed trees occuring in valleys rather thean hill tops.

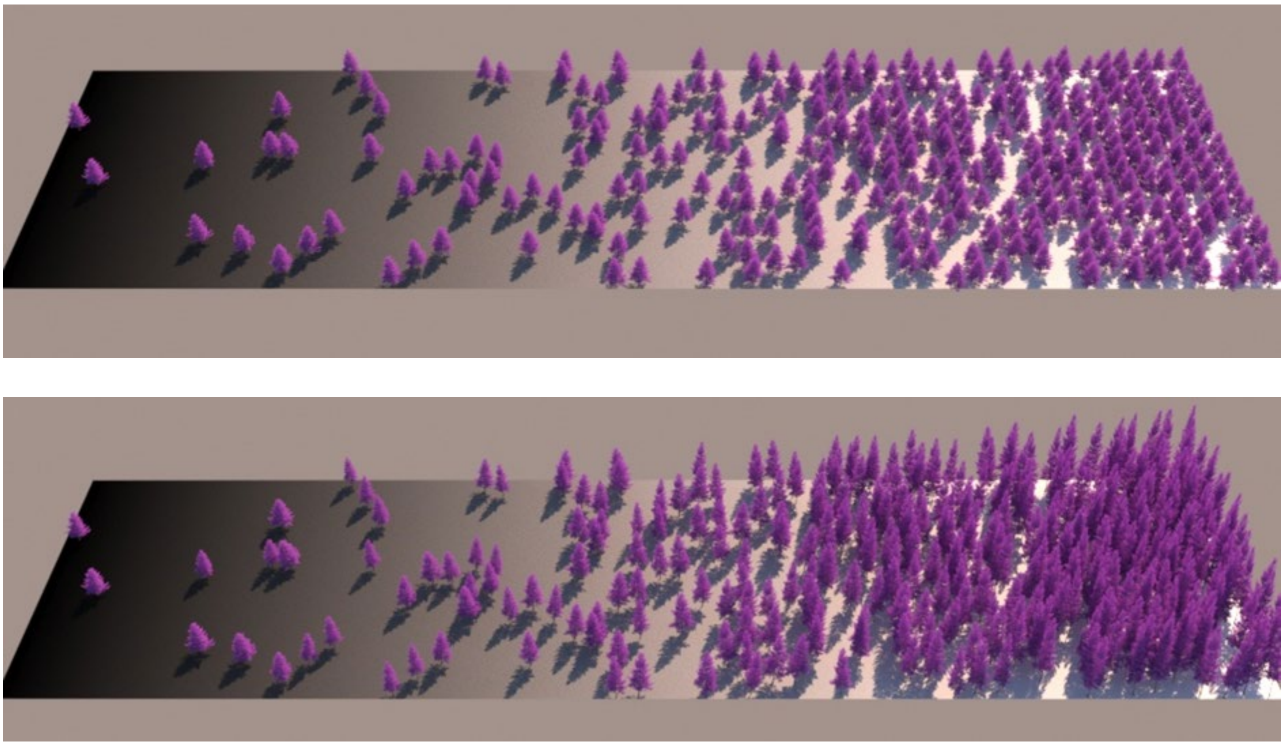


Figure 86: Top diagram showing gradient ramp driving distribution density, bottom diagram showing gradient ramp driving both distribution density AND growth habit (in this case height).

Outcomes

Using a texture mapping approach, a 2D grey scale image generated from flood mapping could be geolocated over a city model, with the pixel intensity used to denote flood depth.

Though it might seem analogous to build a model of a site which floods without including the topography as a 3-dimensional mesh it is entirely possible to do so and has the co-benefit of avoiding issues of data or analysis replication which occur when consultants use a different topographic model, software or methods for flood simulation. The same technique could also be applied to soil conditions such as salinity gradients to select for salt tolerance but also to light conditions such as overshadowing in higher density development to select for shade tolerance [this will be explored further in Chapter 7: *Synthesis City (hot flooding city)*].

5.3.4 Trees and flood: Closing loops between management and design

This 'petri-dish' test responds to the key challenge of the divergence between tree management practices and tree-scape design. In this 'petri-dish' a spatial data set of tree records for the City of Port Philip, which were made publicly available in 2017 were used to inform a spatially explicit 1km square model visualisation model of a portion of Elwood's urban trees. Within the GIS environment (QGIS) the tree species were grouped by visual similarity i.e: *Corymbia sp. Eucalyptus sp*. and *Angophora sp*. are all grouped under the common term Eucalypts, as they are visually very similar. The RGB values for each group were recorded, and these values were used to inform the colour ID for the visualisation tree geometry model.

To bring the data into the visualisation environment, I printed the tree data as a map with discrete RGB colour values for each visually common plant group. That map is then imported into the 3dsMax site model, via AutoCAD to retain geo referencing.

Figure 87: Street trees categorised into 16 visually distinct groups B) a sample of an RGB image of grouped species (created using QGIS) used to input into 3ds Max model.

I selected a 3-dimensional tree geometry model to represent each plant group. Each geometry tree model was named to correspond to the group and each was given an RGB colour ID which corresponding to the RGB values assigned to the tree point data. By adding the map to the distribution area only models with the corresponding RGB colour ID could occur in those locations the result can be seen in Figure 88.

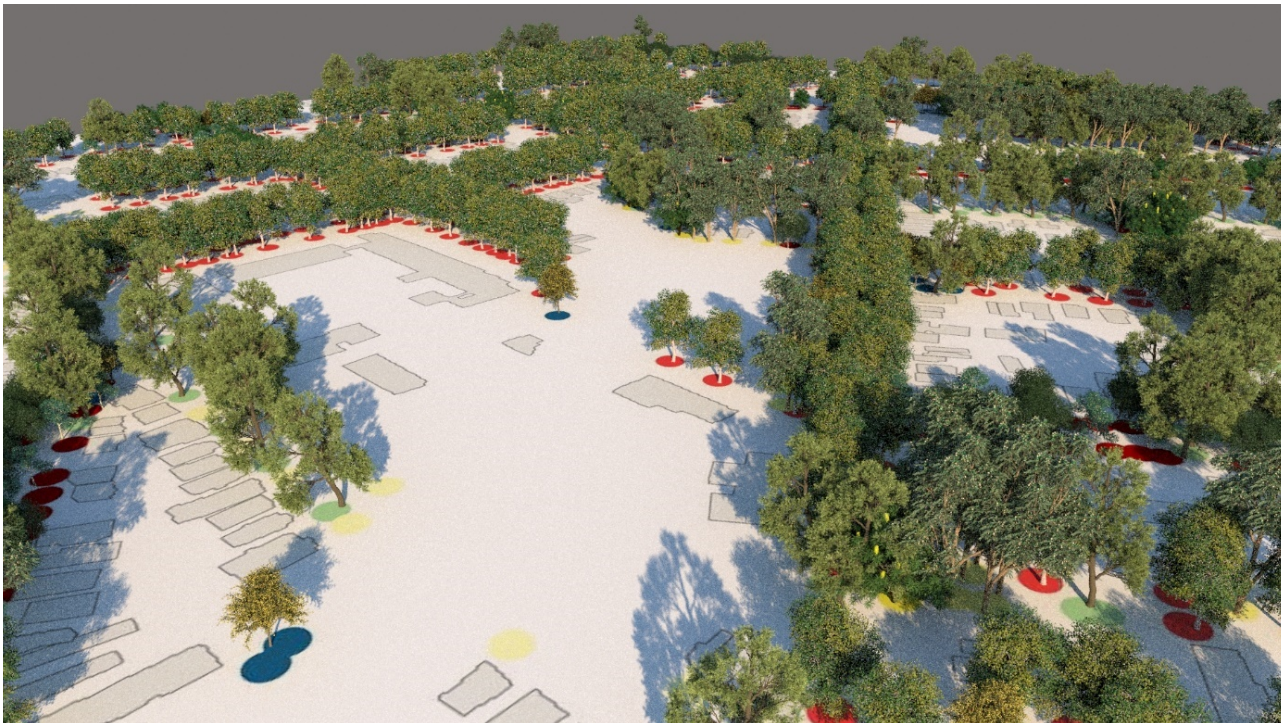


Figure 88: 3d visualisation of tree inventory data classified into visually similar groups and visualised on a map. The map RGB values were then used to drive the suppression or occurrence of representative tree models (Building footprints in grey are left 2-dimensional for clarity).

This process allows a realistic 3-dimensional representation of an area of existing public trees. This petri-dish test was developed after the application of the DDSS to the case-study site, which was completed before detailed data was available. In the case study, existing trees were approximated from aerial photography and single 3-dimensional tree was used. Despite the fact this process was not used for the case study I have included it here as it has the capacity to close loops between GIS based management and tree-scape design decision visualisation. All proxy-object scatters can output cartesian position coordinates and number of models to an .xml format. What this means is that this process could be run in reverse. A tree design can be generated in the modelling base platform and then exported back into a GIS environment, enabling instantaneous feedback into tree quantities and future tree locations or into modelling of green infrastructure scenarios. This 'petri-dish' developed ways of closing loops between GIS based tree management and cartesian based tree-scape scenario design. There were however some limitations to the translation of RGB intensity. Where colours are very similar for example more than one tree geometry model may be placed in a single location and where map circles overlapped models would occasionally be supressed.

5.4 Umbrella City case study, DDSS application

In this section, I bring together the DDSS processes developed in the petri-dish tests and apply them to a lower-catchment site facing extensive streetscape change for adaptation to future flood. I have chosen to apply the DDSS to Elwood, a coastal suburb to the south east of Melbourne at the lowest elevation point of the Elster Creek catchment, within the Local Government Area (LGA) of Port Philip in Victoria [Figure 89]. Prior to European settlement Elwood was a swampy flood plain which most often drained into localised sub-catchments and only occasionally out to Port Philip Bay (MMBW, 1979). The swamp land was reclaimed and the Elster Creek channelized in 1890, but some areas were left below flood and high tide levels, meaning Elwood can still flood if it is not raining but the tide is exceptionally high (MMBW, 1979). Housing in Elwood is predominantly single or at most double story and Elwood's urban forest (due to abundant water availability) is one of the best in Melbourne.

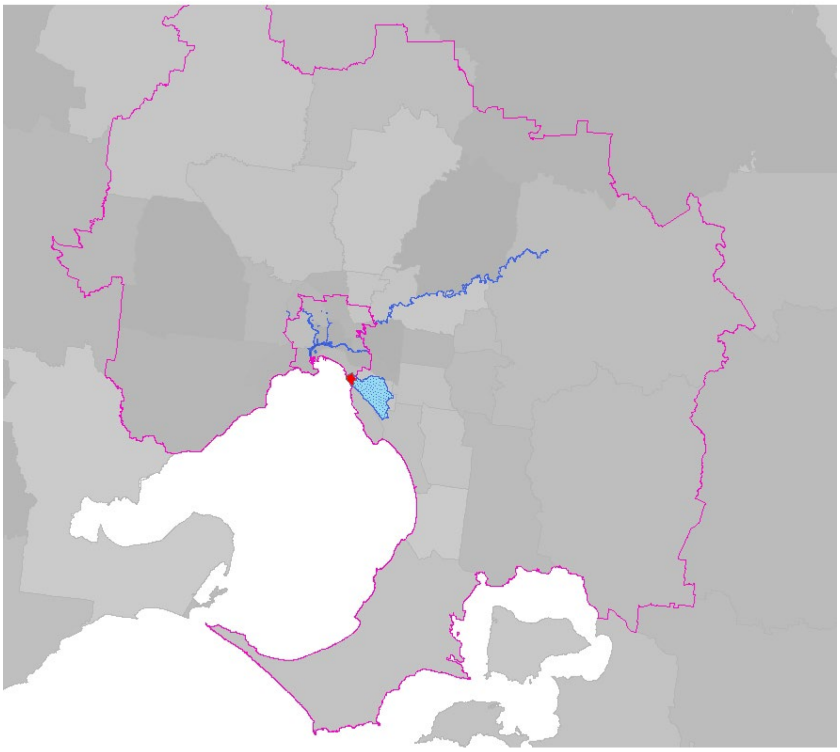


Figure 89: Elwood in red, with the Elster Creek Catchment outline, the inner councils of Melbourne in shades of grey and the Greater Capital City Statistical Area of Melbourne (GCCSA) shown as the outside pink boundary (created using QGIS).

5.4.1 Why Elwood?

In 2012 Melbourne Water released the document *Planning for Sea Level Rise* (2012). The report discusses the impact of the predicted increase of .8m in the 100-year flood level by the year 2100, on flood prone areas such as Elwood in the Port Phillip and Western Port Region of Victoria. Elwood. Under this sea level rise scenario, the channelized creek will no longer be effective for draining overland flow into the bay and will instead act as a conduit for sea water to flow inland. The complex nature of Elwood's future flood made it the subject of flood modelling research within the CRC for Water Sensitive Cities in 2014-16, who developed an urban storm water modelling approach which allows analysis and simulation of iterative urban flooding scenarios. Their research forecast the detailed implications of sea level rise and the multiple possible hydraulic futures of Elwood (Rogers et al., 2016; Urich & Rauch, 2014). In this case study I investigate ways of integrating their findings with streetscape decision-making.

Application of the DDSS and a visual-functional approach to the streetscape adaptation of Elwood is particularly fitting. Critical to Elwoods' future is the decision-making and shared vision of implementation of SSWMS, not only within Elwood, but also across the four LGA's that the Elster Creek catchment spans.

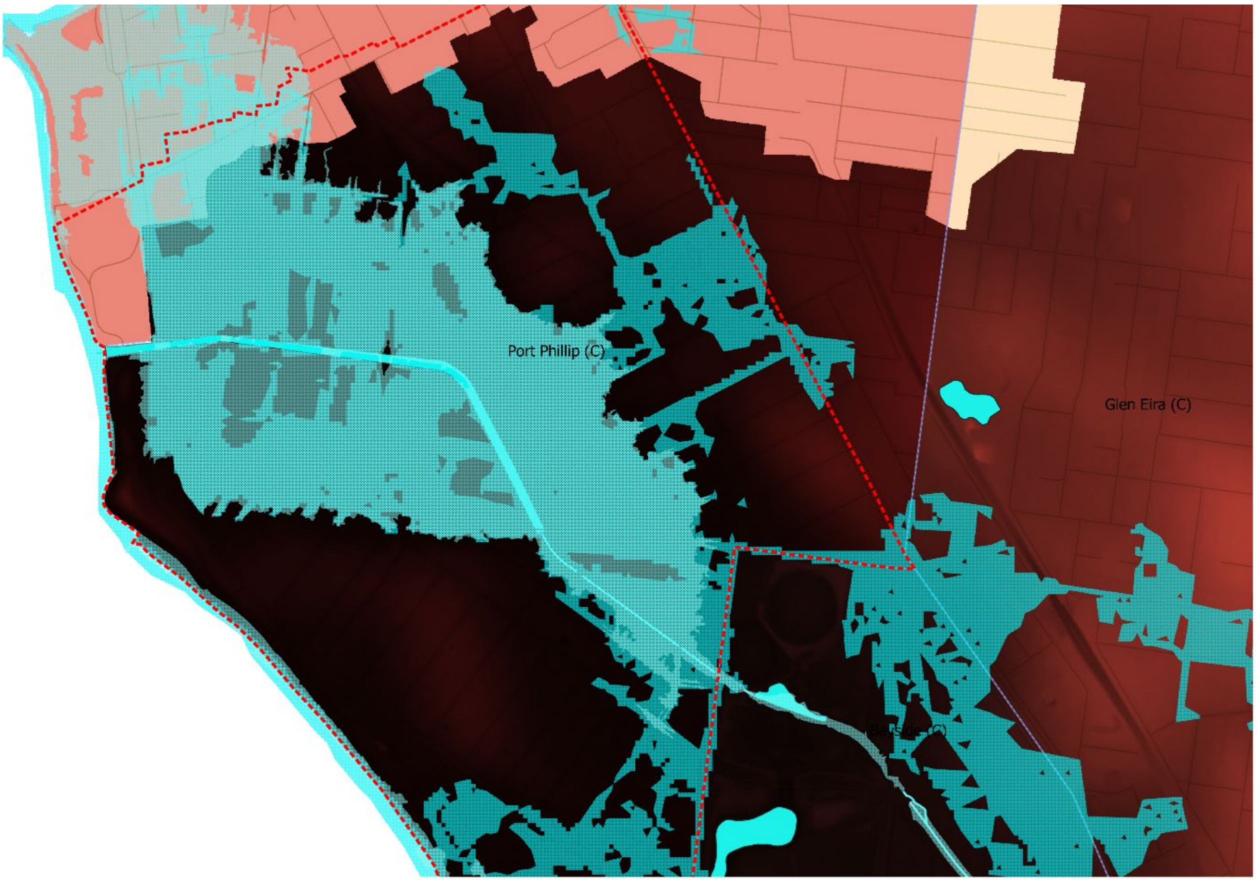


Figure 90: 1: 10,000 Overlay of Melbourne Water .8m sea level rise Elwood flood impact 2100. 1% AEP with CRCWSUD 2100 sea level rise flooding showing additional affected areas (Rogers et al., 2016; Urich & Rauch, 2014) (created using QGIS).

5.4.2 Elwood's existing urban forest

The urban forest of Elwood is considered iconic. Large healthy 1930-1940's plantings of *Platanus × acerifolia* (London Plane) and *Ulmus procera* (Dutch Elm) line streets which lead down to the native planting of coastal species at the foreshore. Elwood's' public urban forest (streetscapes and parks) has an inventory of 7,800 trees, of which 50% (3,900) are street trees. While Elwood's public trees are dominated (68%) by evergreen species, such as *Allocasuarina sp*. (She-oke) and the closely related genera *Eucalyptus, Corymbia and Angophora* (Eucalypts). These native species are predominantly found on the foreshore [refer Figure 91]. Of Elwood's street trees 61% (2,400) are the historically significant, deciduous Dutch Elm and London Plane.

Figure 91: Map showing the breakdown of evergreen (in dark green) to deciduous plantings (pale green), overlaid with the flood scenario mapping 2100 by the CRCWSUD (created using QGIS).

The impact of future flooding on Elwood's' public trees

To see what impact the flood scenario forecasting would have on the existing public trees I brought the street tree inventory data together with overlays of the detailed flood modelling undertaken by the CRCWSUD in QGIS, the open source Geographic Information System [refer 4.4: *QGIS and ArcGIS*] [refer Figure 92]. This revealed that 36% (2,800) of all of Elwood's urban forest (street and park) could be impacted by future flooding, 71.5% (2,000) are on streets and 70% (1,400) of those are the iconic traditional historic plantings of London Plane and Dutch Elm. Elwood can expect to see more than half (58%) of these traditional plantings needing to be replaced[188].

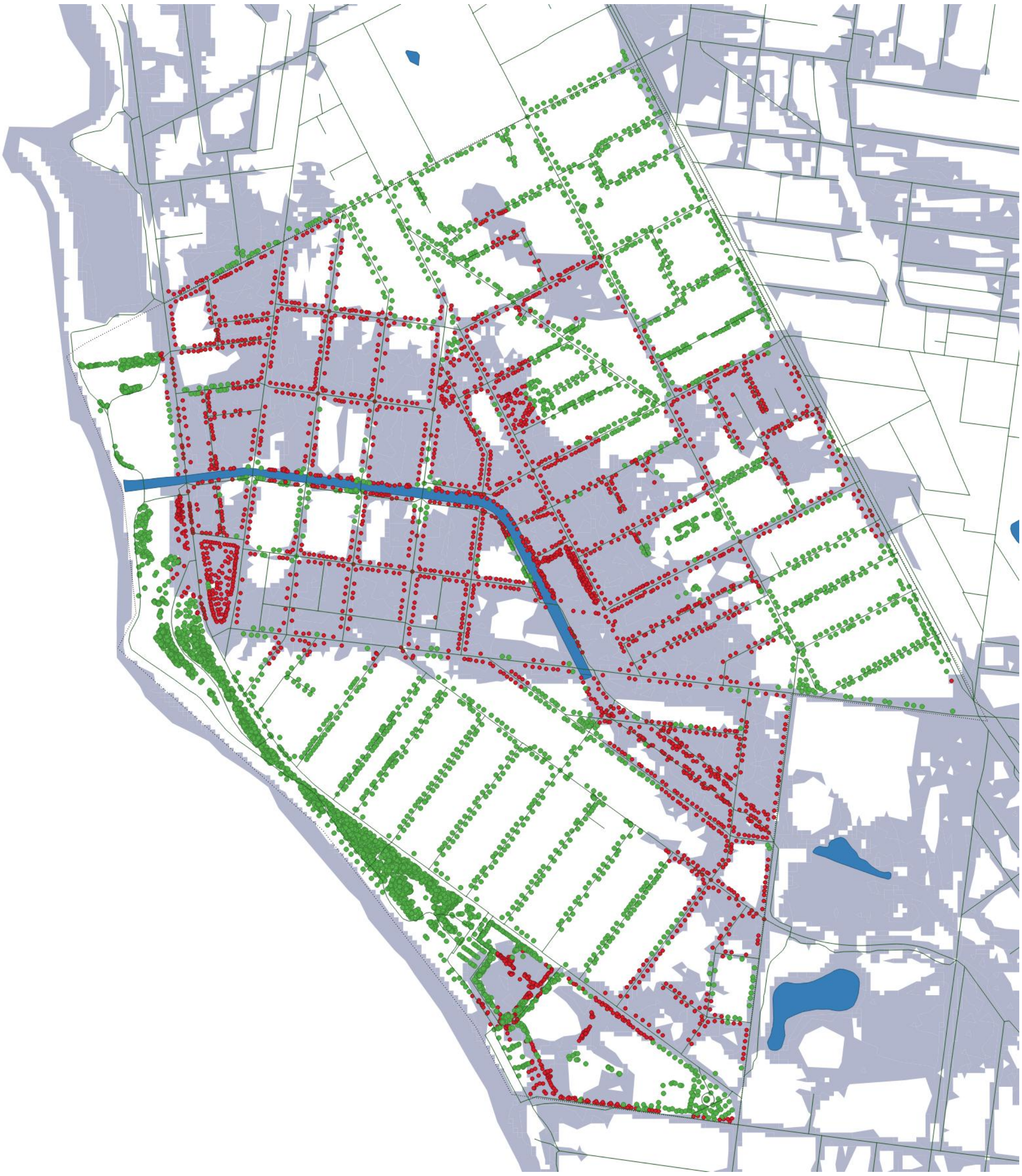


Figure 92: The street trees of Elwood which will be impacted by flood by 2100 shown in red over the future flood forecast mapping of the CRCWSUD (created using QGIS).

5.4.3 Scenarios to be tested

Based on the research developed by the CRCWSUD and long-term weather data from the Bureau of Meteorology [1.1.8: *Research context*] I developed two possible hydraulic futures

[188] As analysed through the useful life expectancy attribute in the dataset.

for Elwood in the year 2100, which would necessitate extensive changes to the existing urban forest of Elwood.

Hydraulic futures

Hydraulic future 01: (storm water) Long-term changes in weather patterns arising across southern Australia of annual rainfall decline and increased occurrence of extreme weather events: increased intensity of storms of short duration (flash flooding and more frequent AEP) and increased occurrence of drought (BOM, 2015b, 2015a). In this hydraulic future, there is a reduced water budget which negatively effects trees *outside* the flood zone.

Hydraulic future 02: (sea water) With a sea level rise of .8m by 2100 and associated possible saline intrusion into the water table (Melbourne Water Corporation, 2012; OzCoasts & Geoscience Australia, 2019), trees in the flood zone could periodically experience long inundation from either rising ground water or tidal storm surge. The anerobic and saline soil conditions in this scenario impacts trees *inside* the flood zone negatively.

Hydraulic future 03: Brings these key challenges together. Elwood is affected by both changes in weather and sea level rise, necessitating changes to trees both inside and outside the flood zone.

Figure 93, shows a visualisation of these hydraulic futures at catchment scale using the DEM of the Elwood imported in to the base platform of as a texture map and used to displace a plane according to the DN values of the DEM pixels [refer 5.3.2]. I applied a proxy-object scattering of tree models to this terrain. For Hydraulic future 01. I controlled the scale and density of the models according to elevation (increasing scale in the lower elevations), and for Hydraulic future 02. I reversed this scaling and density by altitude parameter.

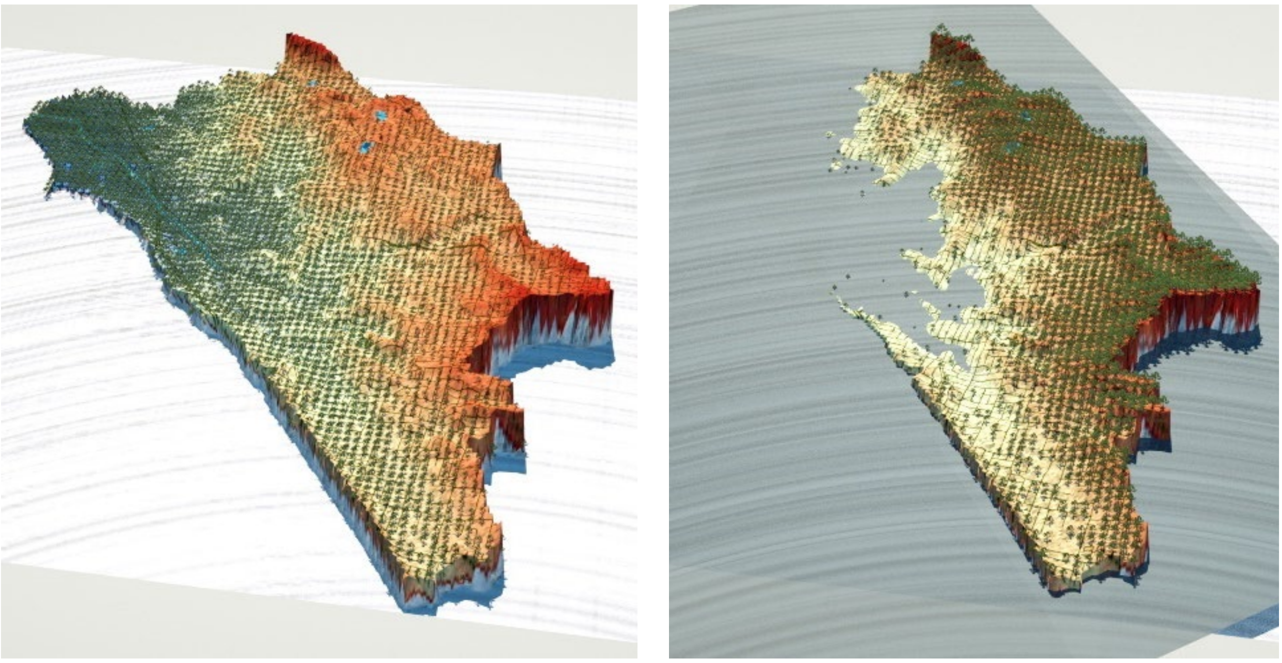


Figure 93: Hydraulic future 01 (LEFT), where trees at the base of the catchment in the flood zone are the healthiest as they have the highest water budget and Hydraulic (RIGHT) where trees inside the flood zone die off due to prolonged periods of possibly saline inundation.

Scenarios to be tested

In this case-study, I developed and visualised three tree-scape design scenarios which respond to these hydraulic futures:

Scenario A: This scenario uses the principles of forest hydrology where trees in the lower-catchment grow more abundantly than trees in the upper-catchment due to increased water availability (Bren, 2015). In this scenario, trees outside the flood zone decline over the coming decades and need to be replace by drought tolerant species or phreatophytes with facultative ground water accessing capabilities and high-water use.

Scenario B: In this scenario, trees in the Elwood flood zone are replaced by plants which survive drought through fast growth rates. In this scenario it is accepted that trees in the flood zone will be subject to prolonged and saline flood and may periodically ‘drown’ due to anerobic soil conditions. In this scenario trees in the flood zone are replaced with fast growing, short lifespan trees such as *Acacia sp.* In the circumstance of prolonged flood these trees may be harvested and used for mulch.

Scenario C: Requires replacement of trees both inside and outside the flood zone as above.

5.4.4 Application of the DDSS

In the application of the DDSS to the meso scale precinct case study of Elwood, I used a combination of the raster-based distribution and the vector-based control of tree models [refer 5.3.2 and 5.3.3]. To construct the digital site model, I sourced contour data from VicMap (elevation data one to five meter contours), land parcel maps and street centre lines from (PSMA Australia Limited 2016), building footprints from (Melbourne Water Corporation 2018), street casements from (Vicmap Property 2017). These data are available through the Australian Urban Research Infrastructure Network (AURIN). Aerial imagery was sourced from NearMap. Figure 94 shows the digital site model with a flood forecasting map applied in black and white and existing building impacted by flood shown in blue (and classified by number of storeys). The NearMap imagery was also used to create black and white texture maps to drive existing tree locations as tree inventory data was not available at the time of this study. Instead, the aerial image thresholds were adjusted until green pixels could be isolated using Adobe Photoshop ™. This map was then overlaid with flood outline to generate two further maps A) existing trees inside the flood zone B) existing trees outside the flood zone [refer Figure 95].

Figure 94: Black and white flood driver map overlaid with building footprints. Dark blue buildings are 2 storey, light blue are single storey and grey buildings are unaffected by flood.

Figure 95: Existing tree data was not available at the time of this study, for the modelling a texture mapping approach was used. Aerial imagery thresholds were adjusted in Adobe Photoshop until green pixels could be isolated. These were then turned into alpha channel maps and overlaid with flood outline to ascertain two maps A) existing trees inside the flood zone B) existing trees outside the flood zone.

Site model construction

To construct the site model, I used a four-step process.

- I set up a GIS base file in which raster images were georeferenced, data was combined reprojected to a cartesian coordinate system (GDA94/MGA94 zone 55) ready to be exported to AutoCAD. Building footprints were also classified by height and flood or not flood effected in this file.
- I cleaned the linework in AutoCAD and specified the exchange point for insertion into the base modelling platform.
- In the base platform I created a TIN mesh using the contour data, extruded the building footprints to the specified number of storeys and projected the raster based (image) texture maps into the TIN mesh.
- Once the raster-based texture maps are accurately projected over the TIN mesh I applied three proxy-object 3-dimensional tree model scatters over the TIN, representing existing and proposed trees with and outside of the flood zone. Scatter 01: Existing trees in the flood zone, Scatter 02: existing trees outside the flood zone and Scatter 03: Proposed trees in the flood zone and Scatter 04: proposed trees outside the flood zone.

5.4.5 Results

Scenario A: Trees outside the flood zone are replaced with phreatopytes

Figure 96 shows a visualisation of the effect of a reduced water budget on the trees outside the flood zone and the survival of existing trees within the flood zone.

Figure 96: In scenario A, reduced and more erratic rainfall events impact the survival of trees outside the flood zone. Tree species in the flood zone remain the traditional Dutch Elm and London Plane.

Figure 98 shows the Dutch Elms and London Planes of Elwood's existing streetscapes outside the flood zone replaced with the evergreen phreatophyte Banksia species. While there are differences in the functional capacities of different Banksia sp. to facultatively take up ground water, they are visually similar enough to one another to use an indicative 3-dimensional Banksia tree model [as seen in Figure 96, Figure 98, Figure 99].

Figure 98 shows the same scenario in autumn, where leaves of the deciduous Elms and Planes have browned. I achieved this effect by procedurally adjusting the colour of the leaves on the 3-dimensional models representing those species. Figure 101 shows the scheme rendered at a closer scale, focused along the channelized canal. While ideally the system would allow for even closer detail, the building footprint data was quite poor quality.

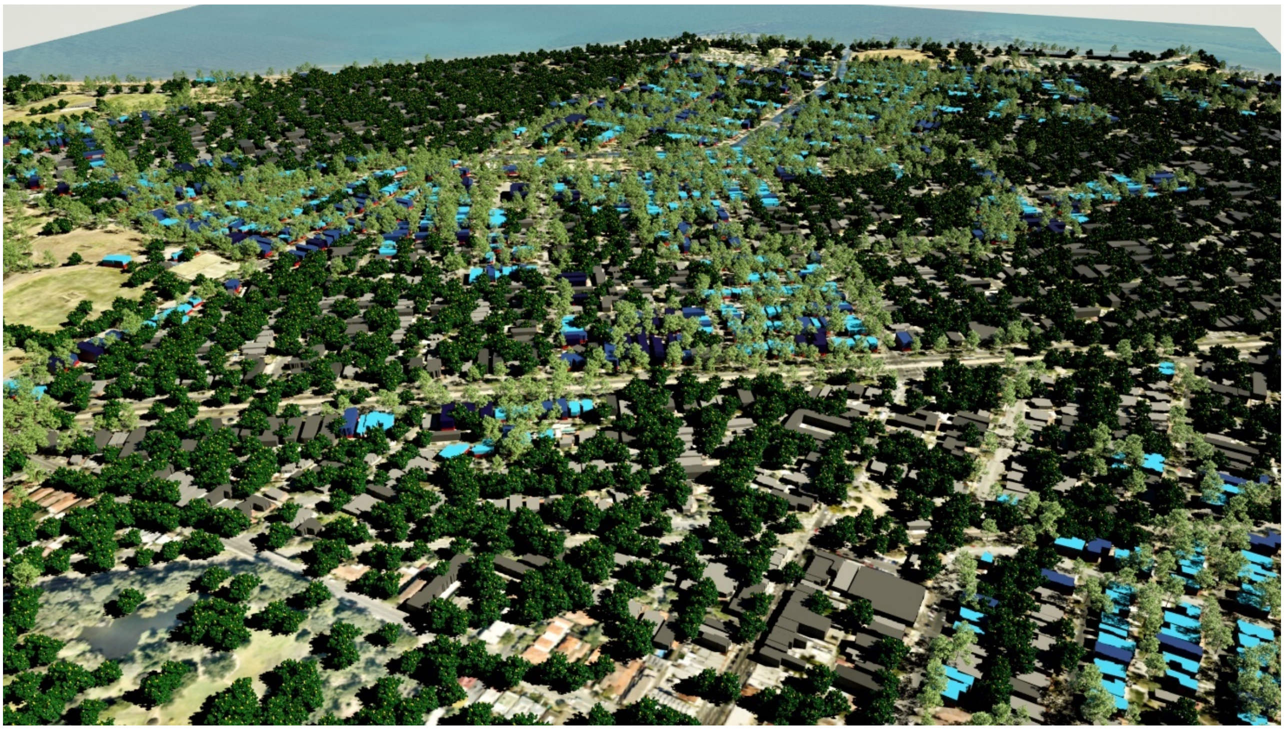


Figure 97: Elwood's existing street trees outside the flood zone, replaced with Banksia sp., inside the flood zone traditional existing Elms and Planes survive.

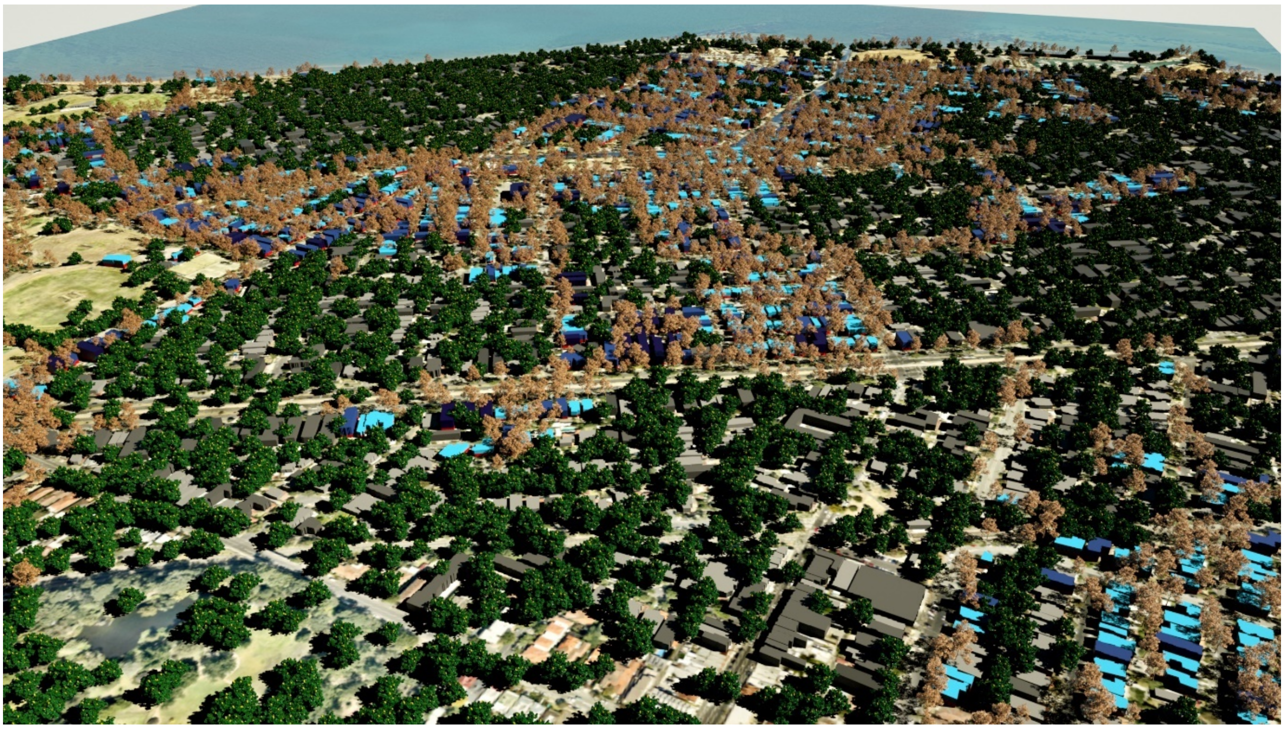


Figure 98: An Autumn render of the deciduous Elms and Planes in the flood zone, with Banksia sp. Outside the flood zone.

Figure 99: Scenario A: Reduced rainfall. Trees outside the flood zone are replaced with ground water utilizing species, Banksia sp.

Scenario B: Periods of prolonged flooding

Figure 100 shows a visualisation of the mass die off trees from prolonged inundation inside the flood zone. Existing trees outside the flood zone remain healthy in this scenario. In this circumstance leaves were removed from the tree models used in the scatter representing flood zone trees, leaving just the bare branch structure. Figure 101 shows a detailed view of this die off.

Figure 100: Scenario B: Prolonged inundation and drought. Traditional species (Elms and Planes) survive outside the flood zone.

Figure 101: Scenario B Existing trees in the flood zone die in the event of prolonged flood, traditional Elms and Planes survive outside the flood zone.

In this case the 3-dimensional tree model in the proxy-object scatter representing trees in the flood zone are replaced with 3-dimensional tree models of Acacia sp. [refer Figure 102, Figure 103].

Figure 102: Scenario B Existing flood zone trees are replaced with a species capable of very fast growth (Acacia sp.). These trees would be harvested in the event of prolonged inundation.

Figure 103: Scenario B Fast growing replacement species (Acacia sp.) in the flood zone, looking back from Port Philip Bay.

Scenario C: Bringing A and B together

As there is every possibility that both hydraulic futures A (increased occurrence of storm water flooding) and B (increased occurrence of prolonged flooding to sea level rise) will happen simultaneously, I brought the two tree replacement strategies together in a final scenario (C). Figure 104 shows the Banksia sp. replacing the trees outside the flood zone and Acacia sp. replacing trees inside the flood zone.

Figure 104: scenario C where both long periods of inundation as well as reduced annual inflow happen simultaneously. The existing forest of North American Planes are replaced with Banksia and Acacia species.

5.5 Discussion and conclusion

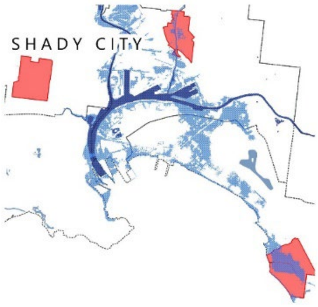
In this chapter I tested the application of a Design Decision Support System for working with flood forecasting data, selection of tree species for flood adaptation and production of traditional design communication visualisations.

Urban water futures have multiple possible outcomes which require an iterative approach to urban drainage decision-making (Urich & Rauch, 2014). Tree-scape decisions are heavily dependent on those urban drainage decision outcomes, so it is important to develop ways to model urban tree and flood forecasting interaction. Substantial visual change to urban streets is required if the functional attributes of trees in those streets are harnessed in adaptation to future flooding. Using evidence-based decision-making, research suggests that planning tree planting for flood mitigation will require greater use of high-interception and high-water use species which are a departure from the current aesthetic of street trees in Elwood.

Using spatially explicit visualisation of tree changes, over accurate topographic site models may be a way to assist public acceptance of environmental decision-making and promote discussion around new tree management strategies such as managing for tree longevity and risk (Dobbs et al. 2014). Using the DDSS modelling framework for the creation of these visualisations allows for a number of additional benefits. As the model is parametric species models can be interchanged. High water-use species need not be native, the US origin *Taxodium distichuum* can tolerate long periods of inundation and the Chinese *Paulownia tomentosa*, known as the fastest growing species in the world could be used instead of the Acacia sp.

While the model works over an accurate topography model it is not necessarily useful to re-simulate flooding in this tree decision model as doing so could lead to errors or ambiguity in flood extent. Using the texture-based raster method is for representing flood is quick, polygon efficient and easily iterates through multiple flood forecasting scenarios. While evergreen trees might be the best for flood mitigation and would also be efficient for provision of shade they would also not necessarily be the best choice for urban conditions where overshadowing becomes a problem in winter. What this chapter doesn't do is consider other urban tree planting criteria. What if mitigating urban heat or increasing walkability, or minimising winter overshadowing was the primary objective? How would tree planning criteria be developed for that?

Chapter 6: Shady City



[…] government policies need to actively pursue land-use planning and urban design interventions that encourage a modal shift towards walking, cycling, and low-emissions public transport to influence the overall health of growing city populations (Stevenson et al., 2016).

6.1 Introduction

In the previous chapter I use the visual-functional DDSS to work with tree-scape considerations for adaptation to flood. In this chapter those considerations shift away from flood, towards protection from solar exposure for active transport modes. Where tree-scape flood decisions relate to the macro-scale of hydrological catchments, tree-scape decisions for solar protection are more meso and micro scaled. In this chapter I investigate ways to optimise tree shade for active transport corridors (bike and footpaths) at a meso scaled walking catchment of a typical eight-hundred-meter radius and at the micro-scale of individual streets. Alongside the shift in scale considerations between tree-scapes for flood and tree-scapes for cyclist and pedestrian solar protection, there is also a temporal shift. Unlike flood which occurs in unpredictable sporadic episodes, requiring one-in-one-hundred-year considerations, the problem of solar exposure has a constant seasonal and diurnal pattern. It occurs in summer months and has an Ultra-violet radiation (UV) peak at 12pm and a heat peak between 15.00-16.00.

Reducing urban heat stress and UV exposure, while simultaneously encouraging uptake of active transport are contradictory issues facing urban design streetscape decision-makers (Tait, 2011). On the one hand, increasing occurrence of heat related mortalities and skin cancer have led to recommendations to limit outdoor exposure (WHO, 2018). While on the other hand, increasing occurrence of human health problems related to a lack of physical activity, have led to recommendations to increase active transport such as walking and cycling (VDoT, 2019). Tree shade can protect active transport users from UV and heat exposure, but only if the canopy of the tree has the required dimensions and trees are positioned in relation to the sun. If tree shade was to be optimised to protect pedestrians and cyclists, departures from traditional species and streetscape configurations will be needed, and those departures will need to be negotiated in public participatory decision-making (PPD) forums.

6.1.1 Aim

The aim of this chapter is to investigate the possibilities of applying the visual-functional DDSS to quantify and optimise footpath shading in pedestrian walking catchments, whilst still communicating traditional visual design performance objectives.

Key Question: *Can environmental performance, spatial constraints and visual impact be integrated into a tree-scape design process?*

Sub Question 01: *Can we utilise growing availability and accuracy of spatial data sets in street-scape design decision-making?*

Sub Question 02: *Can we combine and apply emerging modelling technologies in the entertainment industry (gaming and animation), digital procedural tree modelling, with computer aided design (CAD) and geographic information systems (GIS)?*

In section 6.2 of this chapter I look at the key challenges of tree decision-making for the function of reducing solar exposure of active transport users. While street trees can function to reduce solar exposure of pedestrians and cyclists, the capacity to adjust street configurations for this function is constrained. On the one hand, there are clearance requirements for infrastructure, service and transport and on the other hand there are traditional visual community expectations / preferences. Traditional design methods which are not spatially explicit would be difficult to use to negotiate these functional, visual and spatial constraints.

In section 6.3 of this chapter I develop a series of digital-physical modelling prototype tests (petri-dishes) where I isolate the specific factors and variables involved in making functional solar exposure reduction, tree decisions for streetscapes. I investigate how the DDSS can be used to work with the interrelated variables of solar geometry; street configuration, street orientation, critical footpath use times and tree canopy growth dimensions. Through the petri-dish tests I develop a spatially explicit way to use the DDSS to simultaneously quantify shade outcomes and output imagery for qualitative visual impact assessment. I discuss the results of each of the petri-dish tests in relation to the specific conditions of the case study site.

In section 6.4 of this chapter I apply the DDSS to the Shady City case study, an 800-meter radius walking catchment of a school in the heat vulnerable western Melbourne suburb, Kingsville. I develop three tree-scape design scenarios for the walking catchment of children on their way home from school which balance between level of shade provision, with relative departure from traditional streetscape configuration.

6.2 Part 1: Key challenges

6.2.1 Solar exposure, and active transport

Active transport is associated with substantial human health and environmental benefits. Active transport contributes to individual rates of physical activity which is in turn associated with reduced risk of non-communicable diseases such as mental ill health and cardiovascular disease (Larouche et al., 2014; Sallis, Cerin, et al., 2016). The environmental benefits of active transport include reductions in carbon emissions, reductions in fossil fuel use, and reductions in air and water pollution (EEA, 2010). However, despite these benefits, rates of active transport use in areas, beyond high density urban cores are declining (Charting Transport 2014)[189]. Of particular concern, are the low rates of active transport for daily trips such as school journeys[190]. In Australia less than 30% of young children and 8% of adolescents achieve the Department of Health's daily activity recommendation (Department of Health 2017).

Many barriers to children's selection of active transport modes for this journey have been identified, including poor perceptions of child safety, aesthetics and comfort of the street environment and the risks of exposure to air pollution and harmful levels of UV, the

[189] Car use was found to exponentially increase with distance from urban cores Charting transport

[190] Charting transport: Data from 2007 to 2008 in Melbourne, Australia, showed that 42% of car trips between 3pm and 4pm, coinciding with typical afternoon school run, were reported as 'picking up or dropping off someone'.

leading cause of skin cancer worldwide (Bertazzon & Shahid, 2017; Dirks et al., 2018; Huang et al., 2015; Y.-J. Kim et al., 2018; C. Lee et al., 2013; Sweeney & Von Hagen, 2015). Minimising or removing these barriers can in part, be addressed through strategic placement and selection of trees.

6.2.2 Trees reduce heat stress and UV exposure

Tree canopy cover provides protection from both heat stress and UV exposure (Faulkner et al., 2009; Grant et al., 2003; Green et al., 2011). While tree shade is not the only factor which reduces urban heat and UV exposure, it is often the most important contributor. Tree shade has been shown to lower surface temperatures by up to 20°C (Holst and Mayer, 2011; Mayer et al., 2008) and tree canopies intercept significant amounts of UV radiation (Grant et al., 2003; Holman et al., 2018; Na et al., 2014; Parisi & Turnbull, 2014). Tree shade may only lead to a relatively small reduction in air temperature beneath the canopy, but the change in other climate factors under tree shade, such as relative humidity, wind speed, and overall radiation loads mean that perceived human thermal comfort is greatly improved (Sanusi et al., 2016) [refer 3.4.1: *Modelling tree heat moderation*].

6.2.3 The four variables of streetscape solar exposure

Solar geometry describes the position of the sun in relation to a specific point on the surface of the earth (geographic location). This relationship changes throughout the day responding to the earth's rotation (from day to night) and throughout the year, responding to the earth's orbit around the sun (summer to winter). Because of these constantly changing rotation and orbit, shade size, position and length are dynamic. Shade moves from east to west though the day and lengthens though winter. There are four variables which interact with solar geometry which govern the provision of shade from trees on streetscapes; these are geographic location, the time of day, street orientation and the spatial configuration of the elements of the streetscape. In established developments, only one of these variables can be adjusted; this is the spatial configuration of the street.

Street orientation

Figure 105 shows how street orientation impacts shade position. Using the geographically adjustable sun system included in the base platform of the DDSS and 3-dimensional tree geometry models in a cardinally oriented typical configuration (trees at the curb edge) streetscape. I rendered the tree shade cast at 15.30 on three days over the summer season, to create an aggregate shadow map. In this map the tree model itself is hidden. In these conditions, pedestrians would be solar exposed on the eastern side of north-south oriented streets and cyclists would be exposed on the western side of north-south and the south side of east-west running streets.

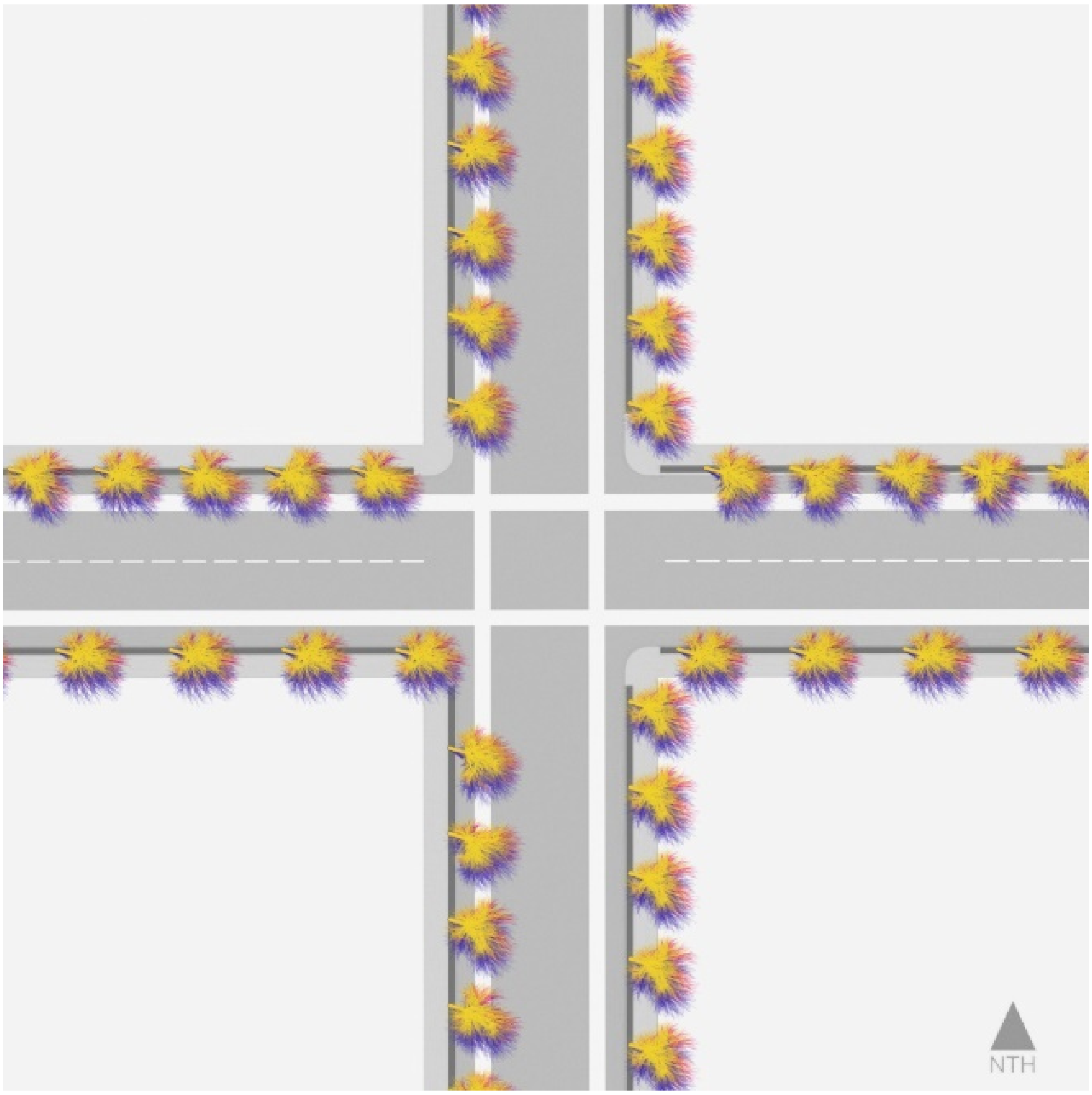


Figure 105: Street orientation impacts the position of shade: Aggregated shadow map summer season 15.30. During summer[191], pedestrians on cardinally oriented streets in Melbourne would be solar exposed on the eastern side of north-south oriented streets and cyclists would be exposed on the western side of north-south and the south side of east-west running streets.

[191] 15.30 November 21 to February 21st

Season

Figure 106, shows how seasonal change impacts the position of shade. In this aggregate shadow map, I rendered the shade of the 3-dimensional tree geometry models at 15.30 on four days in the year (mid-winter, spring, summer and autumn). The long mid-winter shadows are shown in brown, the short mid-summer shadows are shown in yellow and early spring shadows are shown in purple. This aggregate shadow map shows that intra-seasonal variation in shade cast is less dramatic than inter-seasonal variation in Melbourne.

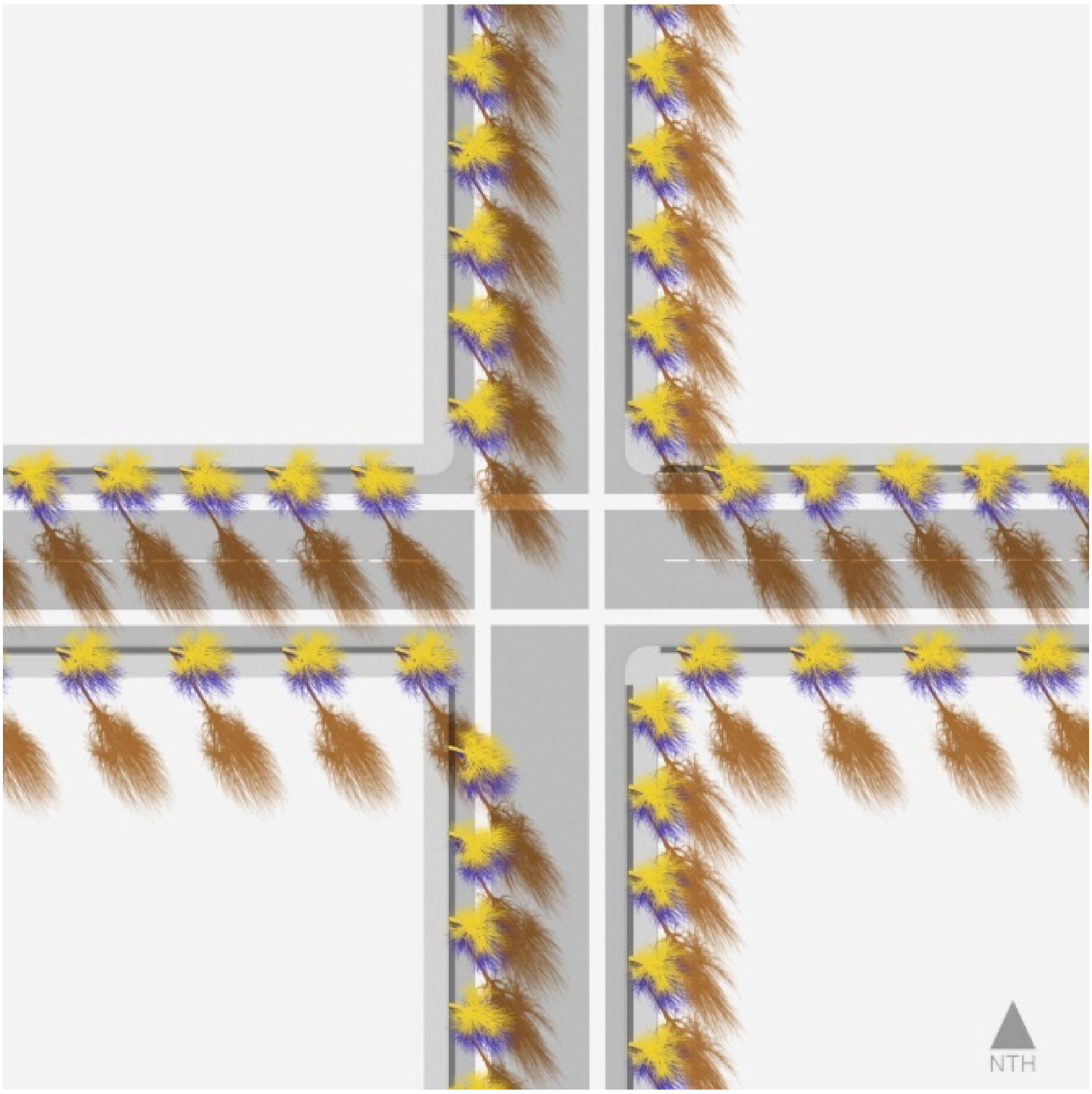


Figure 106: Seasonal impacts shade positioning Aggregate shadow map Annual shade variation 15.30. December (yellow) February (purple) and June 21 (brown).

Time of day

Figure 107 shows how time of day impacts the position of shade. In this aggregate shadow map, I rendered two-hour increments of shadow change over a single day in summer. This map shows that over the selected day, east-west oriented streets remain in shade while north-south oriented streets would have time dependant shade. In cases where active travel time is fixed, such as the homeward journey from school, better shading could be achieved by adjusting the configuration of the streetscape, integrating considerations of geographic location, season and street orientation. However, even minor streetscape re-configuration is complex, particularly in existing established street conditions.

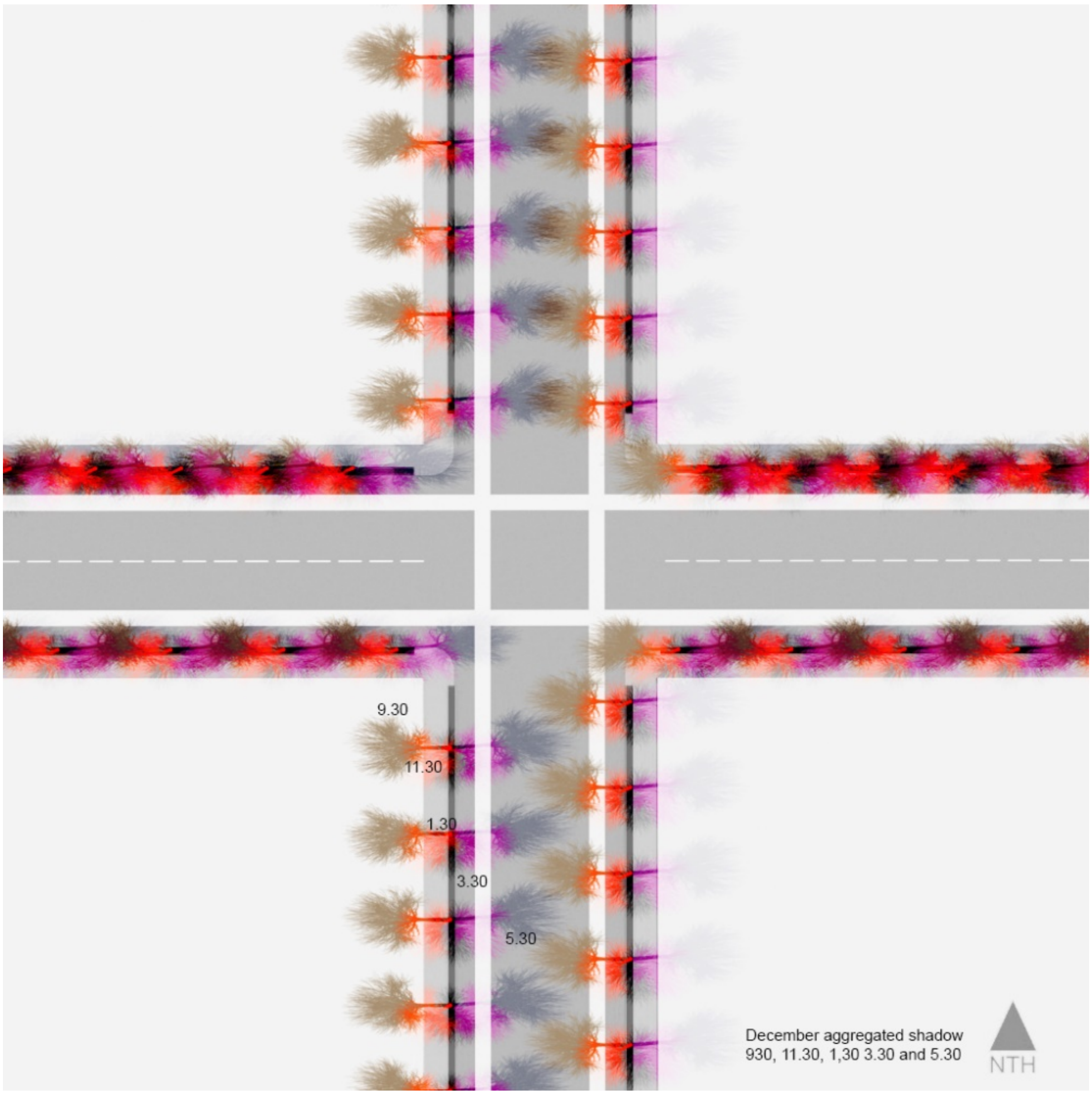


Figure 107: Aggregated shadow map for 1-day mid-summer 9.30 – 17.30.

6.2.4 The spatial constraints of street reconfiguration

Tree planting options are spatially limited in streets due to building vehicle access, vehicle visibility requirements and parking manoeuvre space [refer 3.5.1: *Transport planning*].

There are six available locations for tree planting in streets [Figure 108][192]. Each of these locations has varying degrees of achievability, outlined below.

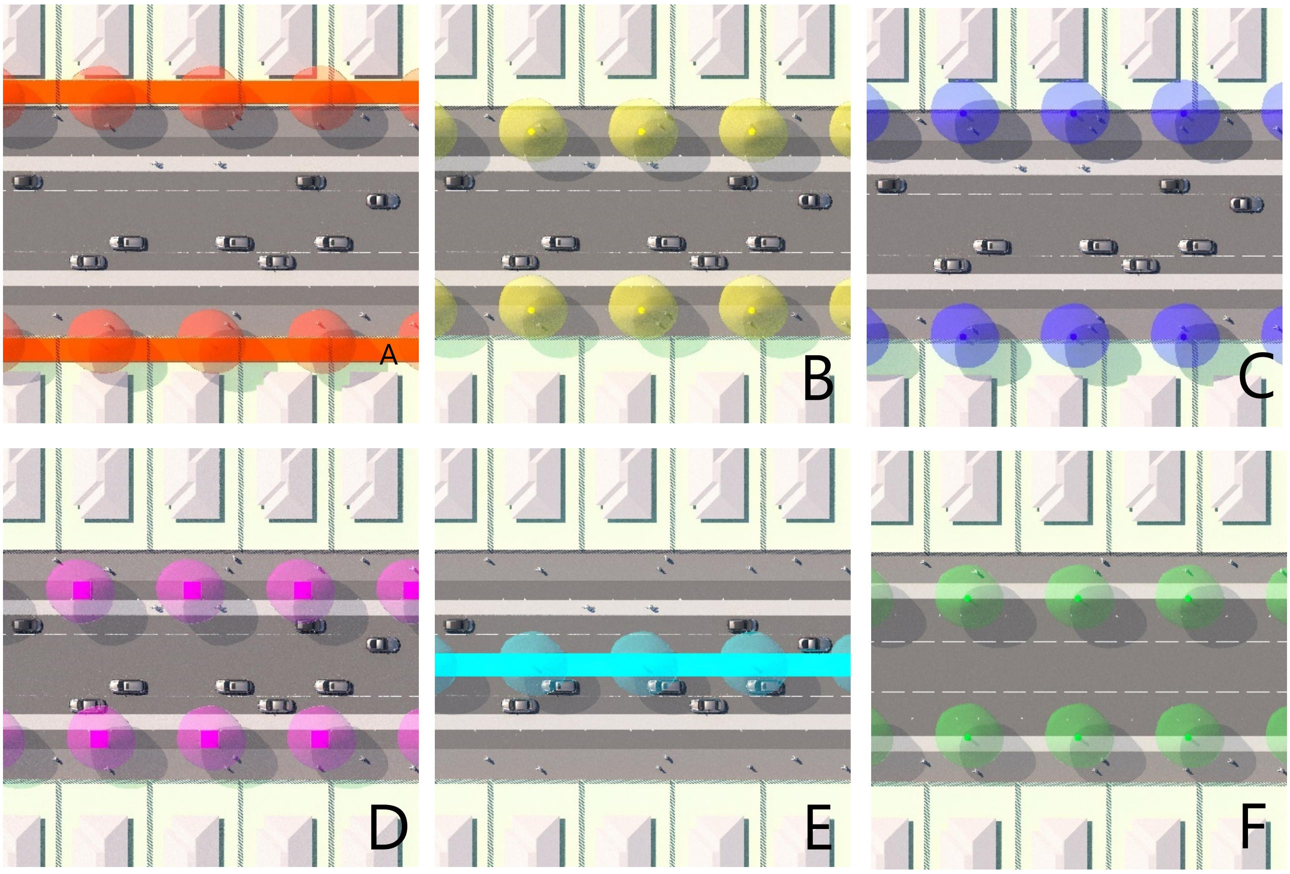


Figure 108: Six possible tree planting positions from top left: A) Trees in private front yards, B) Trees at the property boundary C) Trees at curb edge D) Trees between parking bays E) Trees in median/road planting F) Trees between the bike path and road.

Position A) Trees in privately owned front yards (red). This location can be controversial as there are substantial difficulties associated with regulating vegetation occurring within private property (Parmehr et al., 2016). While some planning policies in Australia stipulate inclusion of canopy trees in front yards, these are rarely regulated to specific street orientations or specific tree sizes (City of Brimbank, 2015; DELWP, 2019, secs. 55.03-8).

Position B) Trees on the property boundary (yellow) is unusual and can only be achieved where surrounding built form has a front yard setback. There can also be issues with conflicts between trees, front gates and fence footings.

[192] While unusual possibilities for tree placement have been trialled occasionally, such as in Leonard Circus, London (Jaluzot, James, and Pauli 2012) experimental tree locations still require a great deal of driver behavioural change to work effectively (Kennedy 2014).

Position *C)* Trees at the curb edge (purple), is the most common position for trees in streets in Melbourne, though there are often still conflicts with private driveway clearances [refer 3.5.3: *Land use planning*].

Position D) Trees between parking bays (pink), can be met with community resistance due to parking space loss and is also constrained by parallel parking bay dimensions and maneuverers. In general this requires a 14m spacing between trees (2 parking bays) (Standards Association of Australia, 1993).

Position E) 'Trees in median (road centre) (cyan), is common, but only achievable in wider road casements (usually greater than 20m wide).

position F) Trees between bike path and road (green), is only achievable if bike paths are located adjacent the footpath rather than the traditional location in Melbourne of adjacent the parking lane. With bike paths in this location, cars entering and exiting parking bays do not conflict with trees.

6.2.5 Decision-making opportunities for change

Opportunities to reconfigure streets are limited by municipal timelines and budgets and often only arise when coupled with planned or emergency hard infrastructure upgrade projects[193] (Jaluzot et al., 2012; Local Government Victoria, 2006). Even when coupled to these infrastructure upgrades, opportunities for tree-scape reconfiguration can be missed because traditional tree placement might be implemented without design consultation or consideration of alternatives. Despite recent development of decision support tools seeking to increase the functional considerations of trees in design implementation[194][195], these have been difficult to operationalise as they are neither linked to this process of infrastructure decision-making nor that of qualitative visual decision-making undertaken in PPD forums (Grêt-Regamey et al., 2017; Jaluzot et al., 2014; Laurans & Mermet, 2014).

[193] Pavements are a substantial government asset which are unlikely to be removed or replaced unless dangerous, has reached the end of its useful life expectancy or underground services need emergency repair work.
[194] Norton suggests a decision prioritisation model for moderating heat issues where selection of areas for priority canopy cover increase based on use of thermal imagery to identify hot spots coupled with vulnerability indexing and behavioural exposure analysis.
[195] The Citree model is a database approach designed for use in community consultation. Tree selections are filtered for tolerance and traits suitable to the site environmental constraints, which are then brought together with community preferences (Vogt et al., 2017).

6.3 Part 2: 'Petri-dish' tests responding to key challenges

In the following section I describe a series of micro-scale, abstract street intersection, digital-physical design experiments (petri-dish) which focus on the specific factors of visual and environmental impact of tree decisions in isolation [refer 4.2*: Test part 01: Petri-dish*]. I use the petri-dish tests to prototype the use of the DDSS to respond to the specific challenge of optimising daytime streetscape heat and UV protection for pedestrians and cyclists, while also outputting traditional visual impact imagery. The petri-dish experiments developed in this section are then applied at the meso scale of the case study site.

In this section I investigate quantification of tree shading to pedestrians and cyclists (active transport paths) using tree shadow maps output from spatially and visually accurate modelling. I create the aggregate shadow maps using a texture baking method commonly used in the animation industry. I then combine these shadow maps with a simple agent-based tool intended to analyse the accessibility of key destinations of a given street network (PedestrianCatch.com).

6.3.1 Street configuration; shading active transport

In this first petri-dish I look at three variables of streetscape configuration; tree canopy dimensions, bike path location (adjacent footpath or adjacent a lane of parking) and presence or absence of a central median. Figure 109 shows the two positions for the bike path: A) adjacent the footpath or B) adjacent a parking lane. Figure 110 shows the same bike path configuration with additional tree planting space in the central median. Figure 111 shows the tree canopy parameters (standard, wide or tall) from which I selected to achieve optimal shade for active transport paths on either side of north-south and east-west oriented streets. (four active transport paths in total).

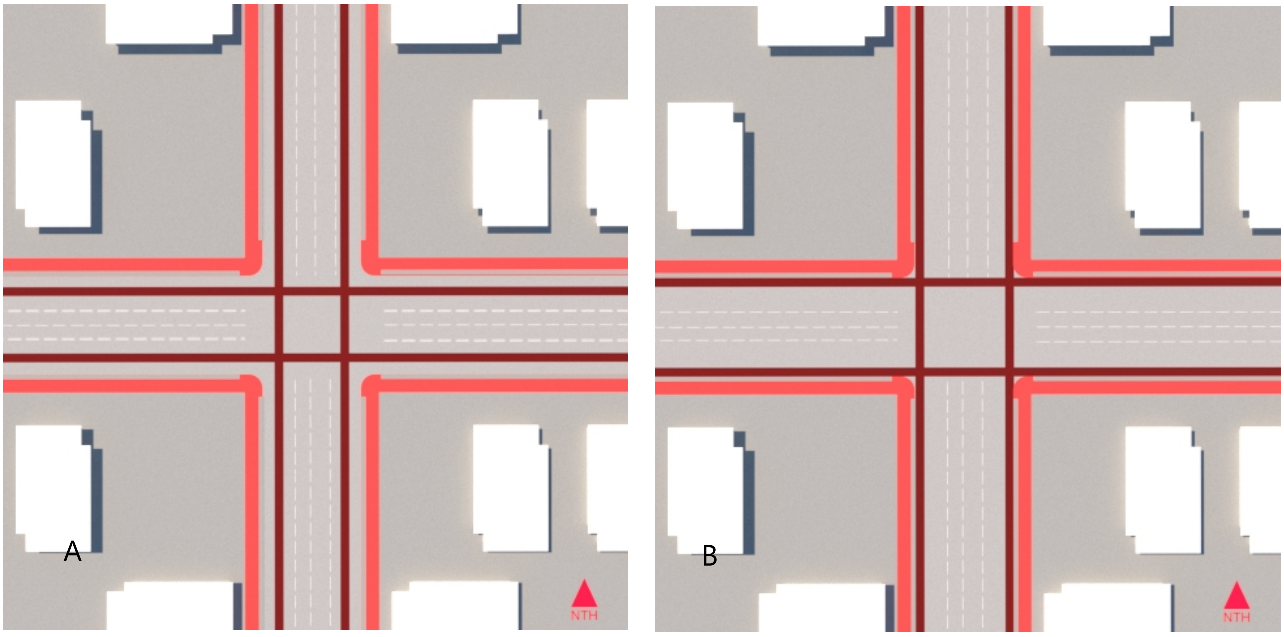


Figure 109: A) shows the bike path (dark red) adjacent the footpath B) shows the bike path adjacent the parking lane.

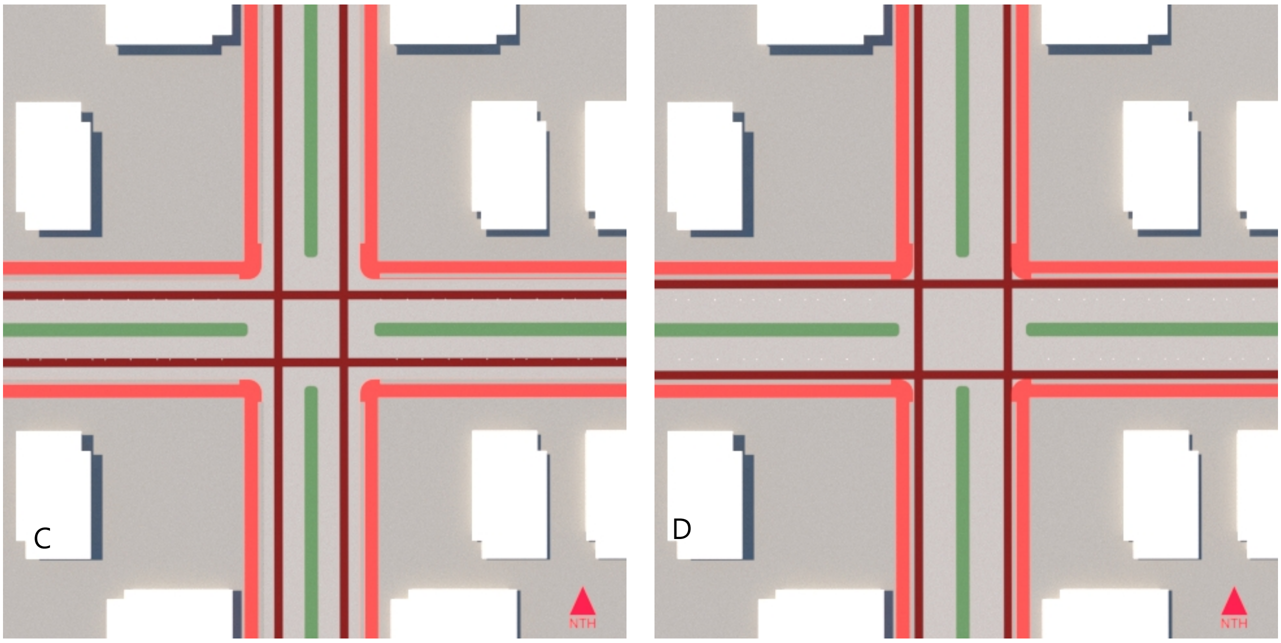


Figure 110: C) shows the bike path adjacent footpath with central median available for tree planting D) shows the bike path adjacent a parking lane with central median available for tree planting.

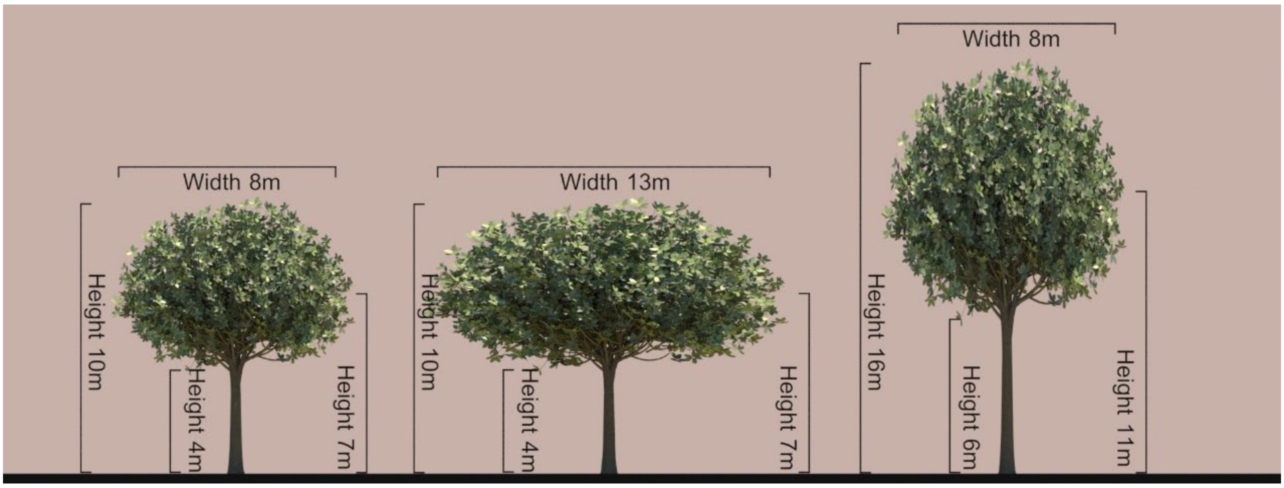


Figure 111: Tree model dimensions from left to right (standard, wide, tall).

The purpose of this petri-dish was to see which street configuration (A,B,C or D), combined with which canopy dimensions, (standard, wide or tall) would provide shading for the greatest number of bike and footpaths at 15.30, mid-summer in Melbourne using the least number of trees.

I distributed 3-dimensional tree geometry models at 13m spacing along street centre lines, offset to occur in the curb side verge. [refer 4.4: *Proxy-object modelling*]. I rendered each scenario in plan using a technique of rendering the effects of objects (such as their shadow) while the object itself is rendered invisible. This allows the tree shadow to be assessed without interference from the tree-model canopy in plan view [refer left side images in Figure 112 and Figure 113]. I also rendered each scheme in perspective view with the tree models visible. Where canopies with taller or wider dimensions were required to achieve shading, these tree models were coloured blue for clarity [refer right side of Figure 112 and Figure 113].

Table 4: Configuration B.2: Bike paths adjacent the footpath, no median, all tree canopies wide.

	Footpath	Bike path
North-south oriented street		
East side (wide canopy)	shaded	Partial / full shaded
West side (wide canopy)	Partial / full shaded	shaded
East-west running street		
North side (wide canopy)	Partial / full shaded	shaded
South side (wide canopy)	shaded	shaded
Total trees 32		

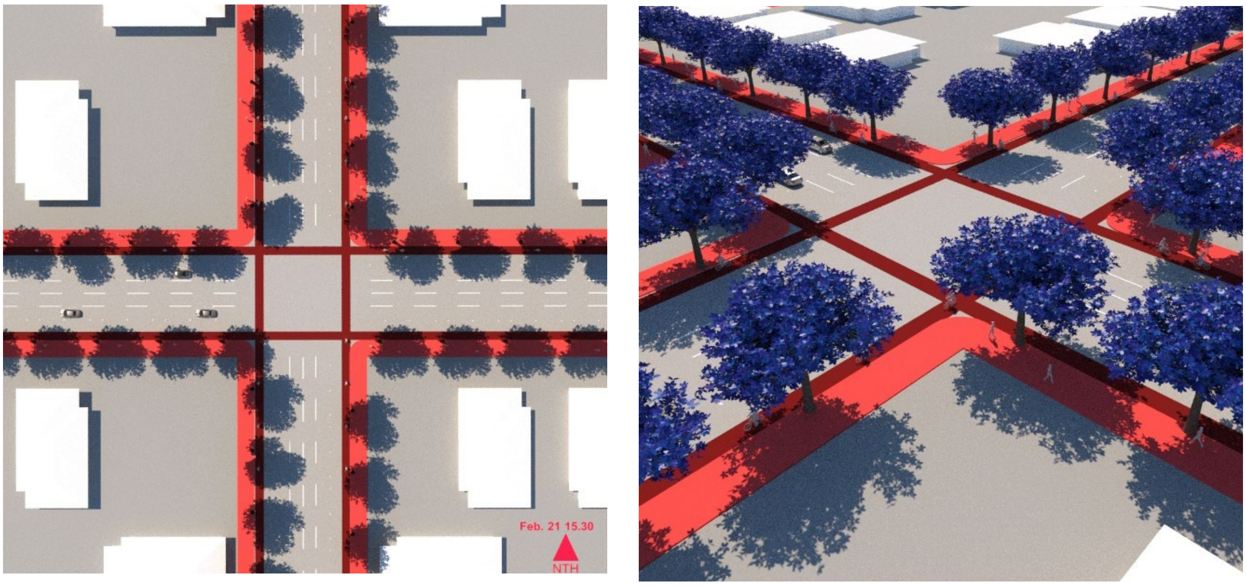


Figure 112: Configuration B.2 (LEFT): Shade in plan. (RIGHT) Wide canopy trees shown in blue.

Table 5: Configuration C.2: Bike paths adjacent parking lane with central median planting and taller trees on east west streets.

	Footpath	Bike path
North-south oriented street		
East side	shaded	shaded
West side	exposed	shaded
East-west oriented street		
North side	exposed	shaded
South side (taller trees)	Shaded	shaded
Total trees 48		

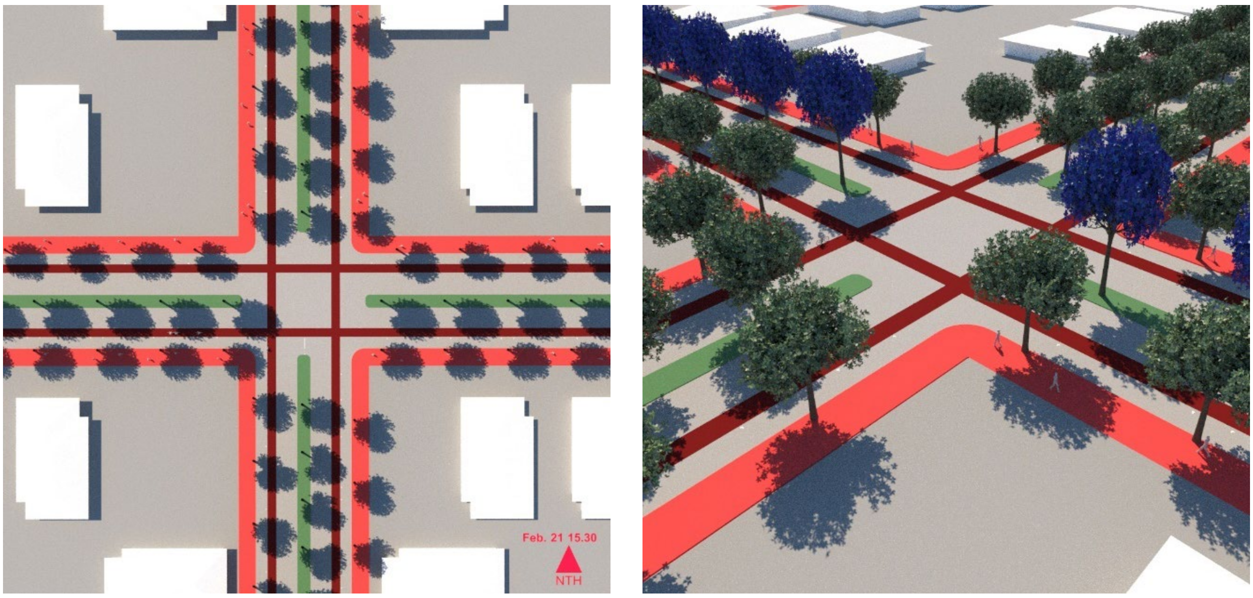


Figure 113: Configuration C.2 (LEFT) shade in plan. (RIGHT) Trees shown in blue need to be tall to achieve shading to east west street bike path on the south side.

Table 6: Results of testing each shading scenario.

Configuration		Tree canopy parameters	No. of trees required	No. of shaded paths
Bike path adj. to parking no median	A.1	standard tree	32	4
	A.2	E_W North side wide canopy	32	5
Bike path adj. to footpath no median	B.1	standard tree	32	4
	B.2	All tree canopies wide	32	8
Bike path adj. to parking with median	C.1	standard tree	48	5
	C.2	E_W South side tall canopy	48	6
Bike path adj. to footpath with median	D.1	standard tree	48	4
	D.2	All canopies wide and or N_S median tall	48	8

Outcomes

This study shows that in cardinally oriented streets in Melbourne, typical streetscape layouts could shade a greater number of total active transport paths if bike paths were located adjacent footpaths and wider canopy trees were used. All eight active transport paths were shaded in this condition even without the addition of central median planting when tree species were selected for wide growth habit. In this petri-dish I only tested a small number of variables, a single street orientation and a single tree position, however, even with these simplified constraints an extensive number of configurations can be tested. While the original intent of this petri-dish was to set up a type of look up table for streets of varied conditions (orientation, time, season, tree position options), it became clear this would be an untenable quantity of configurations to generate. Instead, it would be better to just re-run the model input with the site-specific constraints as required.

Optimising bike path position was not an option that I explored further in this Shady City case-study as moving bike paths would be a major infrastructure disruption in an established area. I do however use the findings of this petri-dish test in the Synthesis City case-study as that site is an urban renewal condition and allows for greater levels of infrastructural change [refer 7.2.2: *Higher density, sunlight and planning for* active transport].

6.3.2 Tree-shade mapping using texture baking

Another common practice in the gaming and animation industry to increase computing efficiency, is a process known as 'texture baking'. 'Texture baking' is where calculation of lighting effects such as reflection, refraction and global illumination are 'prebaked' or rendered into a texture or material which is applied to a receiving surface. This eliminates the need for lighting to be calculated 'on the fly' and helps maintain screen refresh rates of models which run in real time. In this petri-dish test, I use the texture baking technique to output black and white images (also known as an alpha channel) of the shade cast by 3-dimensional geometry tree models at 8.00 and 12.00.

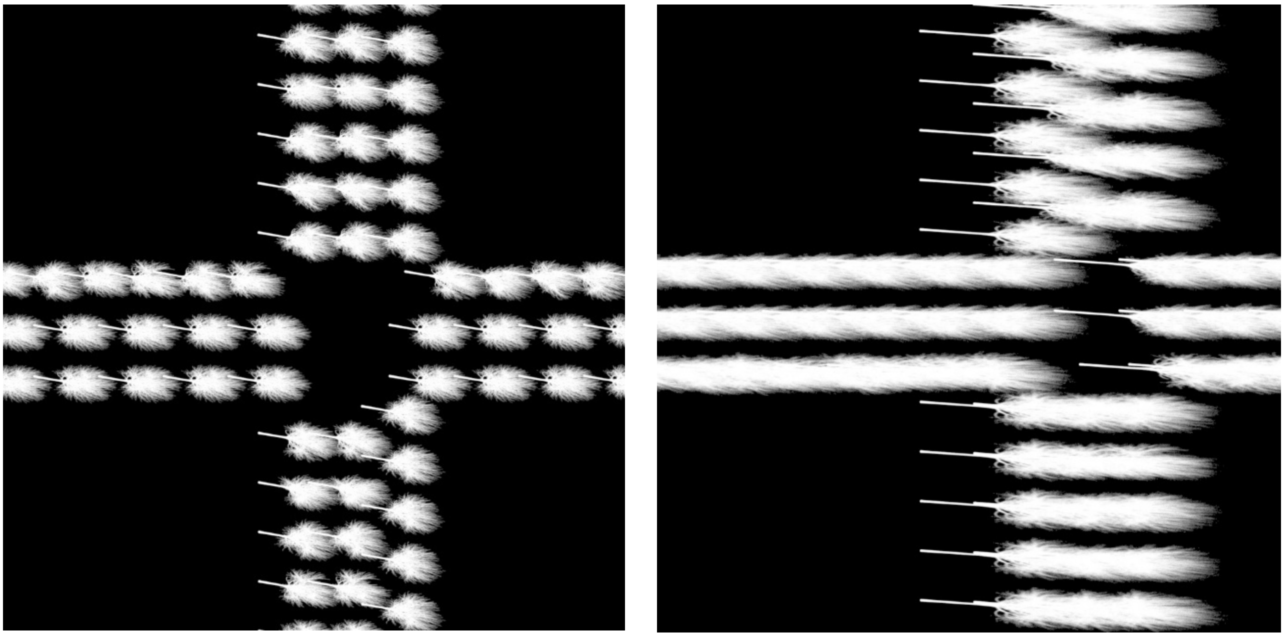


Figure 114: Alpha channel 'baked' shadow maps, output for multiple times in winter and summer

Outcomes

This study is similar to the petri-dish 5.3.3: Trees and flood: DEM approach to species selection, where I used a black and white gradient map to drive the distribution of tree models. However, in this case, the process is reversed. Rather than using a black and white map as an input to control the occurrence or suppression of tree models, I generated a black and white map of the shade cast, which in turn becomes an input for the accessibility analysis tool discussed in the next petri-dish test.

These black and white maps can be used to quantify shading in a number of ways: For example a count of the number of white pixels could be transposed to a measurement of area per meter^2 in shade. They can also be used in conjunction with an agent based model, where agents are programed to sample pixel intensity of reference image under their path of travel as is invetigated in the next petri dish (White et al., 2017).

6.3.3 Agent based shaded walking path analysis

In this petri-dish test I use a prototype simple agent-based accessibility analysis tool which was developed in the software platform Rhinoceros 3D™ with the visual scripting language Grasshopper. The tool is able to simultaneously analyse the accessibility of a vector based street network while sampling the pixel intensity of a black and white image referenced under the path of travel of the agents (White et al., 2017). The tool sends agents along a vector based footpath network from a single destination at an adjustable speed (usually 1.33 m/s). The agents stop upon sampling a maximum number of black (solar exposed) pixels which is representative of a sun exposure time threshold.

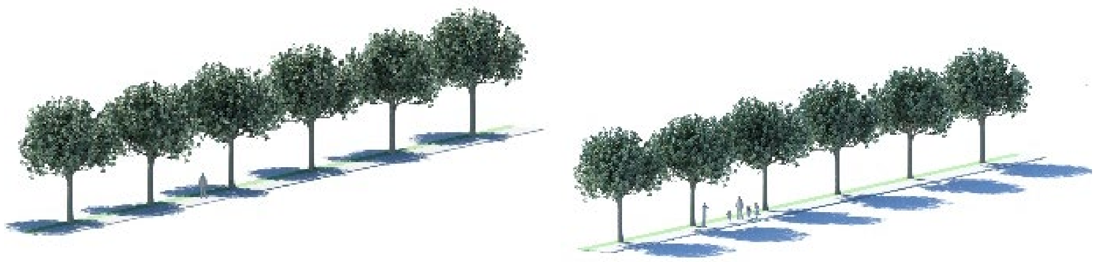


Figure 115: North South street Western side, (LEFT) 12.00 and (RIGHT) 15.30, diagrammatic render shows how the footpath is shaded at lunch time but not at 15.30, the time of the homeward journey from school (Diagram by Langenheim, N. originally published in (White et al., 2017)).

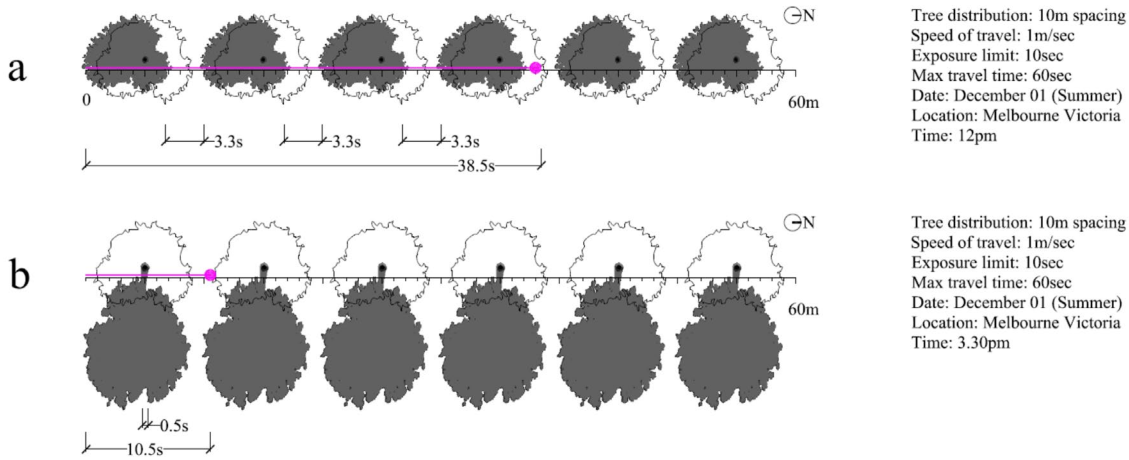


Figure 116: The progress of an agent (in pink) traversing the street, while sampling the intensity of underlying pixels. The agent terminates after it has sampled a certain quantity of white (unshaded pixels) school (Diagram by Langenheim, N. originally published in (White et al., 2017).

Outcomes

The outcomes of this study show it is possible to use the shadow maps output from petri-dish *6.3.2 Tree-shade mapping using texture baking* and quantify distance agents can travel before reaching dangerous solar exposure levels. The study demonstrates that the shade outputs from my modelling system can be imported and used in White's agent-based pedestrian modelling tool.

6.3.4 Tree crown-form and shade

Aspects of tree form such as height of trees, canopy height from ground, canopy width and form impact the shape of shade. In this petri-dish, I test the geometry of seven common tree crown-forms. These are, from left to right, rectangular (box pleached), broadly columnar, vase, broadly oval, globe, umbrella and columnar. I tested the crown-forms on east-west and north-south oriented streets at three times of the day [refer Figure 117 - Figure 122].

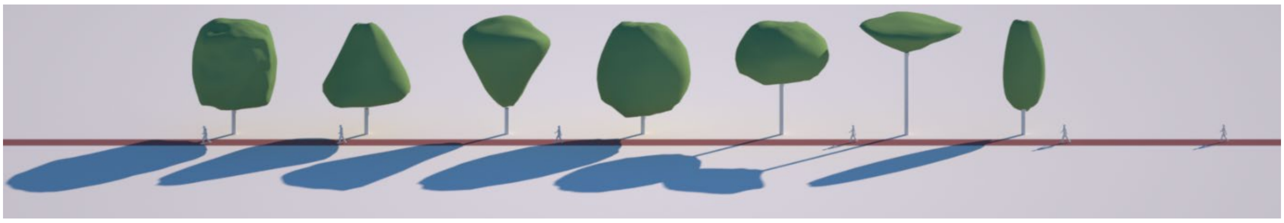


Figure 117: East West oriented street August 15th at 9.30.

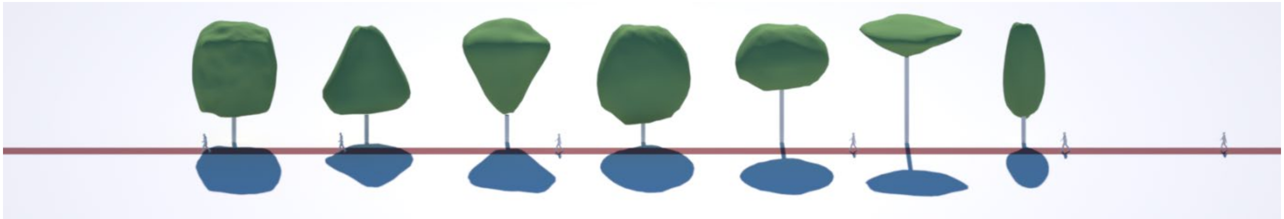


Figure 118: East West oriented street August 15th at 12.30.

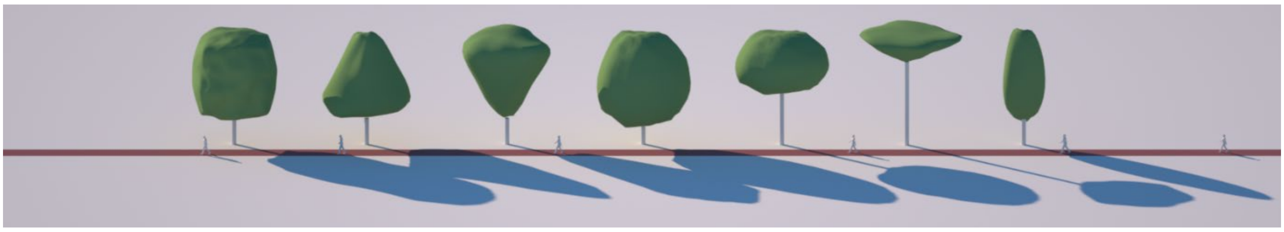


Figure 119: East West oriented street August 15th at 15.30.

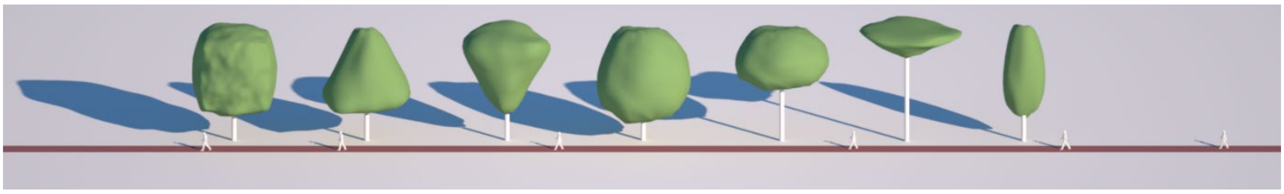


Figure 120: North South oriented street August 15th at 9.30.

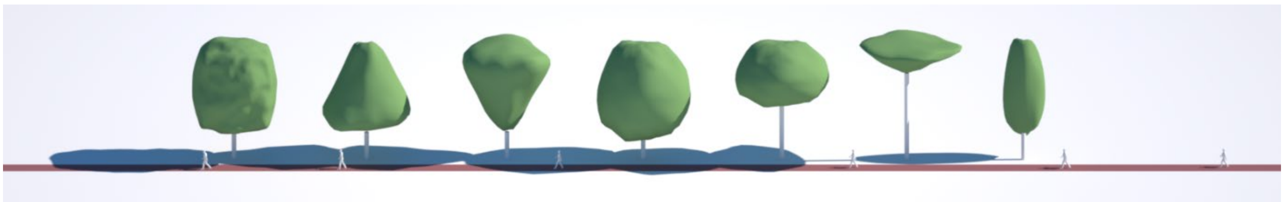


Figure 121: North South oriented street August 15th at 9.30.

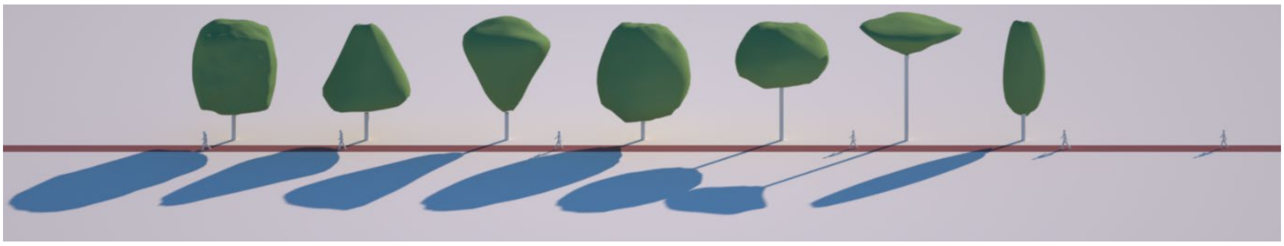


Figure 122: North South oriented street August 15th at 15.30.

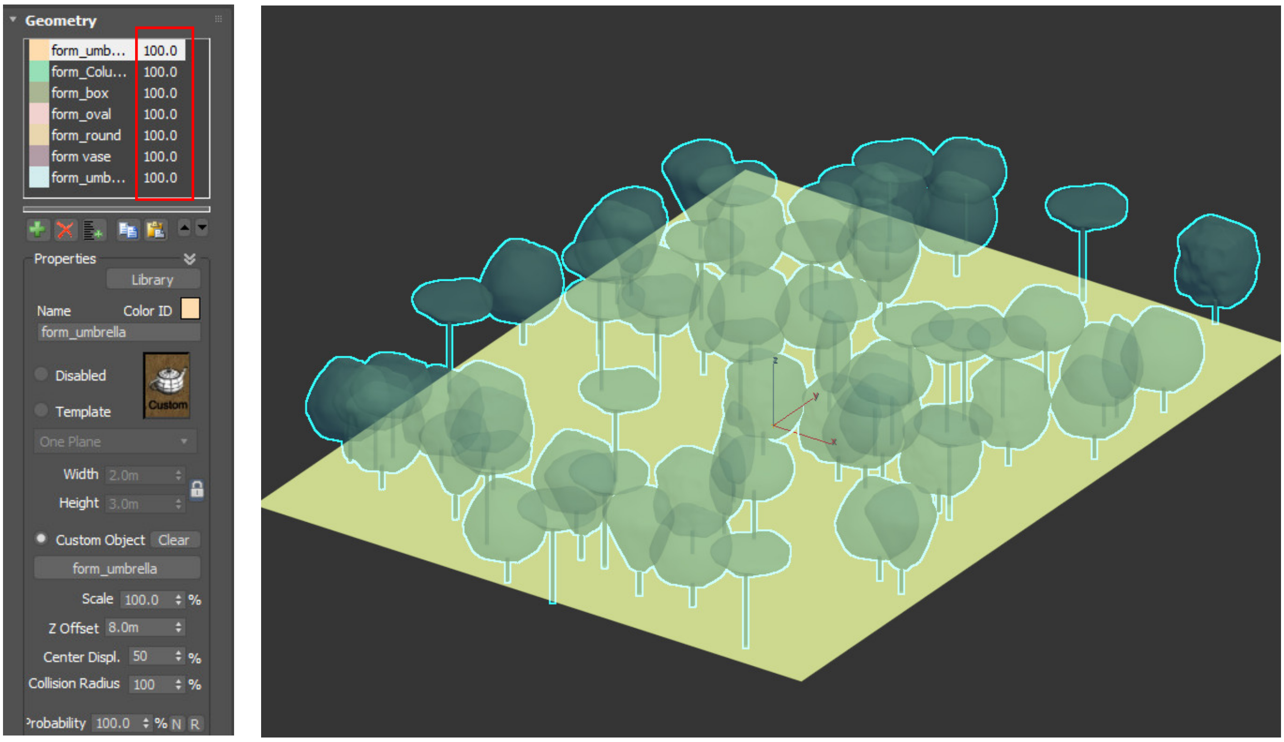


Figure 123: Screengrab of Forest Pro™ proxy-object scatter of all seven crown-form models with equal probability of occurrence.

To select between crown-form models I added all seven variations into a single proxy-object scatter. The probability of the form can be adjusted by changing the probability [refer Figure 123]. When the probability of each model is the same an equal number of each model will appear in the scatter. To have only one model appear all other model probabilities can be set to zero.

Outcomes

This study shows how canopy form is a major contributor to levels of footpath shading. The position of the footpath in relation to the tree which is shading that path is critical. Broadly columnar tree crowns are good for shading paths which are close, while vase shaped crowns are good for shading paths that are a greater distance from the tree. In relation to the case study site, I categorise a list of tree species used frequently by the local council[196], by their crown-form in order to filter species to meet specific shading objectives. Refer 6.3.7 Fitting tree species models for visual impact assessment and Table 7.

[196] See https://www.maribyrnong.vic.gov.au/files/assets/public/planning-services-documents/city-design/strategies/maribyrnong-street-tree-planting-strategy.pdf for list.

6.3.5 Street orientation and shade

In this petri-dish I test the impact of street orientation on tree shading to footpaths, using a single street intersection model. Testing different orientations can be achieved in two ways; Either the intersection model itself, or the compass of the geographic sun positioning system in the base platform can be rotated. As the compass is a single object and the intersection model has multiple components (trees, road and footpath surfaces, there is less opportunity for error if rotating the single object (compass). I also wired the rotation parameters of the compass, the north point and the overhead camera used to render images.

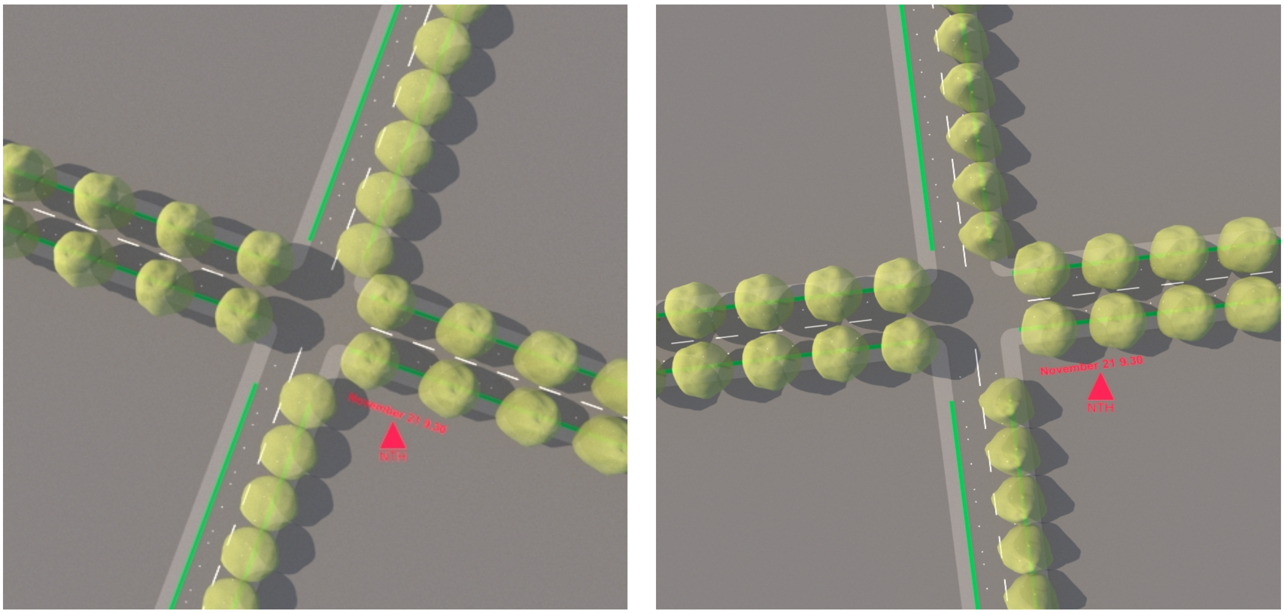


Figure 124: Rapid petri-dish testing of changes in street orientation on the position of shade through parameter wiring of the compass, north point and camera rotations.

Outcomes

With the camera, compass and north point set up in this way I can rapidly test different street orientations the intersection with a consistent north (up the page) [refer Figure 124]. The model showed the substantial impact orientation has on the location of tree shade. For instance, footpaths and bike paths of streets oriented between N30°W and N45°W with trees in the traditional curb edge location, would be well shaded at the school home time frame, while paths of cardinally oriented streets could be almost entirely exposed. This petri-dish shows the critical importance of classifying streets by orientation for optimising the shade of tree plantings as was identified by Rantazoudi and Georgi (2017). I undertake this categorisation process in both the Shady City and Synthesis City case studies.

6.3.6 Street orientation, tree geometry, positioning and spacing brought together

In this petri-dish I bring together the critical variables of street configuration for optimising tree shade; street orientation, tree crown-form and canopy dimensions, critical footpath use time and tree positioning within the street section. In this street intersection model, I set the time and location to 15.30 (the critical footpath use time of the homeward journey from school) in summer in Melbourne Australia. With these parameters set, I adjust the offset of trees from the street centre lines into the best shading provision position of the six possible, as identified above in section 6.2.4 The spatial constraints of street reconfiguration. I applied a simple colour material to the tree models according to their selected position matching that of Figure 108.

Depending on the direction shade and the distance from the footpath I then select the optimal tree crown form and the spacing between trees. I also adjusted the scale (height and width dimensions) of the tree models until reaching the shading objective (or at least as close as possible). I wired the scale adjustments I applied to the trees to a text object within the model. That text object provides the calculation of the scale adjustments (height and width requirements) to achieve the shading objective. The outcome of this process and the shade map it produces can be seen in Figure 125 and Figure 126.

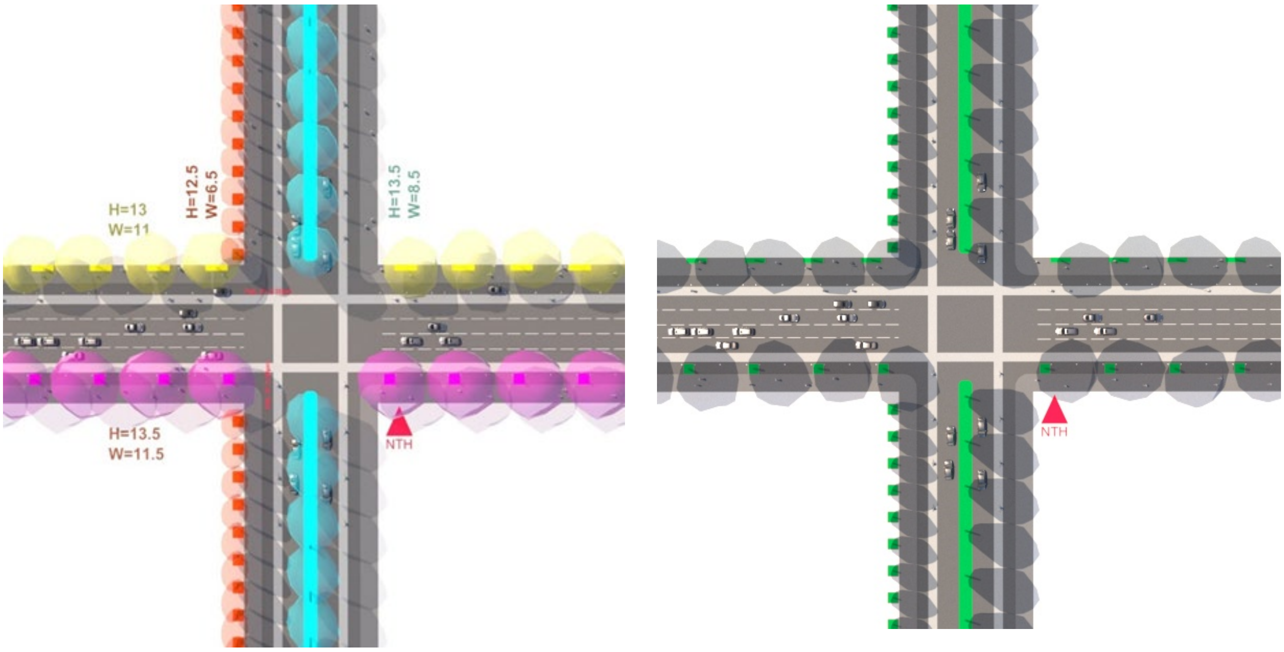


Figure 125: (LEFT) Plan rendering of the intersection with colour coded trees best crown form, placement, scale and spacing to achieve optimal shading. Trees in private front yards (red), Trees on the property boundary (yellow), trees in the central median (cyan) and trees between parking bays (pink) (RIGHT) Shade map of the same.

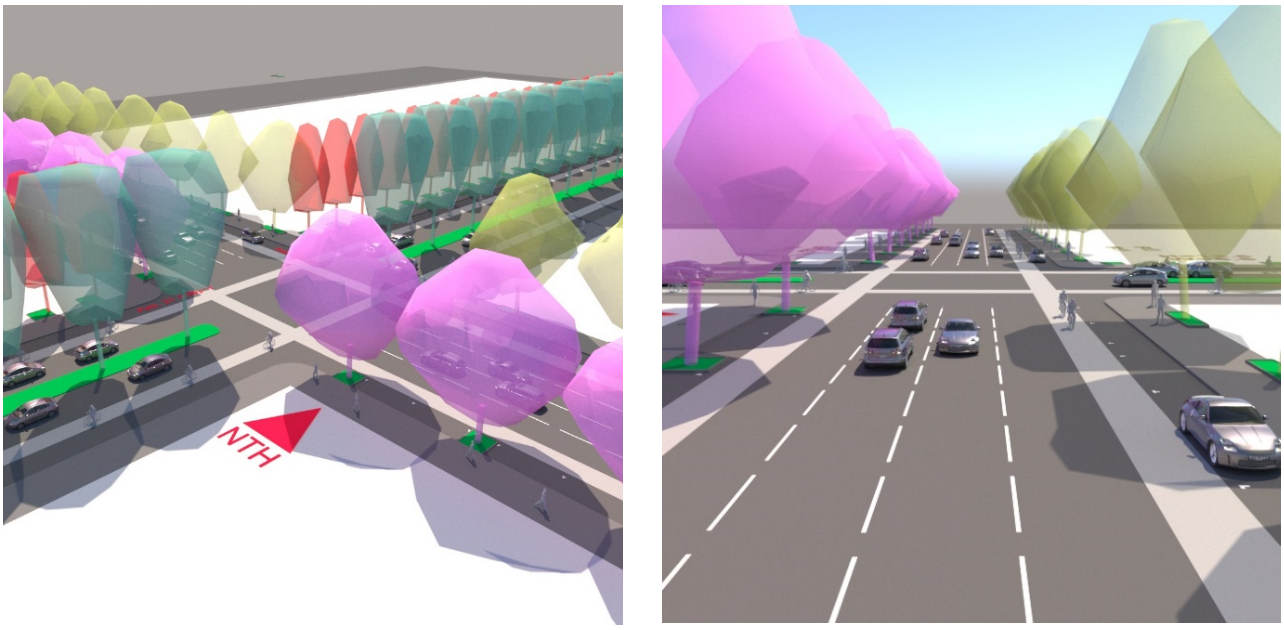


Figure 126: Perspective rendering of the intersection model with trees adjusted scale, form, position and spacing adjusted to achieve shading objective.

Outcomes

The process I used in this petri-dish, if applied to tree decision-making processes, could improve the functional shading outcomes of those decisions. This petri-dish begins to identify locations where planting on private property or on the property boundary is critical to achieving optimal shading outcomes. If applied at precint scale, this process could be used to formulate a performance-based planning control overlay to mandate specific private property tree planting regulations. However, these two locations (within and on the property boundary) are controversial and would require substantial community negotiation. To negotiate implementation of private property tree planting regulations, it would be important to be able to simultaneously assess the visual impact of these decisions. To enable the functional outcomes of this modelling process to be useful for visual impact analysis (VIA), the abstract, coloured tree crown-form models must be 'fitted' to actual tree species selections.

6.3.7 Fitting tree species models for visual impact assessment

This final petri-dish builds on the process developed in the previous test 6.3.6, adapting it to enable output of visualisations useful for PPD forums or VIA. This petri-dish is twofold. Firstly, I selected tree species from a local government 'preferred tree species list'[197], fitting tree species to the height and width requirements output from the process used in 6.3.6. Secondly, I fitted that species selection to a 3-dimensional visually accurate tree model. I then used these visually accurate tree models to replace the abstract tree geometry objects shown in the renders of the previous test [refer Figure 125].

Step 1 fitting species to output dimensions

Local government prefered tree lists are tree species known to do well in the local area and are developed over many years of observation, trial and error. I took the tree species list for the City of Maribyrnong (the LGA of the case study site) and classified these trees by their mature canopy height and width dimensions[198]. Of the seventy species on the list only two had the capacity to develop the mature canopy width of 11.5m and a height of 13m required for optimal shading of east west streets. Five species had the capacity to develop mature canopy dimensions required for shading on north south streets but only one of these five had the required vase crown-form[199].

[197] In this case I used the Maribyrnong council tree list from https://www.maribyrnong.vic.gov.au/files/assets/public/planning-services-documents/city-design/strategies/maribyrnong-street-tree-planting-strategy.pdf as this is the LGA of the case-study site.
[198] Note that tree mature dimensions are dependent on growing conditions. Poor soils and low rainfall result in trees which are smaller than their counterparts growing in idealised conditions. This process would therefore need to be informed by observation of mature specimens of each species within the specific site.
[199] This tree species fitting process can only be utilised as a guide as tree growth is variable, impacted by growing conditions.

Step 2 fitting visual models of species selections to crown-form models

Once species, most likely to reach the required dimensions were established, I could select a visually acurate 3-dimensional tree geometry model from a tree asset library or create a proceedurally grown tree. In this case I used the Xfrog model OC35 variation 3 to represent *Ficus microcarpa hillii* and BL14 variation three to represent *Populus nigra* 'italica' and I proceedurally generated the 3-dimensional models for *Zelkova serrata* 'Green Vase' and *Eucalyptus mannifera* [refer 4.4: *Procedural tree modelling*]. I then added the 3-dimensional tree geometry models to the proxy-object scatters of the crown-form models in the intersection model and adjusted their probability to 100% [refer Figure 127].

Table 7 shows the process for a cardinally oriented street. I then added the 3-dimensional tree geometry models to the proxy-object scatters of the crown-form models in the intersection model and adjusted their probability to 100% [refer Figure 127].

Table 7: Fitting crown-form and canopy dimensions to preferred species.

30m street width (cardinal bearing) Intersection model output										
Street. Side location	*Position*	*Spacing*	*Crown-form type*	*Crown-form model*	*Height*	*Width*	*Prefered species*	*Alternate species*	*Image prefered species*	*3-dimensional tree geometry model*
E-W sth	*Between car parks*	*14.5*	*Round Oval*		*13.5*	*11.5*	*Ficus microcarpa hillii*	*Ginko biloba*		
E-W nth	*Property boundry*	*9*	*Round Oval*		*13*	*11*	*Eucalyptus mannifera*	*Olea europa 'Sativa'*		
N-S wst	*Front setback*	*7*	*Vase column*		*12*	*6.5*	*Populus nigra 'Italica'*	*Pyrus calleryana 'Bradford'*		
N-S est	*Central median*	*9*	*Vase column*		*13.5*	*8.5*	*Zelkova serrata 'Green Vase'*	*Angophora costata*		

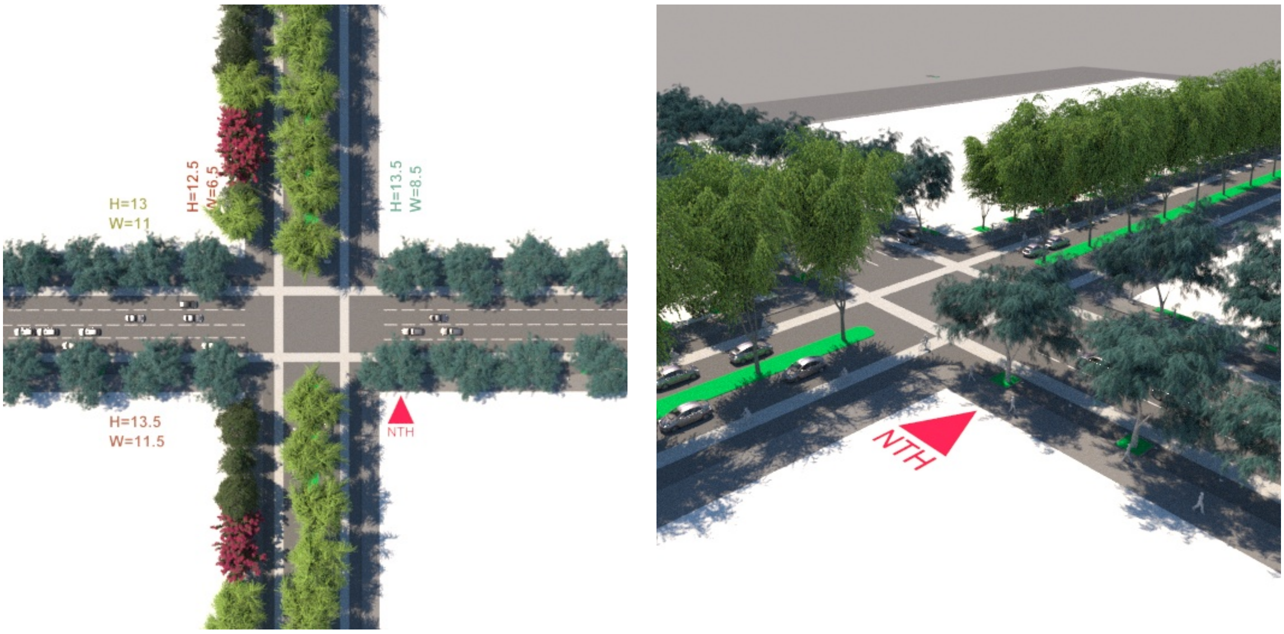


Figure 127: The intersection from petri-dish 6.3.6 with visually accurate 3-dimensional tree models in this case Zelkova serrata 'Green Vase' and Eucalyptus mannifera and assorted species in the private yard planting (species with growth dimensions to achieve desired shading).

Outcomes

On the east side of north-south streets, shading was best achieved through front yard planting of trees on private property. As this is a controversial location which is difficult to control, I fitted multiple tree species to the crown-form and canopy dimensions output through the abstract modelling process. This is important for enabling community and resident agency in a process which will ultimately have a large impact on the character of their neighbourhood and their private property [refer 3.3.1: *Design visualisation modelling*]. The process would also be useful for demonstrating to residents the value of their private property trees in protecting pedestrians, cyclists and children on their way home from school from damaging levels of solar radiation.

The process of fitting tree species from a council prefered list to required canopy dimensions and crown-forms also revealed issues for tree managers. Certain crown-forms and canopy dimensions were not well represented in the preferred species list while others were over-represented. In particular, there was a paucity of wide canopy trees. This process could therefore be used to inform strategic trial of alternative species with more suitable mature canopy dimesions for shading objectives in the future.

6.4 Shady City case study, DDSS application

In this section, I bring together the DDS application processes developed in the above petri-dish tests and apply them to a site where heat vulnerability and UV exposure of children who walk home from school is a problem. I have chosen to apply the DDSS to Kingsville, one of the most solar exposed western suburbs of greater Melbourne[200] located within the Local Government Area (LGA) of Maribyrnong in Victoria. Kingsville suffers from solar exposure due to three converging factors. The west of Melbourne has lower levels of rainfall resulting in low levels of evaporative cooling from soil surfaces during hot weather. Second, while urban soils are highly disturbed, the Volcanic Plains (basalt clay soil) underlying Melbourne's west still negatively impacts the growth of trees, (Victoria, 2019) and third, much of the built form of the west of Melbourne, in particular Kingsville, evolved to support factory and industry workers after the second world war (Morrow, 2012). This development pattern manifests as high plot ratios (high ratio of building footprint to plot size) of low-rise single storey buildings on small lots (an average of <300m2) limiting opportunities for trees [refer 3.5.3: *Land use planning*]. Tree canopy cover is further restricted by the high percentage of hard to permeable surfaces and large vehicle access requirements associated with Kingsville's industrial past (private and public) (B. Jacobs et al., 2014).

6.4.1 Why Kingsville?

In 2013, researchers within the CRC for Water Sensitive Cities and the National Climate Change Adaptation Research Facility, developed a spatial vulnerability index map of the GCCSA[201] of Melbourne, identifying areas vulnerable to heat during extreme events (Loughnan et al., 2013). The LGA of Maribyrnong was identified as having a heat vulnerability of 8 out of 10. Several infrastructure renewal projects have been proposed within or close to Kingsville over the next five years such as the East-West Link[202] and the

[200] Melbourne's climate is classified as temperate oceanic (Cfb) in the Koppen Geiger system. Humidity is low (below 20% for most of the year) and winds speeds vary between 8 to 10mph. In this type of climate shade is critical for HTC as shown by Coutts (2016). It is acknowledged here that in higher humidity climates and areas of low wind speeds tree canopy cover and transpiration can interrupt wind flow and thus contribute to discomfort rather than improve it, for example (Yahia & Johansson, 2013), though even in these environments overall shading has been found to improve HTC.

[201] Greater Capital City Statistical Area.

[202] Plans for the East-West link were later abandoned.

Truck action Plan (Maribyrnong City Council, 2012), which will disrupt existing streetscape infrastructure and thus provide an opportunity to optimise tree replacement decisions for improving shade.

6.4.2 Kingsville's existing urban forest

In the report by the institute of Sustainable Futures, 'Benchmarking Australia's Urban Tree Canopy', the percentage of canopy cover of the LGA of Maribyrnong was found to be 7.4%, 4th from the bottom of Victoria's 34 LGA's (B. Jacobs et al., 2014). In response to this report, the City of Maribyrnong increased funding allocation towards improving canopy coverage percentages. However, they needed a strategy for decisions about where new trees should go and how to stage and prioritise their implementation. In conversation with the sustainability officer at City of Maribyrnong, who was developing an Urban Tree Renewal Strategy, there was a desire within the organisation to use this tree planting opportunity to improve the streetscape conditions for school children, using active modes of transport for their homeward journey from school.

Maribyrnong's tree records were in the process of being updated but, clearly show an urban forest in excess of 60,000 trees. At least 6,000 were recorded as 'missing' awaiting replacement and 29% assessed as being in 'poor condition'. This large-scale need for tree replacement, coupled with dedicated funding for increasing canopy cover and proposed infrastructure renewal present a unique opportunity to re-imagine Kingsville's streetscapes, optimising for shade.

6.4.3 Scenarios to be tested

The scenarios developed for this case study reflect the range of opportunity for streetscape renewal, from the 'very little', working within the confines of the existing infrastructure, to transformative reconfiguration. Responding to these different levels of opportunity I developed a three-scenario response: 1) ***the existing tree-scape***, 2) ***improved tree-scape*** to optimise shading conditions accepting the existing infrastructure constraints and 3) ***improved tree-scape with footpath infrastructure constraints removed*** to fully optimise tree shading conditions. I devised these scenarios around three questions: What amount of shading was being provided by the existing urban forest?

What amount could be achieved with new tree plantings without disruption to current infrastructure? and what amount could be achieved if strategic changes to infrastructure could be made? I then quantified the differences between each shading scenario through a count of the number of households whose children could reach home with less than three minutes solar exposure time.

6.4.4 Application visual-functional DDSS

The application of the DDSS for this case study is an eight-step process:

i. Define the ten-minute walking catchment around the two schools using the pedestrian accessibility catchment calculator 'PedestrianCatch.com'.
ii. Classify the street network by orientation and width.
iii. Using individual intersection models, define the optimal placement, position spacing and size of crown-form model trees within the street casement to optimise footpath shade at 15.30. (Repeat process for each scenario).
iv. Fit tree species selected from the council 'preferred species list' to the output canopy dimensions and crown-form of the previous step.
v. Apply the outcomes of the above intersection models to a spatially explicit model of the precinct.
vi. Output shade maps from the precinct model using the texture baking technique [refer 6.3.2] onto a plane at approximately children's head height (1.2m).
vii. Reference the shade map under the footpath network in the pedestrian accessibility model (Rhino version of PedestrianCatch.com) and set an exposure limit (in this case three minutes) and analyse the shaded walking catchment.
viii. Finally overlay the shaded walking catchments with the building footprint data to quantify the number of houses which can reach the school with three minutes or less solar exposure time.

6.4.5 Spatial data sets used to produce a precinct model

To create the spatially explicit case study site model I used land parcel maps and street centre lines from (PSMA Australia Limited 2016), building footprints from (Melbourne Water Corporation 2018), Street casement data from (Vicmap Property 2017). These data are available to Australian researchers through the Australian Urban Research Infrastructure Network (AURIN). In addition, I used two further data sets obtained from the City of Maribyrnong; one showing existing tree species and locations and the other showing footpath location and condition. I exported these data from ArcGIS to AutoCAD [203], and specified a transfer 0,0 point in order to import them into the base platform.

Both the pedestrian catchment tool and the proxy-object scattering tool calculate the footpath as an offset from the street centre line. This diminishes the issue that real streets often have multiple width variations within a casement (intersection to intersection segment) as minor street width variations are then taken up between the curb edge and the land parcel map.

6.4.6 Results

i) Define the ten-minute walking catchment

I calculated the ten-minute walking catchment of the school zone using the online tool www.PedestrianCatch.com. The main school gate was set as the single destination/start point, walking speed of pedestrians was set to 1.33 m/s, and a 50 m offset buffer isochrones-type [Figure 128]. The resulting catchment area was 1,276,256 m2 compared with the as the crow flies circular catchment of 2,003,595 m2 (0.637 pedestrian catchment ratio).

[203] For a detailed workflow covering this process see https://www.youtube.com/watch?v=KR8sws4Xpc4&t=110s

Figure 128: (LEFT) Pedestrian catchment isochrones (using www.pedestriancatch.com and (RIGHT) Example of categorised streets - each colour represents a different category of orientation and width. School location indicated with red marker.

ii) Classify the street network

I classified the streets in the walking catchment by width and orientation (Rantzoudi & Georgi, 2017) [Figure 128]. This process had to be completed manually as neither VicMap street casement data, nor the PSMA street centre line data contained a street width attribute field. The narrowest width of each casement was used as the base line for locating a curb edge. Most of the precinct conformed to a grid pattern N7°W with either 15m or 20m wide streets, apart from a major transport thoroughfare which bisected the precinct. Streets narrower than 12m in width were excluded from tree planting consideration for practicality, limited tree planting options and minor variations in width. This process was quite time consuming even for a small precinct (3-4 hours). If the DDSS were to be adapted for widespread use, road data collection protocols which include footpath data and average street segment widths should be adopted by street and road data collection agencies. The street centre line data was then divided into different layers based on the street classification [refer 4.3: *Transport modelling data*].

iii) Define the optimal tree placement

Each scenario needed a separate strategy as each had different constraints.

For *Scenario 1,* 'Existing shading', the existing GIS tree locations provided by the council were used to inform the location and size of tree models [refer 5.3.4: *Trees and flood: Closing loops between management and design*].

For *scenario 2*, 'Improved shading', I considered two additional (non-infrastructure disruptive) locations for trees: 3) At the curb edge and 4) between parking bays. To ascertain the location of the existing trees I overlaid the municipal tree data set with the municipal footpath vector data, buffered by footpath width[204].

For *scenario 3*, 'Optimal shading' I considered all six possible tree planting positions, under the assumption that infrastructure service constraints were removed in a whole of precinct "upgrade". On most streets optimal shading could be achieved in this scenario in a variety of ways as multiple variables could be adjusted in relation to tree height, canopy width and crown-form. In this case I selected the 'simplest to achieve option'. (least change to the existing infrastructure).

For scenario 2 and 3, I used single intersection models to ascertain specific placements required for each street classification.

iv) Fit tree species

I then distributed the seven, simple crown-form tree geometry models along the street centre lines using proxy-object scatters, and then specified the offset from that line in either direction to achieve tree positioning. Each crown-form model has a probability value zero which can then be adjusted up to test for the optimal crown-form required for shading. The size, height and width of the crown-form models can then be adjusted using transform controls to ascertain required mature canopy dimensions and tree height to achieve the shading objective. Once locations, spacing, crown-form, height and canopy dimensions were established it was then possible to select the best fitting tree from the locally preferred species list [refer 6.3.6] and replace the abstract crown-form tree models in the model with the appropriate 3-dimensional, visually accurate tree model [refer 6.3.6].

[204] The result of this overlay was verified against Google Map Street View imagery and unfortunately the positioning of trees and footpaths in the provided data had many inaccuracies. With planned improvements to both these data sets in the future this process could be used more accurately to refine the identification of existing infrastructure.

v) Apply the intersection model outcomes to the precinct mode

I then applied the outcomes of the individual intersection models (one for each street category) to the precinct model. This process was repeated for both scenario 2 and 3.

vi) output a shade map using the texture baking technique

With the sun position set to 15.30, I was then able to output shade-maps for each scenario by using the shadow-baking technique described in 'petri-dish' 6.3.2, baking the tree shadows onto a 'receiving plane' set to 1.2m height. This resulted in a child's head height, geo-referenced shade map. Figure 129, shows a detail area of the precinct wide shadow map.

Figure 129: Shows a detail of the shadow map. Building footprints black) building and tree shadows in grey.

vii) Analyse the shade maps to generate 'shaded walking-catchment maps

I georeferenced the shade-map for each scenario under the vector footpath network in the prototype version of the PedestrianCatch tool [refer 6.3.3: *Agent based shaded walking path analysis*] (White et al., 2017) and set a threshold of cumulative three minutes solar exposure time for the agents. [Refer left hand side of Figure 130, Figure 131 and Figure 132].

Figure 130: (LEFT) Scenario 01: 'Existing shading' map output from DDSS with 'exposure limited' pedestrian catchment calculated using Rhino version of PedestrianCatch tool (shown in pink). (RIGHT) dwelling count, 320 dwellings can be reach from the school solar exposed for less than three minutes.

Figure 131: (LEFT) Scenario 2: 'Improved shading' map output from DDSS with 'exposure limited' pedestrian catchment calculated using Rhino version of PedestrianCatch tool (shown in pink). (RIGHT) With improved shading more than double the amount of dwellings can be reached from the school solar exposed for less than three minutes.

Figure 132: (LEFT) Scenario 3: 'Optimal shading' map output from DDSS with 'exposure limited' pedestrian catchment calculated using Rhino version of PedestrianCatch tool (shown in pink). (RIGHT) More dwellings could be reached from the school with less than three minutes exposure time, however the, barriers within this walking catchment such as the river and large road reduce the benefit achieved despite substantial infrastructure change.

viii) Overlay the shaded walking-catchment with housing data

Finally I compared the shaded walking-catchments maps using a dwelling count process. I overlaid the perimeter of each shaded walking catchment with the building footprint data and performed a simple ‘dwellings reached’ count to quantify the difference between the shade provision of each scenario.

Under the Scenario 1: ‘existing shading’ conditions 320 dwellings could be reached from the school gate with no more than three minutes direct exposure. In Scenario 02: ‘improved shade’, where shading was maximised within the confines of the existing hard infrastructure layout, the number of dwellings which could be reached before agents terminated under a three-minute exposure time more than doubled, with 794 dwellings. While Scenario 03: ‘optimal shading’, where hard infrastructure was adjusted, showed a moderate performance improvement on scenario 02) at 935 dwellings.

Review of 2016 Census data also showed that the number of households in the area with school aged children was 65%.

6.4.7 Visual impact

I was also able to use the same model used to generate the shade maps to output qualitative visualisation at multiple scales, suitable for use in public consultation. Any adjustment to either the visualisation or the shade mapping would interactively inform the other. There are a number of ways the visualisations could be produced from the precinct model. In the case of Figure 133 and Figure 134, the trees are rendered in the colours representative of their position within the casement [refer 6.2.4 *The spatial constraints of street reconfiguration*]. This style of visualisation could be developed into an online interactive fly through which might allow residents to see how their street could best be adapted to provide shade or to develop planning guidelines for private yard trees where they are needed to contribute to pedestrian shade. The precinct model can also be detailed to a streetscape level for eye-height visualisation [refer Figure 135], and materials can be adjusted to be either realistic leaf colours, abstract position in the casement colours, or a blend of these two.

Figure 133: Diagrammatic overview render of the precinct model with trees shown in the colour representing their position in the casement. Colours reference different tree placement positions (see Figure 108).

Figure 134: Closer overview of the precinct with models coloured according to position (see Figure 108)..

Figure 135: A street view render of the model with trees partially colour overlaid to represent both position in the street but also true leaf qualities. Indicative species in view show Gleditsia triacanthos (yellowish tint planted on the footpath edge), Angophora costata (sage tint planted on the property boundary (note buildings recessed in this area)), and Angophora costata (pink tint planted within the property boundary).

6.5 Discussion and conclusion

In this chapter I applied the visual-functional DDSS to a walking catchment, to aid in functional tree-scape decision-making to optimise shade for school children in pedestrian walking home from school, whilst still communicating traditional visual design performance objectives. I was able to adapt the DDSS to address differences in consideration from flood in the previous chapter to solar exposure and adapt to the change in scale from the hydrological catchment to the walking catchment.

The use of technologies from the gaming and animation industry (3ds Max and associated plugins), allowed for flexibility and accuracy simultaneously. Aspects such as compass rotation, the blending of materials applied to objects and the texture baking of accurate tree shade maps allowed creation of a diverse array of visualisations for both functional and qualitative visual impact assessment purposes.

Streetscape spaces have tangible and inexorable spatial constraints which are under pressure to accommodate multiple uses. Subtle adjustments to traffic lane widths or the location and size of medians, could mean the total success or total failure of street trees capacity to provide ecosystem services. The integration of transport data sets into the application of the DDSS allowed for spatially explicit analysis of street design scenarios which could be integrated with future transport planning considerations and planned or unplanned infrastructure renewal in the future. Using a visual-functional DDSS modelling method to make tree-scape decisions begins to allow the complex interacting considerations of environmental performance, spatial constraints and visual impact be considered holistically.

The research in this chapter tests the DDSS framework for its ability to work with a *single* functional environmental consideration. In the next chapter I will expand this testing to bring together *multiple* functional considerations including flood and heat. Both *Umbrella City* and *Shady City* were tests of the DDSS application to suburban retro-fit conditions. It is important to test the application of the DDSS on a site with higher density, greater land use diversity and capacity for greater change.

Chapter 7: Synthesis City (hot flooding city)

Land use laws are among the most powerful tools local governments have, to create resilient infrastructure that can adapt to climate change and other uncertainties. While land use laws provide an opportunity for local governments to prepare for changes, they have traditionally been drafted and implemented in a way that creates and exacerbates vulnerabilities (Rosenbloom, 2018).

7.1 Introduction

In the previous two chapters, I used the DDSS to work with isolated environmental performance challenges of tree-scape design. In *Umbrella City*, this was for trees to function in flood adaptation, and in *Shady City*, for trees to function in reducing the solar exposure of active transport paths. As I identified in the previous two chapters, tree considerations for assisting in flood adaptation and solar exposure reduction are different. Tree flood considerations are mechanistic (canopy interception, water use and location relative to elevation within the catchment) while for solar exposure, considerations are geometric and configurational (crown-form, canopy dimension, tree position and spacing relative to sun position). In those chapters I demonstrated the significant visual impact of making functional environmental tree choices for streetscapes. For flood adaptation there was a greater requirement for large evergreen tree species, and for solar exposure reduction, tree species of differing canopy dimensions and form were required on either side of the street. Both aspects represent a departure from traditional streetscape design [refer 2.2.2: *Urban reform and the visual function of trees*].

In this chapter I bring the environmental performance challenges of flood adaptation and active transport solar exposure together, applying the DDSS, to a site where both are a problem. The *Synthesis City* case study site, like that of the *Umbrella City,* is situated at the lowest point of a catchment and subject to stormwater flooding, and like that of the *Shady City*, has poor canopy cover and conditions for supporting tree growth. The case study sites for the previous two chapters were both retrofit low-rise conditions. In this chapter, *Synthesis City*, I apply the DDSS to a mid-rise urban renewal precinct near the Central Business District (CBD) of Melbourne,[205] where higher density and a more diverse land use are proposed.

Urban renewal projects offer planners and designers unique opportunities, to create real-world examples which challenge existing norms about the function and appearance of urban development, reconfigure legacy infrastructure, meet contemporary sustainability targets and apply best practice to streetscape design towards functional environmental performance goals (Robinson, 2011). However, the barriers to achieving these goals are substantial[206], approaches are divergent, space is limited, and decision-makers are faced with moderation of multiple, and often conflicting criteria of numerous disciplines and stakeholders.

7.1.1 Aim

The aim of this chapter is to investigate the application of the DDSS to enable the query of environmental performance, spatial constraints and visual impact and layers of spatial data-sets for tree-scape design decisions in sites of higher density, land use diversity and environmental complexity. In this case, to query the visual impact of functional tree selection for flood adaptation and active transport shade optimisation.

Key Question: *Can environmental performance, spatial constraints and visual impact be integrated into a tree-scape design process?*

Sub Question 01: *Can we utilise growing availability and accuracy of spatial data sets in street-scape design decision-making?*

Sub Question 02: *Can we combine and apply emerging modelling technologies in the entertainment industry (gaming and animation), digital procedural tree modelling, with computer aided design (CAD) and geographic information systems (GIS)?*

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[205] Known as either urban renewal in Australia or brownfield renewal in the UK and USA, refers to areas in cities which developed rapidly during the age of the automobile, with uncontained development patterns (sprawl). These cities, now facing rapid rates of population urbanisation, looking to achieve more compact sustainable options for housing growing populations. With the decline of manufacturing in the inner city, under-utilised ex-industrial sites are being re-developed for this purpose (D. Robinson 2011; Newman and Jennings 2008; Beatley 2011; Burton, Jenks, and Williams 2003).

[206] In Australia this issue is related to the cadastre system of land ownership and escalation of land prices over the past few decades.

In section 7.2 of this chapter I describe the key challenges of tree-scape design decision-making in urban renewal precincts. Proposed built form of urban renewal precincts is often a combination of two factors; housing market forecasting and legacy urban spatial structure (streets and blocks). Regulation of the proposed form is provided through written, spatially inexplicit planning overlays that specify building height limits and setbacks (building envelopes) which are in part generated from opinion of the market demand for specific housing types. These market forecasts are based on historic housing norms in the absence of a yet to exist residential population with whom to consult (Newton et al., 2013) [refer 2.2.5: *Composed cities*]. The planning overlays are then applied over the spatially explicit, somewhat immutable legacy urban spatial structure of the site[207]. Unwittingly, the built form which eventuates from these subjective governing guidelines and legacy infrastructure can exacerbate the environmental and social vulnerabilities already present in sites of urban renewal[208] [refer 7.4.1: *Why Arden-Macaulay*]. Section 7.2 focuses on the challenges which arise through the interaction between the height of building façades (the street wall) trees and the street.

In section 7.3 of this chapter I develop a series of digital-physical modelling prototype tests (petri-dishes) where I bring together the variables of tree-scape decision-making for flood and solar exposure in higher density. In the petri-dishes for *Synthesis City*, I investigate how to bring together tree choices for flood (developed in *Umbrella City*) with those for shade (developed in *Shady City*), to inform tree-scape decision-making with a street wall condition. Like the petri-dishes in the previous chapter, I have focused these tests on the micro-scale of a single abstract street intersection, discussing the outcomes of each test in relation to its application to the case study.

In section 7.4 of this chapter I apply the DDSS and outcomes of the petri-dishes to the case study of the proposed renewal precinct; Arden-Macaulay, a low lying ex-industrial site, subject to stormwater flooding with a heat vulnerability index between seven to eight (out of ten) (Loughnan et al., 2013). I develop and test two scenarios on this site, one which

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[207] Urban structure is a result of previous land use planning and current land ownership.
[208] The written, spatially inexplicit nature of planning overlays make it difficult to test proposed built form of urban renewal, against other criteria such as meeting environmental performance goals.

accepts the continuation of existing flood conditions (Land Subject to Inundation Overlay) and one where surface storm water management systems (SSWMS) are integrated into the streetscape redesign.

7.2 Key challenges

7.2.1 Higher density and the 'street wall'

The idea of the 'street wall'[209] is a popular tenet of urban design believed to encourage street activation and provide the streetscape with a sense of enclosure (COM, 2012; Cullen, 1965; Ewing & Clemente, 2013) [refer 2.4.4: *New Urbanism approach to carbon emission reduction*]. While a sense of enclosure provided by buildings has been correlated with positive preference and perceived safety, there is evidence to suggest that this correlation is even greater when enclosure is achieved through tree canopy rather than building façades (Harvey et al., 2015). In urban renewal precincts, with legacy narrow street widths and footpaths, attempts to achieve a street wall through zero lotted building façades conflicts with tree canopies [refer Figure 136]. This can result in extensive pruning of street trees, reducing their capacity to moderate flood, provide shade or visually achieve a sense of enclosure.

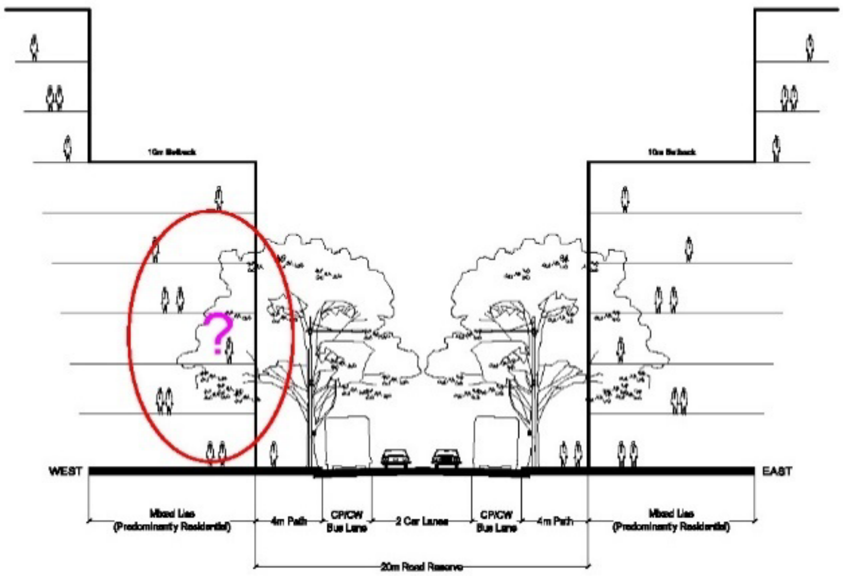


Figure 136: Proposed design for the connector road: priority bus route street: Boundary Road in the Arden Macaulay Structure plan 2012. This drawing shows the proposed street wall (zero lot building façade) and the conflict it has with the canopies of proposed trees.

[209] A street wall refers to zero lotted building façades (built on the boundary of the street frontage).

Divergent tree considerations in higher density

As the structure of built form changes from low to high rise, the tree-scape considerations for flood and heat diverge. In low rise development, there is only a small amount of difference between tree choices for flood or shade. Figure 137, Figure 138 and Figure 139, show a comparison of the street tree decisions which could be made for heat moderation on the left and flood moderation on the right as the built form increases in height. As the structure of the built form shifts to zero lotted mid and high rise, trees become increasingly important for flood moderation (due to associated loss of permeable pavement) and decreasingly important for active transport shading (due to associated streetscape overshadowing from buildings).

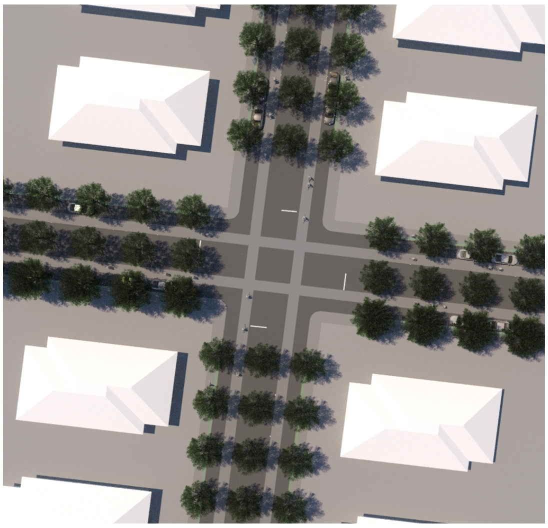
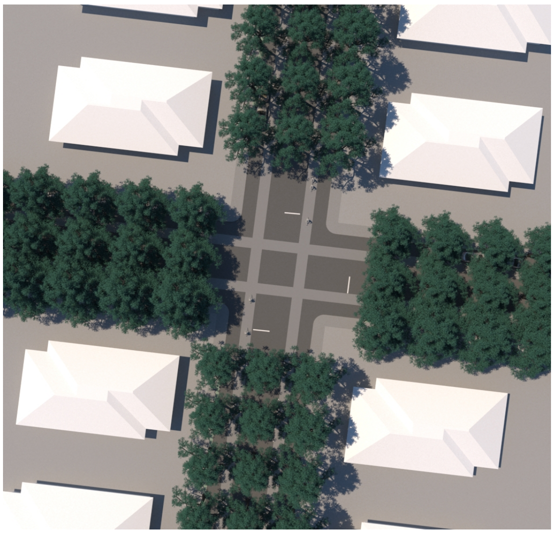



Figure 137: In summer in low rise developments (LEFT) maximum canopy coverage is needed for both summer solar radiation and (RIGHT) rainfall interception.

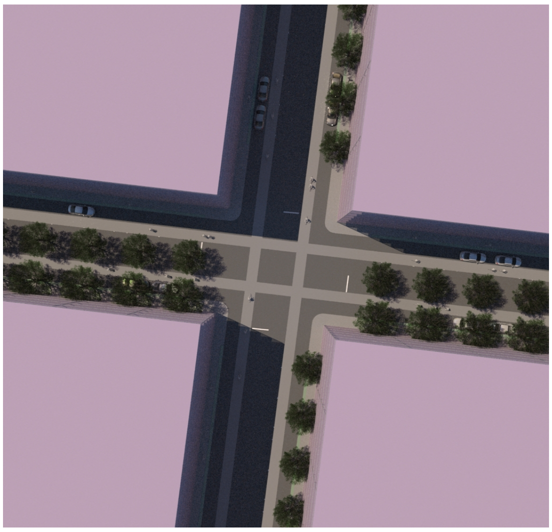
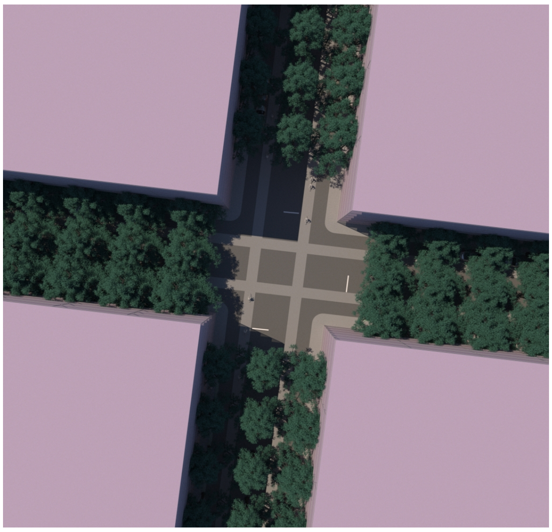



Figure 138: summer in mid-rise developments (equal canyon) (LEFT), buildings provide shade on north-south oriented streets, only the south side of east-west oriented streets require tree shade. (RIGHT) Despite changed site permeability, tree requirements for flood adaptation are unchanged from that of low-rise development.

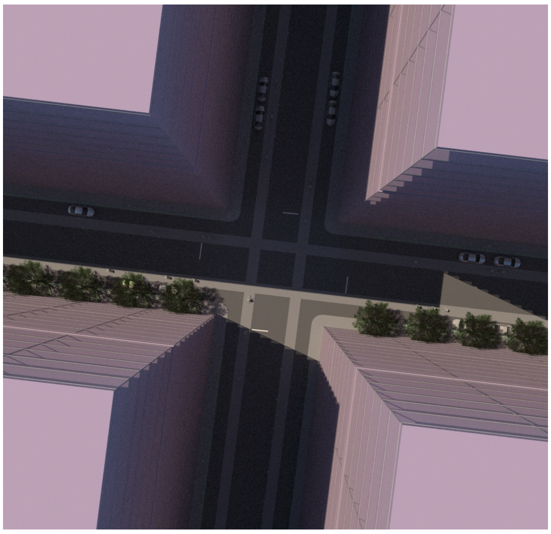
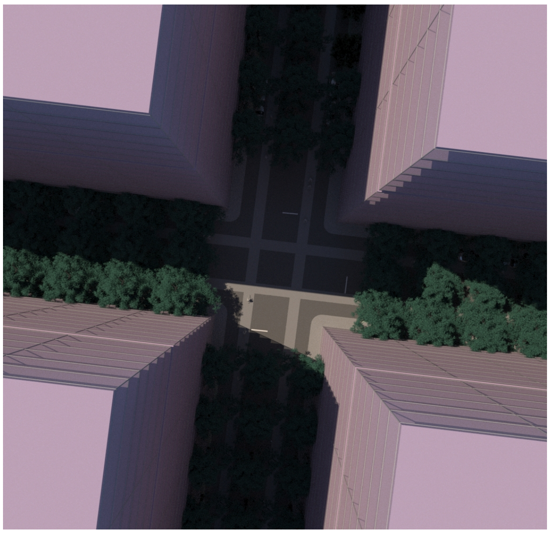



Figure 139: In summer in high-rise development (LEFT) streets maybe overshadowed by buildings and not require trees for solar protection. (RIGHT) However tree requirements for flood adaptation are unchanged if not exacerbated beyond that of low-rise development.

7.2.2 Higher density, sunlight and planning for active transport

Walking and cycling are generally more prominent as a form of transport in high density environments with diverse land uses (Cervero & Kockelman, 1997). In Victoria, Australia, recent analysis of VISTA[210] data revealed that 83% of short trips[211] taken by people living within a three kilometre radius of the CBD were active, dropping to 45% in areas beyond that radius (Charting Transport, 2011). This positive relationship between increasing density and use of active transport modes, suggests that where possible, streets should be reconfigured to accommodate active transport according to future density projections [2.4.5 *The view from the footpath*]. When designing streets with trees this requires long term streetscape design forecasting as mature trees are difficult to move[212].

Peak footpath pedestrian-use times and summer solar radiation exposure

Identification of a pedestrian peak-use time in areas with greater land use diversity is more complicated than in single use areas, such as the school zone used to test the DDSS in the previous chapter. In more diverse land use areas, though numerous destinations are accessed throughout the day under changing shade conditions [refer Figure 141], a usual week-day pattern of three peaks is discernible. A morning peak of work-ward commuters between 8.00-9.00; a midday peak between 12.00 – 13.00, and a longer afternoon peak of homeward commuters between 15.30 to 17.30 (J. Kim, 2017). These patterns can be seen in the 2016 data visualisation by Morphcode based on the City of Melbourne pedestrian counters [refer Figure 140]. During the morning and afternoon pedestrian peaks, UV levels are predominantly below the threshold set by the World Health Organisation as safe (UVI of three or under). However, the lunch time pedestrian peak coincides with the highest daily UV levels[213] and, despite taller built form, high levels of streetscape solar exposure [refer 6.2.2: *Trees reduce heat stress and UV exposure*].

[210] VISTA Victorian Integrated Survey of Travel and Activity (Transport Victoria) an on-going self-reported single-day survey of travel and activity, conducted across Greater Melbourne.
[211] Under one kilometre.
[212] Pedestrian volumes out strip intersection footpath capacity in the CBD of Melbourne at certain times of the day (COM, 2014b).
[213] In Victoria in summer the UVI is regularly above 12-14 at midday (Cancer Council Australia, 2019).

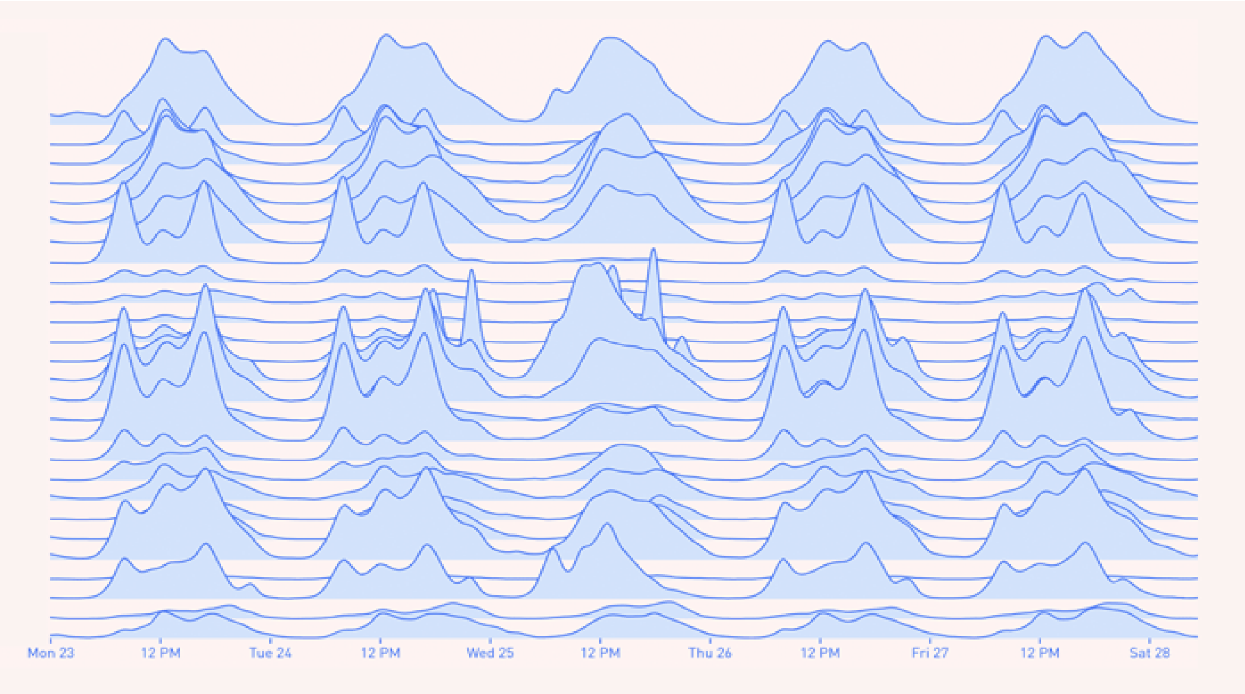


Figure 140: Pedestrian peak use times data visualisation from City of Melbourne pedestrian counters by Morphcode (source: https://morphocode.com/visualizing-pedestrian-activity-city-melbourne/).

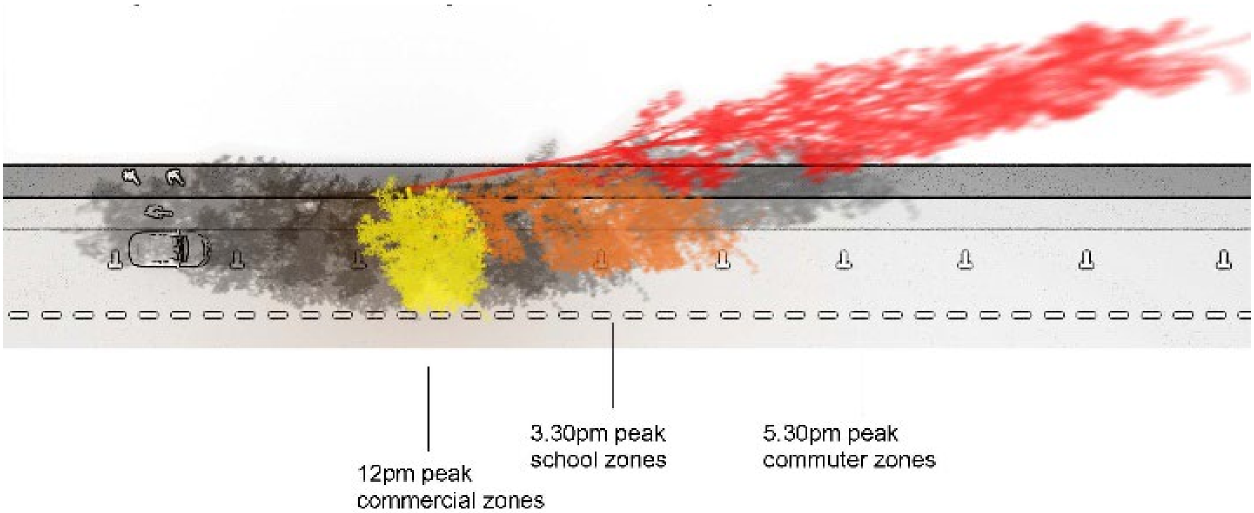


Figure 141: Aggregate shade map showing an overlay of shadow positions from multiple times of day of a single tree and its relationship with peak pedestrian use times, (generated through seven separate renders for each time of day composited in photoshop).

Higher density and winter solar preservation

Depending on street orientation, the comfort of active transport users can be poor throughout the year in zero lotted mid and high-rise environments. In winter solar preservation is difficult to achieve as tall buildings throw long shadows which can be oppressive, and in summer, short shadows still leave active transport users solar exposed [refer Figure 143 and Figure 142]. This key challenge for urban developments with street walls, suggests a tree-scape species selection dominated by deciduous trees to reduce winter overshadowing while maximising summer solar protection. However, this would conflict with tree-scape species selection for flood adaptation where dense canopied evergreen trees which continue to use water in winter are needed [refer 5.2.2: *Tree species selection for stormwater flooding*].

Figure 142: June (winter) aggregate shadow map for mid-rise development with no front setbacks. Image produced using multiple sun systems in base platform, 3ds Max (source: http://citiesoflight.xyz/ by White, M. and Langenheim, N.).

Figure 143: December (summer) aggregate shadow map for mid-rise development with no front setbacks. Image produced using multiple sun systems in base platform, 3ds Max (source: http://citiesoflight.xyz/ by White, M. and Langenheim, N.).

7.2.3 Higher density and flood adaptation

Due to past industrial uses, urban renewal sites are often at low elevations, adjacent water ways, with shallow to the surface water tables and as such, their drainage infrastructure will require support from surface-based storm water systems (SSWMS) in the face of increasing storm event intensity[214] [refer 7.4.1 *Why Arden-Macaulay* and 5.2.1: *Stormwater flood and water infrastructure*]. In cases where these sites also lack open space provision (as is the case with the *Synthesis City* site), these SSWMS, will need to be incorporated into the design of streetscapes. For the Arden-Macaulay precinct, a number of street based, SSWMS are currently being explored, in discussion with the Victorian Planning Authority (VPA) (formerly known as Melbourne Planning Authority), such as biofiltration roadside retention trenches and road casement detention mechanisms which maintain pedestrian connectivity during storm events [refer Figure 144] (MPA, 2016). In many cases these SSWMS will contain trees which will require specific tolerances and functions, or mechanisms related to water management [refer Figure 144].

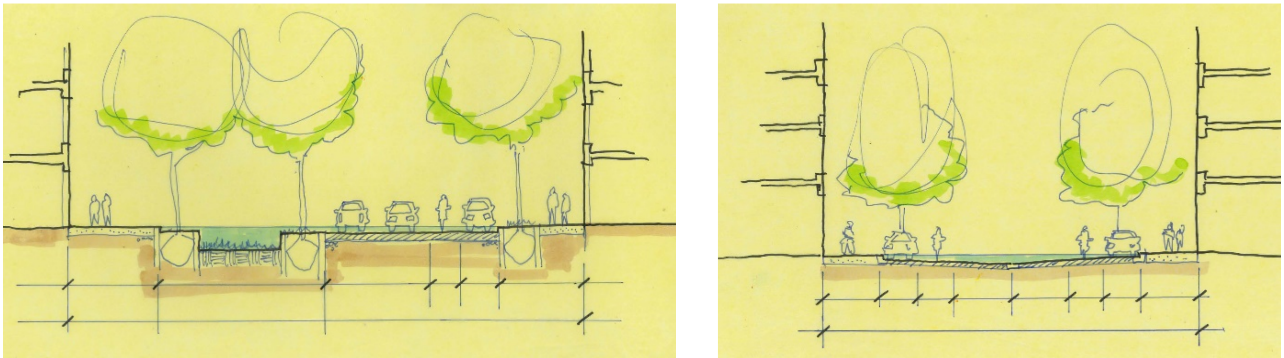


Figure 144: Arden-Macaulay street cross sections showing (LEFT) roadside retention trench (RIGHT) road casement stormwater detention discussion document (MPA, 2016).

In summary, the key challenges of higher density urban renewal sites with diverse land-use and transport, council preferred ‘street wall’ conditions, the complexity of seasonal change and integration of SSWMS into streetscapes, will require more sophisticated application of the DDSS than in the previous two chapters.

[214] Urban renewal is often located on post-industrial sites. Colonial industry often required proximity to water which was used for processes such as running steam engines, while waterways were used in industries such as tanneries, soap and candle making, wool washing and sheepskin processing for waste disposal (Frost et al., 2016).

7.3 Part 2: 'Petri-dish' tests responding to key challenges

In the following section I describe a number of abstract digital-physical design experiments or prototypes (petri-dish tests) responding to the key spatial, environmental and visual considerations of flood and heat tree choices in higher density development. In these petri-dish tests I combine the *flood mapping* techniques developed in *Umbrella City*, the *shade mapping* techniques developed in *Shady City* and the additional considerations which occur in a condition of street wall-built form. I discuss the outcomes of each petri-dish in relation to their application to the case study site.

7.3.1 Modelling surface stormwater management systems (SSWMS)

This 'petri-dish responds to the key challenge 7.2.3: *Higher density and flood adaptation*, of road based SSWMS proposed in the case study site[215]. I have been able to integrate most flood modelling in this thesis using 2-dimensional map-based raster methods, however this storm water management proposal is directly related to streetscape configuration, impacting issues such as the ease with which a pedestrian can cross the street (to get to the shady side for instance). In this petri-dish I 3-dimensionally modelled a street casement as digital triangulated meshes (TIN) in order to understand the impact on the pedestrian environments and the spatial / tree implications this flood management strategy would produce. The figures below show the way this infrastructure will operate in dry conditions [Figure 145], mild flood [Figure 146] and major flood [Figure 147]. Figure 148, shows modelling of a larger portion of streetscape (constructed using road casement data from the case study site) showing how the incorporation of trees (in footpath or in road) will be a critical decision for tree-scapes as they may need to tolerate periods of inundation or have high water use mechanisms to remove flood water.

[215] Central drainage is proposed for streets in the site though, unlike precedent streets such as Sonder Boulevard Copenhagen https://ramboll.com/media/articles/water/cloudbursts-what-can-we-learn-from-copenhagen some of these streets may not be wide enough for a central median.

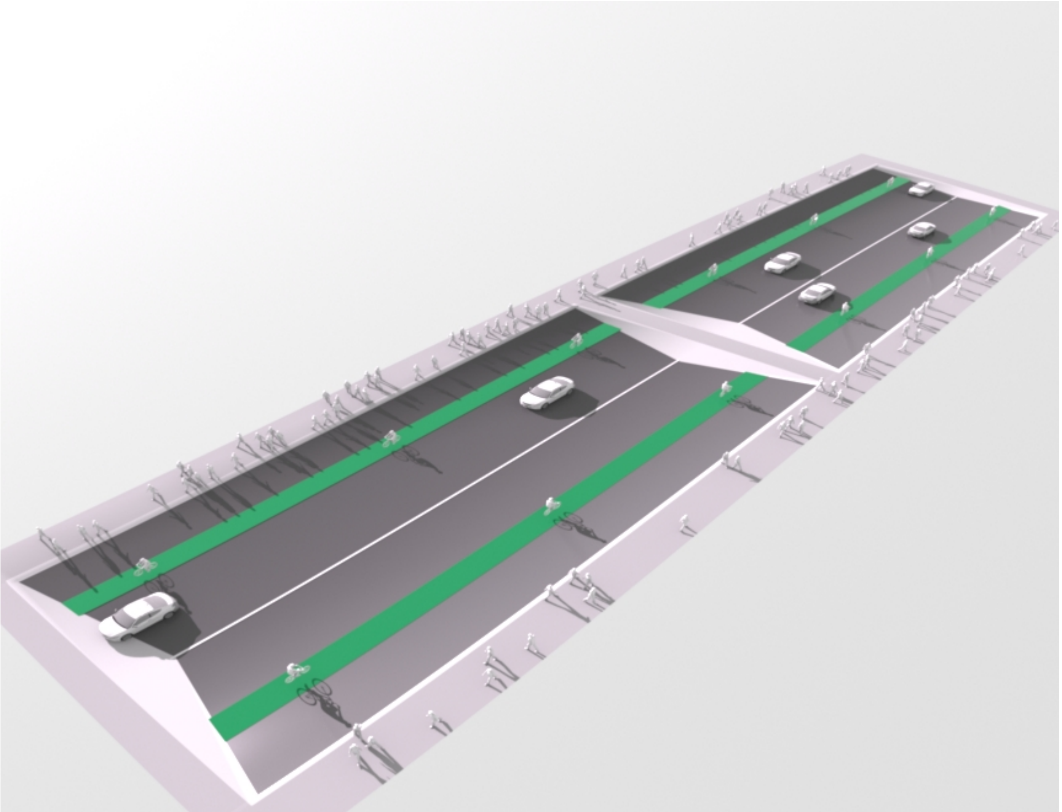


Figure 145: Micro scaled topography model. Street casement graded to hold storm water in the road surface area. Pedestrian crossing points are enabled through raised sections, perpendicular to the road surface.

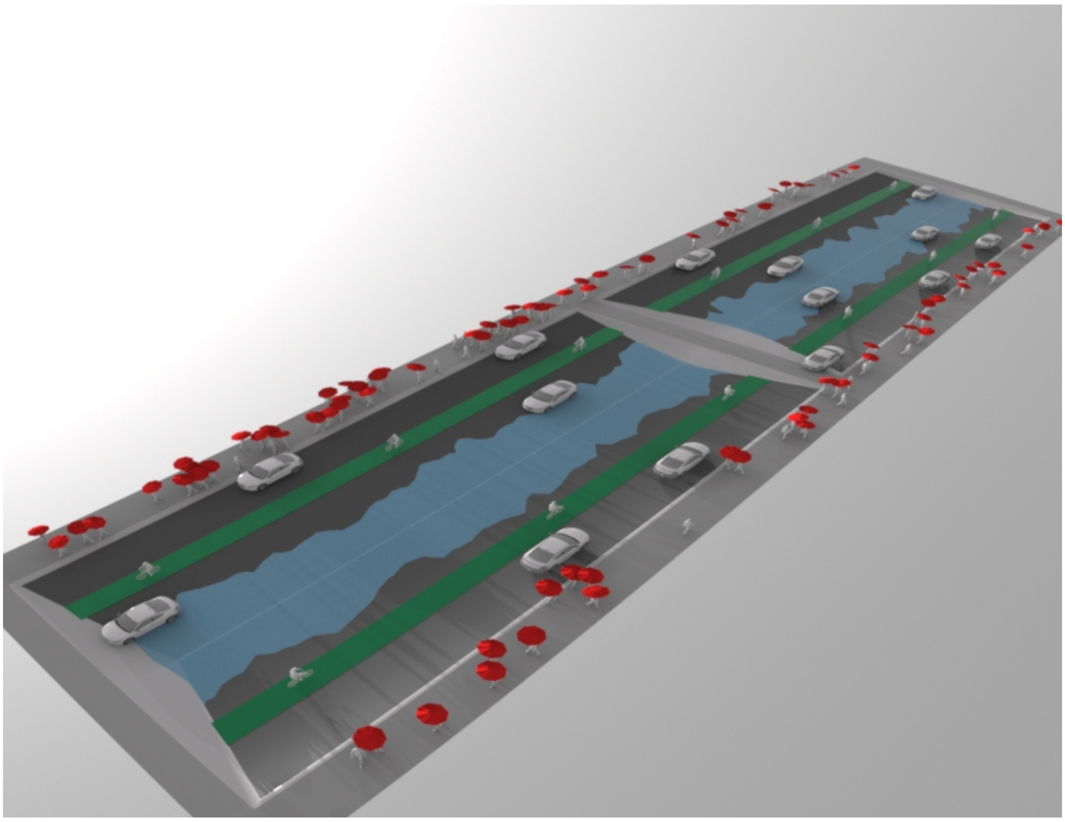


Figure 146: Micro scaled topography model. In mild flood storm events, storm water flows are contained in the centre of the road.

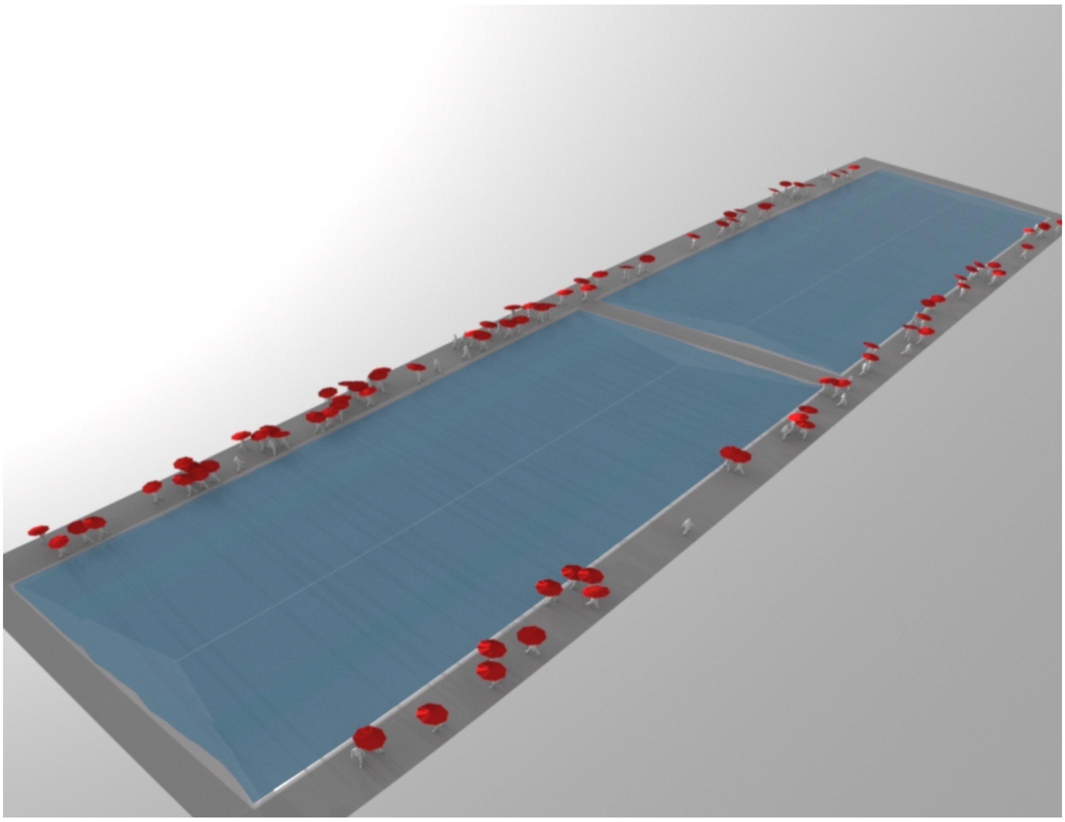


Figure 147: Micro scaled topography model. In major flood events, pedestrian connectivity is still maintained.

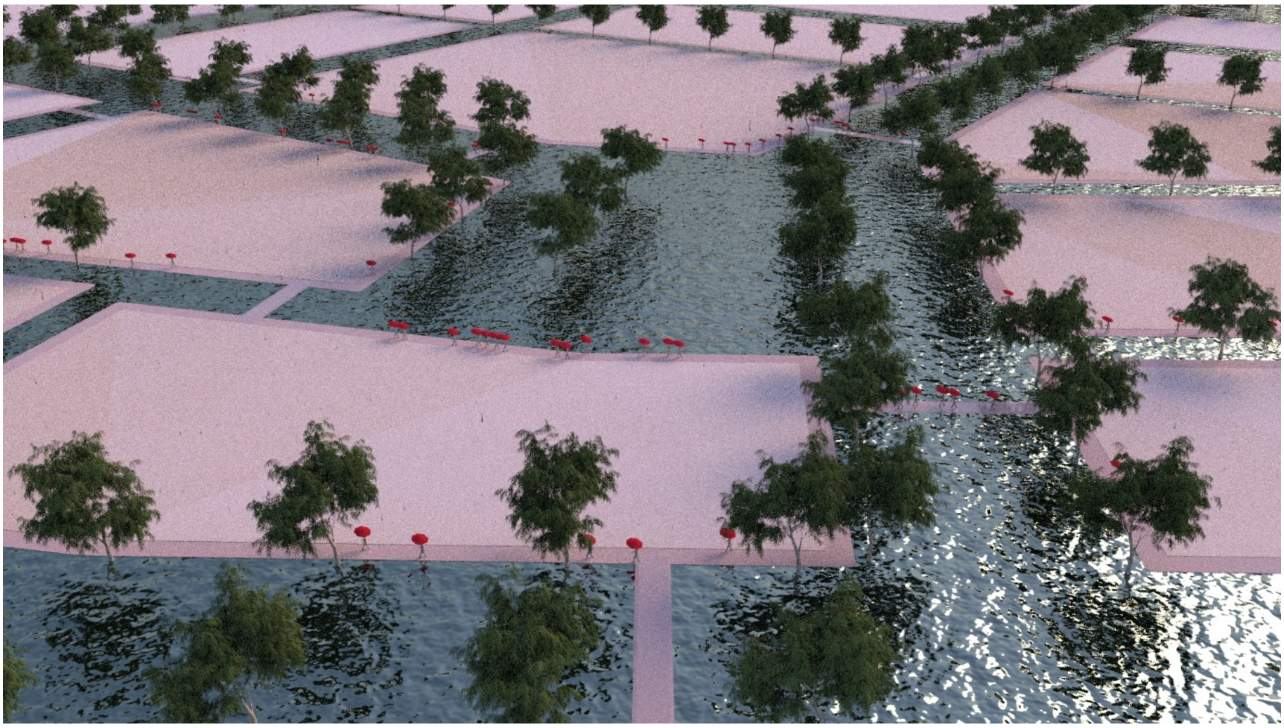


Figure 148: Micro scaled topography model. The road-based SSWMS applied at a larger scale (with buildings hidden), shows the way trees are included in this system will be critical to their success. If included in the road surface, they will need to be tolerant of inundation, if they are included in the footpath this will limit their possible positioning in the streetscape to provide shade.

Outcomes

I was able to use the model of the road based SSWMS to understand where stormwater would go if this infrastructure was implemented. I was also able to use this 3-dimensional model to output a 'flood driver map' which could be used in the same way as explored in *Umbrella City*.

While this was a valuable process to understand, and I have used it to generate a flood scenario map for the case study, it would have been simpler to generate the 'flood driver map 2-dimensionally for this speculative project. This study was complicated to model even on a notionally 'flat site'. If this proposal for road based SSWMS were to be implemented, the required 3-dimensional modelling could be accurately[216] and efficiently modelled in a program such as Autodesk's Civil 3D™. A live link, interoperability component already exists between Civil 3D and the base platform used for the DDSS. This interoperability component could be used to link an accurate Civil 3D model of flood infrastructure into the DDSS, allowing for direct generation of spatially explicit flood maps from the civil infrastructure model.

7.3.2 Balancing winter solar access and summer solar exposure

This 'petri-dish' responds to the key challenge 7.2.2: *Higher density, sunlight and planning for* active transport. In this petri-dish I investigate the difference between the winter and summer shadow of the street wall and how it impacts the comfort of pedestrians and cyclists. I constructed a digital-physical intersection model of twenty-metre-wide streets with simple (vertical façade) zero lotted, six storey buildings (20m height) (Canyon ratio of 1H:1W) with the daylight system set to Melbourne, Australia. I used the approach outline in the *Shady City* petri-dish, [refer 6.3.1] both rotated -7° to enable the intersection to represent streets oriented (bearing N7°E). This intersection model represents the proposed building envelopes in the planning scheme for Arden-Macaulay and the dominant existing precinct urban spatial structure (street width and orientation) (Melbourne Planning Scheme, 2014). Figure 149, shows the impact of seasonal change on the pedestrian environment with this condition. In summer many of the active transport paths are exposed at 12.30, the midday pedestrian peak time, and in winter, at this time, solar access can only be preserved on the west side of north-south oriented streets.

[216] The modelling for this infrastructure would need to be integrated with existing topography. This would be a highly detailed TIN file and the only way to calculate actual water holding capacities.

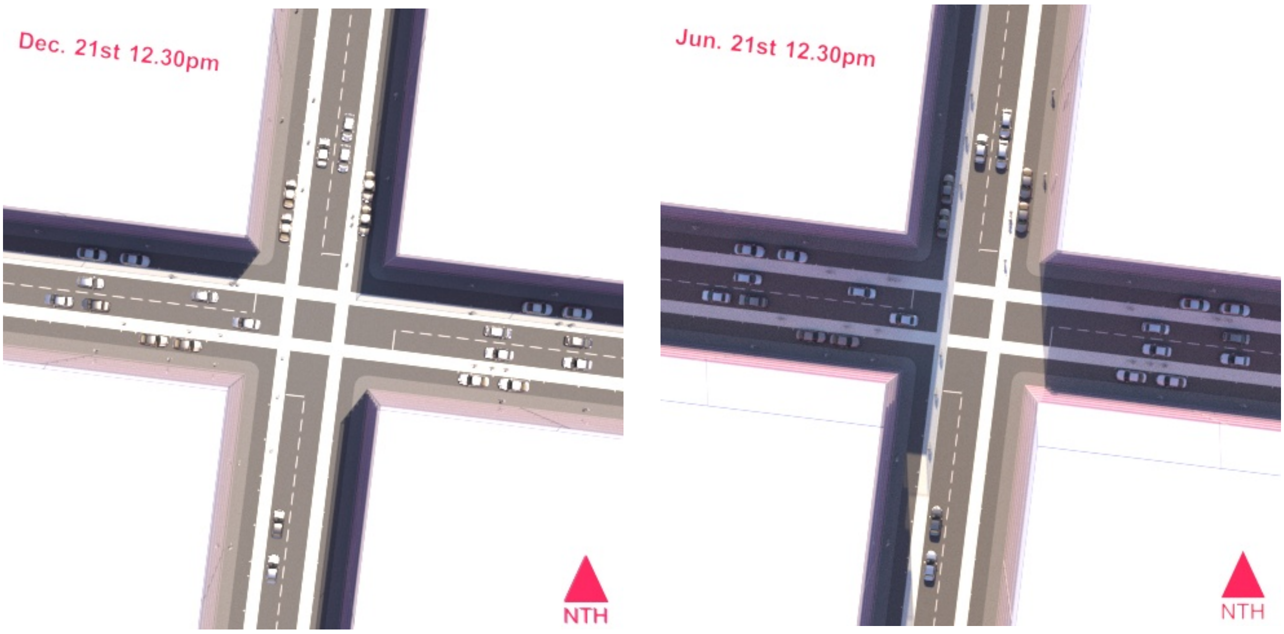


Figure 149: An intersection of a street with equal building height to street width ratio. LEFT 12.30 in summer, RIGHT 12.30 in winter. Higher density can still leave pedestrians exposed in summer, on this orientation, winter solar access could be preserved on the western side of north-south oriented streets.

Cross referencing winter and summer conditions

To test this street canyon condition further I then set the sun position for two additional afternoon peak pedestrian times in both winter and summer. I chose the afternoon as this is the peak associated with the homeward journey from work. Often, in the summer months in Australia the UV is still above three during this time. I did not test the morning 9.00 peak as UV is below three at that time. The selected times were adjusted for daylight savings, with 15.30 corresponding to 14.30 in summer. I then tabled which active transport paths were exposed and which ones were in shade for all six time and season variations. Figure 151 and Table 8 show where active transport paths are exposed and where they are shaded in summer, and Figure 151 and Table 9, show where they are exposed and shaded in winter. I then cross referenced the outcomes of these two tables to ascertain two facets: 01) Where deciduous trees would be required in order to preserve winter solar access and 02) Which position trees would need to be placed to optimise shade for active transport paths in summer [refer Table 10].

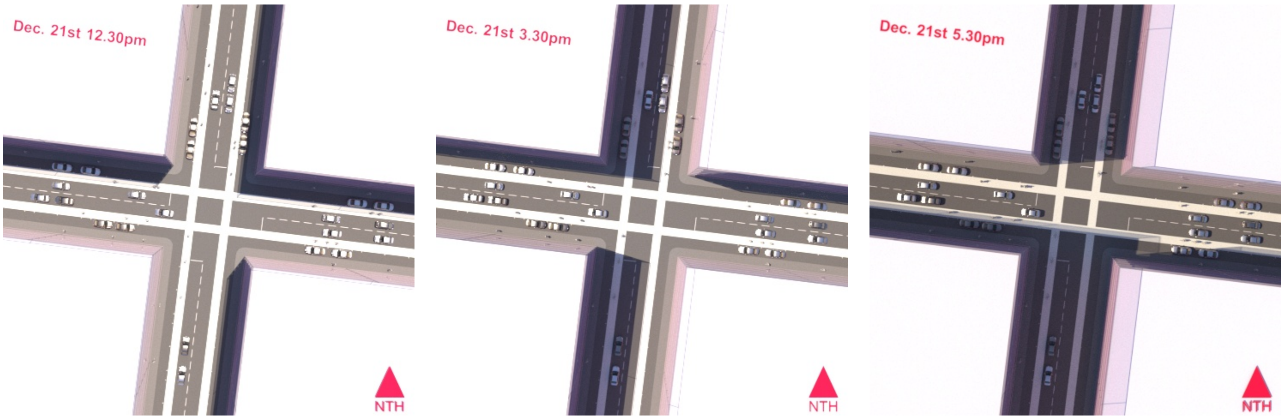


Figure 150: December 21st 12.30, 15.30 and 17.30 shows cyclists and pedestrians are solar exposed

Table 8: 20m wide streets with bike path adjacent parking summer solar exposure

	E-W_N		E-W_S		N-S_W		N-S_E	
SUMMER	Footpath	Bike pth	Footpath	Bike pth	Footpath	Bike pth	Footpath	Bike pth
12.30	Shade	Exposed	Exposed	Expose	Exposed	Exposed	Shade	Exposed
15.30	Shaded	Exposed	Exposed	Expose	Shade	Shade	Exposed	Exposed
17.30	Exposed	Exposed	Shaded	Shaded	Shade	Shade	Shade	Shade

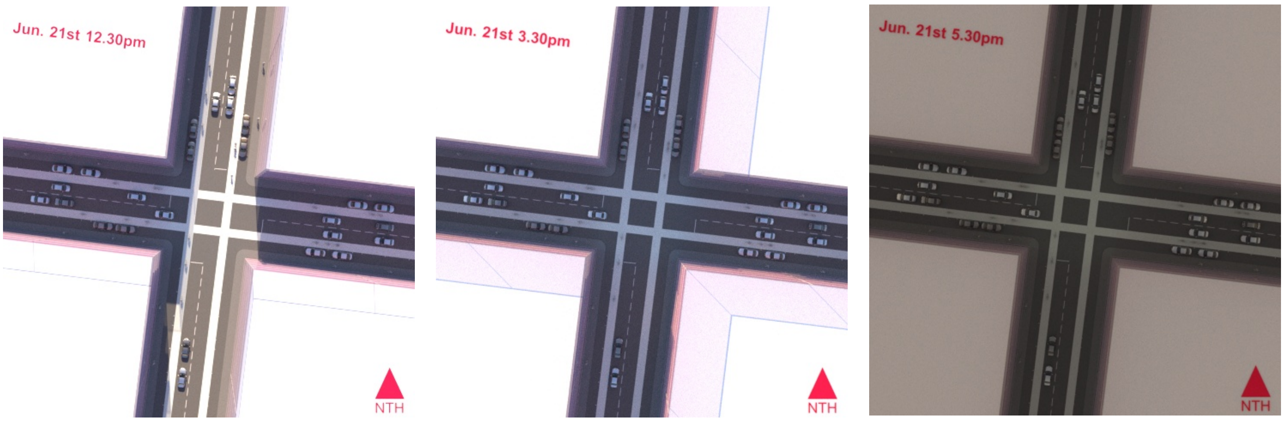


Figure 151: June 21st shows solar amenity is only preservable at 12.30 in mid-winter in higher density

Table 9: 20m wide streets with bike path adjacent parking winter solar possibilities

	EW_N		EW_S		NS_W		NS_E	
WINTER	Foot	Bike pth	Foot	Bike pth	Foot	Bike pth	Foot	Bike pth
12.30	shadow	shadow	shadow	shadow	shadow	shadow	sun	sun
15.30	shadow	shadow	shadow	shadow	shadow	shadow	shadow	shadow
17.30	Shade	shadow	shadow	shadow	shadow	shadow	shadow	shadow

Table 10: Cross reference of winter solar access possibilities and summer active transport shading: Tree planting locations and types to achieve both.

	EW_N		EW_S		NS_W		NS_E	
	Foot	Bike pth.	Foot	Bike pth.	Foot	Bike pth.	Foot	Bike pth.
12.30	Building shade	Curb edge	Curb edge /between bays	Not able to be shaded	Curb edge	Between bays (partial)	Building shade	Between bays /curb edge **Deciduous**
15.30	Building shade	Curb edge/ between bays	Curb edge	Between bays	Building shade	Building shade	Not able to be shaded	Between bays
17.30	Curb edge	Between bays	Building shade	Building shade	Building shade	Building shade	Building shade	Building shade

Outcomes

The results of this study show that the most suitable time for preserving mid-winter sun is during the lunch time pedestrian peak. In winter, by 15.00 these same streets are entirely overshadowed. To achieve mid-summer solar exposure protection, I used the six possible positions approach developed in *Shady City* [refer 6.2.4: *The spatial constraints of street reconfiguration*]. However in this zero lotted development scenario with 20m street widths, tree positions are limited to; between bays (Pink) or at the curb edge (yellow) [refer Figure 152 and Figure 153]. In the case where bike paths are located adjacent footpaths the third position (green) [Figure 155]; Trees between the bike path and road could be utilised [refer Figure 154] however this is difficult to achieve on 20m wide streets.

This study shows that winter solar access could be preserved through strategic use of deciduous trees on the east side of north-south running streets, while all other active transport paths, which are already overshadowed in mid-winter could use evergreen trees for solar exposure protection, and thus, with an optimal number of evergreen trees, help to fulfil objectives for storm water regulation.

7.3.3 Constraints of tree crown-form and canopy dimensions in higher density

This petri dish responds to the key challenge of the intersection of street walls and tree canopies and the need for shading of the south side of 20m wide east west streets even in high density environments [refer 7.2.1: *Higher density and the 'street wall'*]. Figure 152 and

Figure 153 look at the tree crown-form constraints if using the typical planting location of 'in the footpath'. In 20m wide streets in this location tree crown-form would need to be either columnar or pruned where they intersect with building façades. Figure 154, shows that wider growing crown-forms could be used in the 'between bays' position but this would also require canopy pruning or training to achieve required canopy width dimensions at a spacing of 14m apart (two parking bays) [refer Figure 154 right hand side]. Figure 155, shows how trees in the 'between bike path and foot path position could be effective, however this configuration can be difficult to achieve in 20m wide streets, as it requires traffic lane width reduction.

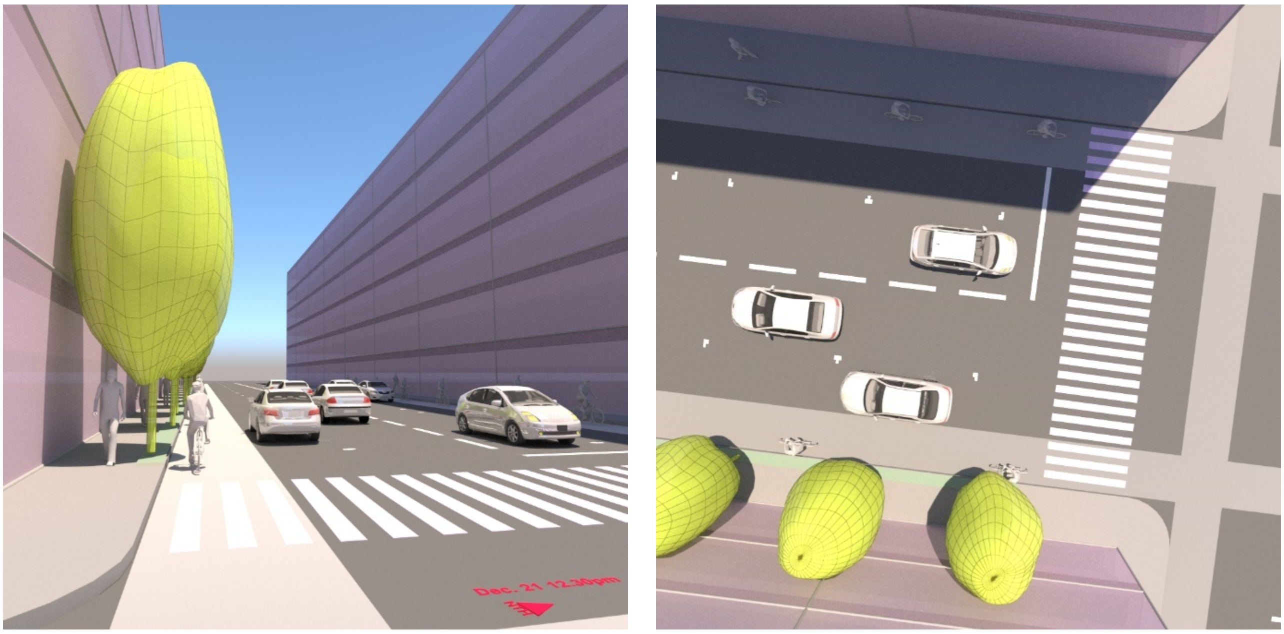


Figure 152: Shows curb edge planting on the south side of a 20m wide east-west oriented street: The column crown-form is used here due to the narrow space allowance for the canopy.

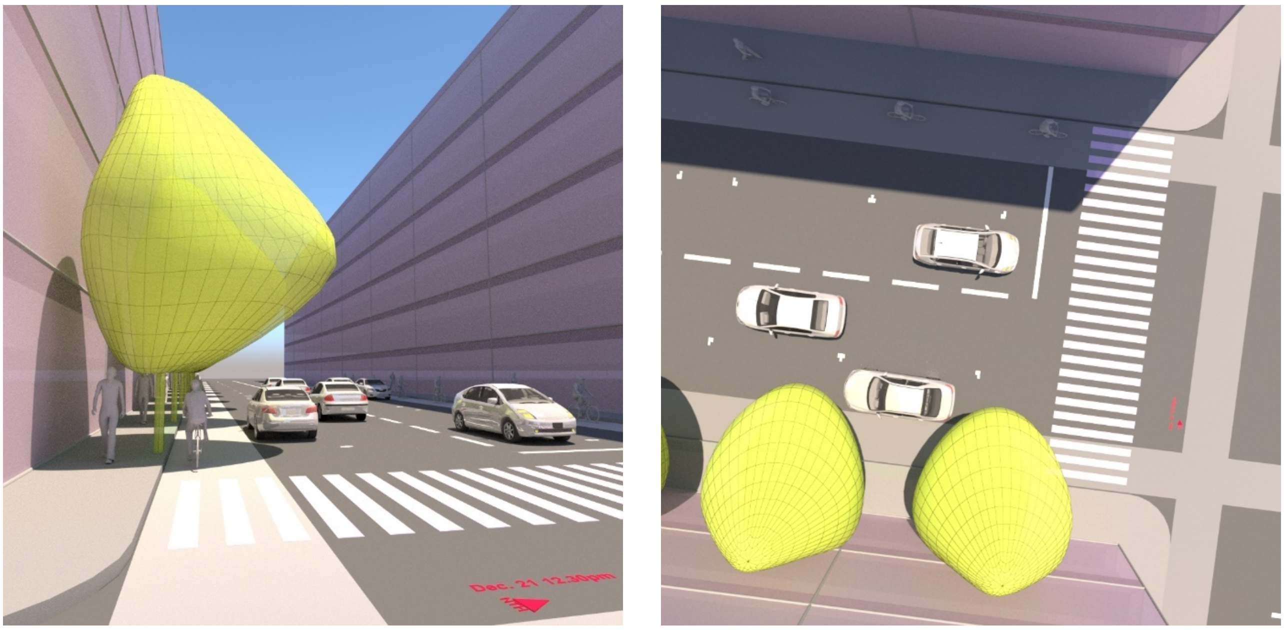


Figure 153: Shows curb edge planting using a species with wider canopy dimensions used to achieve shading objective but pruned against building façade.

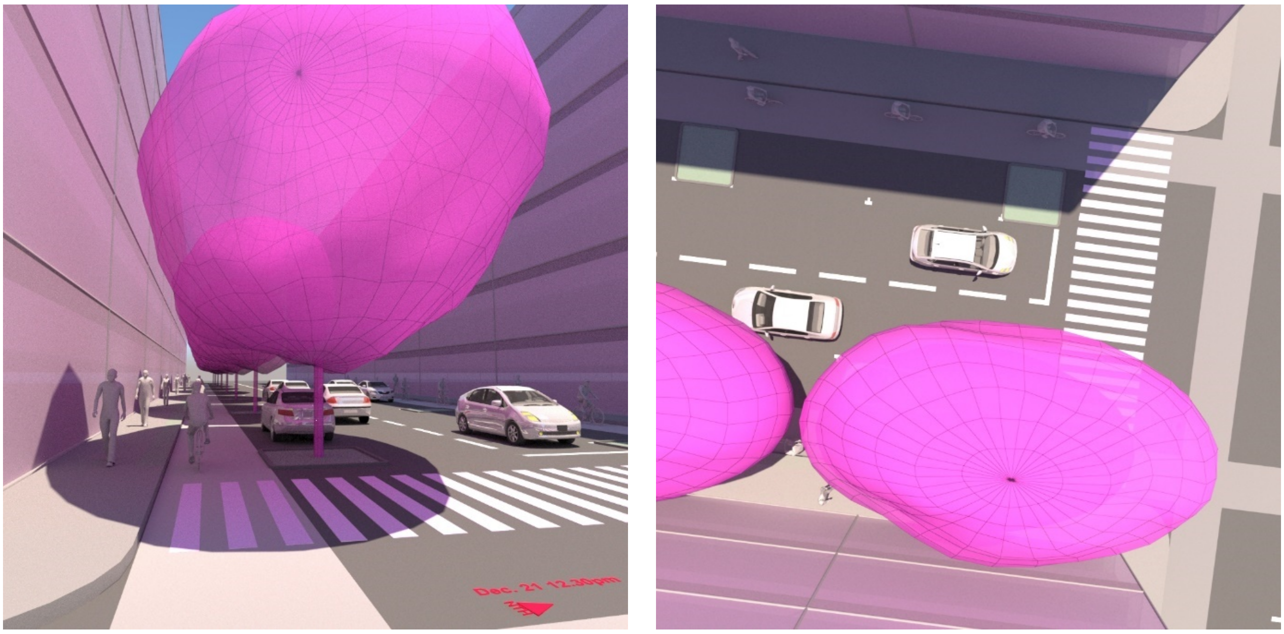


Figure 154: Shows trees in the Between bays planting position. This could be made to work well, to shade both bike and footpaths particularly if using a slightly taller tree, however two parking bays require a 14m spacing trees and would require a species which with wide canopy growth dimensions. These growth dimensions would intersect with building façade.

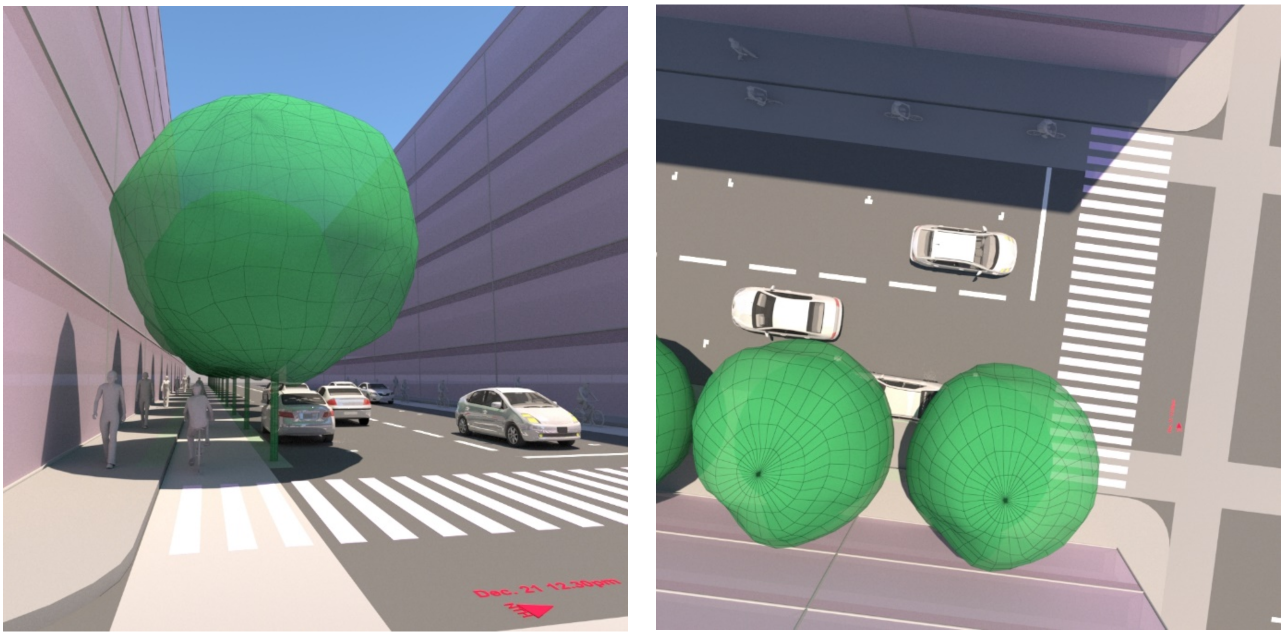


Figure 155: Bike path edge planting allows an 8m canopy width and spacing between trees, but this configuration also requires narrowing of car lanes.

Outcomes

The outcomes of this petri-dish study show optimal positioning for shade, tree crown-form, canopy dimensions within the street casement could be used to provide a first pass at species selection requirements. The next step would then be to ascertain what the outcomes of this study are against what that means for road based SSWMS and required tree tollerances for flood [refer to section 7.3.1: *Modelling surface stormwater management systems (SSWMS)*].

7.3.4 Using pseudocolour and digital meters to quantify shade

This petri-dish test responds to the key challenge of quantifying differences in levels of shade using an architectural lighting analysis technique, built into the rendering engine plugin I have incorporated into the DDSS framework. Shade quantification in the previous chapter was handled as a Boolean function (a black and white map representing a binary condition of either in or out of shade). In the real-world, the depth of shade[217] provided by a tree varies with tree height, distance from the trunk, canopy density and leaf characteristics. Most of these subtle shade variations are at a level of detail not required for streetscape decision-making particularly when considering shade and water regulation simultaneously. However, it can make a difference when there is a requirement to select between two possible tree positions or where an exposure threshold needs to be more nuanced than simply exposed / shaded.

In this petri-dish I set an indicative optimal shading time of summer at 15.30, when tree shading is clearly needed on the west-side of north-south oriented streets and on the south side of east-west oriented streets. All other active transport paths are shaded by buildings at this time.

[217] Deep shade (umbra) which occurs close to the tree base and shallow shade (penumbra) which occurs as a result of shading from the topmost parts of the tree.

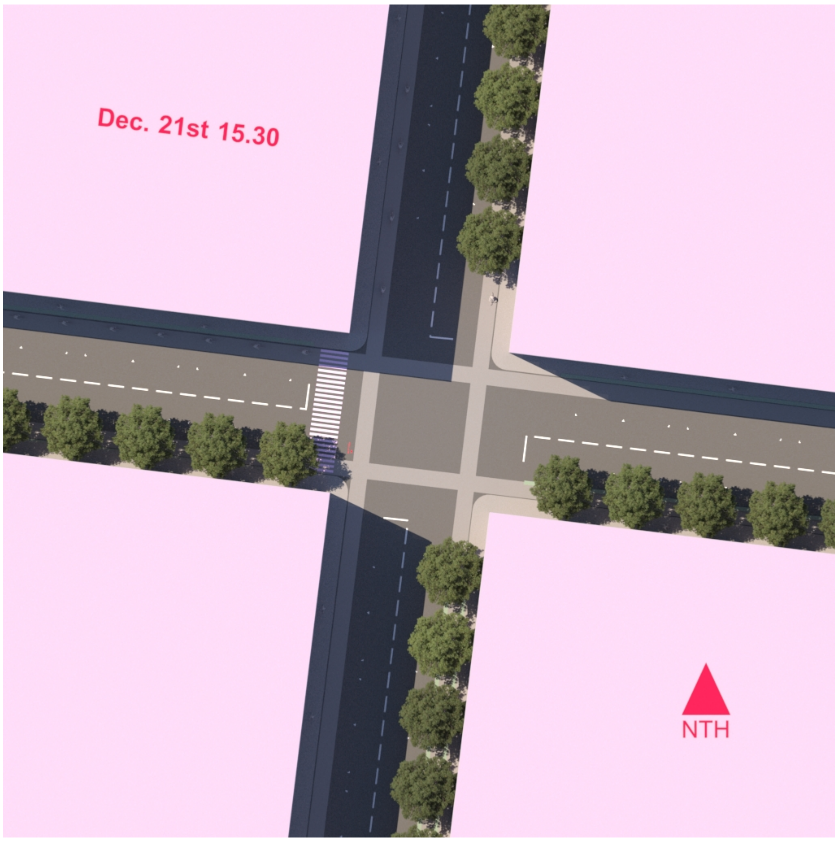


Figure 156: Shows the shading of an indicative intersection with a building height to street ratio of (1H:1W)

The rendering plugin allows digital light meters to be used two ways. Either the entire scene can be rendered as a 'false' or 'pseudo colour' image[218] [refer Figure 157], or alternatively, adjustable grids of digital light meter 'helper objects'[219] can be selectively placed in the model [refer Figure 161]. The first method allows for rapid production of a data visualisation with lux level scale bar of entire scenes, while this second method, though it cannot be rendered to an image, has the advantage of allowing the light meter lux level readings to be exported as a .csv format to analyse in Microsoft Excel™.

In this petri-dish I analysed the output of adjustable lengths of light meters (1m x 50m, placed at 1m intervals, along the length of the foot and bike paths on the south side of an east-west oriented street, one length adjacent the bike path and the other adjacent the building edge. I graphed the light meter output from each path and set an exposure threshold of 20,000 Lux[220]. Figure 160, shows section of east-west oriented street (top) in

[218] 'False or pseudo colour (as opposed to true colour) rendering is the process of making image data, particularly that of the electromagnetic spectrum more comprehendible. Originally it was used by radio astronomers working with grey scale images, where each shade of grey represented an intensity of a radio emission from a particular part of an object. They converted these grey scale images into a colour scale (from red to blue to make them visually clearer).
https://starchild.gsfc.nasa.gov/docs/StarChild/questions/question20.html
Note pseudo colour is a variant which only uses one colour channel whereas false colour can use two or more channels.
[219] Helper objects are not renderable, they are used to help calculate or expose accurate analysis of objects within the scene.
[220] 20,000 Lux is the reading for shade illuminated by entire clear blue sky, at midday https://en.wikipedia.org/wiki/Daylight

plan and a perspective image taken from the recently integrated Interactive Photorealistic Rendering (IPR) viewport (2019). Figure 161, shows a detailed view of the light meter helpers which I exported as a .csv file to graph in Excel™. I then used this numeric data to assess tree shade impact along block boundaries [Figure 162] and along the designated bike path [Figure 163].

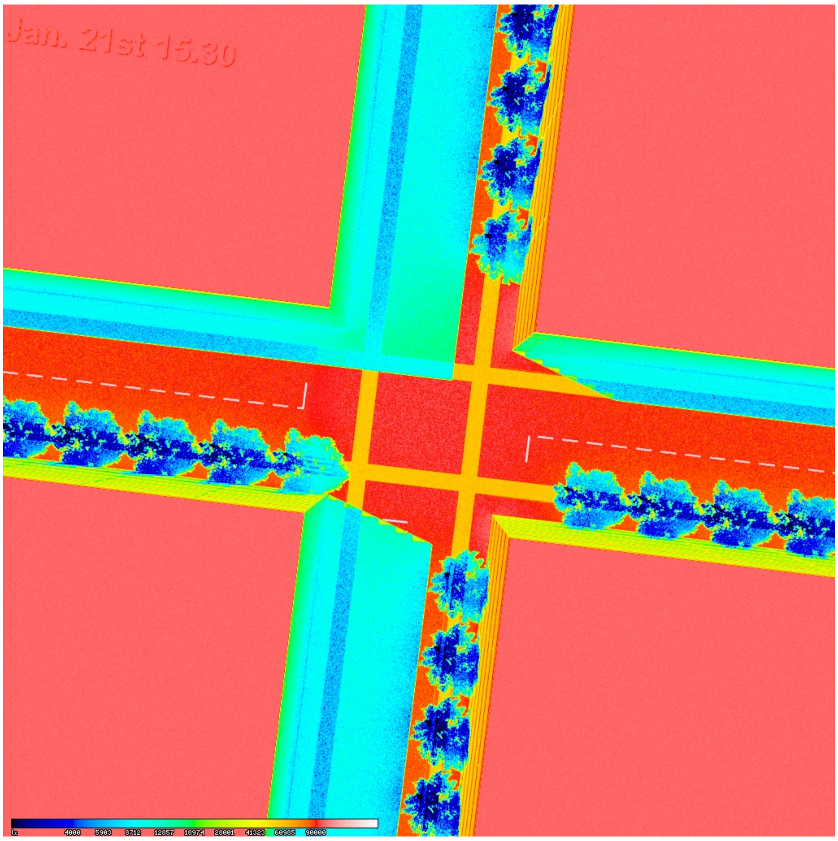


Figure 157: Pseudo colour render of an intersection mid-summer at 15.30. The camera has been clipped so the tree models are not visible but the effect of their shade on the light levels beneath them can be recognised. Where the shade falls over the white coloured bike path light levels appear further reduced

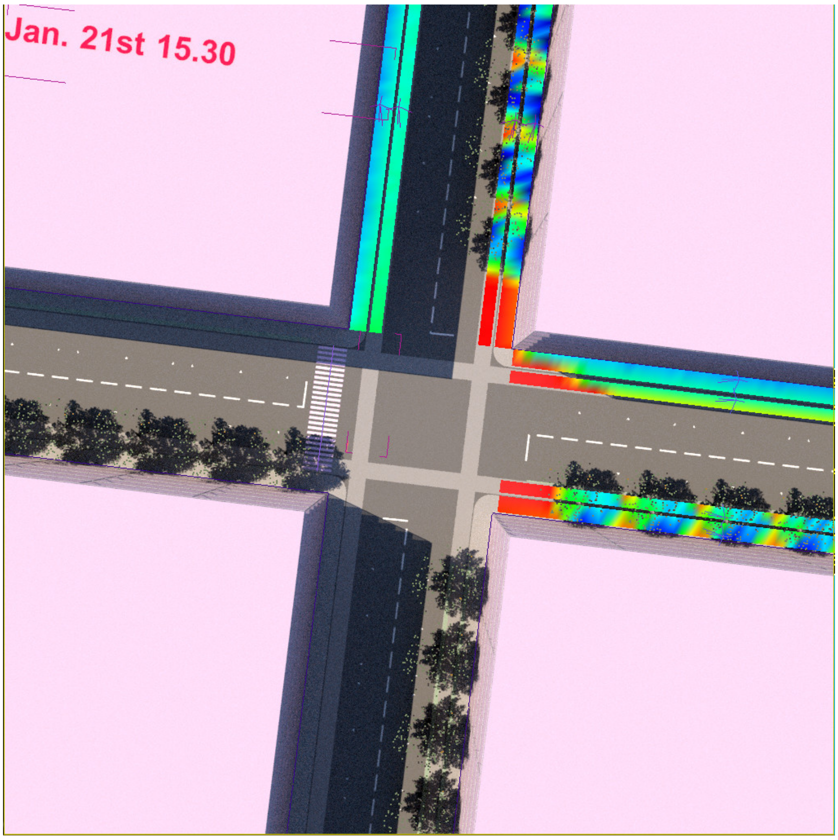


Figure 158: Shows lines of pseudocolour light meter helper objects spaced 1m apart distributed over bike and footpaths. Logarithmic calculation.

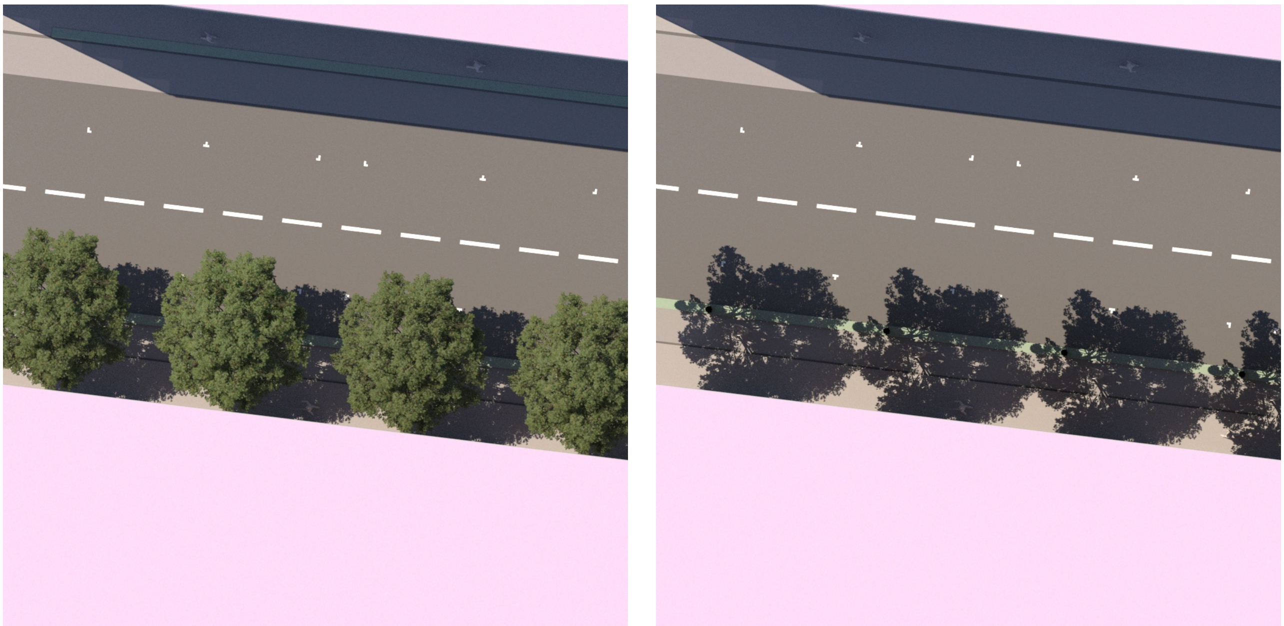


Figure 159: Detailed top view showing the shadow of the east-west oriented street with trees not hidden (LEFT) and hidden (RIGHT).

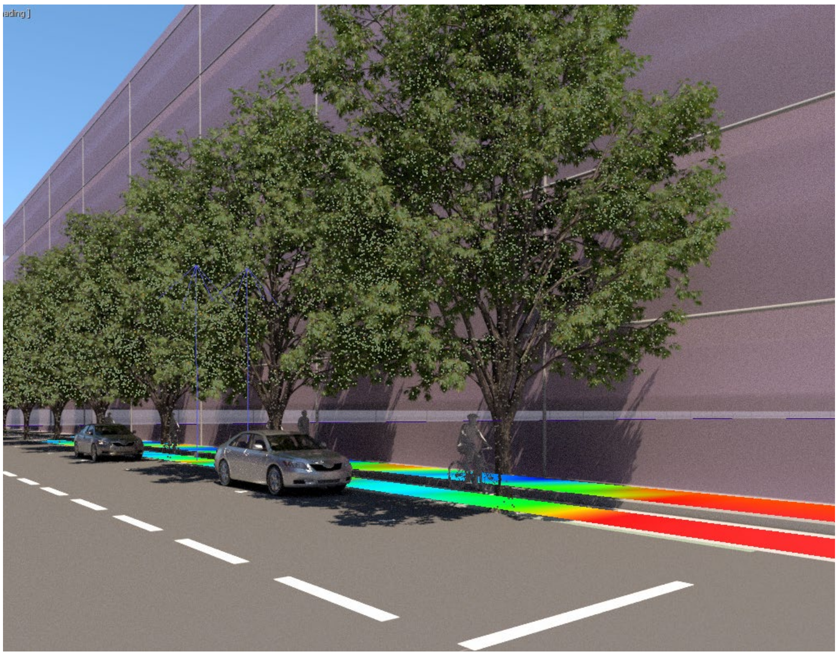


Figure 160: Perspective view of east-west street orientation taken as a screengrab using V-Ray 'Interactive Viewport Rendering (IPR).

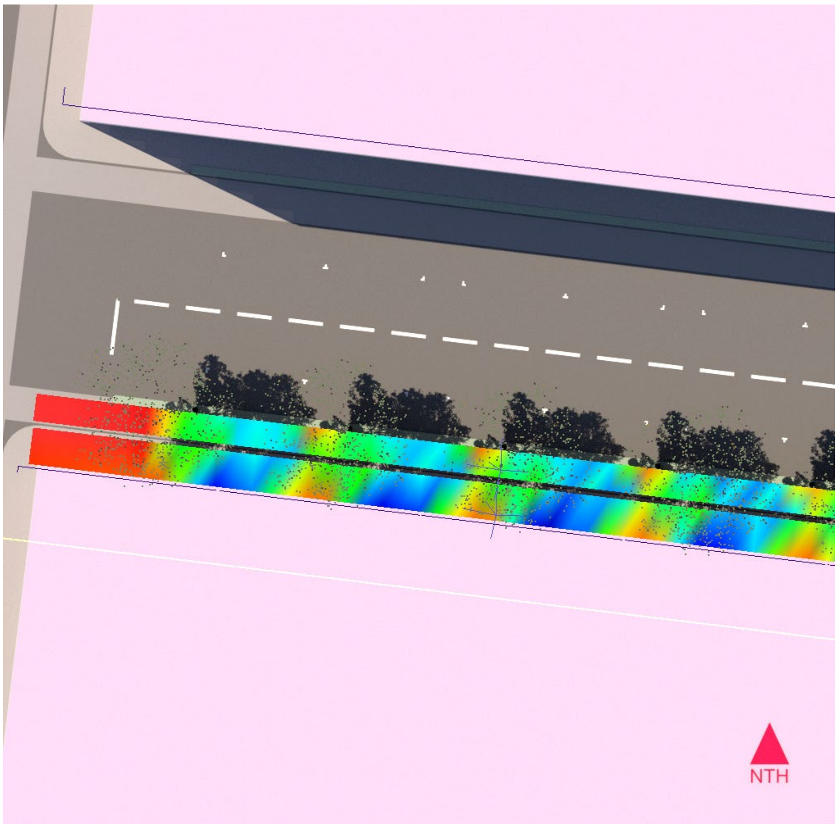


Figure 161: Grids of light meters (helper objects) set up along the footpath and bike path of the western side of a north-south oriented street, showing pseudo colour lux levels under the trees. The readings of these light meters can be exported and analysed in other programs.

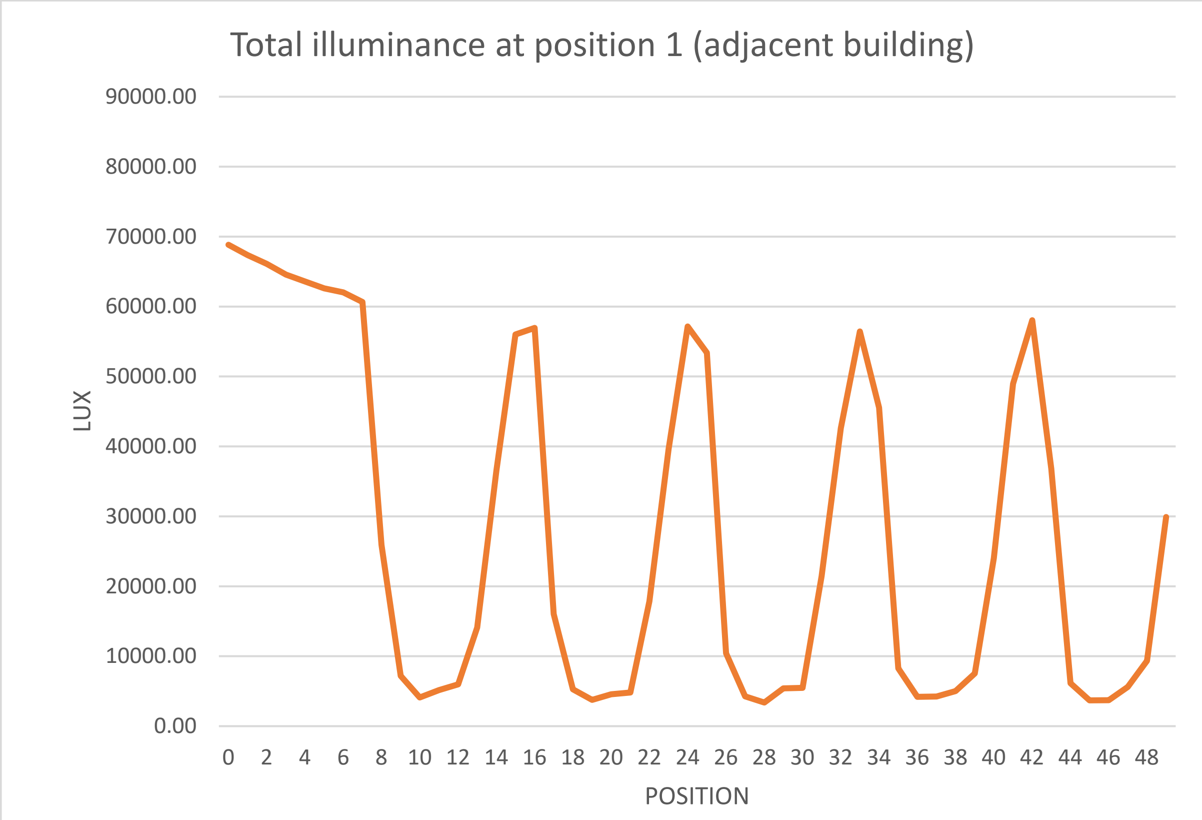


Figure 162: Shows a graph of the Lux level readings adjacent the building edge. Only 26% of readings were under the 20,000 Lux threshold.

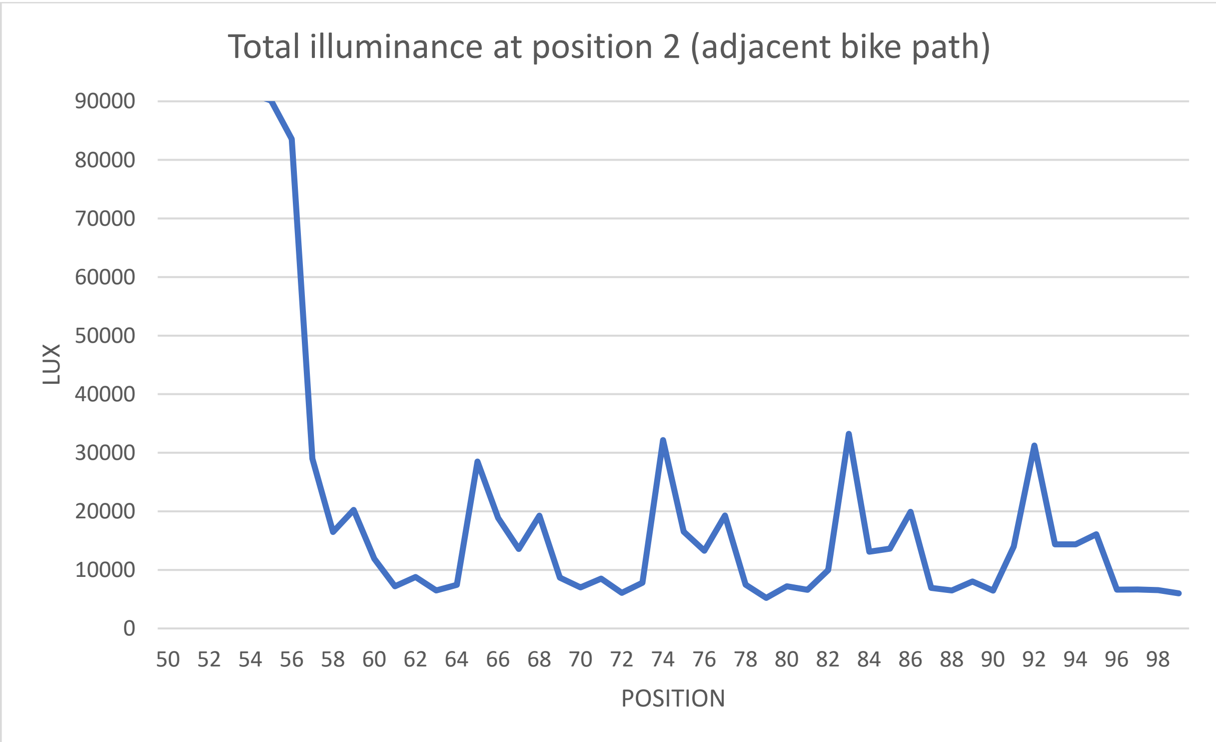


Figure 163: Shows a graph of the Lux level readings from the bike path. 50% of these were under the 20,000 Lux threshold.

Outcomes

Both the detailed lighting analysis method and the broadscale pseudo colour lighting rendering have great potential for more nuanced analysis of shade conditions and could be used to extend the use of the DDSS into comprehensive design uses and larger scale visual analysis of solar impact. Shade depth can be used as predictor of incident UV protection, making its quantification important in assessing tree-scape decisions which increase the desirability of active transport[221]. In relation to the case study however, this level of detail was not required. I intend to develop this petri-dish in further study beyond this thesis. The broadscale pseudo colour lighting rendering shows a clear visual similarity with discrete light meter lux levels under the trees. For large scaled analysis (such as the case study site) this level of analysis is rapid and powerful when assessing design iterations.

7.3.5 Divergent criteria for shade and flood (multi conditions mapping)

This 'petri-dish' responds to the need to bring together the sometimes-conflicting street tree functional considerations for summer solar protection, winter solar access and water regulation, in sites which have a street wall. As I established in 7.3.2: *Balancing winter solar access and summer solar exposure*, the most suitable focus time for preserving winter solar access while still ensuring summer shading is the 12.00 lunch time pedestrian and UV peak in this development morphology. And as I established in the *Umbrella City* chapter, evergreen species needed for water regulation can contribute to overshadowing in winter.

In this petri-dish, I overlay a flood map [refer left of Figure 164] to drive the suppression or occurrence of trees depending on flood conditions (in a flood area, not in flood area) with a midday mid-winter building overshadowing map [refer right of Figure 164] (winter overshadowing, or winter solar access). I bring these two maps together to govern the suppression or occurrence of trees in the four conditions which result from their overlay [refer Figure 164]. Each of the four conditions governs a set of basic tree requirements. For example: A location which floods and is not overshadowed in winter, would best be served by a deciduous high water-use species [refer Table 12]. According to these basic parameters I then selected a tree model representative of each tree type, colour coded red (dry) and blue (flood).

[221] Note, Lux levels were found, not to be a good predictor of level of protection of ambient UV (only incident UV) by Parisi and Turnbull as ambient governed by nature and qualities of surrounding materials (Turnbull & Parisi, 2003).

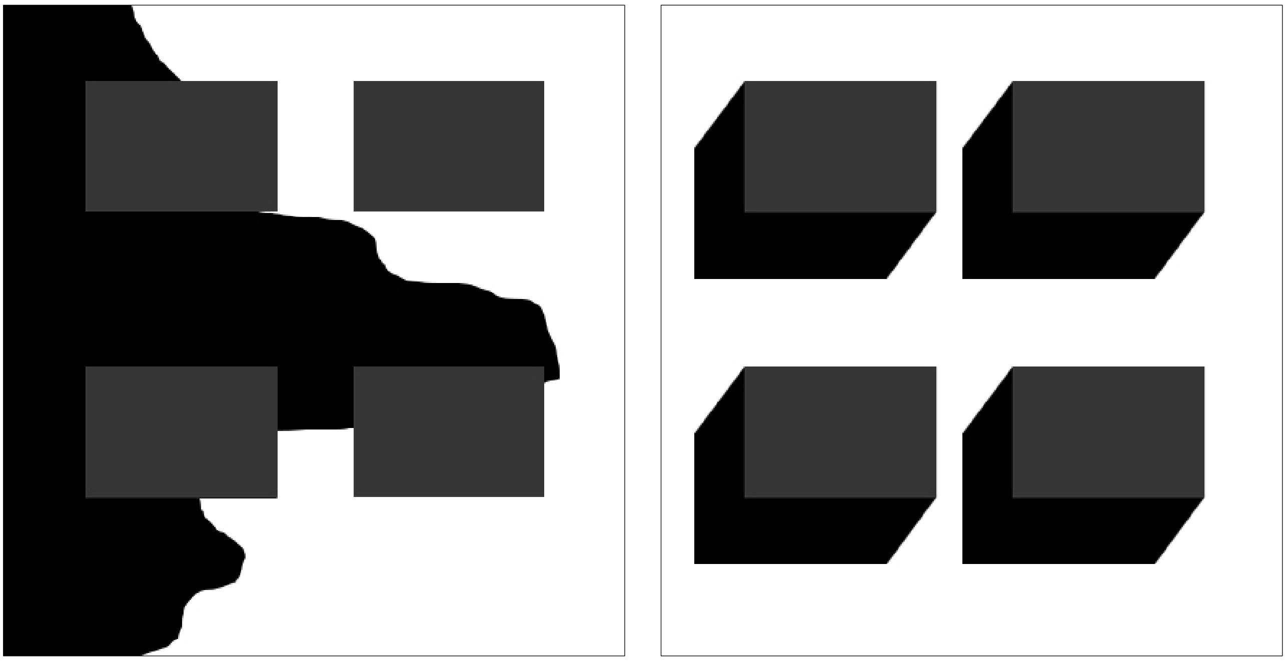


Figure 164: Shows four buildings (in grey) at an intersection. (LEFT) shows indicative flood map for the intersection (flood areas in black) and (RIGHT) shows the winter building overshadowing map at 12.00 (shade in black).

Table 11: The four conditions which occur when overlaying the flood and overshadow maps

	IN FLOOD	NOT FLOOD
WINTER SUN	Solar access preservation + water regulation	Solar access preservation + dry
WINTER SHADOW	No solar access preservation + water regulation	No solar access preservation + water regulation

Table 12: Tree types needed for each condition

		IN FLOOD		NOT FLOOD
WINTER SUN		Deciduous flood tolerant		Deciduous dry tolerant
WINTER SHADOW		Evergreen flood tolerant		Evergreen dry tolerant

To use the intersections between the flood and overshadowing maps in a spatially explicit manner, to supress or allow trees to occur, I created 'inverse copies' of each map before I overlaid them. To do this procedurally, I performed an invert operation onto a copy of each map within the material editor of the base platform [refer Figure 165]. Then using a 'masking operation', I overlayed the four maps in different configurations to create the four maps on the right. Each of these four maps can be considered a 'driver map' which suppresses models which occur in the black areas and allows models to occur in the white areas (which represent the specific overlap of conditions) [see Figure 165][222].

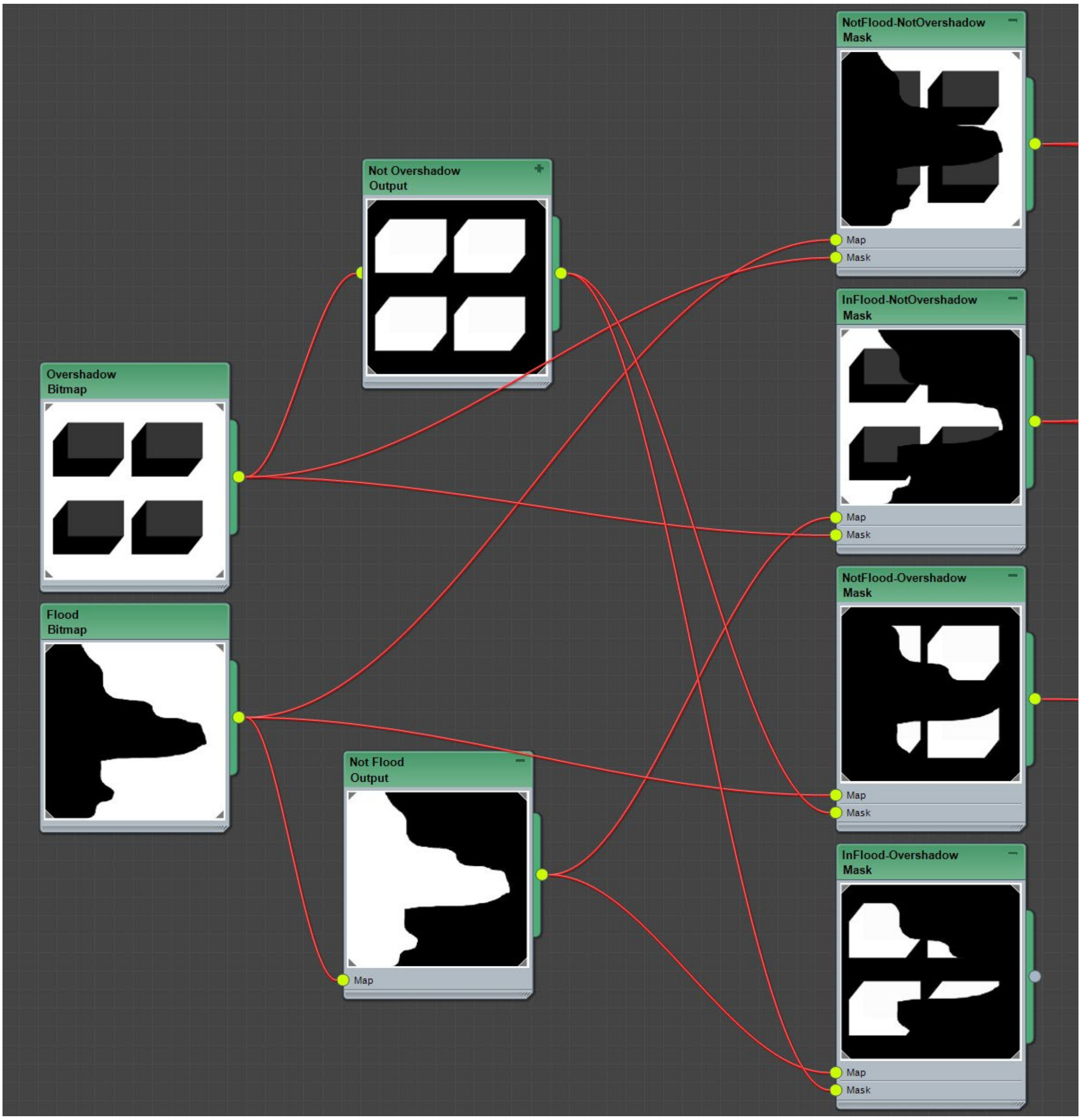


Figure 165: Generation of diagrammatic 'presence-absence' data of conditions final four areas of white space fit together to cover the whole site.

To use these maps to inform tree placement I brought them together into a single material texture which I then mapped onto the ground surface of the intersection model (using a process known as UVW mapping)[223]. Each (presence or absence) condition needs to be

[222] This is a similar approach as taken by the developers of Fragstats (a DSS plugin for ArcGIS) (McGarigal et al., v4)
[223] 3-dimsional material texture mapping, the third dimension (W) allows textures to wrap onto complex geometry with three dimensional surfaces.

mapped to the ground surface, which can be achieved by assigning a different 'material ID' for each condition. Because this process is procedural, any changes to the flood map (such as flood extent) or the overshadowing map (such as height of the street wall, time of day/year) can be updated by simply replacing the initial map. This avoids error prone repetition of creation of multiple 'driver maps'. Figure 166, shows the intersection model with the proxy-object tree model scatter with trees distributed 'by lines' (lines offset parallel to site boundaries). Trees are suppressed where they occur over black areas of the map (flood and overshadowed conditions) and are allowed to occur over white (areas that don't flood but do have winter solar access). The tree models contained in the scatter are representative of the species requirement for that condition [refer Table 12], in this case a deciduous species which can tolerate dry conditions. For the other four conditions the process is the same, each time using a new proxy-object scatter containing a single tree model, representative of the conditions in which it is allowed to occur [refer Figure 167].

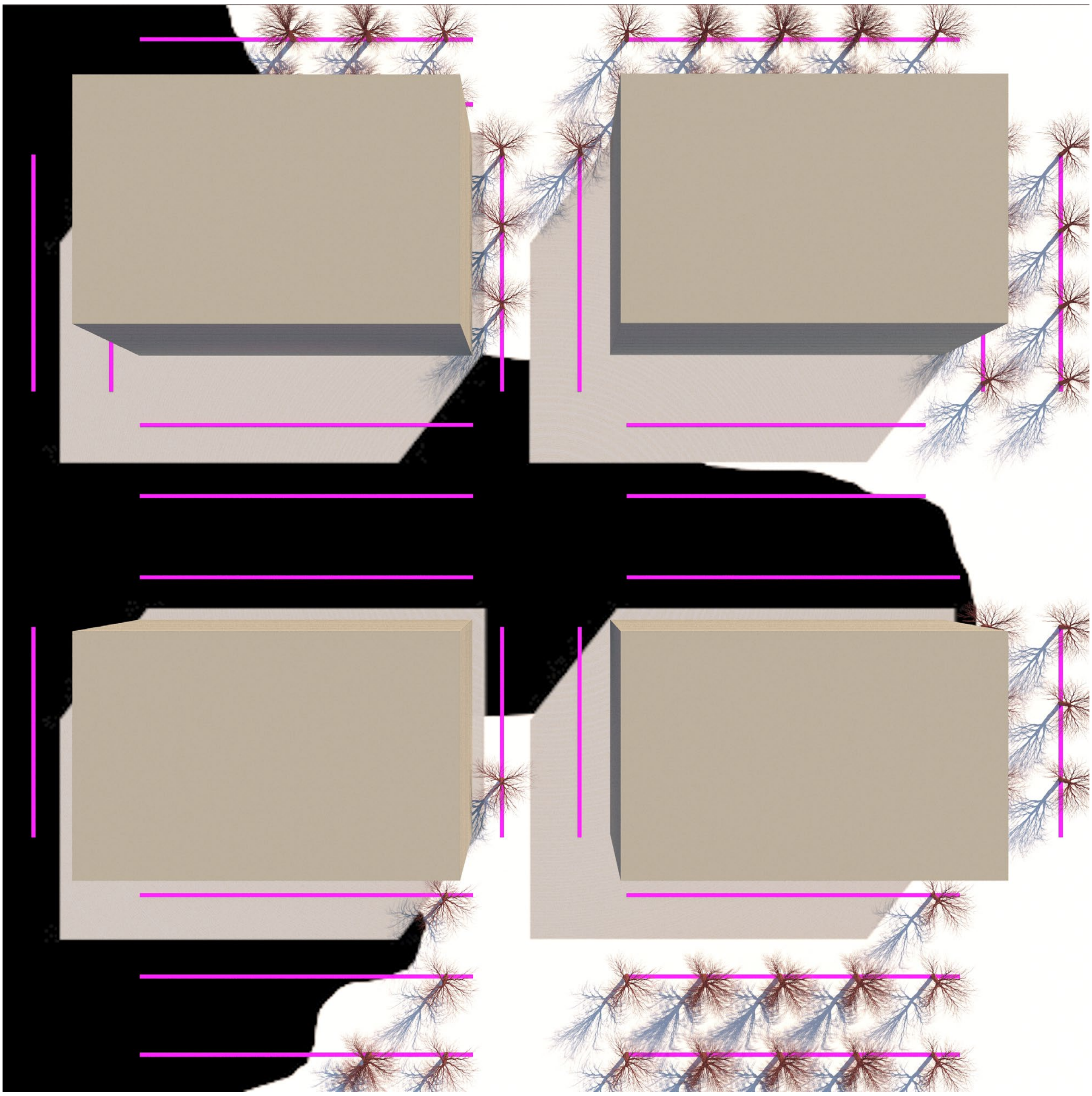


Figure 166: Shows tree models suppressed in the black sections of the map. In this map, black represents areas which are both overshadowed by buildings and affected by flood. The tree models are then only allowed to occur in the white areas representing conditions where winter solar access is possible, and flooding does not occur.

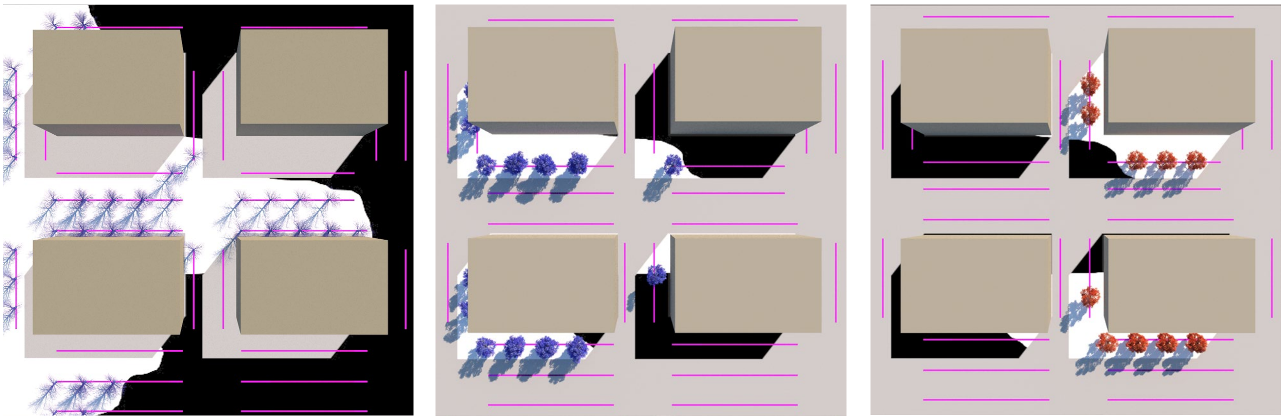


Figure 167: Shows the three other conditions maps controlling the suppression or occurrence of trees in each proxy-object tree scatter. NOTE: due to the use of the 'masking operation' beige, also work as a black suppression area.

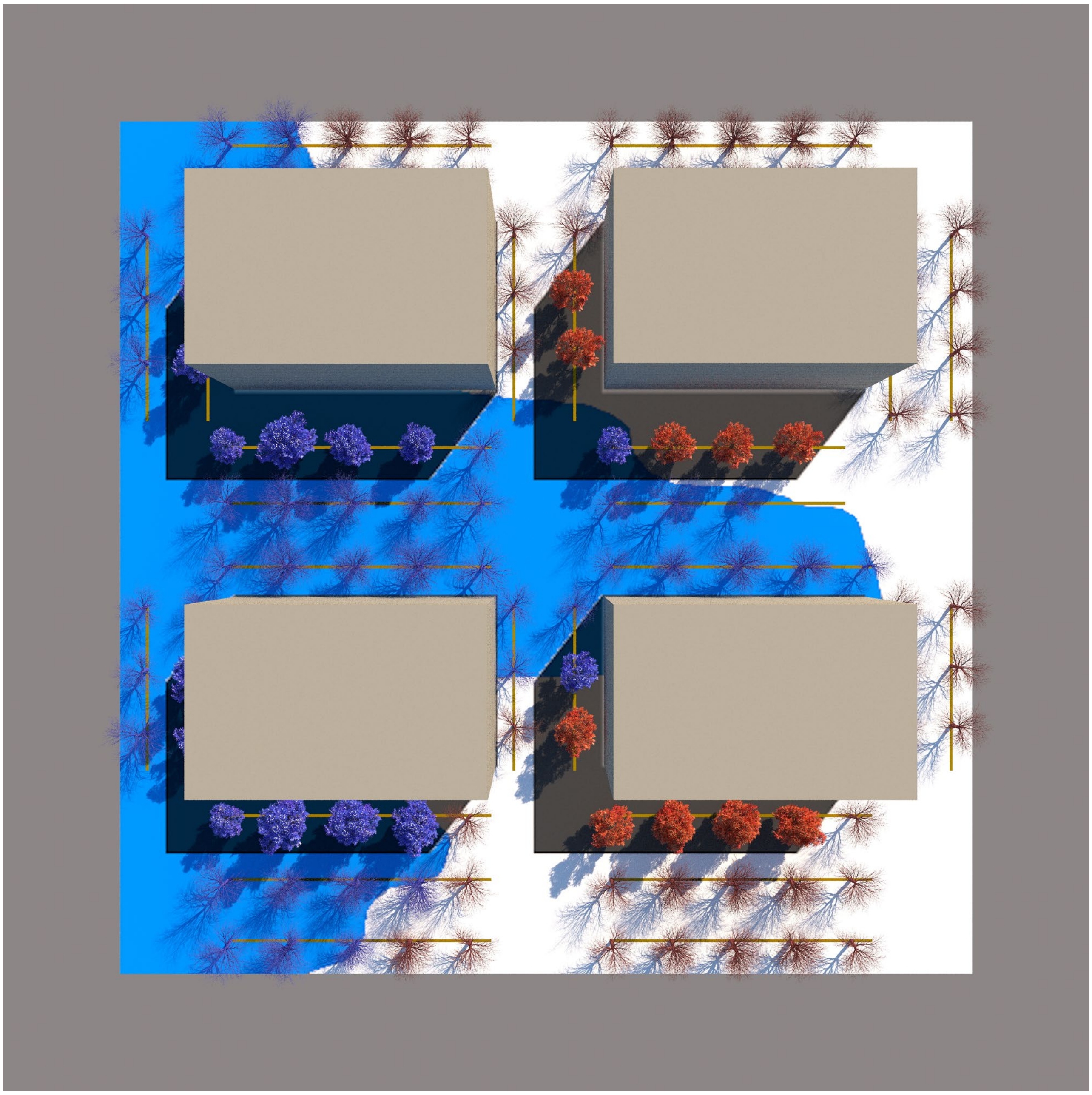


Figure 168: Shows the four map-controlled proxy-object tree scatters with blue deciduous models occurring in flood + solar preservation, red deciduous models occurring in dry, solar preservation, blue evergreen models in flood overshadowing, red evergreen models in dry overshadowing. NOTE: flood is depicted in blue for clarity.

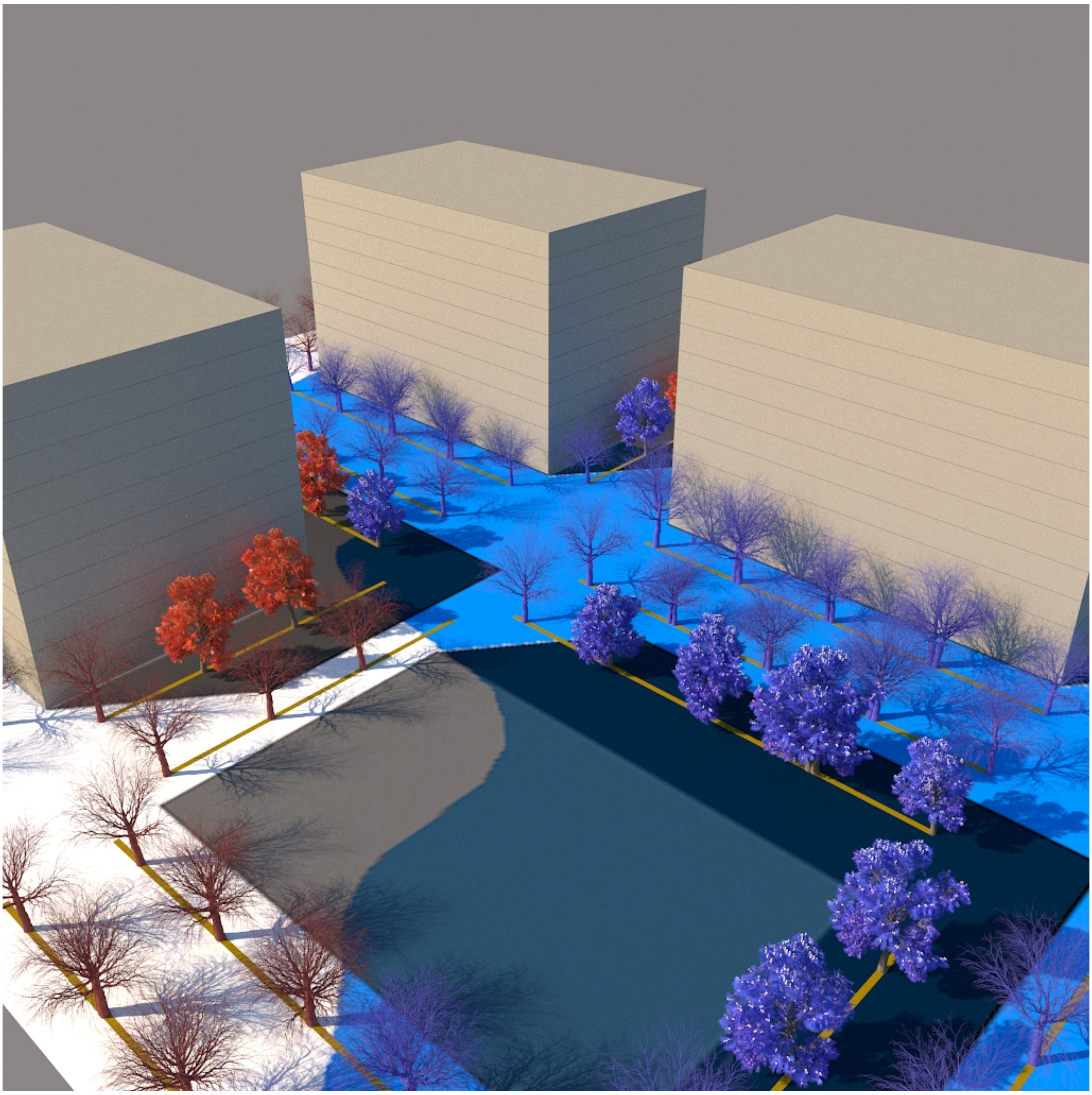


Figure 169: Shows a perspective view of the intersection model (with a foreground building mass removed). The models are colour and form coded to their respective condition. These models are now ready to be adjusted to the requirements of solar exposure protection (crown-form, canopy dimensions, position and spacing).

Outcome

In this petri-dish test I set up a process which allows for iterative data feedback regarding species functional requirements for specific environmental conditions. Any number of different flood scenarios, adjustments to the proposed built form, or changes to the critical overshadowing time can be tested using this process. In addition, the trees can be further adjusted from this point to take into consideration their placement, crown-form and canopy dimensions as required for protecting active transport users from solar exposure. The tree models currently used in the model are visually realistic appart from their colour. I used this type of representation to show how this model will eventually progress to also be useful for visual impact assessment.

7.4 Synthesis City case study, DDSS application

In this section, I bring together the DDSS processes in the petri-dish tests developed over all three case study chapters and apply them to the post-industrial urban renewal precinct of Arden-Macaulay, three-kilometres from the central business district of Melbourne. Arden-Macaulay is a low lying, 145ha site which spans a waterway (the Moonee Ponds Creek) subject to both frequent flood and heat vulnerability. As the site was not originally intended for residential use, it lacks the open space provision typically associated with Colonial residential development (Freestone, 2010, Chapter 8). The generous 30m width streets with tree lined central medians in the adjacent residential area from the east, taper down to predominantly 20m wide streets with narrow footpaths and no central medians as they reach the precinct. It is these comparatively narrow streets which are under pressure to fulfil open space provision for the intended 20,000 new residents arriving over the next two decades.

7.4.1 Why Arden-Macaulay?

The precinct is bordered to the east and west by existing low-rise residential areas with a density of approximately 50 people per Ha. Arden-Macaulay is expected to accommodate approximately 135 people per Ha by 2050 [refer Figure 170]. Aiming to achieve this level of density, a planning scheme, regulating new building heights has been proposed which have an approximate building height to street width ratio of 1H x 1W [refer Table 13] (Melbourne Planning Scheme, 2014, p. 190). The street wall, built form proposal for the Arden-Macaulay precinct, the need for streetscape flood adaptation and the desire that active transport modes will dominate, make it an ideal site to test the DDSS for its ability to deal with multiple tree functions and greater site complexity.

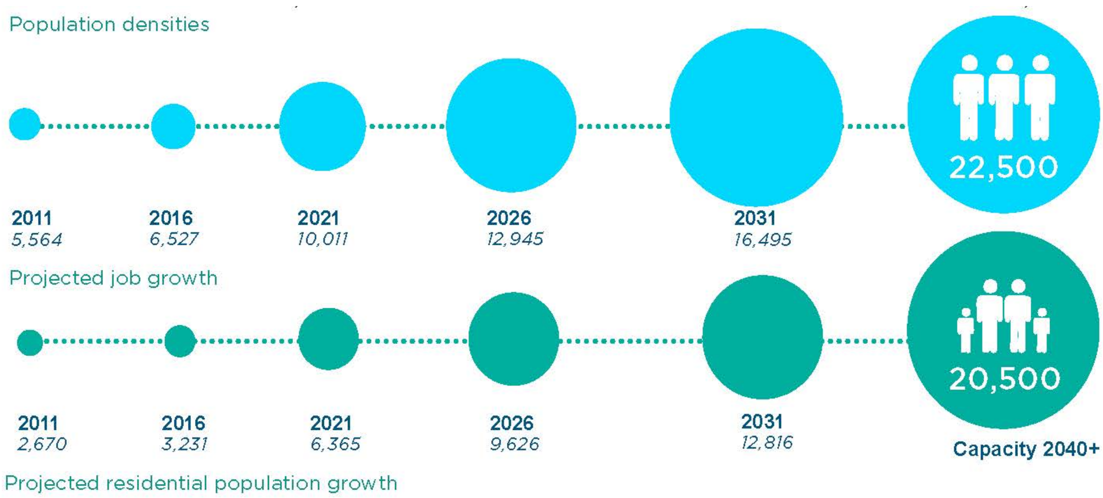


Figure 170: Shows the Arden Macaulay Structure plan (COM 2012) projected increases in employment and housing to be accommodated in the precinct by 2050.

Table 13: Arden and Macaulay Precinct development overlays.

Street wall height and setbacks Macaulay Precinct (Abridged from the Planning scheme Amendment C190 Design and development overlay Schedule 63, table 03)	
Interface type	***Street wall height /Setback of buildings above street wall***
20 and 30-metre-wide renewal street	Development at the frontage must not exceed a height of 6 storeys. Development should be set back 1 metre for every metre of height above 20 metres.
15-metre-wide renewal street	Development at the frontage must not exceed a height of 4 storeys. Development should be set back 1 metre for every metre of height above 15 metres.
10 to 15-metre-wide renewal street	Development at the frontage must not exceed a height of 3 storeys. Development should be set back 1 metre for every metre of height above the street wall.
Laneway	Development along the laneway must not exceed a height of 3 storeys. Development above the street wall should be setback 4 metres. In addition, development on the northern side of an east-west laneway should be set back 1 metre for every metre of height above the preferred maximum height.
Street wall height and setbacks Arden Precinct (Taken from structure plan)	
	9 storeys maximum height limit

7.4.2 Arden Macaulay's existing urban forest

Arden-Macaulay's current public trees provide the precinct with an 11% canopy coverage (similar to that of the *Shady City* site)[224]. Aspirations are stated in the structure plan for increasing this cover to 40%, in line with the rest of the City of Melbourne canopy cover targets. As open space is limited in the precinct and the planning scheme for the area has

[224] The Arden Macaulay structure plan refers to the 'Urban Forest' but does not include private property trees in that analysis.

no ground level setbacks this three-fold increase in the number of trees will largely need to be accommodated in streetscapes [Figure 171].

Figure 171: Projected threefold increase in number of trees (source: Arden Macaulay Structure Plan (COM, 2012).

7.4.3 Scenarios to be tested

In the *Synthesis City* case study, there is pressure on streets to perform as comfortable active transport corridors as well as storm water adaptation infrastructure. With the street wall development proposal, the functional street tree considerations are threefold, 1) They must provide summer shading for active transport users, 2) they must preserve solar access for winter active transport users and 3) they need to maximise use of dense foliaged evergreen planting for flood adaptation. In this case study I will investigate the capacity for the DDSS to output visualisations for visual impact assessment as well as moderate and optimise between functional tree requirements for flood and active transport comfort. To test the potential of the DDSS to respond to these conditions, I developed two flooding scenarios which would have quite different visual impact.

Flood scenario 01: 'Land subject to inundation': No new control measures are implemented for the current extent of 1 in 100 year flooding of the site (also known as the planning overlay for: 'Land Subject to Inundation (LSIO) in the Melbourne Planning Scheme) (COM, 2016) [LEFT Figure 172].

Flood scenario 02: 'Road-based SSWMS': Flooding is controlled using road based SSWMS which utilise the street casement as detention ponds [refer 7.3.1: *Higher density and flood adaptation*] [RIGHT Figure 172].

I test these two flood scenarios against the 12.30 mid-winter overshadowing maps which I generated from a 3-dimensional model of the proposed building envelopes outlined in the

Arden-Macaulay Structure plan and the C190 planning scheme (COM, 2012; Melbourne Planning Scheme, 2014, p. 190) (process discussed in the next section). Responding to outcomes regarding the capacity for trees to shade both foot and bike paths identified in previous petri-dish tests [refer section 7.3.2] the bike path is located adjacent the footpath rather than a parking bay lane.

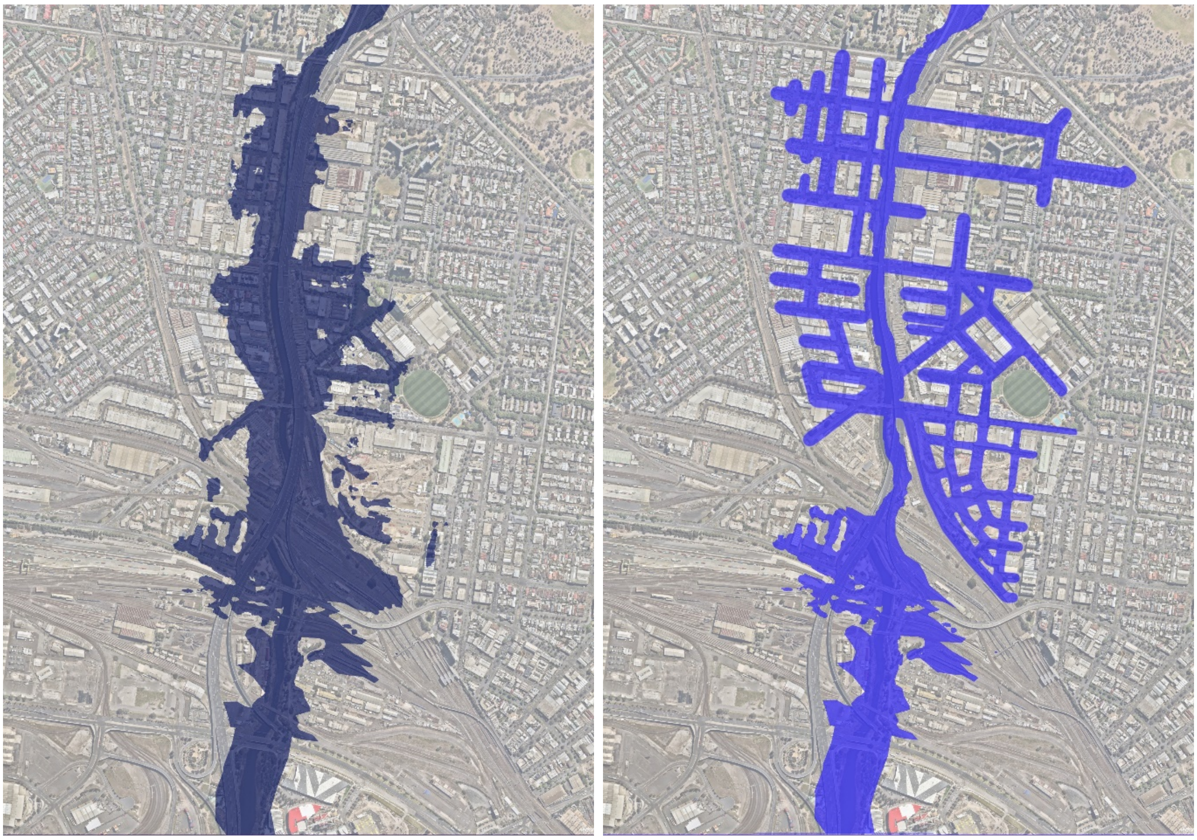


Figure 172: (LEFT) Map of Flood scenario 01: 'Land subject to inundation' flood zone as modelled by Melbourne Water 2016 with no infrastructure changes and (RIGHT) map showing Flood scenario 02: 'Road-based SSWMS' Surface storm water infrastructure implantation within the street casement. (Image created using QGIS).

7.4.4 Application of the DDSS

In this precinct scale application of the DDSS, I combine both raster-based (map) and vector-based control of tree location and spacing. As with the previous case studies I constructed a digital site model. In this case high quality existing 3-dimensional building models of the LGA of City of Melbourne were sourced from Harrison and White Architects. Land parcel maps and street centre lines from (PSMA Australia Limited 2016), street casements from (Vicmap Property 2017), water bodies and flood extent from Melbourne Water corporation and City of Melbourne Urban Forest data, available to Australian researchers through the Australian Urban Research Infrastructure Network (AURIN).

Site model construction

The construction of the site model for this precinct was more complicated than the previous two case studies. The models of the currently existing site buildings were supplied in 'geo chunks'[225] for each suburb within the Local Government Area (LGA) and needed to be amalgamated into a single model from which the focus area could be selected. Each individual building model also had a Z elevation and a 'pivot point which sits at an average centre point to the volume of the object. These required 'flattening' and pivot point adjustment which was achieved using the digital script '*centre pivot base*'[226] as well as some manual adjustment. As the site has several heritage-registered buildings, I began by classifying the building models into two groups, (retain, demolish and partially demolish). Heritage registration is an important part of this process as heritage registered buildings will remain as single or double storey and will therefore not have the same overshadowing impact on the street as the future (proposed) built form. The process of creating the site model is shown in Figure 173 with existing built form classified into buildings to be retained, removed or partially removed. I added simple aerial photograph-based material textures to the existing base geometry [refer Figure 174]. For the proposed buildings, I 3-dimensionally modelled the building envelopes over the existing structure of the site from the written regulations specified in the planning scheme. Figure 175 shows the local government's proposed maximum building envelopes and height limits based on planning scheme C190 amendment.

[225] Portions of the municipality that do not necessarily align with traditional suburb boundaries or Statistical Area divisions. This is the term used by the municipality.
[226] http://jimjagger.com/tools/index.html

Figure 173: Top view of 3-dimensional models of study area of existing buildings, separated into 'buildings to be retained (red) buildings to be demolished or partially demolished (blue and beige) using data from Heritage Victoria. See https://www.melbourne.vic.gov.au/SiteCollectionDocuments/arden-macaulay-structure-plan-2012.pdf for detailed study area boundary drawing.

Figure 174: Model of site with existing buildings and context and aerial photograph-based texture mapping.

Figure 175: Massing model of maximum building envelopes regulated in the C190 amendment: Dark red 10.5m interfacing residential areas, up to pale pink height restrictions up to 60m.

DDSS application procedure

From there the application of the tree-scape DDSS to the *Synthesis City* case study site is a seven-step process with an optional lighting analysis step.

i. Generate the overshadowing maps for mid-winter and import into the material manager.

ii. Generate the flood scenario maps [refer Figure 172]. Use the masking operation in the material palette to overlay each of the flood scenario maps with the building overshadowing map as described in petri-dish in section 7.3.5: *Divergent criteria for shade and flood (multi conditions mapping)* [refer Figure 177].

iii. Categorise the street network as outlined in the petri-dish in *Shady City* in section 6.3.5: *Street orientation and shade.*

iv. Apply four proxy-object tree scatters to each side of each street with distribution controlled by the street centre lines and their suppression or occurrence controlled by the (presence, absence) conditions masking maps, [refer 7.3.5: *Divergent criteria for shade and flood (multi conditions mapping)*].

v. Select indicative tree species, suitable for the conditions [refer Table 11 and Table 12].

vi. Adjust tree line positions [refer *Shady City* 6.2.4: *The spatial constraints of street reconfiguration*] and spacing between trees for best possible shade provision in summer to active transport users at 12.00. Note: species could also be adjusted at this point if different crown-forms were required for shading. As the offsets of the tree lines are adjusted, the suppression or allowance of models to occur, procedurally updates.

vii. Output multi scale visual impact renderings [refer *Shady City* 6.3.6: *Street orientation, tree geometry, positioning and spacing brought together*.

viii. Optional light level analysis.

7.4.5 Results

i) Generate 3-dimensional indicative urban form for overshadow map generation and visualisation

In the site model, I set the sun position to 12.30 mid-winter to produce the overshadowing map onto a plane at head height [Figure 177] and then imported the rendered shadow map generated by this process into the material editor. For visualisation purposes, to allow these same building models to appear less abstract (realistic enough for understanding the scale of development i.e. apparent floor levels and windows) I used two scripts. These were the Vu-normalise spline and Tom Hudson's Greeble[227].

[227] Tom Hudson's Greeble plugin to 3ds Max http://max.klanky.com/plugins.htm

ii) Generate conditions masking maps

For the flood map of the existing conditions I created black and white images [refer Figure 172A] from the one-in-one-hundred year flood overlay provided by Melbourne Water, and the other flood map I generated by building a 3-dimensional mesh of the road-based surface storm water proposal outlined in the MPA discussion document (MPA, 2016). This process is outlined in petri-dish 7.3.1: *Modelling surface stormwater management systems (SSWMS),* [refer Figure 172 right]. I brought these maps into the material editor and overlaid them (and their inverted forms) with the building overshadowing map to create the conditions masking maps [refer Figure 176], which I then applied to the site. Figure 177, shows the two flood scenarios (without building shadow overlay). Figure 177, shows each flood scenario overlaid with the building overshadowing map.

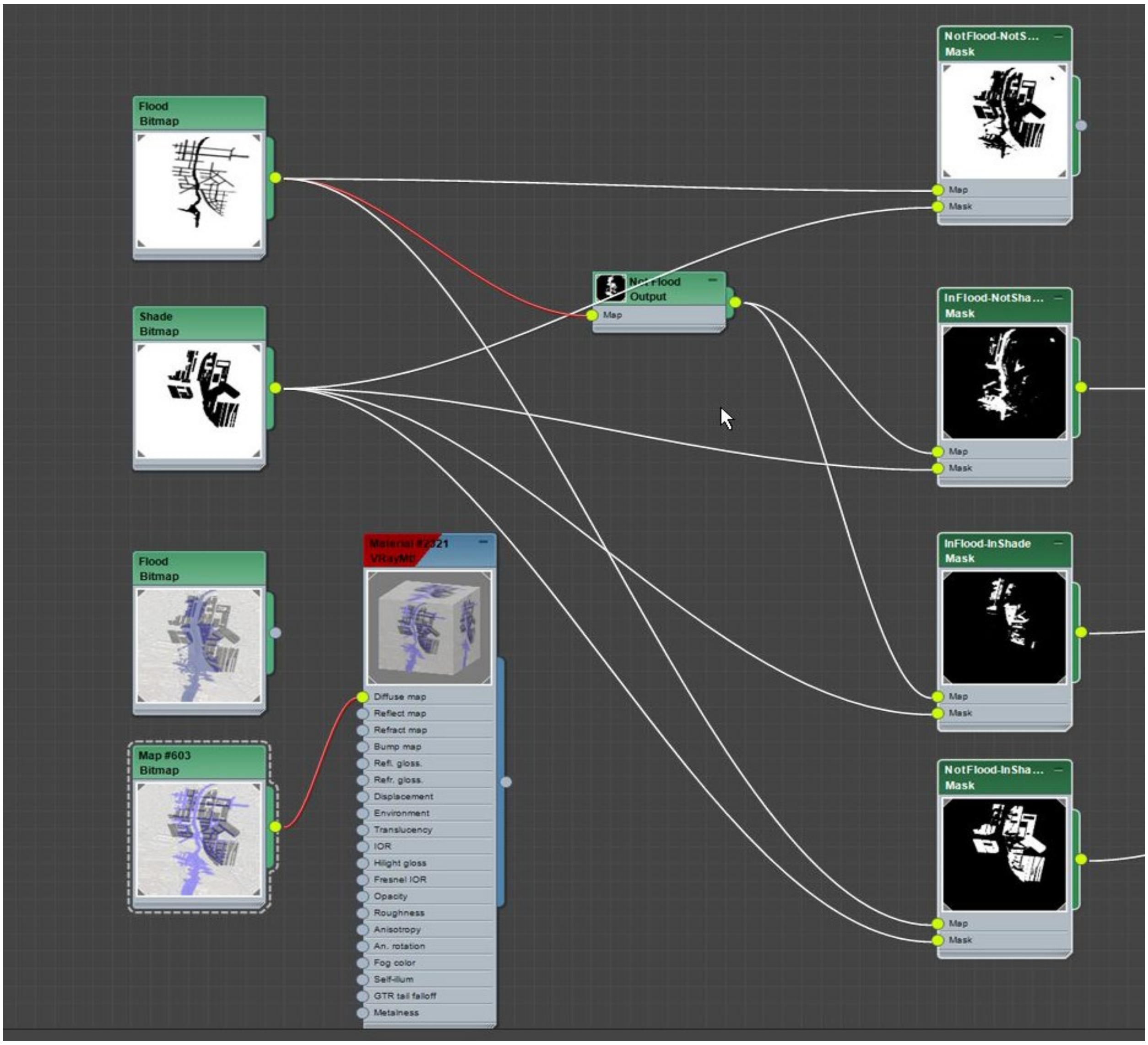


Figure 176: Conditions masking maps used to drive the suppression and occurrence of tree models within the proxy-object scatters over the entire precinct

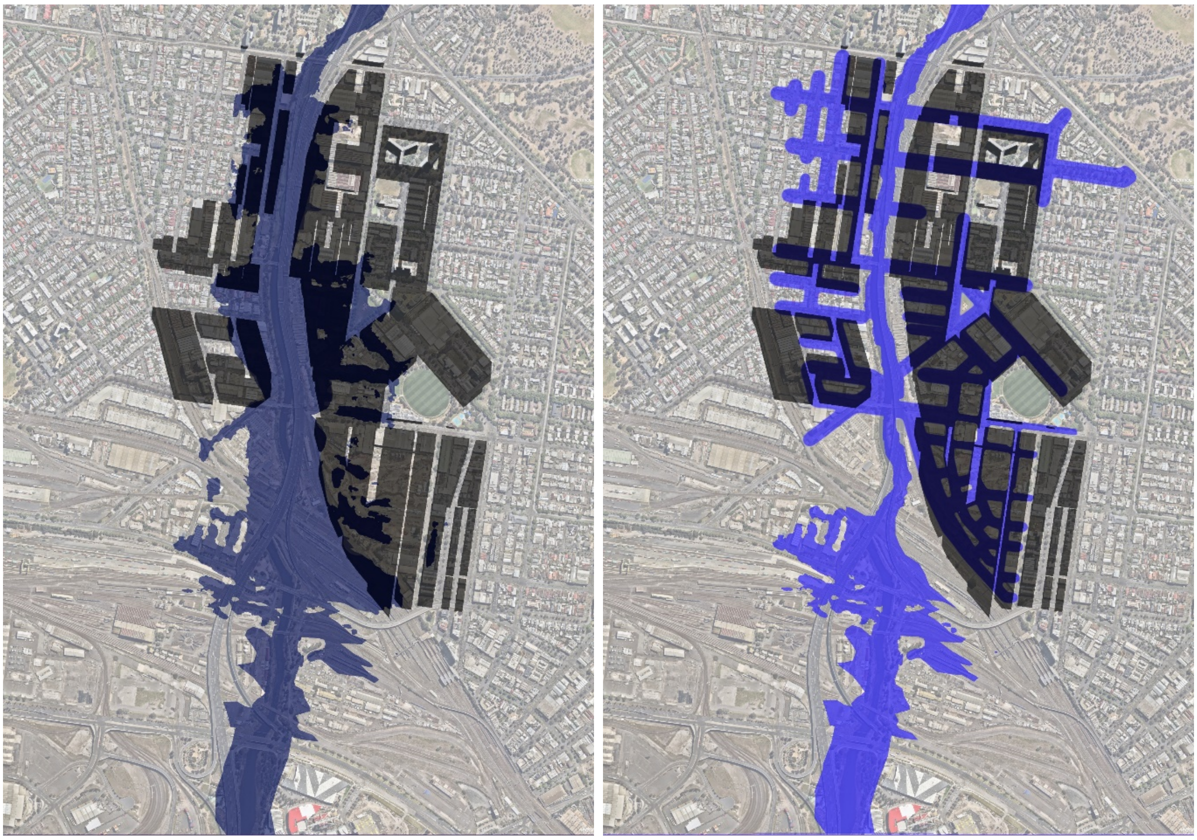


Figure 177: Both flood scenario 01 and Flood scenario 02 are overlaid with the shadow mapping generated from the structure plan's proposed maximum building envelopes. The shadow map is taken at 12pm mid-winter. (Image created using QGIS and Adobe Photoshop).

iii) Categorise the street network by width and orientation.

To be able to adjust the tree positioning to optimise shade for summer active transport users [step vi], I separated the PSMA street centre line data into different layers according to their width and orientation. Some complication occurs in the transfer of this process from the petri-dish test to the case study site in that road widths vary. I compensated for this in the same ways as was done in the *Shady City* case study in *Shady City* section: 6.2.4.

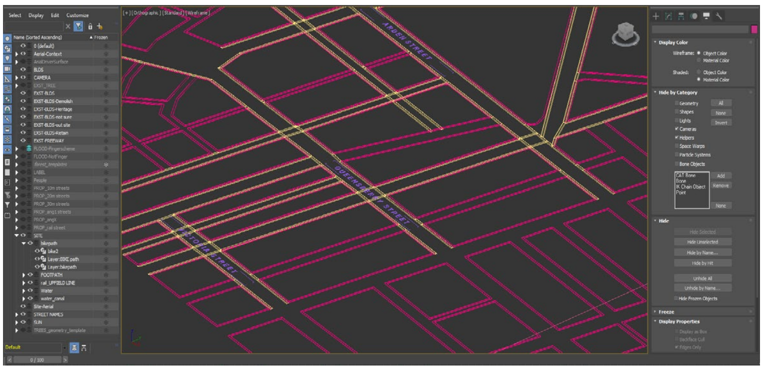


Figure 178: Screen grab showing street categorisation according to method detailed in section 6.2.4.

iv) Create sets of proxy-object scatters

I applied a proxy-object scatter of each tree type [refer Table 12] required for the four specific site conditions [Figure 164], with suppression/occurrence controlled by the requisite conditions masking map [Figure 176]. Figure 180, shows the model with lines of trees along the streets responding to (supressed or occurring) according to the driver maps of overlay conditions.

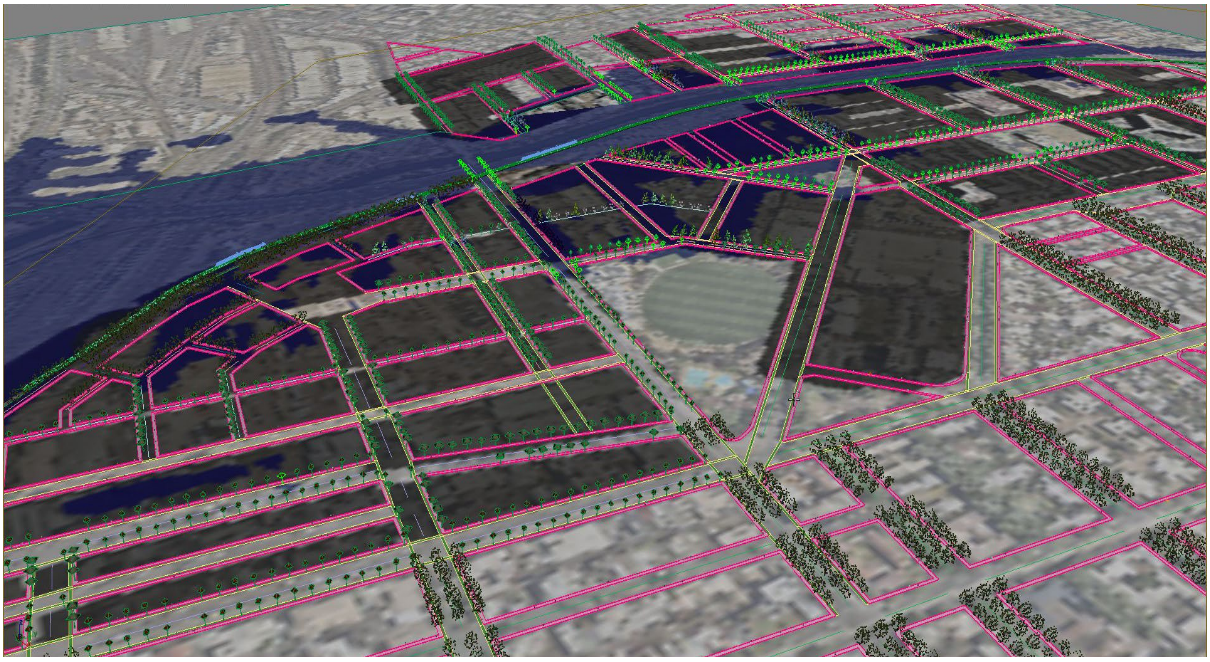


Figure 179: Aerial view screen grab of scenario1) 'Land subject to inundation' showing tree geometry models species placement responding to flooding conditions (in flood or not in flood) and shade conditions (in shade or not in shade). Tree models are displayed as simplified to point-clouds and simple shapes for computational efficiency.

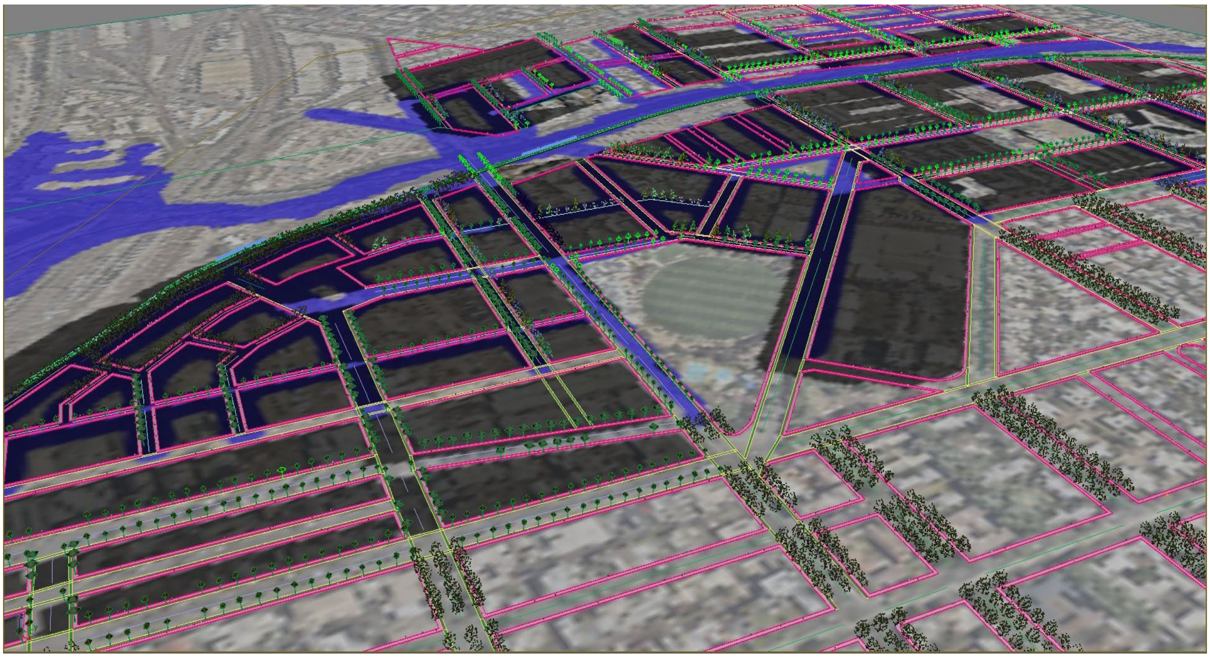
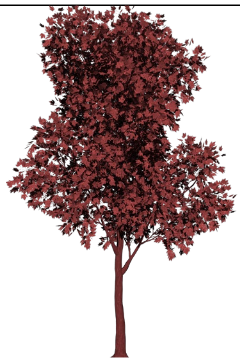
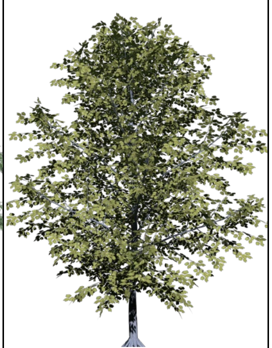


Figure 180: Aerial view screen grab of scenario 2) showing tree geometry models species placement responding to flooding conditions (in flood or not in flood) and shade conditions (in shade or not in shade). Tree models are displayed as simplified to point-clouds and simple shapes for computational efficiency.

v) Select indicative tree species, suitable for the conditions

In this step I fitted the tree 'type models' for procedurally grown or library assets of 'indicative tree species' that would be suitable for the conditions present in the underlying maps. In this case I selected models of species as shown in Table 14: This level of specificity regarding the criteria for tree selection was quite restrictive in some instances, such as; 'in flood, not shade: Wet tolerant deciduous species'. This is an uncommon condition in Melbourne and species expected to survive would require additional water resources in dominantly dry conditions. In a situation where the DDSS was to be applied, species 'fitting' would require coordination with tree management practices and provision of infrastructure to allow irrigation.

Table 14: Indicative species selection to respond to flooding conditions (in flood or not in flood) and shade conditions (in shade or not in shade).

Condition	**Not Flood/ Not Shade**	**In Flood/ In Shade**	**In Flood/ Not Shade**	**Not Flood/ In Shade**
Requirements	Dry / deciduous	Wet / evergreen	Wet / deciduous	Dry / evergreen
Indicative species	*Fraxinus pennsylvanica (Ash)*	*Pinus strobus (White Pine)*	*Nyssa sylvatica (Tulepo)*	*Angophora costata (Smooth-barked apple)*
Notes	Many trees are suitable for this condition *Red over-toned for clarity in renders*	Would require additional water resources in dry conditions	Would require additional water resources in dry conditions.	A species which has better canopy interception qualities might be better here (Baptista et al., 2018).
				

vi) Adjust tree line positions

Once the tree scatters are in place, fitted with species suitable for the condition of winter solar preservation and storm water regulation, I adjusted the position/offset from the street centre line and the spacing of trees to optimise solar protection of active transport users at mid-day. As I adjusted the position / offset of the lines of indicative trees, the occurrence/ suppression of trees would update in response to the underlying conditions maps. Figure 181, shows the adjustment to the lines of trees based on street orientation with buildings hidden for clarity. In this circumstance, as the optimal 'peak pedestrian time' is 12.00, and tree shadows are not elongated according to sun position, it was not necessary to include the 'crown-form' fitting undertaken in SHADY CITY. It would be possible to add this step if a different peak pedestrian time was to be optimised for, and the outcome of that process could be added to the 'tree types' table, setting a third criteria for species fitting / selection, though this would restrict the range of suitable species considerably.

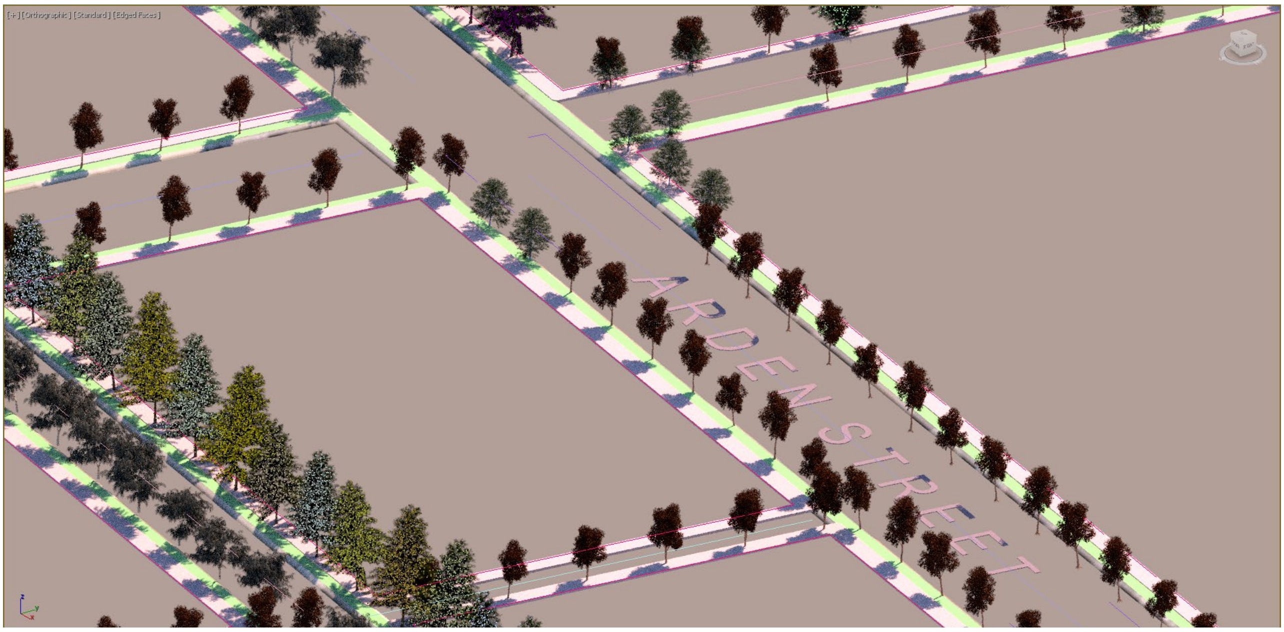


Figure 181: Screengrab of offset adjustments made to each tree line based upon street orientation, width and side of street to maximise tree shade in summer. Buildings are hidden in screengrab view for clarity.

vii) Output multi scale visual impact renderings

Once visually accurate tree models are fitted to the proxy-object scatters, full visual impact renders (also known as 'beauty rendering in the CGI industry), can be output at multiple scales. Figure 182 and Figure 183, show flood scenario 1: '*Land subject to inundation*' in dry and flooded condition, at precinct scale looking north-west. The lines of

Pinus strobus[228] (in flood/overshadowed condition) can be seen switching over to *Fraxinus pennsylvanica,* (red over-toned tree model) as the street runs past the oval and comes into the condition of dry and not overshadowed by buildings. Figure 184, shows how in scenario 2: *road-based SSWMS,* that at this same point, the tree species switches instead from *Pinus strobus to Nyssa sylvatica*, responding to the underlying map of the road-based detention basins which continue through the length of the street [SSWMS in flood can be seen in Figure 185]. Figure 186 shows a comparison of the detail area discussed (red square) on the left scenario 1) and on the right scenario 2) whilst in flood. Figure 188, shows a view of the model looking east, comparing the change in tree species occurrence and suppression responding to the two different flood scenario driver maps. With scenario 2) Road-based SSWMS, the changes in species are more regular as flood conditions are more controlled than in scenario 1.

Figure 182: 'Beauty' rendering, aerial view looking north-west under dry conditions for scenario1) 'Land subject to inundation', showing the 30m wide symmetrically planted tree lined streets of the existing residential area leading in from the suburbs to the north of the precinct and the trees of the precinct changing according to the underlying conditions maps.

[228] All tree species are indicative only. The intent is to demonstrate the potential of the DDSS to output criteria for tree species, which would also need to be informed by several other criteria of landscape management which are not currently included.

Figure 183: 'Beauty' rendering, aerial view under flood condition for scenario1) 'Land subject to inundation'. This results in changes of species which may cross-roads or alter with no physically apparent infrastructure.

Figure 184: 'Beauty rendering, aerial view, in dry condition for scenario 2) road-based SSWMS. This scenario results in more regular tree planting, with variation occurring according to position in the street (similar to Shady City).

Figure 185: 'Beauty rendering', aerial view north-west under flood condition for scenario 2) road-based SSWMS.

Figure 186: Detail (LEFT) Flood scenario 1) (RIGHT) Flood scenario 2).

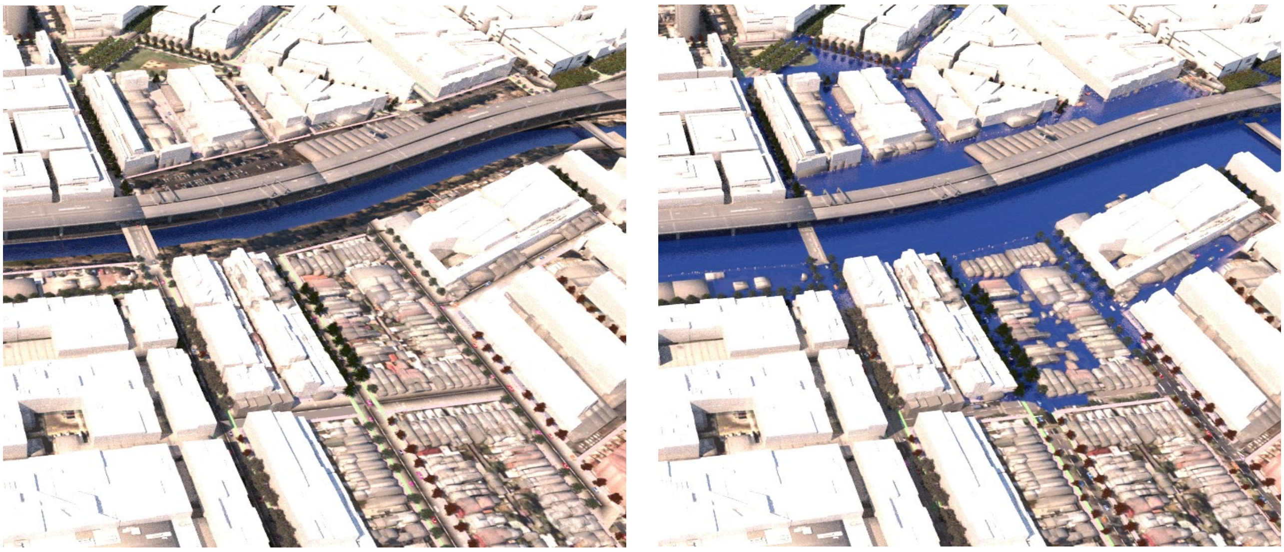


Figure 187: Detail 'Beauty rendering', aerial view looking east for scenario 1) 'Land subject to inundation' (LEFT) under dry conditions (RIGHT) under flood conditions.

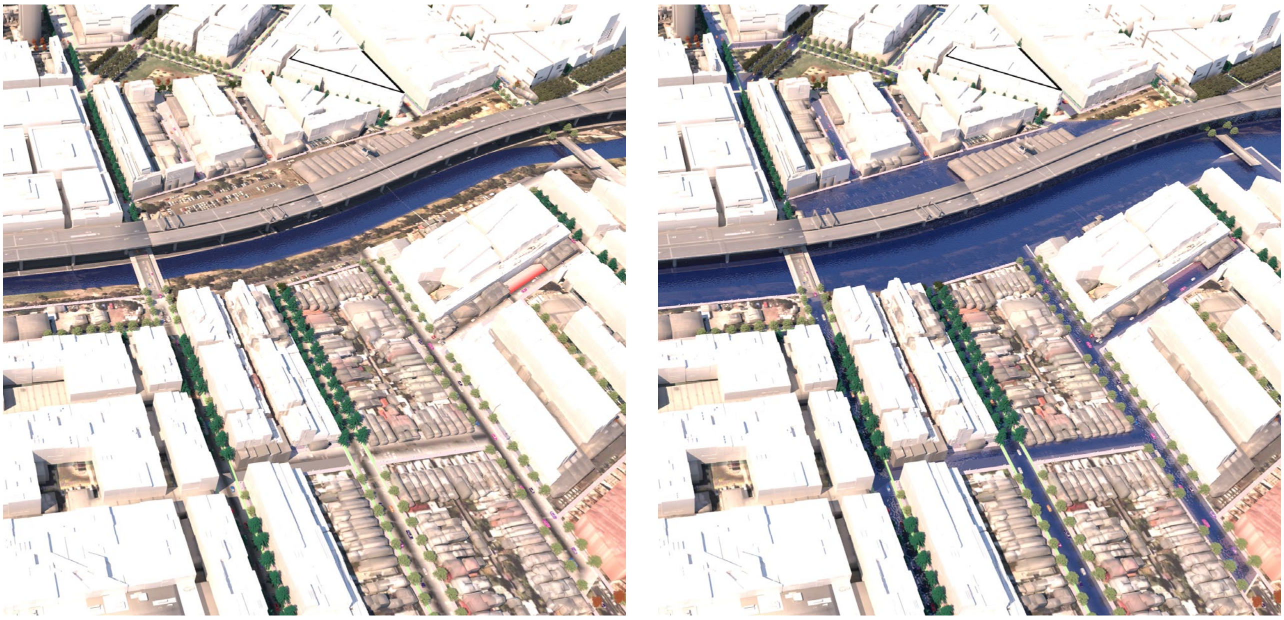


Figure 188: Detail 'Beauty rendering', aerial view looking east for scenario 2) road-based SSWMS (LEFT) under dry conditions (RIGHT) under flood conditions.

At the streetscape level, the visual impact of these different flood scenarios can be assessed in detail. Figure 189, shows a view down Macaulay Rd of the tree-scape outcome during dry conditions for flood scenario 1) and Figure 190, shows the same for flood scenario 2). In flood scenario 1, patches of symetrical planting occur such as can be seen in Figure 189 where the *Angophora costata* model occurs in response to the map of a dry and overshadowed condition. However, in flood scenario 2) where flood conditions continue the through the length of the street, trees planted in the road are different from those in footpath as they must tollerate inundation. In scenario 2) there is more longitudinal symetry, with species changes most affected by their position in the road to achieve the summer shading objective. Figure 191 and Figure 192 show the same views of Macaulay road but in flooded condition. Figure 193 and Figure 194, show the intersection of Macaulay Road and Arden Street in dry conditions for scenario 1) and 2) respectively and Figure 195 and Figure 196 show the same in flood. These images show how the different flood scenarios affect the tree-scape outcomes. Figure 197, shows Macaulay Road during winter, demonstrating the system allowing evergreen trees to occur in dry winter overshadowed conditions but deciduous species occuring where winter sun was able to be preseved.

Figure 189: Macaulay Road view of Flood scenario 1) 'land subject to inundation' during dry weather. Several changes in tree species can be seen in the background responding to the underlying flood condition map, but symmetrical planting across the street section. This image also shows the asymmetric tree positioning.

Figure 190: Macaulay Road view of Flood scenario 2) 'road-based SSWMS' during dry weather. In both schemes trees on the right-hand side are positioned in the road just beyond the bike path to achieve summer active transport objective.

Figure 191: Macaulay Road view of Flood scenario 1) 'land subject to inundation' during flood (which can be seen in the background). The Angophora costata in the mid-ground occur over a symmetrical condition (dry and overshadowed in winter).

Figure 192: Macaulay Road view of Flood scenario 2) 'road-based SSWMS' during flood. Trees in this sceme do not occur over symmetrical conditions. Trees planted in the road (right hand side) experience wet and overshadowed condtions and thus the species switches to Pinus strobus, while trees in the footpath still experience dry overshadowed conditions and thus remain as Angophora costata.

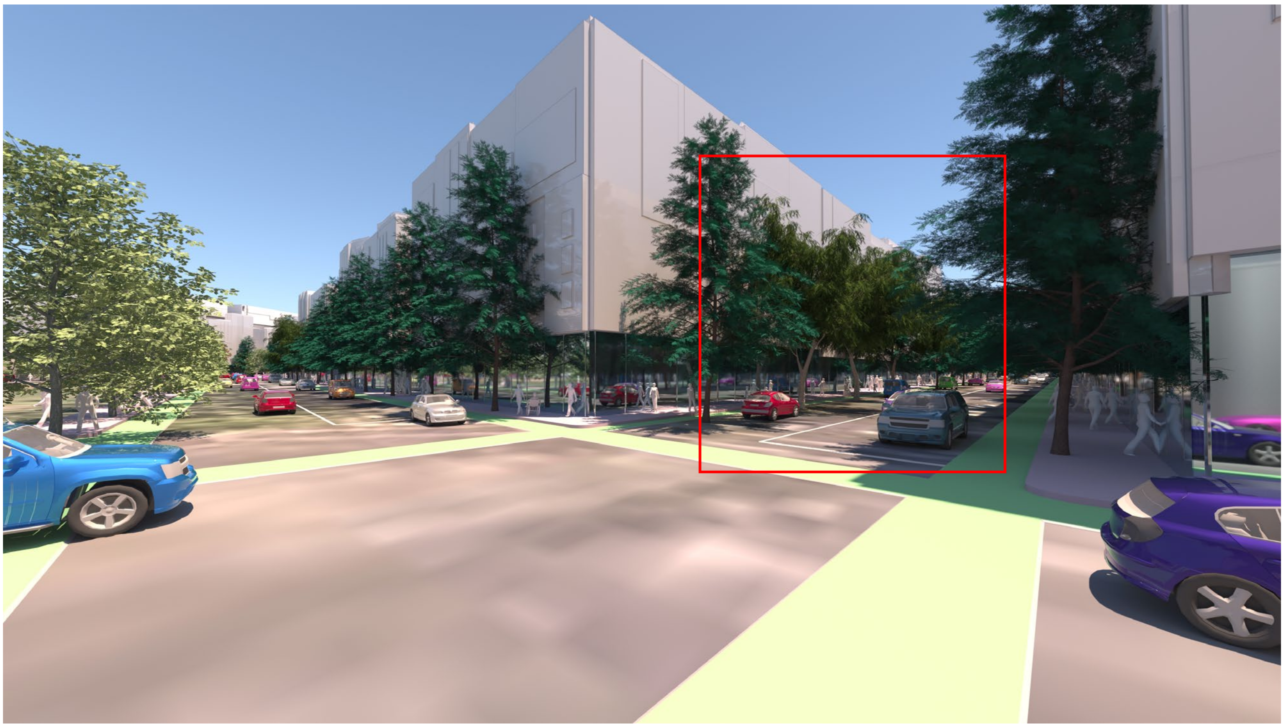


Figure 193: Macaulay Road intersection: Flood scenario 1) 'land subject to inundation' during dry weather. Nyssa sylvatica to the far left occur in the flood, not overshadowed condition, Pinus strobus occur in the flood, overshadowed condition and three Angophora costata occur in a small patch of not flood, overshadowed condition within the row of Pins strobus (red square).

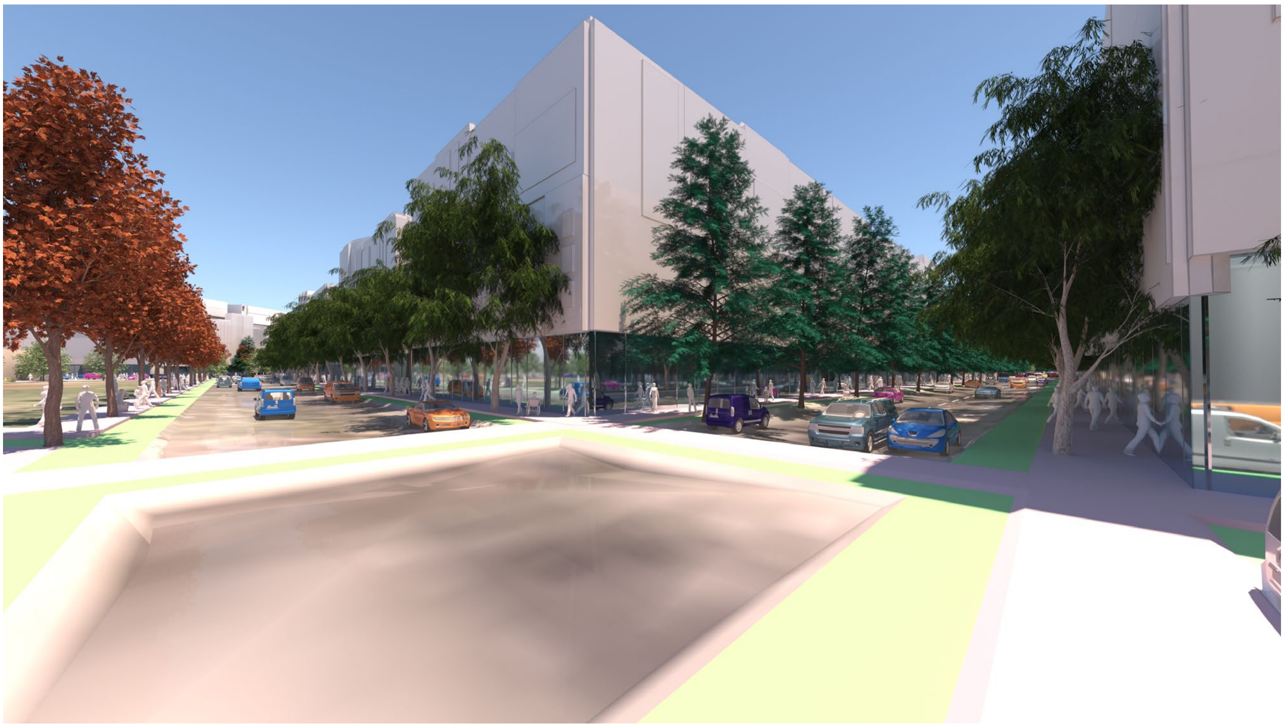


Figure 194: Macaulay Road intersection: Flood scenario 2) 'road-based SSWMS' during dry weather. Species changes are more regular than in flood scenario 1, as they are based on position within the street section (if in road or in footpath).

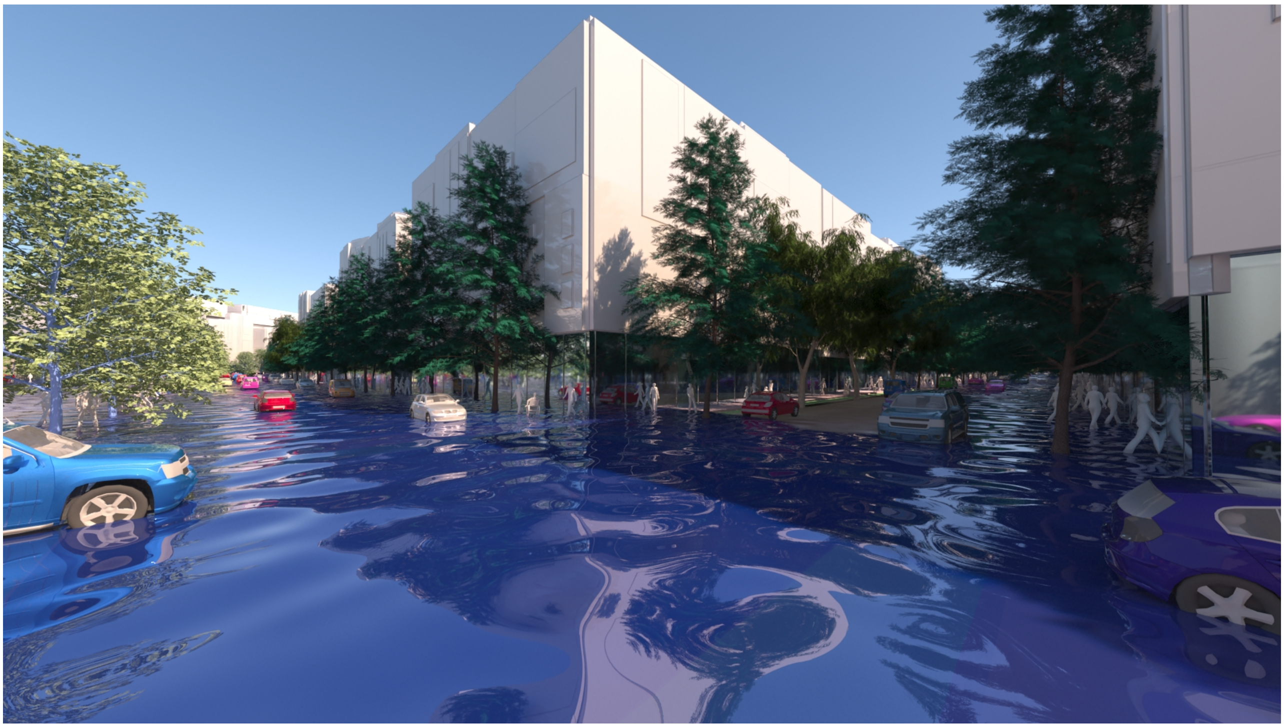


Figure 195: Macaulay Road intersection: Flood scenario 1) 'land subject to inundation' during flood. Shows the Angophora costata in the small patch which does not flood.

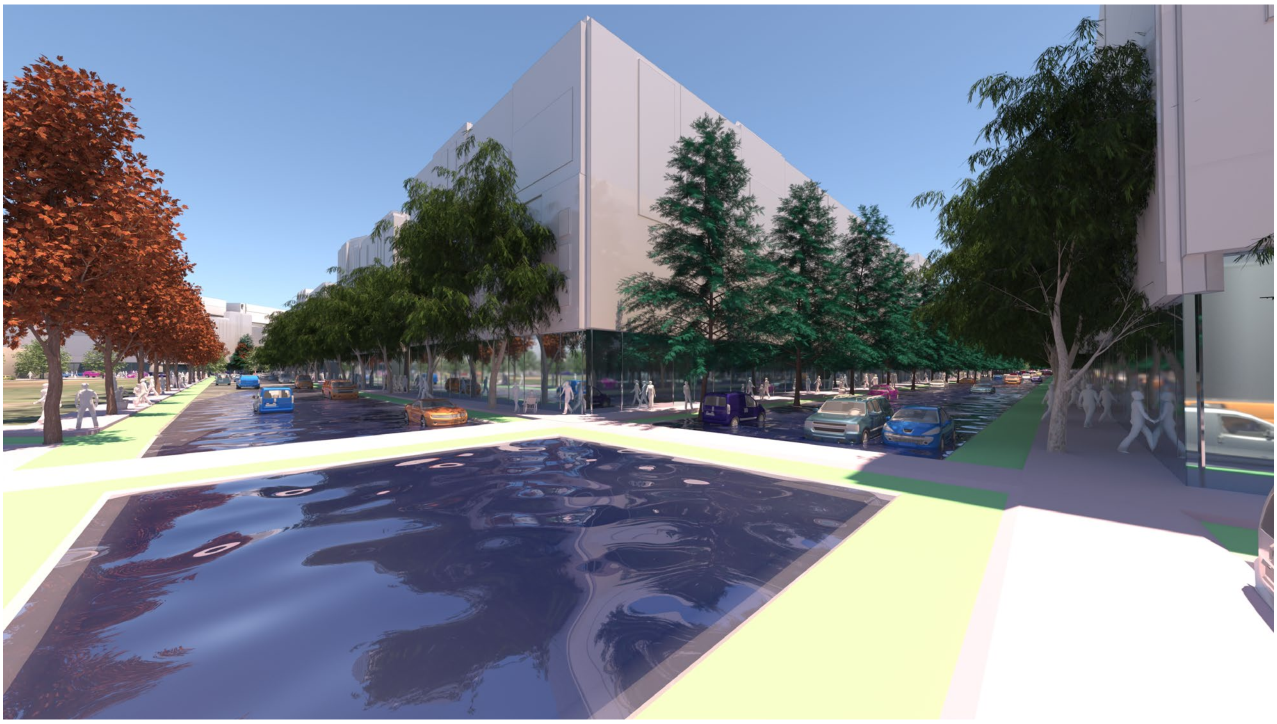


Figure 196: Macaulay Road intersection: Flood scenario 2) 'road-based SSWMS' during flood. Shows the raised street sections to maintain pedestrian and cyclist access during flood.

Figure 197: Shows a winter view of Macaulay Road. On the righthand side the evergreen trees (Angophora costata) occur in the (dry/overshadowed condition), and on the left-hand side, where winter solar access to the footpath can be preserved deciduous species occur (wet or dry tolerant depending on the flood scenario).

Finally, Figure 198, Figure 199 and Figure 200 show the possibilities of using the lighting analysis function available in the system for rapid analysis of footpath and bike path shade (or overshadowing) outcomes in both winter and summer. The lighting analysis can be done at both precinct and streetscape level giving a quick indication of levels of shade. While this was not explored in detail in this thesis, there are a number of ways these images could be used to quantify that shade.

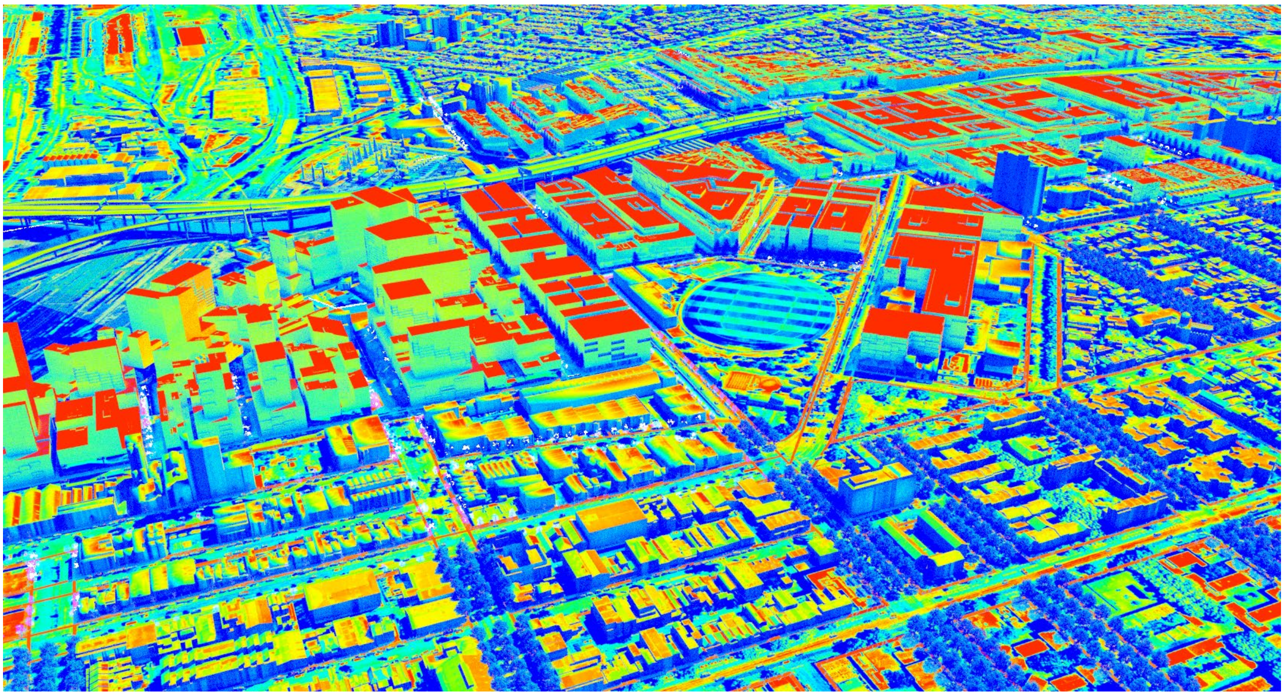


Figure 198: Pseudo colour render for quick visual analysis of Lux levels throughout the precinct.

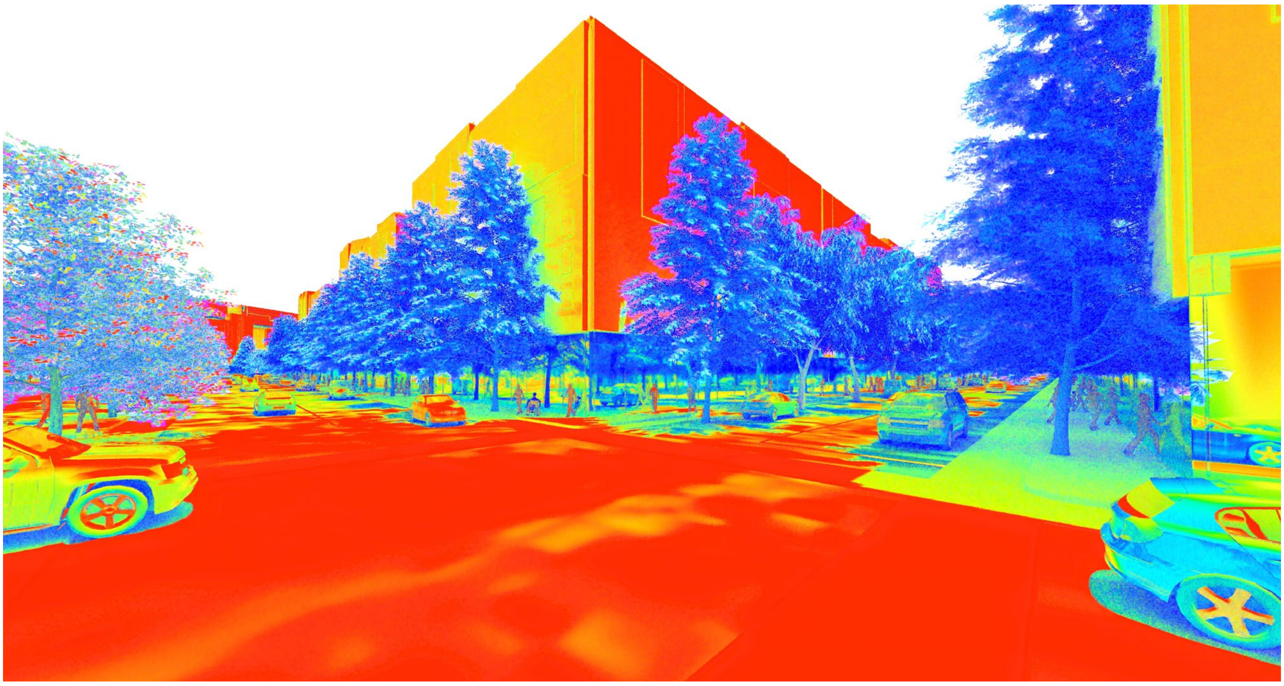


Figure 199: Pseudo colour render for quick visual shading analysis at streetscape level

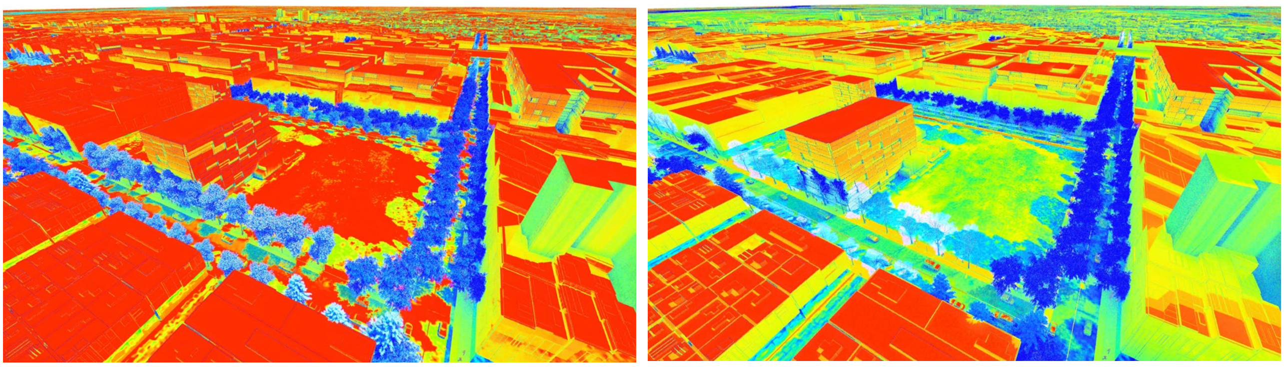


Figure 200: Pseudo colour winter/ summer seasonal comparison

7.5 Discussion / conclusion

In this chapter I adapted the DDSS to be able to query multiple divergent objectives of tree-scape decisions in a higher density urban renewal site. In this case the three objectives were: Preservation of streetscape solar access in winter, maximisation of evergreen trees for flood adaptation and 'optimisation' of shade for active transport in summer. Ultimately the visualisation output from application of the DDSS demonstrates how tree decisions based on functional criteria may lead to quite different aesthetic experiences on streetscapes from the traditional symmetrical plantings of the 19th century, though some symmetries still occur. In scenario 1) Land subject to inundation, several changes occur along the length of the street but are often symmetrical across the street. In scenario 2: Road-based SSWMS the opposite occurs. Street tree species, responding to the controlled flood map for the road surface, remain fairly constant along the length of the street (changing only in response to light conditions) while across the street, due to the different tree positioning for achieving the summer shading objective, species change.

In this case study I converted the written building development guidelines into 3-dimensional geometry in a spatially explicit precinct model. This process raised many questions about exactly how these regulations were expected to perform, or inform the performance, visual or functional of the precinct. By spatialising these written regulations, I was able to bring trees into simultaneous consideration with transport. Ideally this spatially explicit streetscape design process might be used to revise or inform the building envelopes and transport planning of the precinct in a way that allows trees to be a primary consideration (rather than a last moment consideration), towards design for future cities. The benefits of using the spatially explicit method of investigating the outcome of design decisions about water regulation infrastructure, transport, built form and trees, avoids the application of rule-based regulations which can be applied incorrectly given the number of design variables. While rule-based guidelines are useful, small but critical opportunities can be missed, such as winter solar access at intersections and in places around lower heritage registered buildings.

While any digital-physical model is time consuming to set up, once constructed it is capable of rapid and flexible iteration resulting in significant time savings. The input shade and flood maps of the conditions masking maps are simple to change and immediately update the streetscape tree design. The issue of initial set up may also be mitigated through long term use of the model. It is expected that the model would remain 'live', and continue to inform transport, planning, tree-scape decision-making and management on a permanent basis.

Chapter 8: Discussion and conclusion

– identification of problems is plentiful but evidence identifying solutions is scarce (Sallis, Bull, et al., 2016).

8.1 Introduction

In the previous chapter, I demonstrated the application of the visual-functional DDSS applied to a complex urban renewal case study. That study demonstrated an iterative visual process for urban tree-scape decision-making that considered the dynamic interaction between tree functional performance criteria; in this case, the interaction of flood adaptation with seasonal change in light conditions on the comfort of pedestrians and cyclists. In this chapter I summarise key findings of the thesis and discuss its contribution to the field of tree-scape design with respect to the aim and hypothesis. The aim and key research question of the thesis stated in section 1.1.5: *Research aim* was:

Aim: To develop and test a new tree-scape design approach that is simultaneously visual and functional, that responds to site conditions to inform decision-making about placement and species choice of trees in urban streets.

Key question: Can environmental performance, spatial constraints and visual impact be integrated into a tree-scape design process?

To answer this question, a series of sub-questions required answering, the findings of which will be discussed in this chapter.

In section 4.1.2: I stated my *Hypothesis*.

That: E*merging modelling technologies from gaming, animation and architectural sciences can be combined with techniques from geospatial analytics, algorithmic botany and urban forestry, to create a performance-based design-decision-support system, which assists practicing landscape architects to coalesce divergent criteria of visual, spatial and functional aspects of tree-scape design.*

This chapter has five sections. First, I will provide a brief summary of my findings with respect to the research questions. Second, I will discuss the specific contributions of this thesis to the research field. Third I will outline further limitations of the study. Fourth, I will make recommendations for further research, and finally, I will draw my conclusions in response to my thesis aim and hypothesis.

The developed DDSS is invested in working with three things. These are the use of rapidly growing quantities of spatial data to inform tree-scape design decisions, integration of transdisciplinary research to increase decision accuracy, and the expanding possibilities of visualisation technology to improve the clarity of those decisions. The multidisciplinary nature of streetscape modelling and decision-making required extensive formative research including broad reading and extensive software trialling.

8.2 Findings

8.2.1 Historical context – trees in streets

In Chapter 2: *From Pretty City to Sustainable City*, I sought to answer the question:

What are the past and present decision drivers behind inclusion of trees in streets?

To answer this question, I undertook an historic investigation that outlined the three paradigm shifts in tree-scape decision-making over the past 200 years, in young, gridded cities laid out during British colonisation, that developed in tandem with the advent of motorised transport. This section demonstrated the shift in tree-scape design decision drivers, from a visual streetscape embellishment (in the *Pretty City* era), to a driver safety risk (in the *Transit City* era) through to a functional (green) infrastructure consideration (in the *Sustainable City* era). I found that initial *visual* drivers, informed by classical ideals of order, harmony, unity and proportion, form the contextual foundation of contemporary tree-scape planting; still predominantly single species symmetrical compositions. In the *transit era*, street design objectives focused on the efficiency and safety of transport infrastructure, shifting tree-scape considerations to the view from the road. Finally, in response to growing awareness of *environmental* problems, streetscape design objectives shifted towards trees as a form of green infrastructure. I found that in this last shift, the desire for trees to help reduce urban flood and heat problems will require tree selections that diverge from the symmetrical, predominantly deciduous historic norms of the Pretty City era. In the Sustainable City era, concurrent paradigm shifts in transport planning and urban storm water management offer opportunities to reclaim portions of streetscape space, but there are divergent views on how this space should be repurposed.

A key finding of this investigation was the identification of these three dominant street design drivers, from the compositional, to transport oriented, through to environmental performance, and the requirement to concurrently address them in contemporary streetscape design decision-making.

8.2.2 Decision-making context – modelling

In Chapter 3: *Modelling for decision-making*, I sought to answer three questions.

What is the context of tree-scape design tool development (past and present)?

What are the visual, spatial and environmental modelling tools under development or available for streetscape decision-making?

How do design and modelling approaches differ in different discipline sectors?

To answer the first two of these questions, I investigated the decisions made about urban streets and the complex negotiation of spatial constraints, environmental performance and societal preferences they require. I found that multiple disparate disciplines are involved in streetscape design and all develop models for forecasting future streetscape scenarios and guiding their decision-making. In design disciplines, these forecasting models are used to produce either, abstract visualisations to aid decision-making in public participation forums, or advocacy visualisations that express qualitative visual impact of designs for public consultation[229]. I found that the methods designers use to produce these visualisations are still primarily 2-dimensional and in being so, lack a capacity to interoperate with models produced by services and infrastructure engineering or

[229] Currently the most publicly recognised outputs of these models are ones used in PPD; highly abstract, 'viewer oriented' 2-dimensional or 2.5-dimensional visualisations. It is possible that the purpose of these design visualisations and the methods used to produce them is misunderstood, leading to the criticism often levelled at designers from other discipline sectors, of making decisions based primarily on aesthetic concerns. On the other hand, these criticisms may be entirely fair at times.

environmental science. On the other hand, scenario modelling and forecasting, in environmental science and transport/ land use planning, are predominantly handled through mathematical modelling or written regulations. The forecasting of these disciplines too, address *either* environmental or spatial conditions, rarely both, and neither address visual concerns beyond a rudimentary level.

By outlining the evolution of forecasting and decision-making modelling methods for street design, developed in multiple disciplines, I was able to demonstrate how the discipline specific criteria divide into three concerns; the qualitative visual, the spatial and the quantitative environmental. The outcomes of this chapter suggest that, though individual discipline modelling in which these concerns are *isolated* has become increasingly detailed and accurate, modelling which *spans them* is still lacking. It is this lack which formed the research gap investigated in this thesis, outlined in section 4.1.1: *The research gap*.

To address the third question in this chapter: *How do design and modelling approaches differ in different discipline sectors*? I interrogated how the two spatial paradigms (geodetic and cartesian) and the two dominant computer graphic representation methods (raster and vector) are used differently in each discipline, serving to further widen individual discipline model interoperability issues. I found that environmental disciplines predominantly work on geospatial platforms while engineering and design disciplines work on cartesian platforms. Engineering and design sectors working on implementation of spatially explicit, highly detailed designs are predominantly using 'vector based' methods while environmental sciences often work at larger spatial scales using raster-based methods. This division of computer graphic representation is also found within the design discipline, where raster-based methods are used in the early stages of a project and vector based are used for design documentation. This is an important finding because, to address the three, driving tree-scape design factors discussed above requires literacy in both geodetic and cartesian spatial data and both vector and raster-based computer visualisation methods, either/or literacy increases the disciplinary silos.

8.2.3 Developing the framework for a Design Decision Support System

Each different street design discipline decision criteria and their ways of meeting objectives have their strengths, many of which are irreplaceable in a holistic cross-sectional modelling approach, but simplification is required for any aspects of these discipline specific models to be combined, or more closely coupled. I do not consider the system I have developed, to be a replacement for existing single discipline decision-making approaches but as an enhancement to them and an improvement to cross disciplinary communication of street design criteria and outcomes.

In addition, there are models and computational techniques being developed in fields outside of streetscape design which also have potential to be used in addressing streetscape problems; these are computational plant modelling and daylight simulation modelling. In reviewing how light and plant modelling is undertaken in several fields I found that recursive, procedural tree models used in the animation industry, alongside architectural daylighting simulation software and proxy-object modelling useful for streamlining large polygon heavy workflows was the most suitable combination for landscape architectural / streetscape design. I found that these techniques can be used in a cartesian environment which more readily exports to spatial engineering sector software and addresses streetscape scale engineering concerns better than a GIS based platforms.

I found it was possible to loosely couple an adaptable framework of software in common use (or commonly available with changed licencing arrangements[230]) in design offices to develop a modelling method which could be used for both visual and functional tree-scape design considerations. This approach to tree-scape design decision-making and modelling, differs from all other current approaches because it can simultaneously quantify some environmental benefits, communicate qualitative outcomes, as well as coordinate directly with engineering disciplines. This system begins to bridge visual and functional considerations and decision criteria for streetscapes.

[230] In 2016 Autodesk switched their licencing agreements over from a perpetual to yearly subscription model. In that change, Autodesk also bundled their software into 'Industry Collections'. The most used software in the Landscape Architecture industry is AutoCAD https://thefield.asla.org/2019/09/26/design-software-survey-results/ . For offices purchasing a subscription to AutoCAD means purchasing a subscription to the Architecture, Engineering and Construction Industry Collection' which also includes 3ds Max.

Both computer visualisation paradigms of vector-based geometry and pixel-based texture mapping were used in ways that are unfamiliar to landscape visualisation in design offices. Vector based work is often reserved for elements such as site topography while trees are handled as pixel-based billboards added to visualisations towards the end of the design process. In my approach, the site topography could be included as either a 3-dimensional vector-based mesh or it could be treated as a plane onto which conditions could be mapped where increased detail was not warranted or helpful to the decision-making process. Trees, on the other hand which are usually simplified to billboards in game engine-based systems can be included as full vector geometry allowing for accurate shade mapping and in future work obstacle avoidance or site specific pruning practices.

8.2.4 Testing the DDSS on case studies

In Chapter Five, Six and Seven, I aimed to answer two questions.

Can we utilise growing availability and accuracy of spatial data sets in street-scape design decision-making?

Can we combine and apply modelling technologies emerging in the CGI industry (gaming and animation), with computer aided design (CAD), urban forestry and geographic information systems (GIS)?

In chapters 5, 6 and 7, I tested the DDSS on three sites in Melbourne with a specific set of environmental problems which could at least be partially addressed through strategic tree functional choices. The case studies tested how the DDSS could be *applied* to design scenarios with differences in scale, time, objectives and site conditions. Sometimes the decisions required were very subtle, for example, adjustments to streetscape configurations such as narrowing traffic lane widths by 100 millimetres, delivering critical but often very small (less than half a meter) room for tree growth or positioning for better shading outcomes. At the other end of the scale spectrum, decision factors which needed to span multiple municipal boundaries could also be tested using the approach in application for example to flooding sites.

Through the case study testing I found the DDSS flexible to both changes in scale as well as changes in priority considerations. This was particularly evident in the change of scale between flooding sites which need a catchment wide site consideration and heat affected sites which required a walking catchment sized consideration.

I also found the model to be reasonably extensible, though the complexity level for *Synthesis City* which had three considerations, periodic flood, summer shading and winter overshadowing was quite high. There is considerable potential for the DDSS to incorporate more than three considerations, as well as different considerations than those trialled in this study but this requires further research.

8.2.5 Discussion of case studies with respect to historic and contemporary decision-making context

Functions of trees in a Pretty City context

Overall the thesis proposed a way to design tree-scapes for three projects which respond to modern environmental imperatives but in relation to their historic context and with the ability to incorporate public participatory processes. In Umbrella City, the issue of designing a tree replacement strategy for a site expected to experience increased occurrence of flooding in the future was explored. The scheme was a simple binary, either in the flood zone or outside of the flood zone and had a closer relationship with the symmetrical rows of tree planting of traditional tree-scapes than the next two projects. In *Shady City*, tree-scape design strategies were based on a required tree geometry to meet shading requirements for a specific time period. This scheme required a different species on either side of the street and positioning according to solar geometry. This scheme departed from traditional symmetrical compositions, though species remain consistent within each alignment and in doing so the scheme creates a different type of symmetry consisting of symmetrical footpath shading conditions. The final scheme *Synthesis City* wholly departs from the historic concept of symmetrical rows by using Boolean raster overlay maps of site conditions to inform species selections and vector driven shading requirements to inform positioning. The resulting tree-scapes are asymmetrical and hyper site specific, responding to localised historic building heights, and future development light conditions. In some ways they combine the 'ecological approach' of Ian McHarg (1969) and the 'compositional enclosure approach' of Henry Arnold (1980), not symmetrical in traditional visual sense, but symmetrical with their underlying conditions (eco-compositional) and maybe not enclosed from the viewpoint of the centre of the road but enclosure from the viewpoint of the shaded pedestrian or cyclist.

Urban re-reform

Urban design today is faced with responding to a new set of living condition challenges, different from the concerns which drove the Reform Act of 1832 but not dissimilar. Urbanisation, extreme heat and increasing occurrence of flood require new street design strategies. Flood requires a re-consideration of the use of evergreens and increasing selection of larger growing species, while heat and the effect of higher density winter overshadowing problems requires deciduous selections with specific growth habits and forms. In the case studies this was handles using Boolean subtractions and additions between different site conditions.

The results of Chapters 5, 6 and 7 demonstrate that with the application of my DDSS, it is now possible to begin reconsideration of urban priorities in a manner that combines multiple environmental and climate related factors *and* aesthetic aspects simultaneously.

The view from the footpath

With the rise of the Transit City, streetscape design was considered as a symmetrical experience from the vantage point of a driver or 'view from the road'. As we undergo this period of re-prioritisation, aiming to return cities to walkable environments, the primary vantage point of the streetscape design shifts to the footpath and is no longer symmetrical experience. In this thesis meso and macros scale environmental considerations are brought into focus in this micro-scaled view from the footpath.

This time the implications of urban re-prioritisation can be better understood by using the approach described in this thesis, as multiple factors can be looked at simultaneously and a better balance of criteria can be achieved. The approach could, and hopefully will, be integrated with traffic modelling in future research.

By modelling the green infrastructure of the city, it can be elevated to equal footing with hard infrastructure. This is not something that has been possible in the past except at very abstract levels and with no capacity to convey qualitative concerns.

8.3 Contribution to the research field

8.3.1 A design approach which speaks to engineers and the community

This thesis focused on the development of a tree-led visual-functional DDSS for tree-scape designers and in some cases tree-scape managers, to use when faced with possible conflicts in public participatory decision-making, evidence-based environmental design decision quantification and negotiation with service engineering sectors.

By using a single model for forecasting visual, environmental and spatial streetscape constraints siloed thinking, an issue which causes constant problems in multi-disciplinary spaces like streetscapes, can be broken down.

Developing visual models, circumvents some of the issues of definition ambiguity, where different (albeit nuanced, specialised and interesting) terms have arisen to describe fundamentally the same space or phenomena in siloed disciplines. While I came across many of these terms, the most fundamental to this thesis was the description of streetscape space; As a street canyon in environmental science, a street casement in engineering and a street section in design. Numerous other examples of these ambiguities in terminology arose due to the intensely diffused nature of disciplines which study urban space, urban flooding, sunlight and trees. With the accurate simulation of these phenomena in computational fields other terminology ambiguities arise, a natural phenomenon such as leaf light interactions (in scientific fields: leaf transmittance, absorbance and reflectance) is described as 'Sub Surface Scattering' in visual computing (Hanrahan & Krueger, 1993).

In some ways, this thesis describes a change in working processes which will inevitably occur in design offices as design continues to transition from a manual to a computational profession. However presently, there are still industry perceptions that the workload, technical skill required, expense and limitations of requisite software and hardware for working this way is prohibitive (Groulx & Lewis, 2019; Lovett et al., 2015; Paar, 2006). The results of this study show that it is now completely feasible to complete this shift to computational methods but there are important implications for industry, research and education.

Comparison to other approaches

Though I have placed this DDSS within the field of Environmental Visualisation (Bishop, 2011; Gill, 2013; Lange & Bishop, 2001; Sheppard, 2012), which sits within landscape planning rather than landscape architecture, it does not necessarily strictly belong to either field. It could just as well have resided in the field defined by Stephen Ervin in his seminal work *Landscape Modeling: Digital Techniques for Landscape Visualizatio*n, as that of 'landscape modeller (2001) or the more recently defined 'computational landscape architecture' by Cantrell and Yates (2015). There are also similarities with modelling arising in ecosystem service science where functional tree benefits are not output in financial units but as something which is relatable and useful in a PPD forum. These include Olander's benefit relevant approach (2017), Rosenthal's decision-relevant framework (2015) and the multi-criteria decision-support tool (MCAS) developed by (R. D. Brown et al., 2008)[231].

8.3.2 Implications for research

Beyond disciplinary communication

Environmental visualisation that incorporates transport planning concerns, constraints and criteria will be useful for traffic engineers to negotiate and express the geometrics which drive their decision-making and would be capable of integrating 3-dimesionally modelled services of other engineering sectors. The modelling method then suggests that it would be valuable for all engineering to be done in 3-dimensional formats to produce richer spatial/data sets and provide a more integrated picture of the complex workings of streets.

Many models have been developed for environmental impact analysis and decision-making that can incorporate public consultation outcomes, but the scientific modelling results are often too abstract to feed back into highly specific site geometry and cartesian

[231] This tool also uses a material masking method and is based on game engine technology.

space driven platforms used by inter-sectoral streetscape disciplines such as services and transport engineering. It would be possible to instead use the new DDSS in community consultation decision-making, reducing or increasing spatial complexity as required through layering, and including community objectives directly into the model.

While environmental problems are necessarily simplified in environmental visualisation, it is not after all environmental modelling, the approach provides away for GIS-based environmental layers to be brought together with both human and engineering decision criteria. The outcomes of the latter qualitative or environmentally driven decisions need to be translated to explicit geometric terms if they are to be included in those disciplines' decisions. Currently this simply does not happen. GIS modelling does not easily transfer to spatial design platforms and manual work arounds are needed. Future research into better integrated models would benefit holistic decision-making.

Social science

There is a great deal of potential to develop this project in a number of different research directions. One clear standout would be to use the imagery in community consultation particularly in a project where substantial change to the street layout was imminent or possible, to see if attitudes to parking loss or decisions about affordance could be changed given more quantifiable graphic decision impact material.

Further large-scale cross-sectional studies could be done using outputs from the modelling approach. It would be possible to test perceptions and visual/cultural preference responses to evidence-based design decisions such as those arising in the *Synthesis City* scheme. It would also be possible to collect responses to schemes with reduced and controlled variables, an issue which has plagued visual response and forest preference research.

8.3.3 Implications for education

Like many professions in the digital era, profession re-tooling has become necessary. This has led to the integration of AutoCAD ™, Photoshop ™ and Rhinoceros™ into design education over the past two decades, but the future is going to require more than just a small handful of digital tools.

Students of landscape architecture and urban design will need to be prepared to work with a rich array of both environmental and urban spatial data with the growing need for generalists who can interpret results of specialists. This is difficult to achieve as spatial data has only recently become abundant and limited experience with its use in novel ways exists.

This approach also implies a need for change in the teaching of landscape architecture, re-invigorating horticultural knowledge bases while also increasing digital design and tree modelling.

Data literacy

There are global changes to the way spatial data is stored, shared, accessed and curated. Examples of these changes are the Australian Urban Research Infrastructure Network with 5,000 data sets and The Atlas of Living Australia, occurrence records of plant and animal species.

Having students use data sets for purposes other than what they were first collected for, allows these future designers the opportunity to feed back into data attribute collection and data formats which may have been overlooked within the initial collection purpose. As these data collection and data-use-in-scenario-modelling feedback loops increase in number and improve in iterability, real time integrated models of urban environments will become possible.

Although this integration of data literacy is necessary, design education is already a notoriously heavy workload – urban problems are diverse, complex and interacting, while visualisation techniques are laborious and time consuming to develop. While published design works often appear to be overtly focused on visual representation of design fantasy / scenarios – a large portion of design training is dedicated to engineering / construction rules / calculation.

The generation of case studies informed by spatial data sets and the writing up of those case studies can feedback into informing the data set content, collection methods, attributes and formats. This would be a way of using unbuilt works as research translation

Visualisation and visual training

Visualisation technology is evolving through popularity and growth of new industries such as gaming content creation and studio animation. While these industries are still driven by output of compelling graphic output, their production methods are increasingly based on scientific discovery and application of real-world phenomena. This is not only a modelling skill but also a rendering skill which utilises illumination engineering realistic sky models, an understanding of 'rigging' for realistic human body movement and artificial intelligence when applied to learning behaviours of pedestrians. These factors put additional pressure on students to 'know what they are doing' in these complex visualisation environments.

Cartesian and geodetic space

Design work crosses over the discipline boundaries of science and engineering. While spatial scientific analysis is naturally geared towards GIS methods, engineering is geared towards construction industry cartesian based methods. Landscape architecture courses in Australia are currently accredited based on demonstration of students engineering construction documentation skills. GIS skills are not necessarily required for that accreditation[232]. However, to effectively work with spatial data, design student will require greater integration of GIS training into design education in the future.

Vector and raster-based methods

Students of design are well-versed in working with both vector and raster data as traditional, or at least recently traditional methods of producing visualisations. This requires raster-based methods in the early stages and vector-based methods in the construction documentation phases. This places design students at relative advantage to students of many other disciplines who work predominantly in one of these two methods.

[232] For example see the Australian Institute of Landscape Architects policy for accreditation which has no mention of GIS https://www.aila.org.au/imis_prod/documents/AILA/Governance/Accreditation%20Policy_v3_%20July%202016.pdf

One of the surprising outcomes of this study is the possibility of expedience and accuracy switching between efficient and computationally light raster-based landform data and vector-based microtopographic detailed mesh landform. In this study, the model did not always require the incorporation of a mesh-based landform, and instead could work with topographic data through georeferenced 2-dimensional raster-based externally generated flood mapping, soil conditions and urban geometry. This approach is consistent with other toolsets generated for multicriteria decision support such as MCAS-S and environmental analysis tools such as ENVI-met.

8.3.4 Implications for industry

It is the design industry which is predominantly responsible for mediating decisions about public spaces, including streetscapes, with both the community and with engineering sectors. Traditionally this has been done using decoupled visualisation techniques; raster-based for the first and vector-based for the second. To make modelling an integrated process means that there is an urgent need for literacy and 're-tooling' in computer modelling both raster and vector as well as an understanding of how these representational paradigms are used in computing complex earth processes such as the behaviour of light and vegetation alongside data acquisition and manipulation methods, analysis and reconfiguration. These skills range from understandings of how overland flow works in a hydrological catchment, how heat works with urban materials, the architecture of trees, through to the movement of pedestrians and traffic modelling.

This 're-tooling' which design professions are undergoing, may also see designers needing to take on more responsibility for decisions (Braidwood, 2017) and greater responsibility for the interpretation of scientific research results into a visual narrative.
This is a deep change to current approaches to community consultation which as much as possible attempts to recognise and fulfil community decisions and requires visual aids which need to appear non-deterministic. Outputs from modelling which are informed by data will necessarily have a higher level of determinism, suggesting that the role of the designer is bidirectional. The designer must both help to translate research results to the community but also help to translate community expectations to engineering sectors.

Adoption of this modelling approach could provide a level of agency to tree-scape designers which I have found to be currently missing. It could help the community better understand what landscape architects do and help communities and landscape architects work together better.

Veracity

There are good reasons why landscape modelling has not been adopted for smaller scale design projects. The workload involved is greater and the outputs require a level of veracity as decisions are both made and justified against the output. Thus these visualisations become legally and morally more complex objects (Millington et al., 2011). Most environmental visualisation modelling is GIS-based though much of it relies heavily on game and animation techniques, which are as applicable to fantasy, advertising and promotion as they are to physical truth and veracity. In addition, all modelling (conceptual, physical and or mathematical) involves assumptions which, if wrong, compromise the veracity of the output. While the potential improvement to landscape architect's design processes are clear, if the visualisation and ecosystem services modelling developed in this thesis were to be expanded to set legally binding planning rules or restrictions, the degree of accuracy of the simulations would need to be quantified in more detail, and compared with existing methods accepted in the scientific community, or physical environmental sensor measurements, and be able to be expressed statistically.

Rigour

Adoption of the approach could improve the rigour of decision-making about trees for specific ecosystem benefits, similar to the increased rigour offered by approaches such as Vogt's database method, but in this case also responding to spatial conditions of sites and land use planning (2017). Criteria are developed first – to which a species can then be 'fitted'.

Cost benefit

The quantification of services and disservices of trees in urban environments is yet far from clear. Biogeochemical processes are highly inter-dependant and including them in decision deliberations may have unintended and even negative consequences such as depletion of water tables and reduction in the efficiency of solar roof panels (Andrew, 2014; Kirkpatrick et al., 2012). As they develop, cost benefit approaches could be attached to this model as tree numbers positions and species can be extracted from it, exported to an .xml file with each model given a unique identifier. These can then be plotted back into a GIS format and attached to the required attributes for costing.

Decision impact quantification

Application of evidence-based decision-making tools for industry mean that, in addition to producing traditional qualitative, visual decision support material for PPD, they also need to provide quantitative decision impact material. These aspects are difficult to resolve because street tree decisions are not entirely made by designers but by community groups who's decisions may be based on complex, conflicting, mutable preferences and personal affordances rather than higher societal objectives to improve environmental or human health (Irvin & Stansbury, 2004).

Application of research outcomes to design decisions is key for evidence-based decision impact quantification, but this can only be achieved if designers are able to engage with and create scenario forecasting models such as the one developed in this thesis. Translating research into spatial decision-making is the aspect of research which is sorely lacking in industry (Moloney et al., 2015; Sallis, Bull, et al., 2016). This is particularly difficult in design scenarios where generalised or transferable outcomes are not necessarily possible.

Urban data collection standards

Data collection methods, longevity and storage, veracity and data refinement methods have come under great scrutiny lately with the advent of public data sharing portals and online decision support systems and through increasingly availability and finer resolution of satellite/aircraft/drone imagery. Some of the issues that become clear through this process is that urban data is substantially lacking in standardisation across councils or urban management authorities. Naming protocols such as the ecological data equivalent of the Darwin Core[233] and parity in equivalency of collected information are lacking and cause problems across these arbitrary political boundaries. Fundamental data sets such as the PSMA (Public Sector Mapping Agency) are also collected on the basis of motor vehicle prioritization, not pedestrian needs. Building footprint data are collected by water authorities and do not include shed structures or driveway locations making them poor for site permeability analysis.

8.4 Limitations of the study

Any cross disciplinary research will necessarily simplify many aspects: As mentioned in the introduction, there were many possible paths for a study of this nature from visual perception to tree model verification.

The study area was also limited to a few case studies in Melbourne, and while Melbourne is a good case study due to its development history and unique and extreme climatic issues the outcomes are yet to be tested for applicability on a wider range of conditions.

The developed approach is heavily invested in working with three things; use of growing quantities of spatial data to inform design decisions, expanding possibilities of visualisation technology to improve clarity of those decisions and integration of scientific research to increase accuracy of those decisions.

8.4.1 Photometry or radiosity

This study utilises existing architectural lighting analysis used for assessing internal light levels in buildings. Lighting analysis tools include radiosity functions but those have been scaled to account for the human eye's specific perception of the electromagnetic spectrum. As plants use invisible parts of the spectrum, the measurement of lux or illuminance constricts possibilities for the use of these architectural sun systems for modelling impacts of shading on plant growth or heat/ microclimate calculation. There are some (over simplified) methods of transposing illuminance to irradiance which could be explored in further research however these calculations are currently more accurately

[233] The 'Darwin Core' is an evolving standard which governs field and attribute names for species data collection which enables those data to be comparable with the data of other collectors / scientists https://www.gbif.org/darwin-core.

handled in other software such as ENVI-met and UMEP (with integration of SUEWS and SOLWEIG) (Bruse, 2004; Lindberg et al., 2018).

For the purpose of making design decisions which lead to a more comfortable environment for pedestrians and other active transport users, the problem is not quantification of heat anyway, the problem it is negotiating the right trees into the right position and selecting forms which will attain height and width required for adequate shading or other ecosystem benefits. This is the first step – and currently there is no modelling approach which helps it to be taken.

Using a different base software might have allowed greater integration with climate modelling or spatial resolution of human thermal comfort modelling as was recently undertaken by Rakha coupling ENVI-met with Rhino3D (2017), though these are very recent advances in both those software platforms.

8.4.2 Bidirectional tree growth

Trees can be included in the system as either a mesh object with editability limited to aspects such as leaf quantity or they can be included as procedural trees with editability, of all aspects of tree growth such as branching angles, leaf density, leaf orientation and leaf type. Currently the tree models whether they are mesh objects or procedural are formed or selected at the discretion of the modeller. Their *condition* is not linked to locational circumstance, only the model *placement* itself can be linked to a conditions map. I found that this meant the only way to resolve having tree *growth* appear more responsive to site conditions was by adding multiple model meshes to the proxy-object scattering tool representing known, 'prebaked' growth responses under different conditions. This is really where the difference lies between structural-functional models of plants and these procedural visual models. Linking plant growth to environmental conditions may not currently be possible within the existing modelling framework, however, there are promising developments in this area.

There is potential to improve the accuracy of the 'prebaked' models in order to extend the accuracy of the modelling approach as the tree models can be 'photographed' in the same way as living trees for measurement their Leaf Area Index or Leaf Area Density or Plant Area Density. The sun system can be calibrated to include measured weather conditions and the recently inbuilt digital-physical cameras can be calibrated to a few common proprietary physical-digital camera settings and lenses.

The application of the above method may even have an accuracy advantage over urban ecosystem service calculators which use allometric equation models such as i-Tree. This goes back to the implications for education, which would suggest that building plant modelling into landscape architecture courses would beneficial.

8.4.3 Rapid software and hardware development

In the time period it has taken to do this thesis much has developed in both software and hardware. Renderings which took several hours to complete in the initial stages of the project now take only a matter of minutes. This incredible increase in the speed of production of renders is predominantly due to the rapid development of technology around the use of the GPU to operate as an additional and many times more powerful CPU and thus breaking the long standing "Moore's Law 'about the speed at which computers improve.

However, within new hardware capability came a need to re-write long-standing software packages. Linked annual and biannual software and operating system updates, though the period of writing this thesis were sufficiently substantia, sometimes buggy and complex that on occasion they would 'break' the way my models and workflows operated and I was required to reconstruct new, often improved methods. These crucial, rapid updates and maintenance of proprietary software, limit the ability to and applicability of developing a re-useable interface 'skin' for the system, which would quickly become inoperative without ongoing maintenance.

8.4.4 Social science

One aspect which was excluded from this study includes the use of the output material in community consultation or for a visual perception study which I will discuss under further research.

8.5 Recommendations for further research

8.5.1 Asking deeper questions using 3D and 4D models

The act of model building for design decision-making, if it can include at least a basic level of quantification of environmental analysis becomes a critical undertaking for future city designs. 3-dimensional models allow analysis from any perspective and are object oriented rather than viewer oriented, though their use in industry for the moment seems to be predominantly employed in making ever more alluring visuals rather than investing in simulation and analysis possibilities. If design modelling is to evolve beyond visualisation it will need to look to other profession to see how this can be achieved.

The act of modelling trees as 3-dimensional entities in a geometric space if implemented would put also allow tree decisions to be 'up front'. The model would be used like any other data set, could be live linked and allow tree placement options to be attached to infrastructure changes.

8.5.2 Book of street patterns and tree shape selections

The modelling method is currently quite complex and is not easily repackaged as an online tool for general use. In the absence of this possibility, the outputs can be packaged as a form of 'look up table', for street type, bike path location, parking provision, orientation, width and presence or absence of driveways – with the best tree geometry and location for provision of shading. This would need to be time zone and geographically specific.

8.5.3 Rainfall interception modelling

The properties of water and its behaviour when in contact with leaf geometry, surface texture and overall canopy structure would be an area of immediate research. Water modelling platforms such as Real Flow™ and the recently integrated fluid simulator Bifrost in 3ds Max, are particle modelling systems which can be programmed to behave like water and would be good to investigate.

8.5.4 Expand upon the time and destination-based tree-scape design

The Victorian Integrated Survey of Travel and Activity VISTA data, an ongoing survey of household travel data collected Victoria wide could be used to inform precincts for different tree-scape design types, rather than relying on land use patterns which become unidimensional.

8.5.5 Modelling could potentially be done on other platforms

My approach uses the software outlined in chapter 4, but as software and hardware evolves, there is potential for alternative options. Currently using a loosely coupled set of software allows for 'swapping out' of individual components and given that industry, organisations and government agencies such as councils rarely use the same software platforms this is an advantage. Investigating and comparing the utility of these evolving alternatives and the outputs each is capable of producing would be of great value to industry which essentially must 'take a punt' at software purchase and associated skill development. Two strong contenders in this area are integration of ESRI's City Engine with Sketchup and V-ray and or McNeel's Rhino3D with GH (Ladybug) + V-Ray, though at the time of writing, these platforms do not have the proxy-object scattering capability.

8.5.6 Alternative 3D data-set integration

There is also potential to include point cloud site scan data though these are not as yet readily available. Point cloud scans from photogrammetry and lidar can be linked into the base platform where they are treated as pseudo solids. This means the point clouds can be rendered and can also cast shadows though they may not currently be capable of receiving shadows. Point cloud data can also be 'meshed' in 3D point cloud and polygon mesh editing software such as CloudCompare, but the resulting meshes have extremely high polygon counts and not feasible for testing design scenarios as the large files are both computationally expensive and also very difficult to edit (Lin, 2016). This area of technology is however under rapid development. As an increasing amount of point cloud data becomes available through growing access to affordable unmanned aircrafts (UAVs), software improvements in file optimisation, and hardware improves, there will be increasing potential for point cloud data types to be integrated into the system.

The selection of 3D data tested in this thesis was limited to what was freely available to me as a researcher and to what was relevant to the selection of street trees to respond to two key climatic variables. The system has potential to include many other 3d data sets such as those available from Geoscape and the Public Sector Mapping Agency (PSMA), as well as 3D data from companies like Aerometric and AAM.

8.5.7 End-user expansion and further testing

The testing of the DDSS has been done by me as a 'typical' landscape architect end-user employing the system on challenging urban projects. It should be noted however, that through the duration of the thesis, my skill level has developed to be more akin to a high-level or expert end-user. While this doesn't disprove the results and conclusions that outline the usefulness and effectiveness of the system, the useability of the system requires further end-user testing. It would be desirable to develop training user-guides and resources for the DDSS and deploy it in a variety of different scales and types of landscape architecture practice. Feedback from practitioner end-users could then be collected to help develop the system further but also gauge the level of uptake in the short and long term.

There is also potential to undertake testing of the effectiveness of system in communicating and/or advocating design decisions with stakeholders and the broader community. Comparisons with traditional design and communication approaches could be conducted. This additional analysis could build upon the growing body of research in this area including the environmental visualisation work by (Gill et al., 2013; Lange & Bishop, 2001; Schroth et al., 2011), Public Participatory GIS (PPGIS) work by Sieber (2006) and public aesthetic preference such as the work of Dobbie and Gobster (2013; 2007).

8.5.8 Time-based modelling

This thesis only briefly touches on the capabilities of animation software to express both city and tree growth over time. Due to the choice of base software (including animation software), further adaptation of the models to achieve time-based animation is possible. This would be ideal for communication with communities in describing the likely visual impact of tree replacement and growth over time.

8.5.9 Game engines or living city models

There is potential for gamification of decision outcomes which could be very useful in community decision-making arenas. These formats allow spatial decision consensus and path dependent visualisation of design decision outcomes. This turns models into live entities rather than something that is archived after job completion.

8.5.10 VR and AR

Although the 3D modelling and rendering used in this thesis provides a significant improvement in integration of visual and functional modelling when compared with current landscape architectural practice, and the quality of the visual impact assessment possible is comparatively high, there is great potential to further understand the visual impact of streetscape design through the use of virtual reality (VR) and augmented reality (AR). With GPU improvements and continuing efficiency developments in software over the past two decades, it is beginning to be possible to simulate designs within real-time AR and VR environments including (somewhat simplified) trees. Though the design tools currently available are extremely limited, with the hardware improvements expected to come over the next decade, it is likely that the level of polygon detail in trees possible to display within AR and VR will soon match that which is described in my thesis.

It is also expected that there will be ways to combine the AR and VR modelling with sophisticated environmental modelling. This may become possible in two ways, either through the development of new environmental modelling plug-ins for common game engines used in the production of AR and VR (such as Unity and Unreal), or through the reduction in the current divide between modelling software (such as 3ds max or Maya), and AR/VR game engines. We are already seeing signs of this through Chaos Group's V-Ray render which now includes a 'real-time' 360-render option, (though at the time of writing this thesis, the 'real-time' nature of the renders are not of suitable quality to use for more than a few minutes without suffering VR sickness).

8.5.11 Implementation on built projects

Though this thesis tests the design approach on a series of projects that relate to actual sites and design projects currently occurring in practice, the case studies remain theoretical and not implemented. I have drawn upon my experience of over twenty years in landscape architectural practice to ensure that the design processes used in the case studies were realistic (though optimistic in terms of what would be implemented); ideally, there would be scope to implement this approach on the real projects. However, given the growing tree replacements needs that have arisen in response to mass die off or other infrastructural changes, there are likely to be many opportunities in the foreseeable future to further test the design approach through on-the-ground implementation.

8.6 Conclusion

Trees have been considered '*expensive ornaments*' by service and traffic engineering sectors aiming to achieve efficient systems (Jonnes, 2017), '*flexible tools for environmental design*' by science sectors aiming to reduce heat and flood related urban environmental problems (Oke, 1989) and symbols of democratic empowerment by community sectors (Fisher et al., 2015). Within and between each sector, the criteria for decision-making is diverse and often contradictory.

As designers shift to 3-dimensional computational methods of creating visualisations, whether they are for construction or for decision-making purposes, analysis and simulation possibilities arise. More accurate physical/computational models inform more accurate mathematical analysis and simulation possibilities and have better spatial integration with engineering discipline modelling methods.

The core aim of this thesis is: To develop and test a new tree-scape design approach that is simultaneously visual and functional, that responds to site conditions to inform decision-making about placement and species choice of trees in urban streets.

This thesis addresses the aim of the study by developing a design approach which can simultaneously express qualitative outcomes of tree choices and quantify key functional aspects of tree alternatives responding to evolving urban morphological, spatial and environmental conditions. It offers a novel method for simultaneously addressing visual implications of tree choices alongside quantification of functional benefits and a tool for negotiating street space with transport and engineering disciplines.

In answer to the main thesis question, this thesis demonstrates that it *is* possible for environmental performance, spatial constraints and visual impact to be integrated into a tree-scape design process, and I have illustrated how this can be achieved and applied to three different urban design scenarios.

This thesis is important in light of the urban re-reprioritization and changes to infrastructure which need to take place over the coming decades in urban areas in relation to critical issues such as climate change. It can be used to help negotiate streetscape space towards improved environmental and human health and can also give designers agency to communicate the complexity of the decisions needing to be made to the community in order to achieve these higher societal goals.

The thesis makes a significant contribution to the field of landscape architecture as it offers a novel method for simultaneously communicating visual implications of tree choices alongside quantification of relevant benefits and a tool for negotiating street space with engineering disciplines.

The result is the development of a DDSS which allows tree-scape decisions to be more tree centred and enables tree changes, to be readily coupled to infrastructure changes.

While it is not surprising that animation industry software is suitable for modelling landscape design, particularly since architectural offices have been utilising this type of software for some time, the irregularity, detail and change over time of landscape forms such as trees and landform has made landscape design more difficult to work with in computational environments. Landscape is also inherently connected to complex earth processes which make landscape a less controlled environment than a building.

In the case studies presented, the interplay between vegetation type, tree canopy, topography, walkability and agent behaviour has been modelled to act as a performance-based method for articulating scenarios and outcomes. Combined with a site-specific approach, stakeholders can be engaged in an informed way. This interaction is critical in achieving a shared understanding of the risks and threats faced by a locality and presents the opportunity to build consensus and influence passive and active behavioural changes over the long term. With these mechanisms in place, we have the capacity to build longitudinal studies that can quantitatively measure the impact of a policy or design intervention at the local level. The thesis provides important insights and site-specific, replicable methods for landscape architects to use for balancing subjective cultural preferences with environmental performance-based tree-scape design. It branches in the direction of adaptation to climate change and towards encouraging healthy, thriving and resilient communities.

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