Digital Workflow for Novel Urban Green System Design Derived from a Historical Role Model

Ferdinand Ludwig[1], Michael Hensel[2], Thomas Rötzer[3], Albin Ahmeti[2], Xi Chen[1], Halil Ibrahim Erdal[1], Astrid Reischel[3], Qiguan Shu[1], Jakub Marcin Tyc[2], Hadi Yazdi[1]

[1]School of Engineering and Design, Technical University of Munich/Germany · ferdinand.ludwig@tum.de

[2]Department of Digital Architecture and Planning, Vienna University of Technology, Vienna/Austria

[3]School of Life Sciences, Technical University of Munich/Germany

Abstract: By studying how historical green systems were designed and managed, strategies and methods for developing novel urban green systems can be gained. However, this potential often remains untapped due to the high complexity of historical approaches. New methods and tools in the areas of 3D scanning, data-driven modelling and simulation, computer-aided design, information modelling, knowledge engineering, machine learning and decision support systems can serve to tackle this complexity. In this paper we review the related state of the art and conceptually outline a digital workflow to achieve this aim. We conclude with discussing how this approach can change the role of landscape designers in the future.

Keywords: Urban trees, computational design, target-driven design, data-driven design, knowledge graph

1 Introduction

Rapid urbanisation and environmental degradation draw increasing attention to the value and delivery of ecosystem services (ES) that plants can provide in cities. Climate change affects urban heat islands (CORBURN, 2009) and causes droughts, hailstorms and flooding in urban areas (GÜNERALP et al. 2015). Future urban green systems (UGS) can mitigate the consequences of urban climate change by improving outdoor living quality and protecting buildings and people from the consequences of extreme weather. By studying historical examples, the design, planning, and management of UGS can adapt strategies and methods that were used in the past. One example is, for instance, the adaptation of traditional rural hedge rows as a novel urban green system (HÖPFL et al. 2021).

Historical systems are based on a rich diversity of traditional knowledge on plant management, but they require complex, foresighted, and often sophisticated maintenance schemes. Novel methods and tools in the areas of 3D scanning, data-driven modelling and simulation, computer-aided design (CAD), information modelling, knowledge engineering (knowledge graphs), machine learning and decision support systems (DSS), in the long term also the use specialised technologies for maintenance purposes, can address this complexity and thereby allow for historic practices to become a viable option to support the provisioning of ES in contemporary urban contexts.

Throughout history, humans have invested considerable effort, time and resources into manipulating trees and other woody plants for a variety of purposes. The German *Tanzlinden* are long-term projects that provide social gathering points and tie communities together over generations (Fig. 1 left) (GRAEFE 2014). *Hedge-laying* techniques are field barriers specific to their landscape and the cattle or crops they protect, whilst acting as ecological corridors

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(LAWTON 2010) and wind protection (ALEGRE & RAO 1996) (Fig. 1 right). These practices have been developed specifically for certain contexts with the aim of achieving diverse but precisely defined functions. They are based on a set of techniques such as coppicing, pollarding, pleaching or grafting, which are applied locally in different forms (KURZ & MACHATSCHECK 2008, STUBER & BÜRGI 2001).

Fig. 1: Left: So called Tanzlinde (Peesten, Germany) created by perpetual manipulation of the branches through pruning and bending (photo (cc): Reinhold Möller). Right: Laid hedge in the UK following the traditional practice of creating "living fences" (photo (cc): Zorba the Geek)

Today, UGSs are usually designed with the aim of providing some services while minimizing maintenance. Procedures of tree care are standardized and mainly aim at a "natural growth form" (KLUG 2016, FLL 2006). The techniques described above are rarely used and if so, usually in a simplified and formalized topiary-like manner (RUEMLER 2002). In view of the fact that the urban context is characterized by complex and diverse conditions (SIEGHARDT et al. 2005) and demands (LOW et al. 2009), the practice of standardized design and low maintenance seems questionable. Until today, the diversity of traditional functional tree manipulation practices and resulting effects on ES provisioning has not been systematically assessed and the potential for the development of novel UGS remains unused.

In this paper, we address this research gap by reviewing the state of the art of related fields of research, describe in detail a historical example that we use as role model and based on this develop the conceptual basics for a digital workflow for novel urban green system design. The ultimate aim of the overall research project is a computational workflow that allows for designing and managing UGS that are employing a combination of historic plant manipulation techniques. More specifically, the aim is to (a) develop new methods to simulate growth reactions of trees to different manipulation practices and to model microclimatic ES and the structural performance of such systems; (b) explore an iterative design and management approach that integrates these methods with a decision support system; and (c) validate these tools by applying them to design cases.

2 State of the Art and Research Gaps

In the following we review the state of the art as well as our preliminary work regarding the various fields of research essential to reach the above-mentioned goals. These include the design and construction with trees in (landscape) architecture within the context of digital design, data-driven performance-oriented design approaches and information modelling as well as the simulation of growth and ecosystem services in urban trees and forests.

2.1 Design and Construction with Trees in (Landscape) Architecture

Naturally growing and artificially formed trees are crucial elements in landscape architecture. However, only few projects feature tree growth as a key aspect of the design concept (VAN DOOREN 2017, VAN DOOREN & NIELSEN 2018, GROSSE-BÄCHLE 2005). A continual and adaptive performance driven manipulation of tree growth has not been explored in landscape architecture yet. However, the design of a development process with the aim of achieving spatial, climatic or constructive functions is a declared goal of *Baubotanik*, a field of research and practice established by Ludwig and coworkers over the last 15 years (LUDWIG & STORZ 2005, LUDWIG 2008). This approach focuses on deriving rules for designing with trees from basic botanical principles through empirical studies and research by design (LUDWIG et al. 2012, LUDWIG & SCHÖNLE 2022) Computational design that builds on the growth processes of plants is rarely investigated so far. Examples are e. g. the design-build-projects *Arbor-Kitchen* (SHU et al. 2021) and *Urban Microclimate Canopy* (SHU et al. 2020) or the research project *flora robotica* (HAMANN et al. 2015). The results of these project provide a conceptual and methodical starting point for novel urban green system design.

In order to design with the growth processes of living trees within a digital framework (YAZDI et al., 2023), a perpetual examination of their geometry is essential. In recent decades optical methods that provide 3D point clouds have been widely adopted in documenting trees (HU et al. 2017, YAZDI et al. 2024, BAYER et al. 2018). Converting unstructured point cloud data into meaningful structural models is a key step for further analysis and simulations (TAGLIASACCHI et al. 2016). Raw point clouds can be converted into topological skeletons (GUO et al. 2020) by a range of methods. While many research projects are dealing with topological abstraction of naturally grown trees, only few have previously addressed manipulated growth specifically, for example the geometrical documentation and abstraction of Living Root Bridges (MIDDLETON et al. 2019).

In addition to the geometry of a tree, its mechanical performance and reliability are highly relevant. Standard experimental methods for examining tree failure are well established for naturally grown trees (WESSOLLY & ERB 2014). These have allowed for statistical methods (HALE et al. 2015) and individual tree models (JACKSON et al. 2019) that examine static and dynamic loading (JAMES et al. 2014). Linear and non-linear analyses of tree statics show that the mechanical performance is strongly influenced by their structure (YANG et al. 2005, MOORE et al. 2018). However, only few studies investigate the dynamic effects of manipulations such as pollarding, inosculation, pruning, and directed growth (DAHLE et al. 2017, BURCHAM 2020). With our study we aim to address this research gap. Standard finite element analysis (FEA) is a useful tool in these two areas of analysis (THÉCKÈS et al. 2015).

2.2 Data-driven Performance-oriented Design Approaches and Information Modelling

Data-driven performance-oriented design approaches (HENSEL 2013) and related computational design methods (HENSEL et al. 2017) are today ubiquitous in architecture, landscape architecture and urban design. Advanced methods often combine algorithmic design generation (TERZIDIS 2004) with analysis (AGUIAR & CARDOSO 2017), and especially micro-climatic analyses (GRAHAM et al. 2020). While the importance of the interaction of the built environment with plants has been recognized, suitable computational design methods that can support and project development over time are currently in short supply. Computational tools for environmental simulations exist in architecture, landscape architecture and urban design and are in constant development, i. e. Envi-met (HUTTNER & BRUSE 2009). This results in the rapid growth of digital data describing our urban environments and their environmental performance. Ever-increasing volume of data becoming a part of design process necessitates development of interdisciplinary data-integration approaches, allowing to recover and adapt the land knowledge for different contexts. This can be achieved, for example, by employing the twofold strategy of *understanding* and *designing environments*, facilitated by interdisciplinary data integration and computational ontologies (SUNGUROĞLU HENSEL et al. 2022). A recent literature review addressing the role of voxel models in computational design processes, identified existing applications of voxel models for 3D plant modelling, environmental simulation, and 3D-scan data integration (TYC et al. 2023). This leads to an assumption that systematic integration of 3D scanned representations of plants and the simulated environmental impact they can provide in the urban environments, necessitates voxel-based data integration strategies. In this context, a synergistic voxel-based 3D-scan and environmental simulation data integration has been demonstrated as a part of the Composite Voxel Model approach (TYC et al. 2022, TYC et al. 2021).

In order to create a decision support system (DSS) in a multi-disciplinary context that aims to fulfil design and target parameters, it is generally required that the data and information to be utilized, i. e., abstracted in a form that can be exploited as knowledge for DSS (GLICK 2013). This abstraction in our case is achieved by modelling data and information and representing them using ontologies and knowledge graphs. Knowledge graphs have been used in the context of design as reported in the survey by (PRUSKI and HENSEL 2022). However, in the context of UGSs, it is essential to integrate and consolidate different data and information into knowledge graphs, such as ecological data (e. g., ES), tree dimensions and their shapes, pruning techniques, historical examples from nurseries. Based on this, the designer will be able to query the knowledge graph based on the defined competency questions – to find a tree with the envisaged characteristics that satisfy the defined design and target parameters. By incorporating approaches described in this paragraph, design can be extended to facilitate multi-scalar data integration and facilitate elements of decision support, addressing the challenges related to urban green systems.

2.3 Simulation of Growth and Ecosystem Services in Urban Trees and Forests

Algorithmic tools for simulating plant growth exist for instance in computer science, i. e. context sensitive L-systems (MCQUILLAN et al. 2018) (PRUSINKIEWICZ et al. 2012). These methods and tools generate self-similar structures, a common feature of plant architecture.

Functional structural plant models describe physiological processes combined with a representation of the 3D structure of a plant (GODIN 2000, SIEVÄNEN et al. 2000). When considering variable criteria (e. g. gravity, object collision, pruning) they can allow for reactive plant growth modelling (PALUBICKI et al. 2009) (PRUSINKIEWICZ et al. 1994). Simulations of growth reactions to specific conditions or manipulations is used to identify suitable pruning points on apple trees in the context of robotic farming (KARKEE et al. 2014). These tools provide valuable basics for simulating tree in novel UGSs, however they fall short in representing the complexity of growth reactions to various pruning techniques. In this regard recent approaches from the field of machine learning which build on the quantitative structure models obtained from LiDAR scanning suggest a possible solution to this question (SHU et al. 2023).

Abstracted representations of plants enable modelling green systems at larger scales, e. g. in forest science or urban forestry (RÖTZER et al. 2010, PRETZSCH et al. 2015, Pretzsch et al. 2002). Principally, functional models calculate photosynthesis along with respiration, carbon- and nitrogen allocation and senescence of trees (PRETZSCH et al. 2008). This requires detailed information such as soil moisture, leaf evaporation, radiation etc. (COURNÈDE et al. 2009). Therefore, functional-structural tree growth models in forest science integrate a broad spectrum of system knowledge. They are used to analyze the effects of environmental changes on tree growth, for testing hypotheses and as decision support systems (PRETZSCH et al. 2008). The empirical growth model SILVA (PRETZSCH et al. 2002) uses a light-cone method (PRETZSCH 1992) to calculate competition indices for every tree based on its size and position within the stand. The eco-physiological growth models BALANCE and CityTree calculate the development of individual trees along with their ecosystem services and estimate the consequences of environmental influences (RÖTZER et al. 2010, RÖTZER et al. 2019). The development of trees is simulated as a reaction to individual environmental conditions whereby the environmental conditions change with the individual tree development. Competition, stand structure, species mixture and management options can be considered. However, so far no such model exists for plants heavily manipulated in their growth, such as pollarded trees.

To address the dynamic development of trees and tree stands, management decision (e. g. thinning) cannot be preset to achieve an optimal result when dealing with accumulated uncertainty in plant growth. In SILVA (PRETZSCH et al. 2002), a feedback loop is used for forest management, where previous stand structure and site conditions that lead to changes in tree dimensions become the base for the new stand structures. Besides building the decision system in the feedback loop, it can also be based on probability distribution. Stochastic growth models are applied in forestry science to forecast the evolution of forest inventory based on Markov decision process (PRETZSCH et al. 2008). The underlying Markov chain provides the methodological basis for decision support in future UGS design. Such systems are already used for analyzing branching and axillary flowering sequences over time and space (GUÉDON et al. 2001) or for analyzing similarities and gradients in growth unit branching patterns in apple trees (RENTON et al. 2006). Hidden semi-Markov chains (HSMCs) are used to describe fate of buds for pruning strategies (SMITH et al. 2007, XIA et al. 2009).

3 Conception of the Workflow

The capacity of UGS to support human health and well-being by providing a suitable microclimate relies on the long-term development of plants and corresponding design and management strategies and methods. Traditionally, practitioners continually manipulate plants as they grow. This can be seen in gardens, tree nurseries, and in historic green systems. These systems exhibit a range of microclimatic functions and manipulation practices that are adapted over time to fulfil changing human needs and match changing environmental conditions (see e. g. the hedge systems described in BECKMANN (1982) or MÜLLER (2013). In contrast, current design often neglects the potential of perpetual design that integrates plant development with adaptive manipulation of plant growth. To tackle the complex dynamics of forward-oriented UGS design and plant growth management through a novel combination of 3D-scanning, simulation, and evidence-based performance-oriented computational design we herewith present a conceptual approach and workflow that couples generative and analytical computational methods and related tools with decision support system.

3.1 Historical Role Model

This workflow is derived from historic examples of trained tree canopies which were traditionally formed by horizontally laying out the branches of trees (mainly plane trees, *Platanus* x *hispanica*) above a specified height, sometimes connecting them to the branches of neighboring trees for stabilization. Shoots are pollarded annually. Examples can be found especially in southern European cities (e. g., Labouheyre, France; Zamora, Spain) for intensive shading of squares (Fig. 2).

Fig. 2:
Horizontally trained and pollarded plane trees in Labouheyre, France. The trees generate a very dense shade with minimal height. (photo: Pierre Cuny, via canalblog.com)

Even though such practices today follow a mere standard procedure, we assume that the emergence and development of such systems historically is based on a workflow in which the actual development is regularly compared with the targeted performance. Based on the practitioners' knowledge and experience, plant manipulation techniques are chosen to reach these targets. This procedure integrates design decisions, physical plant manipulations and growth processes. It can be divided into three iterative steps:

In the first step, general objectives are defined, e. g., where and to what extent shade should be created on a site, where a view should be possible or where wind protection or ventilation should be provided. Depending on these objectives, the local growing conditions (climate, soil, etc.) and the maintenance measures likely to be required to achieve the objectives, a suitable tree species is selected. In the example at hand, plane trees have proven to be particularly suitable.

In the second step, objectives for the arrangement of the plants and their development in the space are developed on this basis. For example, a meaningful arrangement of plants can be developed from the spatial context, the usage requirements, and the set objectives, historically often a grid with specific spacing between the trees. At the same time, it is determined where foliage volumes of certain densities should develop, and which spaces should be kept free. For example, the horizontal plane trees have a much lower height compared to naturally growing trees but create a very dense shade. This can be advantageous, for example, if the exposure of windows of surrounding buildings is to be maintained while the area between the buildings is to be shaded.

The third step consists of a series of iterative sub-steps. At regular intervals (e. g. annually), the development status of the trees is matched with the targets and the necessary maintenance measures are derived from this comparison. In the example at hand, this is e. g. the horizontal bending of the shoots until the desired shade is created in all targeted areas, as well as the pruning of the shoots in order to maintain the crown volume in the desired dimension. The extent to which the branches can withstand mechanical loads is always checked to determine whether temporary supports may be necessary, or the targets need to be adapted to the mechanical capacity.

3.2 Digital Transfer

To transfer the traditional workflow into a digital approach to design novel UGS it is first necessary to adapt it for use in an urban context to meet current needs and conditions. The following section outlines the concept of the intended digital workflow.

Fig. 3c illustrates how information modeling methods described in section 2.2 can be used in combination with data to predict ES (section 2.3) of different tree species or types of pruning to select a tree species and suitable nursery stock (initial shape of the tree) that is most likely to meet the desired general aims of the design project. This corresponds to the first step of the historical role model.

Following the aim of improving the microclimatic conditions of an urban streetscape Fig. 3a uses the example of sun rays and lines of sight to illustrate how the boundaries of the possible growth space can be determined so that so-called target leaf voxels can be defined. How such target leaf voxel can be set and used in design is described in more detail in (Yazdi et al. 2023) (compare also section 2.2). This corresponds to the second step of the historical role model.

In fig. 3b the derived target leaf voxels are shown. Just like in the traditional approaches neither the canopy shape nor the geometry of the branch and trunk structure are defined exactly, but merely with sufficient precision to achieve the desired goals as effectively as possible.

In line with the third step of the historical role model, the aim is now to manage the growth in such a way that the trees develop in accordance with the configuration described by the voxels and thus the performance goals are achieved. To do this, it is necessary to regularly capture the actual development. What is traditionally done by the trained eye of the gardener is now done by regular 3D scanning and corresponding further processing of the point clouds (see section 2.1). This data can then be used to carry out mechanical analyses and predict the development of the plant. (Shu et al. 2023) provide a first approach to this. To properly inform appropriate maintenance decisions support tools that relate these analyses and forecasts to the desired objectives complete the digital workflow.

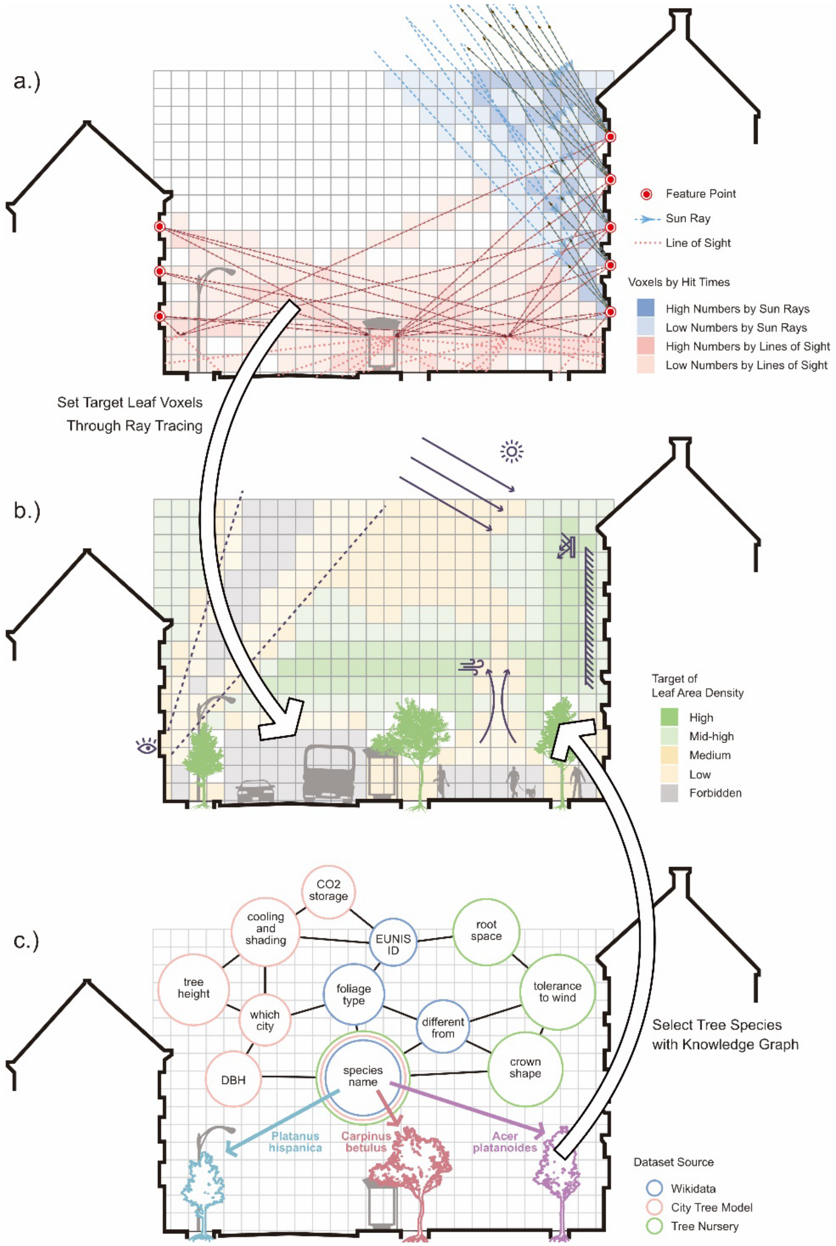

Fig. 3: Concept of the digital workflow. In the middle (b.) leaf area density is set as a target parameter in the design space to inform planting positions of trees and maintenance (pruning and guiding of branches). Above (a.) is illustrated how these targets can be computed from inputs such as shading of certain areas of facades while at the same time allowing for certain views. Below is outlined how different data can be combined via a knowledge graph to inform questions related to tree planting (species, dimensions and pre-shaping of the tree at the point of planting).

4 Discussion and Conclusion

The workflow presented in this paper so far is a merely theoretical approach. It combines a wide range of recent models and tools, some of which are still under development or have not yet been tested. Accordingly, the overall approach cannot be validated yet. The development and investigation of such a workflow triggers many questions and offers many leads for future studies. The work presented here can be described as a starting point in the sense of fundamental research in design, as the underlying ways of thinking about how to deal with trees clearly go beyond the usual concepts applied in landscape architecture design practice. Firstly, this concerns the extensive use of new technologies and secondly the so far unexploited approach of designing trees using target voxels. Thirdly, the design approach differs from the usual practice in that it understands maintenance as a creative act and therefore as part of the design process.

Thus, it becomes clear that the proposed workflow has enormous transformative potential for the discipline of landscape architecture: the designer or planner no longer completes their work with the implementation of the project or a few years of maintenance supervision, but is involved in the design of the development over a longer period of time. This also creates a closer connection between the design discipline of landscape and the field of arboriculture. In the future, even the actual implementation of maintenance measures could also be integrated into the digital workflow when (semi-)autonomous robotic units may take over tree pruning.

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