A Target-driven Tree Planting and Maintenance Approach for Next Generation Urban Green Infrastructure (UGI)

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Abstract: Enhancing ecosystem services (ESS) has become a major concern in planning urban green infrastructure (UGI). The keys to this are urban trees and their dynamic growth in both overall biomass and specific canopy geometry. However, such dynamic growth interacts not only with the abiotic context but also with tree manipulations such as pruning. To address these aspects, this paper proposes a novel theoretical workflow for designing with urban trees by applying a 3D voxel approach. It aims at achieving a quantitative target such as higher leaf coverage without conflicting with other urban functionalities such as traffic and adequate light. We then illustrate how this target guides strategic planning of tree planting and management. Finally, we highlight how this conceptual approach can stimulate further research and technology development to design and manage next generation UGI.

Keywords: Target-driven design, data-driven design, urban green infrastructure, tree engineering

1 Introduction

As a response to increasing urbanization and climate change, urban green infrastructure (UGI) emerged as a concept to improve human health and well-being within urban boundaries. Trees, as a primary component of UGI, are not static elements but follow dynamic growth through their lifecycle. Therefore, the capacity of UGI relies on adequate design and management methods that allow for long-term development of trees.

Ecosystem Services (ESS) describe all functions of urban green infrastructures (UGI) for human well-being. In the field of urban forestry, ESS have been evaluated specifically for every individual tree, based on factors such as diameter in breast height, age, and crown shape. Local environmental conditions affect tree growth (Eleonora Franceschi et al. 2022), which in turn result in different ESS such as carbon storage, shading, and cooling (MOSER et al. 2015). According to Nastran et al. (2022), Palliwoda et al. (2020) and Xu & Zhao (2021) the ESS of UGI increase with biodiversity and total biomass in cities. This could be achieved by the following concept, where a tree's canopy volume is set as a design target. In an example of a natural environment with young trees (see Fig. 1a), around 50% of the theoretically possible canopy volume is achieved. When the same vegetation is simply copied and pasted to a fictive built-up area, human living space and shade is squeezed in (such as shown in Fig. 1b), but further functions are not met. For enabling these functions (i. e., open space, mobility, underground infrastructure), some canopy areas are excluded from the allowed growth space (forbidden areas) for trees. In this approach, it allows a maximum leaf area or canopy volume of trees without impairing other functions and requirements such as exposure or ventilation. To define such a target in a design perspective, human comfort, and aesthetic aspects such as viewpoints are highly relevant as well. A 3D target-driven workflow (section 2.1) can be a solution for meeting these diverse needs. To evaluate trees' performances, a range of decision-support tools for green infrastructure and ecosystem services have been developed in recent years (VAN OIJSTAEIJEN et al. 2020). The performance of trees, after they have

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reached the desired size, can be assessed for feedback on tree planting and maintenance. In this way, tree planting design (i. e., species, position, density) and any common thinning and pruning could contribute to a higher ESS (i. e., thermal comfort and visual aesthetics) (CHEN et al. 2021, KRAYENHOFF et al. 2020, LANGENHEIM & WHITE 2022, Wang et al. 2022).

However, currently such a performance goal cannot be fully met because of the lack of knowledge about the dynamic growth of trees interacting with the abiotic context and the growth of the branches after pruning. For example, without knowing about the effect of the adjacent building on the form of a canopy, targeted ESS cannot be achieved. In this context, developing a visionary tree planting and maintenance design workflow is crucial for increasing the value of the tree's ESS. The specific focus of this workflow will be on urban trees and their integration into the built environment.

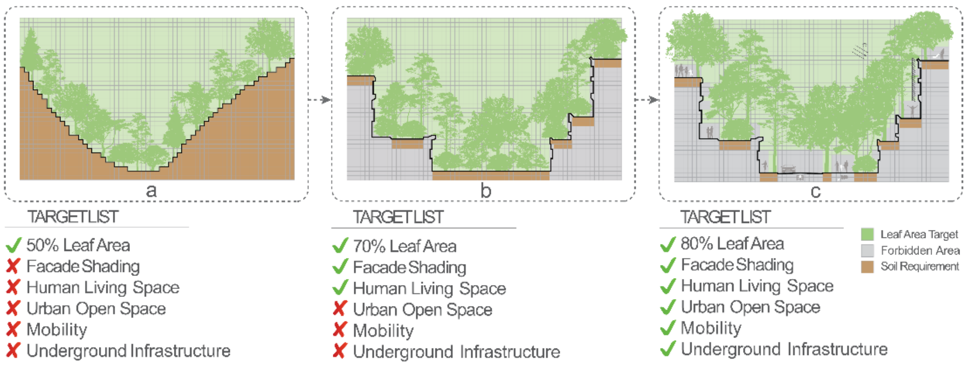

Fig. 1: Conceptual illustration of the target canopy volume approach in cities. To meet this target, trees are planted and manipulated in a specific way to prevent them from growing in the forbidden area.

2 Steps and Research Topics for Completing the Workflow

In the following section, we describe the most important aspects and steps of our approach to illustrate how the digital workflow is supposed to look like. The proposed workflow has three consecutive steps which are structured by the planning and implementation procedure (before planting, planting, and after planting): 1) A tool for setting the target leaf voxel (TLV) to achieve optimal spatial occupation of the tree canopy in a dense urban environment. 2) A tree planting design tool to increase the chance of achieving the TLV. And 3) a tree maintenance and management tool for best approaching the TLV.

2.1 Setting Forbidden and Allowed Space for the Canopy with Target Leaf Voxel (TLV)

For defining volumes for intended tree growth in voxels we will mainly build on CityGML files. The CityGML databases of cities are novel datasets for analyzing and studying urban areas with a data-driven approach. CityGML files provide the materials for voxelizing the non-built above-ground space in urban areas and that are filled as "potential leaf volume". The next step is finding and estimating the quantitative and qualitative limitation factors for growing leaves in cities which are called the forbidden voxels. Some examples of the limiting factors are building openings, street areas, urban objects such as traffic lights or bus stations, urban ventilation requirements, and building entrances. The final voxel model will be the maximum possible potential leaf volume with a consideration of the limiting factors for growing leaves. For a conceptual illustration of this approach (see Figure 2), after filling the model with a 100% TLV, the forbidden area for occupations and different functions are removed to find the maximum possible voxel space for leaves and to determine the necessary growth space for roots accordingly. Like TLV, the necessary root volume can also be determined and represented by voxels. For these root voxels, the limitations, e. g. by foundations or technical infrastructures, are excluded from the potential root space.

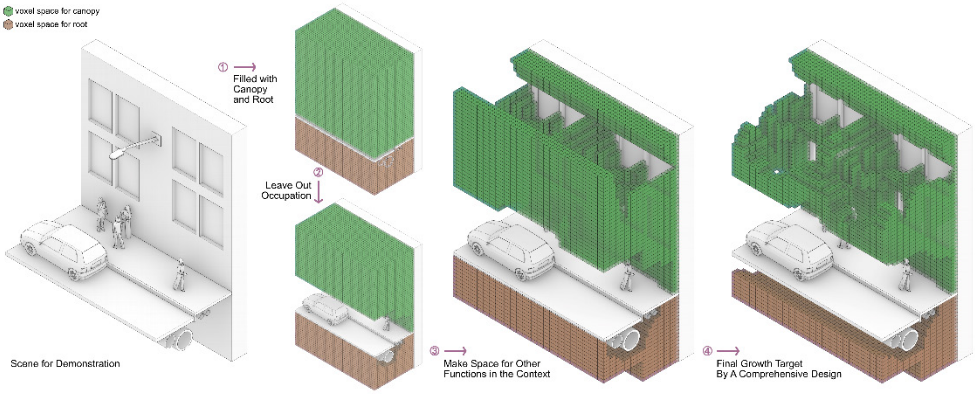

Fig. 2: A conceptual visualization of the intended steps to derive the maximum TLV and corresponding root volume

2.2 Target-driven Tree Planting

The shape and growth rate of tree canopies varies in different locations of cities. For example, the influence of urban microclimate (MOSER-REISCHL et al. 2019), shadow of buildings, and light competition in trees (KOTHARI et al. 2021) are well documented. Different natural and human-made factors affect tree growth in cities. Therefore, it is a semi-natural process that could be digitalized and predicted like other semi-natural processes. A visionary tree planting design workflow requires a reliable prediction of the growth of the tree canopies. Based on these observations, in urban forestry several growth models such as CityTree (RÖTZER et al. 2019, 2021) have been developed to understand the impact of the environmental and surroundings. For such models, the location, where trees are planted plays a crucial role. However, the quantitative impact of such factors on the development of the trees canopy is not precisely evaluated yet. For instance, adjacent buildings change the canopy shape in different directions which is not considered in these tree growth models. A planning strategy without assessing these impacts will fail in ESS target achievement.

Here we propose to use machine learning models to identify specific patterns between the adjacent object and the tree growth rate changes. Geometric features of buildings and trees around can be extracted from the CityGML file together with the accurate geolocation data of the trees. For further analysis, a dataset of the specific tree can be gathered that represents the growth changes in previous years and the adjacent object around it. Data analysis methods show the correlation between the different geometric features of adjacent objects (i. e., direction, distance, dimension, height) and growth rate changes. All in all, a tree canopy growth model can be developed based on abiotic environmental factors.

A tree planting design model can be developed based on this canopy shape growth model. Changing the tree planting position, species, and the number of trees can change the prediction factors for final canopy shape and target achievement. Current practices without concerning the final 3D targets lower the chance of ESS achievement in both underground and subaerial targets (Figure 3). For example, current standardised practices (i. e., linear planted trees in equal distance and age) decrease the ESS target achievement, increase maintenance cost and invade the forbidden areas (i. e., human spaces, mobility spaces, underground infrastructure).

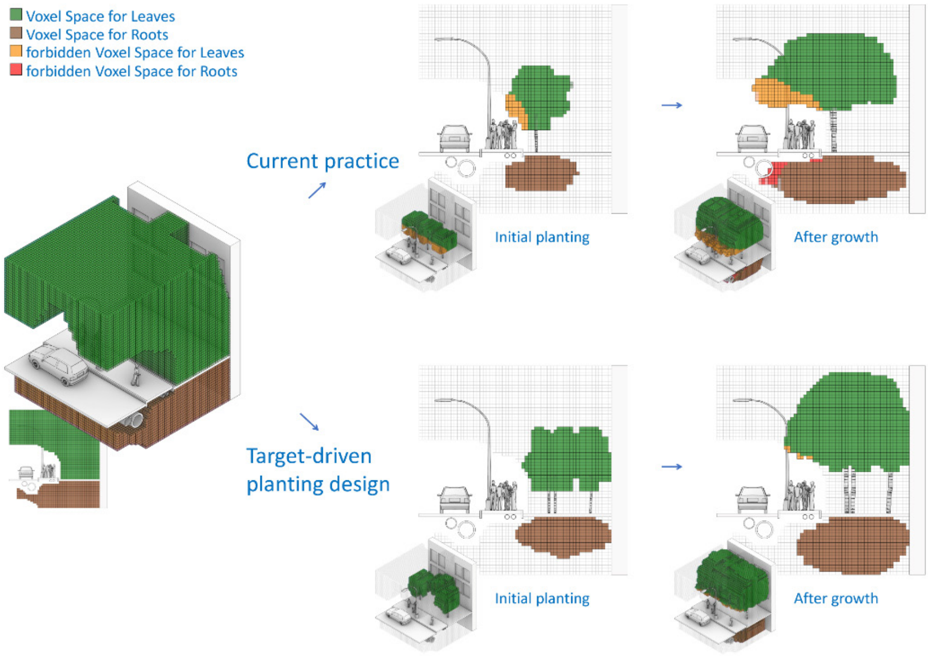

Fig. 3: A conceptual visualization of a 3D voxel target model and the comparison between current practice and a smart target-driven planting design model. An improper planting design can reduce the ESS and increase the cost of maintenance and manipulation in forbidden spaces (yellow and red).

2.3 Detailed Tree Design and Management

From a design and engineering perspective, ESS can be delivered through detailed tree geometry such as the position of branches. For example, branches with dense leaves should avoid being in front of windows to allow light coming through; facades facing the south and west could be isolated with tall branches from the radiation of the late-afternoon sun that heats buildings intensively (ZHAO et al. 2022); opening a canopy at certain points on a street could enhance ventilation for better thermal comfort for pedestrians (SANTIAGO et al. 2019). Achieving these goals requires a tailor-made design for tree branches that sprout at different places to increase ESS.

This design workflow needs to integrate two scales of time: in a short time (1 year), it is necessary to make decisions of how to prune or bend branches to keep them growing in the target voxels; in the long term perspective (10-60 years), it needs to be decided which shoots should be preserved to best support the long term development towards the TLV. The short-term simulation can be achieved through either empirical statistics, functional-structural plant models (FSPMs) (LOUARN & SONG 2020), or machine learning (JORDAN & MITCHELL 2015). The long-term simulation is in parallel to a chain reaction of multiple rounds of short-term growths, which can be evaluated with Markov chain models (i. e., HAJIAGHA et al. 2022). Even with all these simulation tools, the prediction of the tree's behavior in both time scales cannot achieve 100% accuracy. Therefore, an iterative tree monitoring and manipulation procedure is required to annually revise the simulation through the data of actual growth (Figure 4) (SHU et al. 2022). With this approach, the designed TLV for delivering ESS through specific geometry of branches can be best approached.

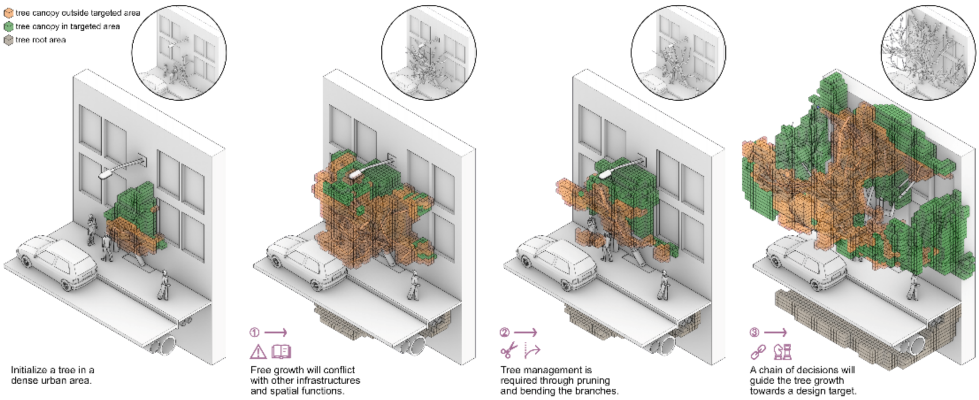

Fig. 4: The proposed workflow for iterative tree monitoring and manipulation. Target-driven tree management through pruning and bending branches will stimulate the canopy to develop towards the set 3D voxel targets.

3 Result and Conclusion

The combination of the steps "setting TLV", "tree planting", and "tree management" descibes a semi-automated tree planning workflow. It is a method for enabling a maximum leaf coverage in cities to increase biomass and ESS without conflicting with grey infrastructures and other functionalities in cities.

The approach is very different from the established way of design thinking, which is thinking in objects. Thinking and designing with voxels is something very abstract, partly even counterintuitive. That could be a hurdle to establishing the approach in landscape architecture and urban planning. In addition, developing the 3D voxel model approach further to consider more qualitative and quantitative factors such as social and visual comfort can be a motivatiton for future research. A 3D voxel model contains quantitative data with geometric features but considering qualitative features such as visual comfort through the 3D voxel is a knowledge gap that still needs to be closed. Therefore, a current limitation is how to translate qualitative factors to a 3D geometry dataset like a voxel model. Moreover, currently, the approach solely builds on a volumetric description of the growth space. Very important factors like soil compaction or events like droughts are not adequately represented. Furthermore, root space influences tree growth and ESS delivery. Fleckenstein et al. (2022) investigated the effect of the different root space conditions on DBH growth, the total number of leaves, and leaf transpiration in some specific species (FLECKENSTEIN et al. 2022). Limited root space restricts root development and tree growth. These problems cause further difficulties of stability and lack of water and nutrients, which could result in xylem embolism and ultimately in tree death (HITCHMOUGH 1994). To include some of these aspects, the approach could be coupled with plant growth simulation tools such as CityTree (RÖTZER et al. 2019, 2021).

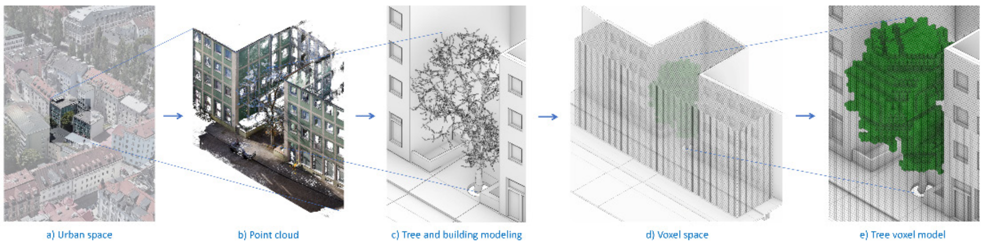

Fig. 5: A proposed approach from an existing urban tree to a voxel model. a) An existing urban tree. b) This point cloud is generated by the photogrammetry method. c) Tree is abstracted into a quantitative structure model (RAUMONEN et al. 2013). d) The virtual voxel space for setting TLV. e) A voxel model representing the current tree canopy.

However, the advantage of our approach compared to other possible approaches is the ability to predict the chance of ESS achievement by designing a target-driven UGI. To provide the best ESS with precise tree geometry, one option is that an urban tree designer directly draws the desired geometry of branches with polylines in 3d modeling software; only branches that grow within a certain distance from these planned polylines are kept, and others will be pruned away every year. But the tree design in this way requires in-depth knowledge about tree growth and manipulation. A bad "design" can easily lead to the failure of branches in realizing the desired geometry. To avoid this, targeted leaf voxel (TLV) is a suitable media to transfer tree design to commands for tree manipulations. By transferring the real condition of the trees to a voxel model and comparing it with the TLV, urban designers can plan to prune and manipulation. For example, they can prune the branches in forbidden voxels or bend other branches to lead them to target voxels. Figure 5 illustrates a proposed approach from an existing urban tree to a voxel model. Furthermore, leaf area density (LAD) (BÉLAND et al. 2014) could be an extra feature in voxels. Urban designers can input the desired LAD for every voxel by coloring them. A darker voxel means desiring a denser canopy in this cubic space. When such a design represented with LAD in voxels is set, it is fed to a decision-making mechanism for approaching a minimum of the deviation between the real LAD in space under potential tree growth and the ideal target LAD. Therefore, the proposed workflow in this research is a target-driven leaf and root voxel design for maximizing the leaf volume and designing a LAD target.

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