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A computer-based tool to link decay information to 3D architecture of urban trees

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Abstract

We present a software application suitable for studies of the decay in trees. The application implements the storage of measurements of stem characteristics (related to decay) and visualization of the three-dimensional (3D) structural model of tree stems and branches built using this material. The application has been constructed on the basis of an existing architectural model of trees. A set of photographs taken from discs cut from felled trees works as the input for the application. The user will define, using the application, the contours of the areas of interest (e.g. healthy wood, decayed wood and cavity) manually in the photographs of stem or branch cross sections. The application then builds a 3D structural model of stem and/or branches on the basis of the input. It is possible to study visually the composition of the stem and/or branches of different types of wood. This helps to evaluate the location of potential hazard and its relation to existing damage in tree stems and branches.

Keywords: Software application; Stem structure; Tree damage; Tree model

Introduction

When trees get older in urban environments they usually are plagued by many stress factors (Sæbø et al., 2003), and very often attacked by decay fungi through injury sites. If the disorder affects the trunk or main branches, it can lead to the premature falling of the whole or part of the tree (Terho and Hallaksela, 2005). In urban areas falling trees can cause significant damage and they thus present a liability issue. On the other hand, urban trees can have high monetary values (Nilsson et al., 2000), and in any case, their replacement is either time consuming (growing a new tree from a seedling) or costly (planting a large tree). In order to minimize the potential damage on one hand and to avoid felling sound trees on the other, risk assessment is crucial in managing urban trees. Decomposition of wood caused by decay fungi is one of the most important factors that decreases the mechanical strength of a tree, and through this increases the risk of a stem collapsing. Yet, the presence of decay does not necessarily mean that the tree is hazardous. Decay fungi differ in their ability to degrade the sapwood (Rayner and Boddy, 1988). Some species are able to cause progressive horizontal decay and colonize the sapwood, and other species cause more stable and predictable heart rot (Terho et al., 2007). To evaluate the risks of stem breakage hazards it is important to know the weakest point of the stem, i.e. the location where the sound wood cylinder is thinnest, and how the weakest point is located in the stem architecture.

In the last decade, many computer models of plant functioning and growth that deal with plant structure at

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a fine spatial resolution have been constructed (Godin and Sinoquet, 2005, New Phytologist, 2005). These models are called functional-structural plant models (FSPMs). They have been designed to make it possible to understand the complex interactions between plant architecture and the physical and biological processes that govern plant growth and development. The FSPMs have been applied to diverse research problems from the development of meristem tissues to forest growth (Godin and Sinoquet, 2005), and to the biomechanics of trees (Fourcaud et al., 2003). As the FSPMs contain detailed information about plant architecture they are well suited for a framework of applications where such information is important. They are suitable for storing information about the measurement of trunk and branch conditions. In addition to storing the measurement information they can be used to analyze various phenomena that depend on the 3D structure of the tree. Such a problem is, for example, analyzing the risk of stem breakage on the basis of crown structure and the properties of the stem and branches of the tree (Sellier and Fourcaud, 2006).

We describe the application (computer software) DECAY that is based on a FSPM (LIGNUM, Perttunen et al., 1996) in this paper. It stores information about conditions (degree of decay, cavities) of stem and branches on the basis of cut discs from felled trees, and allows studying visually the data in a three-dimensional (3D) manner. The application has been constructed in conjunction with a study of urban trees that had to be removed as part of risk assessments by municipal urban tree managers in the Helsinki City Area (Terho and Hallaksela, 2005; Heikura, 2007).

Material and methods

Outline of the system

The computer software DECAY has been constructed for storing and analyzing information from measurements of decayed trees (Fig. 1). In the present application, the information about the properties of the stem and branches is obtained from discs cut from felled (urban) trees. The discs are digitized within DECAY and a 3D model of the stem and/or branches is formed with the aid of them (Fig. 1). DECAY has been programmed with C++. It requires the Qt program library and compiles on several platforms (Linux, MacOS, Unix and Windows). The program can be obtained by request from the authors.

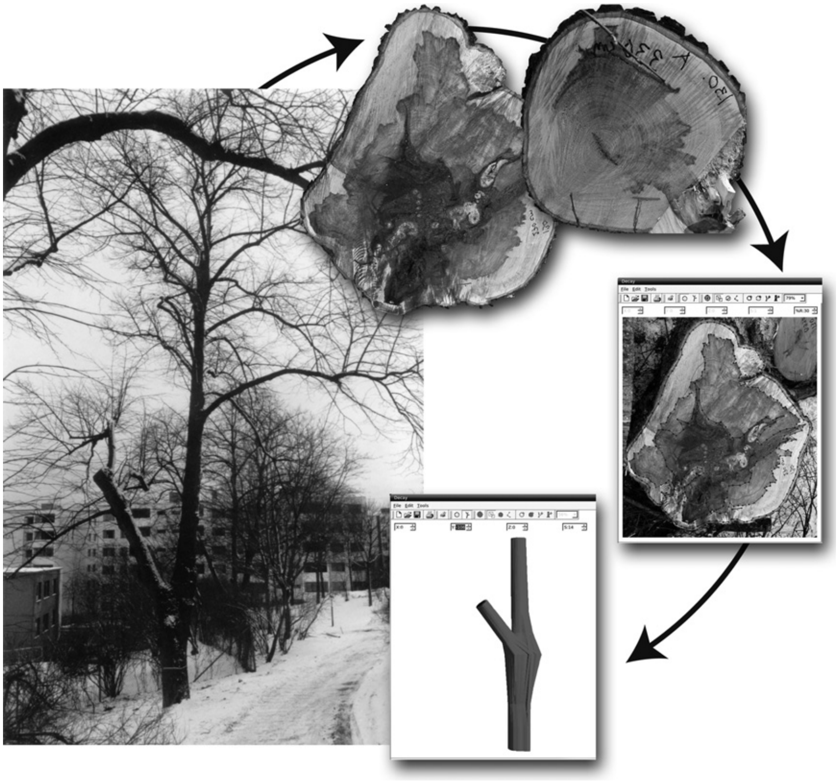


Fig. 1. A summary of the use of the DECAY application: a tree with visible symptoms of decay is felled and discs are cut in the decayed part of the stem and/or branches. The discs are photographed, the photographs are fed in DECAY and the contours of the areas of interest (e.g. healthy wood, decayed wood and cavity) are digitized by hand. DECAY builds a 3D model of the stem and/or branch section from which the discs were taken. DECAY stores the information and allows for visual study of the 3D model.

Tree material

The trees used in the study were felled because they were suspected as being hazardous during 2001–2004 in the central parks and streets of the Helsinki City Area (60°15′N, 25°00′E). Tree care specialists from the Helsinki city administration or private entrepreneurs assigned by the city examined the trees, and the Public Works Department of the City of Helsinki was responsible for the decision-making and felling.

Discs at different heights in the stem and branches were cut from the felled trees. The discs were photographed. These photographs (stored on a computer) were the input for DECAY. Potential hazard characteristics (Terho and Hallaksela, 2005), analysis of fungal species (Terho et al., 2007), and the decay characteristics of the tree woods of the species (Terho and Hallaksela, 2008) used in the present study had been analyzed earlier. The contours of healthy wood, decayed wood and the cavity decay were read from the photographs into DECAY. In the photographs, the orientation of the cross section, cutting height from ground level, the scale and the growth center were marked so that the images could be positioned correctly for creating stem and branch sections in DECAY. External signs of potential decay e.g. wounds, cavities and fungal fruiting bodies, were also marked.

LIGNUM model

The 3D presentation of the stem and/or branches in DECAY was built using the components of the FSPM LIGNUM. It deals with the 3D architecture of tree crowns, both coniferous and deciduous (Perttunen et al., 1996). It was originally designed as a generic growth model for woody arborescent plants. The development of different tree species has been simulated by implementing models for metabolism, dynamics of birth, growth and senescence of the structural units (Perttunen et al., 1998, 2001) and by defining branching rules for species specific tree architectures (Perttunen and Sievänen, 2005).

LIGNUM represents the 3D architecture of trees, both coniferous and deciduous, with simple structural units called tree segment (TS), axis (A), branching point (BP) and bud (B), commonly called tree compartments (Fig. 2). A TS corresponds to a piece of a woody section between two BPs. It consists of cylindrical layers of heartwood, sapwood and foliage. An A is an alternating sequence of TSs, BPs and the terminating B (Fig. 2). A BP is the nexus where one or more axes are attached to each other. Thus the representation of a tree is an assembly of axes. This design captures the topology (i.e. how the structural units are connected) and the self-similar recursive branching structure of trees.

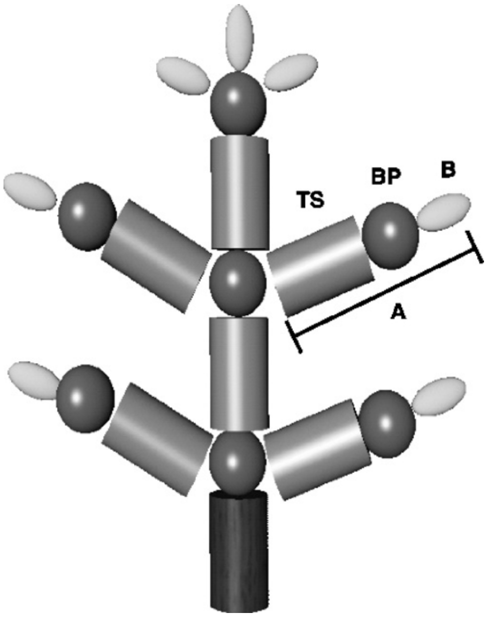


Fig. 2. The structural units of the model LIGNUM: TS = tree segment, BP = branching point, and B = bud. An axis A consists of TSs, BPs and the terminating B.

LIGNUM provides a framework to describe the 3D structure of the tree for DECAY. The design paradigm for implementing LIGNUM in C++ is the generic programming (Stroustrup, 1997). The tree compartments are implemented as C++ classes. The class TreeCompartment captures, for example, geometrical information (position and orientation of the tree part) and the class HwTreeSegment in addition the properties of the cylindrical segment for heartwood trees (size of the model cylinder, proportions of sapwood, heartwood, etc).

DECAY requires the data structures for user-defined contour lines for healthy, decay and cavities from the cross sections taken from the felled trees. This is achieved simply by extending the class hierarchy with DecayTree, a subclass of HwTreeSegment. It contains the implementations for vertex lists that define the contour lines for the three types of regions of interest. In addition DecayTree holds, for example, the digital photograph of the cross section from which the contours of different types of wood (e.g. healthy, decayed and cavity decay) were read.

The topological information (connectness) and the position of each cross sectional photograph of the felled tree are known and the 3D model for the injured tree including the internal damages can be generated after the contour lines for healthy and damaged parts in each photograph have been read in.

Algorithm

The triangle mesh construction algorithm forms segment volumes by connecting two planar outlines (formed from two photographs of adjacent discs cut from the tree) at a time (Fig. 3), starting at the bottom of the tree and working its way up. The planar outlines are broken lines, defined when the contours are digitized (see the section on Construction). The contours of different types of wood (e.g. healthy wood, decayed wood and cavity) are formed separately from each other. The photograph of the disc always defines the upper end of each segment volume in the model. The lowest segment that is generated has identical top and bottom outlines, because the contours of the lowest disc are extended to the ground level.

First, the outlines need to be positioned according to the direction, scale, pith (point in the stem disc representing the first year of growth) and the displacement vectors that have all been defined by the user during the construction phase of the model. The direction denotes the orientation of the cross section according to a fixed direction, e.g. compass north. The stem discs are rotated around the pith so that their directions align with the fixed direction and are stacked so that the piths align vertically. It is possible that there are two visible piths (of stem and branch) on the stem disc if it was cut at a BP, in which case the user has to select a single center point somewhere in the middle of the stem disc on which the visualization should be based on. The displacement vector allows the user to define a deflection from the vertical pith alignment and this definition will result in a bend in the visualized stem. A line segment in the digital images defines the scale of the disc. The outlines are then scaled with using the length of the line segment. The default length of the scale marker in DECAY is 5 cm, but it is possible to adjust this length if a different measurement has been used in the images.

After the stem discs have been aligned, outlines of different types of wood are processed separately. The center of mass is calculated for the outline, and a polar angle is evaluated to denote the advancement along the contour around it. The list of vertices is defined sequentially in clockwise order and the construction is started from the first defined point of the bottom segment. The first point on the top outline is selected to match the starting point of the bottom outline: this is the one that has the shortest distance to the starting point. A line segment between these points is drawn. After this initial situation, there will be only two choices for line segments that connect the top and bottom outlines, since one of the outlines defines exactly one line segment of the triangle to be added to the mesh during this step (Fig. 3). The line segment that was selected during the previous step of the algorithm defines the third line segment of the triangle. The point with the comparatively smaller polar angle towards the advancement is chosen, and the formed polygon is then added to the mesh (Fig. 3). This step is repeated until a stable circular mesh around the TS is created taking into consideration that the polar angles may wrap around (i.e. are larger than 360°) during the process. The next segments are handled independently in the same way until all the outlines have been connected. This method works because the outlines are closed circuits and are defined in the same clockwise order in the sequence.

The algorithm can handle difficult non-convex cases and multiple outlines for each section, although it has been designed to work best with somewhat round tree stems and structures that can be expected in natural trees.

Branches are handled by connecting all the planar outlines to all the matching outlines between the two slices. However, the planar cross sections along the branches are not parallel to the main stem because of the way the trees are cut. The cross sections within each branch or stem can be assumed to be parallel. A main stem outline is connected to the branches at the BP in the same way as described above taking into consideration the angle difference between the planes. The branching angle must be less than 90°, but can also be defined as being zero.

The DECAY application

There are two operating modes in the application—the construction (Fig. 4a) and the visualization mode (Fig. 4b). In the construction mode a set of digital images of cross sections of felled trees is fed in and the contours encompassing the areas of interest are digitized

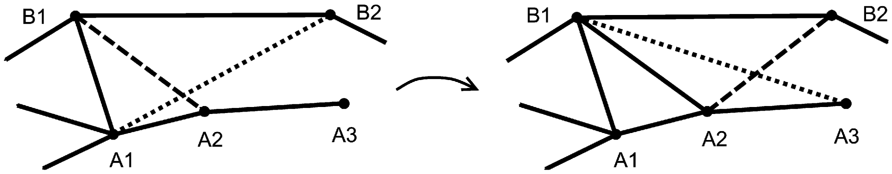
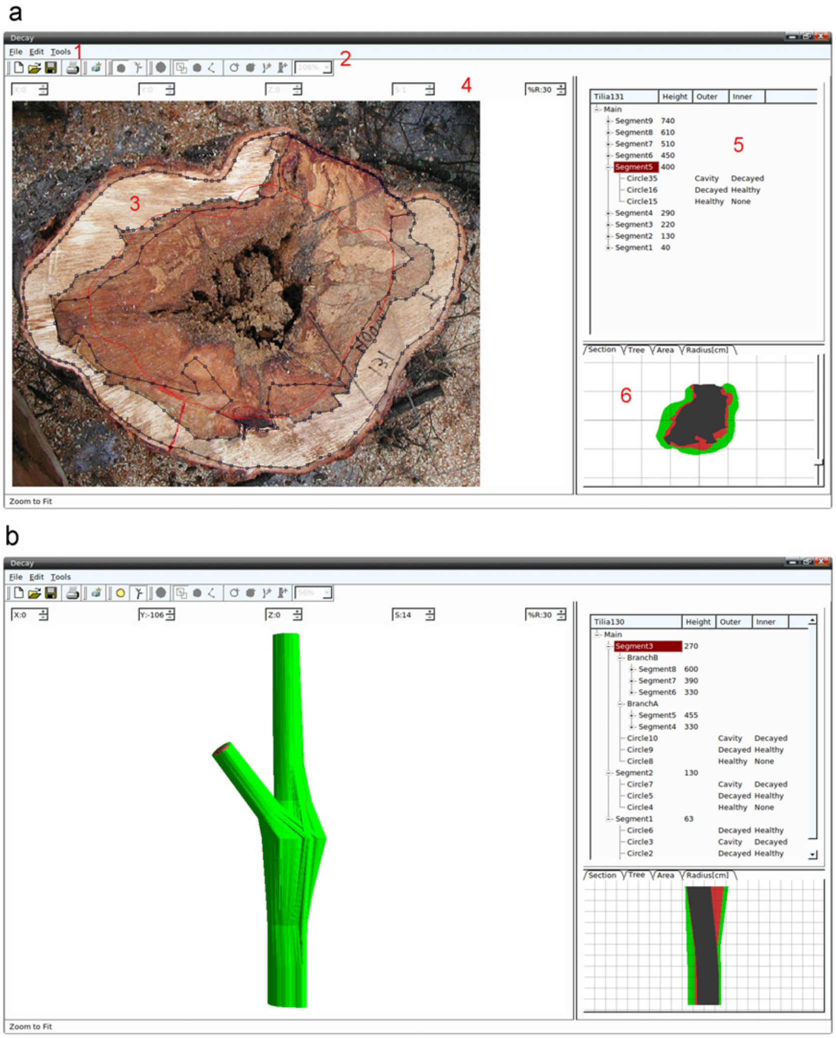


Fig. 3. Two steps of the triangle mesh construction algorithm that connects two planar outlines (upper outline: points B and lower outline: points A). The last connected line segment is A1-B1. The decision has to be made between line segments A2-B1 and A1-B2, but the former is chosen because the polar angle of point A2 is smaller. On the right, A2-B1 has been chosen and the next decision is to be made between A2-B2 and A3-B1. A2-B2 is chosen and the algorithm continues around the outlines until A1-B1 is reached and all the vertices have been connected.



Tilia131	Height	Outer	Inner
Main			
Segment9	740		
Segment8	610		
Segment7	510		
Segment6	450		
Segment5	400		
Circle35		Cavity	Decayed
Circle16		Decayed	Healthy
Circle15		Healthy	None
Segment4	290		
Segment3	220		
Segment2	130		
Segment1	40		

Tilia130	Height	Outer	Inner
Main			
Segment3	270		
BranchB			
Segment8	600		
Segment7	390		
Segment6	330		
BranchA			
Segment5	455		
Segment4	330		
Circle10		Cavity	Decayed
Circle9		Decayed	Healthy
Circle8		Healthy	None
Segment2	130		
Circle7		Cavity	Decayed
Circle5		Decayed	Healthy
Circle4		Healthy	None
Segment1	63		
Circle6		Decayed	Healthy
Circle3		Cavity	Decayed
Circle2		Decayed	Healthy

Fig. 4. (a) The user interface in construction mode. (1) Menu, (2) toolbar, (3) edit area with the red outline denoting the hazard area drawn, (4) visualization controls and the percentage setting for the red outline, (5) hierarchical structure of the tree, (6) color-coded cross section transformed as defined by the scale, growth center and direction settings. The color codes for healthy wood, decayed wood and cavity are green, red and black, respectively. (b) The user interface in visualization mode. The cross section of the main stem through the growth center of the tree is also visible at the lower right hand corner of the window.

on the photographs. In the visualization mode, the DECAY application produces a structural model of the analyzed tree (Fig. 5) and an XML-structured data file storing the information for later studies and archiving.

Construction

In the construction mode, the user adds images of the cross sections and manually defines on each of the cross sections a sequential chain of positions (broken line) on the image to form the outlines of the areas of interest e.g. healthy wood, decayed wood and cavity. The different categories of classified areas of wood are color-coded in different colors (green, red and black). The surface areas of different categories can be studied under the tabbed element at the lower right corner (Fig. 4a).

Several formulas for critical size of a defect area have been developed to analyze the strength loss of trees caused by decay (Mattheck et al., 1992; Matheny and Clark, 1994; Kane et al., 2001). To make use of them, a curve is drawn in red on top of the cross section image (Fig. 4a) in the construction mode. The curve is a scaled down (in the radial direction) copy of the outline stem surface by a given percentage. It can be used as an indication of the critical size of a defect area for analyzing the chance of failure. The default setting for the scale down percentage in DECAY is 30.

Visualization

In the visualization mode, the tree is visualized as three separate polygon meshes of different types of wood, e.g. healthy wood, decayed area and cavity

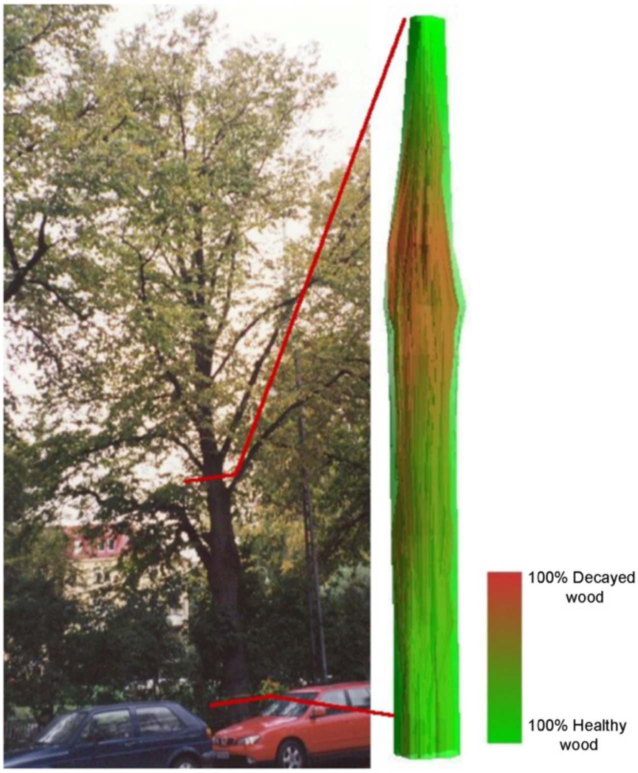


Fig. 5. A *Tilia* tree before felling and taking of the cross section photographs is pictured on the left and the finished visualized model of the tree on the right. The green healthy wood polygon mesh is translucent depending on the proportional surface area of damaged wood on the corresponding cross section pointing out the most damaged part of the tree. The modeled part of the tree is marked on the image.

(Fig. 4b). The meshes for different types of wood are color-coded (green, red and black in Fig. 4), and each of them can be enabled for display separately in the visualization mode. The same colors are used to denote the same areas throughout the application. The user may rotate and scale the visualized model and switch between the visualization and construction modes at any point and continue working on the construction of the model at a later time. The damaged external sections are visualized in the form of spheres in the 3D model.

The color-coded areas of the tree are also visible in the tabbed user interface element (Fig. 4a and b). With the aid of tabs, it is possible to choose planar cross sections, tree cross section along the stem and two pages of evaluated data—the surface areas and the proportional radii for each of the color-coded areas. The hierarchical structure of the constructed model is displayed as a nested list on the side of the application window. The hierarchy and the tabbed element are visible in both the construction and visualization modes.

Fig. 5 shows an example of a tree that has been modeled with the application. The outer green shell of the tree is variably translucent depending on the amount of damaged wood in each cross section. In case there is no decay or cavity within the cross section, the healthy green color has full opacity and reaches full translucency linearly based on the combined area of decayed wood and the cavity. This method makes the most damaged point along the stem in the cross sectional surface area clearly visible.

Concluding remarks

The DECAY application is a helpful tool in the management of research material and in the analysis and evaluation of the propagation and shape of tree decay within the visualized models. The calculated surface areas of decayed wood and its proportional estimates in relation to the outer stem for each cross section give the researcher valuable data on tree hazard characteristics. The adjustable red outline can be used to visualize hazard areas based on the amount of decayed wood in the cross sections.

The most important benefit of the DECAY application is that it provides a possibility to store comprehensive 3D information of tree architecture together with injury and decay profiles of felled trees. A lot of valuable information, which is experimentally very hard to obtain, is lost if old hazardous trees are felled without storing data about them. Databases, consisting for example of 3D information on trees decayed by important species of decay fungi, would help tree care professionals to assess the possible risk of new cases with similar kind of symptoms in the future. In addition, the DECAY application provides a tool to examine both tree architecture and external signs of decay in relation to the point(s) where stem breakage due to decay is most likely. By this way the application could also be a useful tool for educating future tree care professionals. Finally, the application might also serve a new way to study the critical size of the decay column and to determine the degree of hazard in risk assessment of decayed trees (Kane et al., 2001).

In general, the more cross-section samples are provided the better is the final 3D structural model. At a minimum four to five cross-section samples are needed to be able to describe the decay behind each injury in focus. External dimensions of the injury determine three of these as follows: from the lower and upper edge of injury together with a sample from the point of widest extent of horizontal decay. The dimension of decay column then determines the locations of the rest of the samples. Depending whether the injury in focus is situated in the butt or in the middle of the stem, one to two samples are needed for this. For accurate assessment of vertically large injuries e.g. cracks or inspection of true dimensions of hollowed heartwood additional samples are needed.

The current application is based on analyzing discs that have been cut from felled trees. Felling of trees in built-up environments is often complicated and expensive with a need of special skills and equipment as old urban trees are often very large. Getting cross-section samples for the application is time consuming and expensive in this way. The risk assessment of living urban trees can benefit only indirectly from such data, as it is possible to evaluate them only after removing the tree. The DECAY application would be well suited for analyzing measurements of decay from living trees, as then it would be possible to assess the risk of breakage with the aid of computational methods. Devices based on acoustic tomograms can produce maps of decay in cross sections of stems and branches. For example, Picus tomograph (www.argus-electronic.de, accessed 18.6.2008) is able to do 3D imaging of internal cavities directly for analysis. From the point view of DECAY, it would be beneficial if such information could be imported and be used in the place of photographs of discs. In this way the DECAY application could also be used to study decay in living trees, and maybe in the future also visualize the decay process by combining measurements made in different years. If a suitable model of the spread of decay in the stem was combined with the growth model of the tree implemented in LIGNUM (Perttunen et al., 2001), it is conceivable that scenarios for future risk of breakage could be made on the basis of non-destructive measurements of decay.

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