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Methods and workflows for design and engineering in living architecture: learning from living root bridges

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To all at Hollin Bank Farm

Abstract

This thesis describes three investigations into living architecture design and engineering. Living architecture refers to building with trees, both with and without technical elements. A central aspect of this design is an approach that engages with growth and changes over the lifespan of the building – the methods and workflows presented here are founded on this approach. The nascent field draws heavily from vernacular and artisanal knowledge, as well as academic research and practitioners' experience of plant growth and mechanics. The most established living architecture is the vernacular tradition of living root bridges grown by Khasi and Jaintia communities in Meghalaya, India. A preliminary study of the Meghalaya's living architecture, published in 2019, describes a range of key features: the climatic, ecological and geographic conditions in which the bridges grow; the systems of shared maintenance within bridge-building communities; and the structural roles of the aerial roots, inosculations between them, and the networks they form. The first chapter covers the background of living root bridges and *Ficus elastica*, as well as the current state of living architecture, and the development of the three core studies of this thesis.

The first study, presented in Chapter 2, addresses regenerative design in living architecture. Regenerative design relies on whole systems thinking to understand of a project's wide ranging impacts. The core of this is the potential for a project to renew and rejuvenate or degenerate its environment. This concept reflects the embedment of living root architecture in ecological, environmental and societal systems. Here, the LENSES Rubrics, originally developed for regenerative design of prospective projects, are adapted for analysis of existing projects. The Rubrics analysis is applied to 27 focal points in nine groups. Our results show a mix of regenerative, sustainable and ambiguous focal points. By examining a wide range of potentially conflicting impacts, the LENSES Rubrics method used here allows the improvement of degenerative aspects or the transfer of regenerative aspects to new projects.

The second study, presented in Chapter 3 concerns the documentation and representation of living architecture. Geometric irregularity and topological complexity make living architecture difficult to document. Its significant changes with annual growth call for cyclical characterisation for mechanical, structural and physiological analyses, and design. The presented workflow uses photogrammetry to produce detailed point clouds of living architecture at a low cost, suitable for Khasi and Jaintia communities as well as students and architects of designed living architecture. Based on the point clouds, a skeletonisation method using voxel-thinning was developed. The voxel-thinning process informs a volume reconstruction method. The method is compared with alternative skeletonisation methods on seven characteristics beneficial in representing living architecture.

In the third study (Chapter 4) a method of modelling the mechanics of cross-wise inosculations is developed. These inosculations are found in a wide range of living architecture, and are key to several Baubotanik-designed structures. Mass addition (growth in thickness) and fibre orientation are two means of mechanical adaptation in trees. Using finite element analysis, this chapter examines three levels of detail in modelling mass addition and five model constructions based on varied fibre orientations. Four inosculations in living *Salix alba* tree pairs were used for bending tests – the finite element models were compared on their relative accuracy in representing the experimental results. The results show that moderate geometric detail is beneficial, while higher geometric detail is not, and integration of a tension-zone similar to that found in natural tree forks improves model accuracy significantly.

In the final chapter, the methods and workflows are applied to a new living structure built in 2021-22, followed by an outlook on an upcoming living root pavilion and future living architecture.

Zusammenfassung

In dieser Arbeit werden drei Untersuchungen zur Gestaltung lebender Architektur und Ingenieurwesen vorgestellt. Lebende Architektur bezieht sich auf das Bauen mit Bäumen, sowohl mit als auch ohne technische Elemente. Ein zentraler Aspekt dieses Entwurfs ist eine genauere Betrachtung des Wachstums und der Veränderungen über die Lebensspanne des Gebäudes – die hier vorgestellten Methoden und Workflows beruhen auf dieser Perspektive. Dieses im Entstehen begriffene Feld stützt sich auf volkstümliches und handwerkliches Wissen sowie auf akademische Forschung das Fachwissen von Experten in Pflanzenwachstum und -mechanik. Die bekannteste lebende Architektur ist die volkstümliche Tradition der lebenden Wurzelbrücken, die von den Khasi- und Jaintia-Gemeinschaften in Meghalaya, Indien, gebaut werden. Eine vorläufige Studie über die lebende Architektur von Meghalaya von 2019 beschreibt eine Reihe ihrer Schlüsselmerkmale: die klimatischen, ökologischen und geografischen Bedingungen, unter denen die Brücken wachsen; die Aufgabenverteilung zu ihrer Instandhaltung innerhalb der Brückenbaugemeinschaften; und die strukturellen Rollen der Luftwurzeln, ihrer Verflechtungen und die Netzwerke, die sie bilden. Das erste Kapitel befasst sich mit diesem Kontext lebender Wurzelbrücken und Ficus elastica sowie mit dem aktuellen Stand der lebenden Architektur und der Entwicklung der drei Hauptstudien dieser Arbeit.

Die erste Studie, die in Kapitel 2 vorgestellt wird, befasst sich mit dem regenerativen Design in der lebenden Architektur. Regeneratives Design stützt sich auf das Denken in ganzen Systemen, um die weitreichenden Auswirkungen eines Projekts zu verstehen. Im Mittelpunkt steht dabei das Potenzial eines Projekts, seine Umgebung zu erneuern und zu verjüngen oder zu degenerieren. Dieses Konzept betrachtet die Einbettung der lebenden Wurzelarchitektur in ökologische und gesellschaftliche Systeme. Die LENSES-Rubriken, die ursprünglich für die regenerative Gestaltung zukünftiger Projekte entwickelt wurden, werden für die Analyse bestehender Projekte angepasst. Die Rubrikenanalyse wird auf 27 Schwerpunkte in neun Gruppen angewandt. Unsere Ergebnisse zeigen eine Mischung aus regenerativen, nachhaltigen und mehrdeutigen Schwerpunkten. Die hier verwendete LENSES-Rubriken-Methode ermöglicht die Verbesserung degenerativer Aspekte durch die Untersuchung eines breiten Spektrums teilweise widersprüchlicher Auswirkungen oder die Übertragung regenerativer Aspekte auf neue Projekte.

Die zweite Studie, die in Kapitel 3 vorgestellt wird, behandelt die Dokumentation und Darstellung von lebender Architektur. Geometrische Unregelmäßigkeiten und topologische Komplexität erschweren die Dokumentation lebender Architektur. Ihre signifikanten Veränderungen mit dem jährlichen Wachstum erfordern eine zyklische Charakterisierung für mechanische, strukturelle und physiologische Analysen sowie für das Design. Der hier vorgestellte Workflow nutzt die Photogrammetrie, um mit geringem Aufwand detaillierte Punktwolken der lebenden Architektur zu erstellen, die sowohl für die Khasi- und Jaintia-Gemeinschaften als auch für Studenten und Architekten von entworfener lebender Architektur nutzbar gemacht werden können. Auf der Grundlage der Punktwolken wurde eine Skelettierungsmethode mit Voxel-Thinning entwickelt. Das Voxel-Thinning-Verfahren bildet die Grundlage für eine Volumenrekonstruktionsmethode. Die Methode wird mit alternativen Skelettierungsmethoden hinsichtlich sieben Eigenschaften verglichen, die für die Darstellung von Wohnarchitektur von Vorteil sind.

In der dritten Studie (Kapitel 4) wird eine Methode zur Modellierung der Mechanik von quer verlaufenden Inoskulationen entwickelt. Diese Inoskulationen sind oft in lebender Architektur zu finden und sind ein Schlüsselelement mehrerer von Baubotanik entworfenen Strukturen. Hinzufügen von Masse (Zuwachs im Durchmesser) und Faserorientierung sind zwei Mittel zur mechanischen Anpassung von Bäumen. Mithilfe der Finite-Elemente-Analyse werden in diesem Kapitel drei Detailebenen der Modellierung der Massenzugabe und verschieden Modellkonstruktionen auf Grundlage unterschiedlicher Faserausrichtungen untersucht. An vier lebenden Baumpaaren der Art *Salix alba*

wurden Biegeversuche durchgeführt. Die Finite-Elemente-Modelle wurden hinsichtlich ihrer relativen Akkuratheit in der Vorhersage der Versuchsergebnisse verglichen. Die Ergebnisse zeigen, dass eine mäßige geometrische Detaillierung vorteilhaft ist, eine höhere geometrische Detaillierung hingegen nicht. Außerdem erhöhen Modelle, die Spannungszonen integrieren, die denen in natürlichen Baumgabeln ähneln, die Modellgenauigkeit erheblich.

Im letzten Kapitel werden die Methoden und Workflows auf eine neue lebende Struktur angewandt, die 2021-22 gebaut wird, gefolgt von einem Ausblick auf einen kommenden lebenden Wurzelpavillon und zukünftige lebende Architektur

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Contents

List of Abbreviations and Symbols

CLEAR – Centre for Living Environments and Regeneration

CMB – centres of maximum balls

CRP – close-range photogrammetry

DBH – diameter at breast height

DSR – degenerative, sustainable and regenerative

DSLR – digital single lense reflex

E_i – Young's (elastic) modulus in the *i* direction

ELC – ecological land-use complementation

FEA – finite element analysis

G_{ij} – shear modulus in the plane of two orthotropic directions *i* and *j*

(H)BIM – (historical) building information modelling

(k)N – (kilo)newton

(k, M, G)b – (kilo, mega, giga)byte

L, R, T – orthotropic directions of wood properties: longitudinal, radial, tangential

LBC – Living Building Challenge

LENSES – living environments in natural, social and economic systems

LiDAR – laser imaging, detection and ranging

LRB – living root bridge

MST – minimum spanning tree

MP - megapixel

(M,G)Pa – (mega, giga)pascal

NEHU – North Eastern Hill University

OTS – off-the-shelf

PC – point cloud

PCL – point cloud library

TLS – terrestrial laser scanners

TUM – Technical University of Munich

υ_{ij} – Poisson's ratio of deformation in *j* direction due to loading in *i* direction

Chapter 1
Introduction

1.1 Design with living trees

Trees play many roles in the built environment. They enrich depleted urban ecosystems through interactions with soil, water, air and other species[1]; mitigate the extremes of urban heat, flooding, pollution and wind canyon effects[2-5]; and provide health benefits[6] through pollutant deposition, shading, and improved mental health, as well as cultural value[7, 8]. The diverse benefits of trees in the built environment are evidenced by both legislation and public discourse around the world[9, 10]. Ecosystem and societal benefits take time to develop[10, 11], in contrast to the uses of buildings designed with a fixed operational lifetime. Growing organically, a tree's form needs precise and regular documentation, unlike typical static structures defined by simple minimal edges and corners. The heterogeneity and localised adaptations of grown materials need to be characterised and analysed, anathema to the homogeneity of concrete and steel. Methods for design of organic growth must be precise while incorporating uncertainty, change, and long-term planning.

Living architecture is the design and construction of buildings, open spaces and infrastructure by manipulating living trees. Living architecture design is an ongoing process – as trees grow they require continual reassessment and redesign. This thesis develops methods for designing living architecture, inspired by Meghalaya's living root bridges. In developing these methods, four lights have guided my work: the findings of researchers that have come before; the computing revolution that allows ever more detailed design; the systems theories developed in fields such as permaculture and recently adopted in other industries and by academia; and existing living architecture, in particular Meghalaya's living root bridges (LRBs).

I draw on methods from diverse academic fields. The foundation laid by Ludwig (2012)[12] is the basis for several aspects of my work. Regenerative design draws on research in permaculture[12], system structuring[13] and sustainability[14]. Documentation and representation of living architecture is informed by historical surveying[15], applied graph theory[16] and computer vision[17]. Inosculation (graft) mechanics draws from previous work in forestry science[18], finite element analysis[19] and tree junction biomechanics[20]. Many fields have been fundamentally changed by advances in computing power. Cameras and LiDAR have dramatically improved and reduced in price[21], impacting building surveys[22], tree surveys[23] and studies of localised mechanics[24]. Increased computing power has led to more complex analytical tools that can utilise a broad range of data types[25, 26] and are fast enough to integrate into creative design[27]. This has led to projects that utilise grown wood joints[28, 29]. These projects provide useful examples in how to combine computing methods for precise design with complex grown elements. Systems theory is concerned with the interactions of a project's constituent parts. Trees grow in response to environmental factors, and living architecture must reflect this through cyclical design, analysis and growth. After trees are planted, their grown realities must be documented and their mechanics analysed, before manipulation of growth, which must reflect a tree's possible growth reactions to its environment. This draws on ecosystems models to understand and describe environmental effects[30]; causal loop diagrams to quantify uncertainty[31]; and permaculture to define functional yields from organic systems[32]. The examples of living architecture that influence this thesis are detailed below.

1.2 Living architecture

Living wood has considerable structural properties. Per unit weight, green (living) wood has higher flexural stiffness than both steel and concrete (2.4-5.1x steel, (2.0-4.3x concrete) and higher flexural strength than steel (1.6-3.4x in tension, 0.95-1.43x in compression) and concrete (2.7-5.7x in compression, 8.7-13.1x in tension)[33-35]. On the back of this, many individuals and communities around the world have worked with living trees, resulting in a great diversity of methods, functional structures, and societal niches. In order to understand the development of workflows and methods in living architecture we must understand the contexts in which they are grown. Living architecture can be divided into three broad categories: artisanal, vernacular and designed architecture.

Artisans are skilled individuals who develop highly specific handcraft techniques through their practice. Several artisans have been essential in the development of shaping and grafting trees. Axel Erlandson's Tree Circus in California[36] (Figure 1.1a) broadens the horizons of what can be achieved. In their grown furniture, FullGrown in the UK[37] (Figure 1.1b) carefully form inosculations to make the tree's water transport pathways symmetrical so that growth is not imbalanced within the structure. The Casas Vivas de Arboles[38] in Argentina use willow techniques common in domes and arches around the world[39-42] in extravagant structures. Many other artisan horticulturalists and sculptors show what can be done in different settings with different species[43-46]. Some artisanal projects aim to grow solutions to particular challenges, such as Konstantin Kirsch's grown walls[47]. Others aim to inspire with explicit visions of future relationships to living structures, such as Luc Schuiten's Arte Sella[48] and Guiliano Mauri's Cattedrale Vegetale[49] (Figure 1.1c) or (historically) Arthur Wiechula[50]. In general artisans, who often have highly personal and unique goals, approach the trade-off in growth between mechanics, physiology and ulterior function (e.g. environmental or aesthetic) in a very specific way. While some artisans are clearly inspired by or learn from one another, their work is generally isolated and often a single structure; ambitious and pursued out of a wish to learn by doing; and highly locally specific.

Figure 1.1. Artisanal living architecture: (a) Axel Erlandson under one of his trees (photo: unknown/Mark Primack), (b) a chair grown by FullGrown, (c) Arte Sella by Luc Schuiten (photo: Katia Bernardi & Luca Bergamaschi).

Vernacular architecture is typically defined as building without modern professional guidance, outside of academic traditions, and as a local cultural expression. An essential element of vernacular living architecture is the role of a large grower-user community. Examples includes LRBs in Meghalaya, laid hedges in north-western Europe[51], the Vite maritata in Italy[52] and the Hausschutzhecken[53] and Tanzlinden[54] in Germany (Figure 1.2a). These structures, while functional, have taken on a monumental significance as their growth has entwined with local cultural history. Some examples have vernacular and artisanal elements: Laborheyre town square in France (Figure 1.2b) and the Jembatan Akar[55] in Sumatra are single isolated structures but grown and used by a large community. There are many examples of vernacular living architecture that are not well documented but may be interesting to academics or designers. Historic living root bridges in Banten (Indonesia)[56] (Figure 1.2c) and the Tongliang Temple in Taiwan[57] utilise ficus aerial roots while exhibiting clear architectural differences from which designers can learn techniques in *F. elastica*.

Figure 1.2. Vernacular living architecture: (a) Peesten Tanzlinde (photo: Anonymous/Wikimedia), (b) Labouheyre town square (photo: Peggy Lampotang/Blogspot), (c) Baduy living root bridge in Banten, Indonesia (photo: Muhammad Juik Furqan/Wikimedia).

Hallmarks of designed architecture are an active engagement in wider design traditions; methodically tackling problems faced in many settings; and the novel application of contemporary techniques. To do this, designed living architecture draws on the wealth of artisanal and vernacular examples that have come before as well as academic research in relevant fields (such as the botany, ecology and engineering literature referenced throughout this thesis). Some projects draw clearly on pre-existing themes in landscape architecture, such as the 1911 Laubengänge at Wacholderpark in Hamburg[58] in the vein of vine-covered walkways and the 1996 Village de Gites les Tropes[59], taking on the shaped regular forms of the French garden style. These examples highlight the contrast between natural growth and precise design of perfectly arcing and cubic forms. The field has expanded to engage with changing tree shapes and branching patterns, and integrating growth processes into design. Projects, realised and otherwise, from groups in Stuttgart[60], Delft[61], New York[62] and the UK[63] show the diversity of ideas that springs from this. Several buildings have been designed and built in Germany using methods of Baubotanik (design with both living plants and technical elements). In particular this design research has been conducted by the Baubotanik research group, centred around the Professorship for Green Technologies in Landscape Architecture at Technical University of Munich (TUM), where I worked on this thesis. The Plane Tree Cube, Freiburg Pavilion and Baubotanik Tower (all shown in Figure 1.3) utilise cross-wise inosculations and intergrowth between grown and technical elements. The Baubotanik Tower has a footprint of 11.2m^2 and three pedestrian floors which were originally planted in 2009 with hundreds of *Salix alba* trees, then replanted with *Betula pubescens*. 11 trees, 2.5m high, were planted at the base in 2017, and 16 trees on each of the higher floors replanted in 2019. The Nagold Plane Tree Cube was planted in 2012 from several hundred, young, 2.5m high *Platanus* x *hispanica* trees. It has three floors of pedestrian walkways with trees planted on the ground and all floors but the first. It is around 10m high, 10m wide and 10m deep. The Freiburg Pavilion is described in detail in section 3.2.1. Different designed buildings draw on themes developed by artists and artisans. Schuiten's future visions[64] can be seen in the Terreform Fab Tree Hab[65] designs. The line is not always clear between designed, vernacular and artisanal projects. In the UK and Ireland, hedge-laying has moved between vernacular, artisanal and designed practice. The tradition continues today with the help of government subsidies[66] that recognise its social[67] and environmental[68] functions. This has brought some design regulations (such as hedge planting distances and hedge-laying times) to otherwise artisanal work.

Figure 1.3. Three Baubotanik structures utilising cross-wise inosculations: (a) the Plane Tree Cube in Nagold (photo: James Barnes), (b) the Baubotanik Tower at Werkpark Neue Kunst am Ried (photo: Ferdinand Ludwig), (c) and the Freiburg Pavilion in Freiburg Botanical Garden (photo: Thomas Speck).

Comparing these three themes, it is clear there are different ways of developing methods for design of living architecture. Artisans, working within the lifespan of one person, pay close attention to their highly specific trees, environment and desired function. They often make explicit tests, though usually without academic rigour. Vernacular architecture can be developed over hundreds of years and often serves an essential function (e.g. crossing a river, delineating pastures). The development of solutions is a cultural evolution in the face of necessity – similar problems are overcome by different methods. We can compare hedges with stone walls and dykes around Europe[51]; or living root bridges in Meghalaya and Indonesia[69] with traditional Inca grass bridges[70] and Japanese vine bridges[71] that also weave the biological resources at hand to cross rivers. Building a lasting solution requires a deep understanding of the plants used, whether it is the growth patterns of *S. alba* or *F. elastica*, the survival of hedge plants when cut, or the material strength of the bridge-building grass[72]. This knowledge is built up over time, whether by artisans, vernacular communities or the professional/academic community. The 21st century has seen a surge in design inspired by inventive and resourceful vernacular architecture[73]. Given the diversity of vernacular living architecture, this inspiration is an essential part of developing methods and workflows in living architecture design. This thesis looks foremost to Meghalaya's living root bridges for inspiration.

1.3 Living root bridges

The most established living architecture in the world is living root bridges and other structures grown from *F. elastica* aerial roots. Predominantly grown by rural Khasi and Jaintia communities in Meghalaya, India, there are also LRBs grown from strangler fig species (including *F. elastica*) in Nagaland in India, Sumatra and Java in Indonesia, and one example in Foshan, China. At least 75 bridges, ladders, walkways and platforms form an essential part of the rural transport network of Meghalaya, providing access to farmland, homes, markets, and the wider road network of the state[74]. The living root bridges are inspirational when considering the structural, social, environmental and botanical aspects of living architecture. This research began with an expedition in 2017 to many villages and bridges around the East Khasi Hills and West Jaintia Hills in Meghalaya. The resulting paper, which I co-authored, is the result of that research (as well as two earlier expeditions by Patrick Rogers in 2015-16), and is the springboard for this thesis[74].

In this section, the fundamental features of LRBs and *F. elastica* are described, drawing mostly from the 2019 article and covering geography, histories and maintenance, and the basic structures and their constituent roots. This is followed by a summary of the key aspects of *F. elastica* and their relation to LRBs. Then, section 1.4 presents details of the questions pursued in this thesis that arose from our findings in Ludwig et al (2019)[74]. The list of bridges documented in that study (and mapped in Figure 1.7) is given in Appendix A.

Considering the geography of Meghalaya, Ludwig et al (2019)[74] state that "the region is dominated by steep valleys leading from the Shillong Plateau to the Bangladesh floodplain." In the monsoon, between May and September, the rivers of these valleys become torrential. Charrapunji in the East Khasi Hills regularly records the highest rainfall in the world, including 2493mm of rain in 48 hours[75]. "68 of the 71 geo-located bridges are located in the rainforest valleys", mostly between 250m and 900m above mean sea level[74]. Most of the bridges are either clustered around villages or isolated in valleys. Interviews conducted with bridge-builders and members of bridge-building communities (presented in Appendix B and described in Ludwig et al (2019)[74]) shed light on the uses of bridges, their ages, and their maintenance regimes. As stated in that study, "All bridges documented here were grown as part of a river crossing path between villages or from a village to cropland or to markets." Many bridges now serve another purpose as tourism sites, providing income to villages and individuals.

To document the bridges' ages, Ludwig et al (2019)[74] create three categories: "bridges grown by currently living people in the region; bridges built by known ancestors, generally no more than five generations old; and bridges known to be very old but with no known histories other than those tied to village histories". Building and maintenance is conducted by "generations of builders over decades or centuries … rarely with a clear or consistent plan". This long process consists of many small actions, such as "removal of mosses and epiphytes, pruning and tying of roots, laying of material (stones, soil) on the path, clearing of the associated path".

As described by Ludwig et al (2019)[74], "special features of growth and mechanical properties of the aerial roots of *F. elastica* have been well known and utilised for centuries" by the Khasi and Jaintia communities[74]. Their bridge-growing methods are of clear potential interest to others aiming to design with tree growth, whether that is when working with strangler fig species or otherwise. In each pre-existing structure, particularly in repeated vernacular architecture such as the LRBs, certain immediate impressions inspire designers. In the words of Ludwig et al (2019)[74], "the bridge-building technique obviously takes advantage of the mechanical strength of living aerial roots of *F. elastica* and their natural tendency to anastomose and form a mechanically stable structure via inosculations" – a key goal of many living architecture projects.

Structurally, LRBs are very complex. Each root divides and fuses, and changes shape, size and direction along its length. However, there are certain common structural characteristics of LRBs that can be described. Beginning with the lengths, which vary "between 2 and 52.7 m. 58 of 73 measured lengths, or almost 80%, are shorter than 20 m, with frequencies above a length of 20 m falling off sharply ... In some cases, the aerial roots reach more than 30 metres away from the parent tree." Bridge decks vary significantly: some are made for single-file pedestrian use while others are wide enough for several people to walk together.

In addition to basic geometry, common structural systems can be identified. As stated by Ludwig et al (2019)[74]: "LRBs show a very wide variety of structural typologies, with various aspects of particular bridges resembling characteristics of suspension bridges, cable-stayed bridges, arches, trusses, and simply-supported beams." Ludwig et al (2019)[74] highlight that many bridges have been found to have long, relatively straight 'structurally important roots' which run (horizontally) along the bridge and appear to support significant loads. Figure 1.10 (from Ludwig et al (2019)[74]) shows

Ummonoi bridge with five structurally important roots. The bridge in Figure 3.1a is made of a single large structurally important root with handrails made from deadwood. These structurally important roots were often found to have large height-to-width ratios, forming ‘inverted-T’ and elliptical cross-sections. This investment in height may be a response to bending moments – the roots may be acting like horizontal beams that, under (dead and live) gravitational loads, experience tension stresses on their lower side and compressions und their upper side[74]. These cross-sections have been seen in subterranean roots[76]. In other bridges, structurally important roots are not visible. Instead, the structure is formed by a network of intertwined roots. The network provides redundancy: if any single root fails, the structure would remain standing. In addition to the structural benefits of this, there are many paths for water transport.

1.3.1 Important botanical features of *Ficus elastica*

The tropical and subtropical places in which LRBs are grown are within the regions where *F. elastica* grows naturally. While it was first documented in southern Meghalaya[77], the species grows widely in the nearby regions of northern Meghalaya, Mizoram, and West Bengal, as well as Myanmar, western Thailand, Malaysia, Sumatra and Java where it may be native to limestone hillsides[78]. *F. elastica* is not limited to rural settings. As noted by Ludwig et al (2019)[74], Harrison (2017)[79], Jim (2018)[80] and Abasolo (2009)[81], large *F. elastica* specimens grow in densely built-up areas – indeed, there are well-known specimens in Shillong, Meghalaya’s capital.

In Ludwig et al (2019)[74], we describe the process of growing LRBs, beginning with *F. elastica* (Indian Rubber Fig) trees. When growing naturally, *F. elastica* is a “facultative hemiepiphyte that belongs to the group of ‘strangler figs’. In these species, germination of the bird-dispersed seeds in the canopy of a host tree is followed by an epiphytic growth phase” in which the fig’s leaves compete with the host tree’s canopy and aerial roots grow down to the ground, either in the air or clinging to the host’s trunk. The aerial roots “anastomose, form inosculations (natural grafts) and build a scaffold around the host tree’s stem. Canopy shading, root competition and the prevention [by the fig’s root network] of transport in the outer vascular tissue of the host” by the fig’s root can ‘strangle’ the host tree. The hollow cylinder of roots then efficiently supports the canopy.

Looking more specifically at aerial roots, certain growth processes underpin their use in LRBs. As highlighted by Ludwig et al (2019)[74], the roots exhibit three growth phases similar to those studied by Zimmermann et al (1968)[82] in *Ficus benjamina*. Flexible roots initially elongate until anchoring in a substrate. After anchoring, they “temporarily produce tension wood, which causes them to contract. The production of tension wood in the whole circumference of the roots shortens and strains them”. This tension can help the fig strangle its host. In a later stage, the tension is released and the aerial roots can act as props for exploratory branches. The three phases are shown in Figure 1.4. A tree near Rangthylliang village that has produced hundreds of prop roots, colonized a wide area, and supports two LRBs is shown in Figure 1.5.

Figure 1.4. *Ficus elastica* aerial root growth stages: (a) long thin roots reach to the ground, (b) straight vertical roots in tension, (c) large roots in compression support branches above.

Figure 1.5. A large *F. elastica* near Rangthylliang village colonizing the Risam valley via hundreds of prop roots (top left) and guided roots (e.g. top, foreground) and one of the two bridges that it supports (centre, middle-ground).

1.3.2 Use of these features in living root bridges

Figure 1.6 shows how the three phases of aerial root growth are utilized in living root bridges. Flexible roots are woven onto the scaffolding (1.6a), held in place by the scaffolding when they grow in tension (1.6b) and support other roots when they can resist compression (1.6c). While the hemi-epiphytic growth sequence in *F. elastica* is common, it can also grow from the ground, from cuttings, or can germinate on boulders and cliffs. This is well suited to the steep canyons and valleys of southern Meghalaya. In order to grow a bridge, "commonly, a *F. elastica* cutting is planted on one bank of a canyon or river. After reaching an adult stage, aerial roots ... emerge from the branches"[74]. These are then wound onto and directed across a deadwood framework, often a bamboo bridge that is used to cross the river in the short term. Bridge-builders lead vertically hanging roots across the river to implant them on the opposite bank. The roots "then shorten, start to thicken and produce daughter roots, which are trained (wound and directed) similarly… Through the close intertwining of roots, inosculations can be initiated to form a densely interwoven framework-like structure. Alternatively, the initial root(s) used in the bridge can be allowed to grow unaffected and dominate the structure. The addition of handrails, a second deck, underpinning struts, or other features can further influence the bridge's structural system." The inosculations that link roots into one structure are held in place (necessary for inosculation, see section 1.7) by the tension phase of the root's growth that can press root surfaces together with relatively high force (compare Abasolo (2009)[81] and Ludwig (2012)[12]).

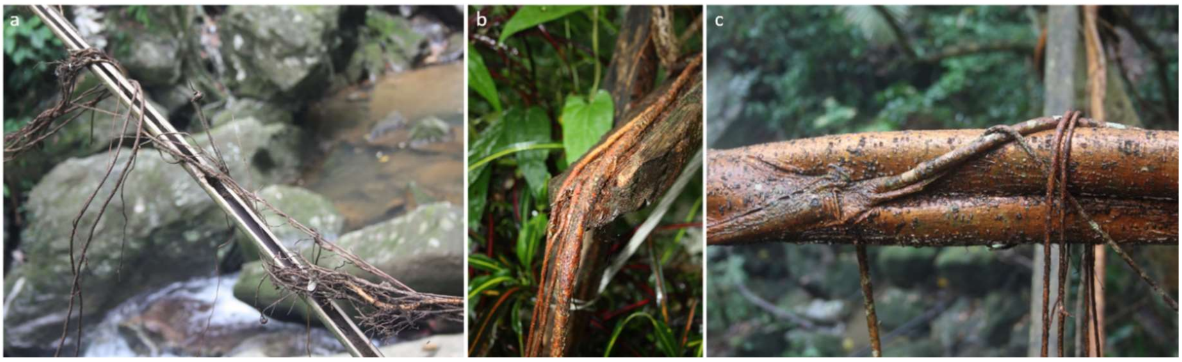

Figure 1.6. Three stages of aerial root growth used in bridge-building: (a) supple roots are wrapped onto bamboo scaffolding, (b) roots in tension guided along an Areca nut palm, (c) a thick root providing a handrail that can resist tension and compression.

Given the number and diversity of LRBs that have been grown, Ludwig et al (2019)[74] find them to be "a unique concept generator for future projects of botanical architecture which will aim at aligning construction techniques and design aims with … growth phenomena". The range of concepts and corresponding research questions generated is broad, from construction and growth sequencing to societal structuring, and from ecological to mechanical analyses.

1.4 Questions pursued in this thesis

As there are many open questions in living architecture design, an important step in this project was identifying the most relevant areas of research. My background in civil engineering, the community of interested academics around the project (at TUM and University of Freiburg in particular), and three expeditions to Meghalaya in 2017, 2018 and 2019 informed these decisions. Three lines of inquiry were chosen. The first, characterizing the regenerative aspects of LRBs, goes further in investigating them and results in a method that can be applied to designed living architecture. The second line of inquiry, engaging with documentation and representation of living architecture, investigates the precise geometry and topology of living root bridges while producing a method for design. The third, drawing on the importance of inosculations in LRBs (but not investigating them further) develops models for mechanical investigation of designed living architecture. The three projects resulted in peer-reviewed papers, which form the central chapters of this thesis. Figure 1.7 shows the progression from investigation of the vernacular LRBs to methodical design of living architecture via the three lines of inquiry in this thesis. Their application in design is discussed in the final chapter.

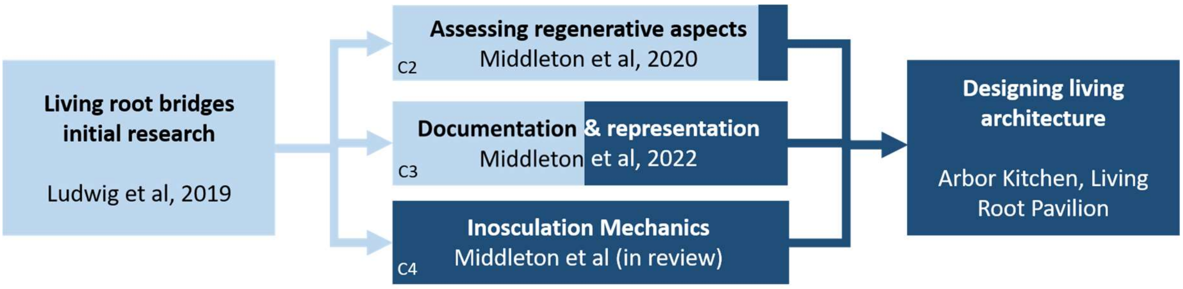

Figure 1.7. Thesis structure: three lines of research (relating to Chapters 2, 3 and 4 of this thesis) sprung from the initial study of LRBs. The first two projects focus more on the investigation of LRBs (light blue), but also contribute to the development of methods and workflows for designing and engineering living architecture (dark blue), which is the main focus of the third project.

The first line of inquiry addresses how living root bridges fulfil users' needs. This is approached from the perspective of regenerative design and development, which puts change and growth at its centre. The question at the core of this is: to what extent and in what aspects are LRBs regenerative, sustainable or degenerative? The findings are a spread between clearly regenerative and more ambiguous aspects. Some regenerative aspects are explicitly in conflict with degenerative aspects, while others are less deeply interwoven. The study is the first to comprehensively evaluate the regenerative aspects of living architecture. The method used can be transferred to other examples of living architecture. In the second line of inquiry, documentation and representation of living architecture was examined. While Ludwig et al (2019)[74] describe LRBs in broad and comparative terms, precise documentation is fundamental to communicating form and function. In addition, a range of analyses (for example of mechanics and physiology) require simple structures on which calculations can be performed. This resulted in investigation of methods for documenting and representing the complex geometries of grown structures, interrogating two questions: can living architecture be documented in sufficient detail with off-the-shelf equipment? And can a skeleton, with the capacity for volume reconstruction, be developed from points clouds (PCs) of living architecture? The third line of research examines a structural component present in all living architecture, from LRBs to Baubotanik design – the cross-wise inosculation. In order to develop a method for modelling a wide range of cross-wise inosculations, the question asked was: "what are the relative benefits of including geometric detail and orthotropic material optimisations in mechanical models that can be used during living architecture's iterative process of design and maintenance?".

Many areas of inquiry adjacent to, or following on from the three lines of inquiry pursued here would make for useful research (Figure 1.8). In the discussion section of each chapter (sections 2.4, 3.4 and 4.4), directions of further research are suggested. These explorations, and the questions that are not addressed here, are part of the ongoing work of my colleagues at TUM and elsewhere. Two questions that would harmonise well with the present research are described in section 5.3.2: *F. elastica* growth and its requirements; and investigation of *F. elastica*'s structural systems benefits.

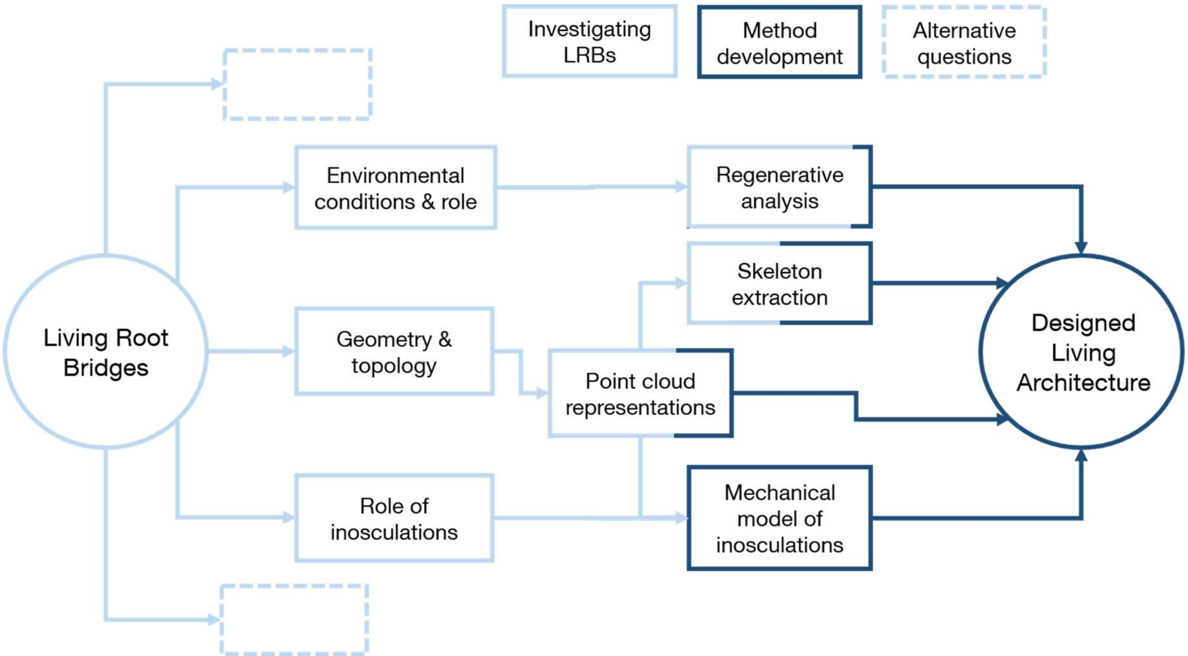

Figure 1.8. Prominent research themes for living architecture design, in the initial study of living root bridges, in the present thesis, and beyond the scope of the thesis.

1.4.1 Methodology

This highly interdisciplinary thesis draws from many fields of study. A general approach of restructuring and recombination of methods from industry and academia is present throughout the project. The LENSES Rubrics are restructured for analysis of existing buildings; methods in photogrammetry and skeletonisation are combined to form a workflow for the specific challenges of living architecture; a model of inosculation mechanics is built using tools from different fields: LiDAR, inclinometric measurements and finite element software. In each chapter, the novel methods are highlighted as such, while the sources of repeated or standard methods are cited.

The methods and materials used are described extensively in each chapter (sections 2.2, 3.2 and 4.2 respectively). Each study is based on prior research that was not directly part of the study, but led up to it, described in sections 1.5.1, 1.6.1 and 1.7.1. In the study of regenerative aspects of living root bridges, this prior research is a survey of bridge builders and users, described in section 1.5.1. In the documentation process, the prior research is a the photogrammetric method, partly described in Middleton et al (2019)[83] and in section 1.6.1. In the investigation of inosculation mechanics, this is the comparison of LiDAR and photogrammetry and the construction of finite element model mesh types, described in sections 1.7.1.1 and 1.7.1.2 respectively.

In sections 1.5, 1.6 and 1.7 the three lines of this research as they developed from the pilot study of Ludwig et al (2019)[74] are described. Figures 1.9, 1.10 and 1.12 are reproduced from that study. The reasoning behind the direction of each line of inquiry and the explicit goals of each study are laid out. While the fields of inquiry are quite diverse, the process of development for the methods used in each study is similar: starting from the findings of Ludwig et al (2019)[74] and other studies the knowledge gap is assessed, adjacent engineering and design fields are examined for solutions to similar questions, and a method for adapting that knowledge to answer the research questions is found. The three studies are presented in sections 2.4. Their application in the ongoing design of Arbor Kitchen, a project with students and researchers from TUM, is presented in section 5.1.

1.5 Characterizing regenerative aspects of living architecture

The goal of sustainable design is to minimise negative impact to the environment caused by built projects. This results in designs that are static and isolated from their environments. In regenerative design, the impacts of a building on its environment are recognised. This invokes a processural, systematic mind-set, in which the changes to a building and its environment are planned. In regenerative design, architects aim to recognise the impacts of their work on a range of environmental, ecological and social systems, stating the positive (regenerative), negative (degenerative) or neutral (sustainable) effects. This has been posited in terms of 'co-evolution' between humans and the natural environment by Cole (2012)[84]; holistic systems by Du Plessis (2012)[85]; and "a change in worldviews from mechanistic to ecological" by Mang and Reed (2012)[86]. The study in Chapter 2 examines the living root bridges in their geographic, ecological and societal context to understand their regenerative, sustainable and degenerative aspects and their potential for transfer or improvement.

The map of LRBs in the Khasi and Jaintia Hills produced in Ludwig et al (2019)[74], reproduced in Figure 1.9, provides an essential foundation for such a systemic investigation. The bridges were geolocated to within 15-30m and overlaid on a topographic map of the region and a tree cover map[87]. More information on the geography of the East Khasi Hills and West Jaintia Hills is given in section 1.3. The bridges are coloured according to maintenance scheme. In the words of Ludwig et al (2019)[74], maintenance is "done by individuals or families (12 of 75 bridges), shared amongst a village community (25 bridges), or by a consortium of several communities (8 bridges). Maintenance is conducted on another 14 bridges, though the maintainer is unknown, and not conducted on 16 bridges (untended)." As shown by the teal coloured bridges in Figure 1.9, some villages (e.g. Nongblai, Nongriat) organize maintenance of many bridges as a community, often led by a small number of elders.

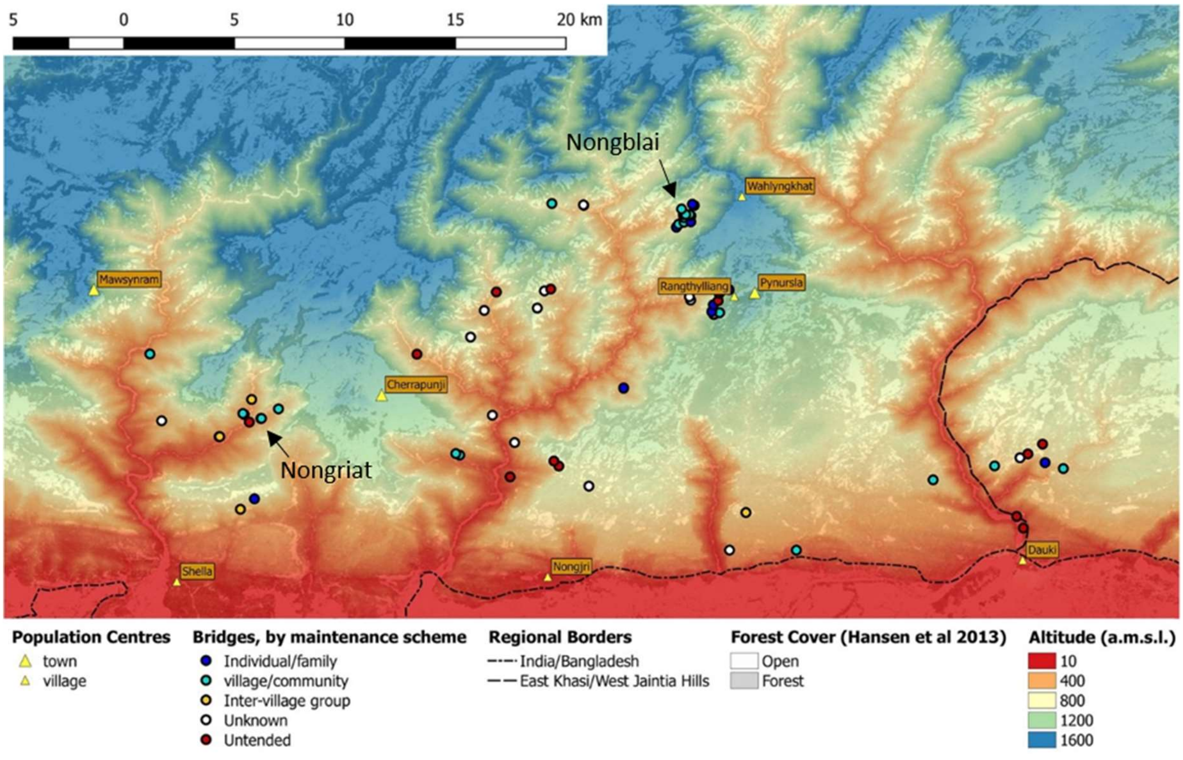

Figure 1.9. A map from Ludwig et al (2019)[74] of the 71 bridges in the Khasi and Jaintia Hills geolocated between 2015 and 2017, overlaying an altitude map and forest cover shading. Major settlements are marked and each bridge is coloured according to maintenance regime.

Maintenance and use of other bridges is passed down through families along with the land they inhabit or access, or passed between individuals or villages. Some bridges are used and maintained by people from more than one community, and maintenance is often a point of collaboration between the communities. The intergenerational and inter-community nature of LRBs points towards their cultural-historical role. More detail on bridge histories is given in section 1.3 and the interviews in Appendix B. Examples of vernacular architecture and landscape architecture around the world are similarly woven into community histories[88-90]. These environmental and societal contexts are the base for an examination of the regenerative, sustainable and degenerative aspects of living root bridges. From the interviews discussed in Ludwig et al (2019)[74] (and in Appendix B), it seems that LRBs have many roles: as cultural heritage, forming a transport network, a medium for inter-village cooperation, and providing ecosystem and environmental services.

A method for investigating these roles is needed. In search of this, we began by looking for the industry standard of multifaceted building assessment frameworks. The commonly used sustainability frameworks assess many areas of negative impact individually, but do not accommodate assessment of the positive impacts of a project or the interconnectedness of these impacts[91]. As explained by Akturk (2016)[92], updating the sustainability frameworks to include positive impacts would not solve the problem. One major problem is that the current commonly used green design standards (such as LEED, BRE and BREEAM) are checklist-based[92, 93]. Akturk describes three important ways in which they are reductive. They lack the interconnectedness necessary for local contextualized regenerative design; they rely on quantitative metrics with little room for qualitative assessments; and they do not allow for multiple, potentially conflicting viewpoints[92]. The need for regenerative thinking is well recognized – the US Green Building Council commissioned the development of REGEN to go beyond LEED[92]. Several frameworks have been developed for regenerative design since then. Perkins+Will[94], Living Building Challenge (LBC)[95] and Eco-Balance[96] provide certain features of a regenerative design framework. Perkins+Will is a philosophical tool that fits many industries; Eco-Balance attempts to structure multi-perspective assessment through many precise lenses; LBC is closer to the traditional 'checklist' approach, with less focus on the practitioner's process. LENSES[97] is a more flexible framework with the capacity to add and remove parts with less primary focus on ecology than the other reviewed frameworks.

We aimed to describe the extent to which LRBs are degenerative, sustainable and regenerative (DSR). The resultant method, using the LENSES Rubrics, is a template for regenerative analysis of other living architecture. By considering the interconnections of DSR aspects, the method encourages transfer of regenerative aspects between projects. The method is applied in section 5.1.1 to Arbor Kitchen, a living architecture pavilion built in 2021/22.

1.5.1 Background methods

Beginning the interview process when investigating living root bridges, two key questions defined the interview (question choice) and survey (interviewee choice) methods. What relevant knowledge can a bridge builder, user or owner impart? And how much knowledge overlap exists between individuals, villages, and regions? These two questions guide the purposive survey method used here[98]. They define the saturation point (when all available knowledge is obtained) of an interview or survey (e.g. within a village) and thus the degree of structure in the questions[99]. Where an individual has a lot of knowledge to impart, unstructured (fewer prompts, less set narrative) discourse reveals unexpected knowledge. When a small amount of new knowledge is available, questions should be more purposive, aiming to fill in the gaps (obvious or unclear). When interviewees have little knowledge overlap, the survey should take in many voices[100]. Where there is a lot of overlap, fewer interviews are needed. The logistics of the interviews are described more fully by Ludwig et al (2019)[74]: "during the surveys, bridges were located through work with guides across the Meghalaya region who established contact with different local communities involved in building and maintenance of LRBs. Photographs, measurements, geolocations, and interviews were taken with these guides, who also acted as translators. The interviews were transcribed in note form." All interviews were conducted before the theme of regenerative analysis was decided upon, and were therefore not guided by this, but rather by general knowledge collection around use, growth, and cultural history.

1.6 Documentation and Representation

The second line of research turns to documentation and representation of living architecture. This is exemplified in the living root bridges. In the words of Ludwig et al (2019)[74], "each bridge, as well as each constituent root, is very complex". The basic measurements presented in that study (and in section 1.3) do not describe the exact geometry of each bridge (for example, Ummonoi bridge in Figure 1.10), its changes over time, or its constituent parts. In order to analyse structurally important roots by comparing radii, or redundancy of networks through connectivity, or a host of other analyses, the roots must be represented as connected objects to which properties can be ascribed. Therefore, a documentation and representation workflow is needed.

A documentation method that captures complex geometry more precisely than the hand-measurements presented by Ludwig et al (2019)[74] is needed. It should be usable in a range of situations, capture the most complex structures and be low-cost enough to be regularly repeatable. As fast growing, complex anastomotic networks, the LRBs are both in need of, and an ideal proof-of-method of, a documentation method. Point clouds and the optical methods that generate them are ideal for the capture of the entire surface of an LRB. A key feature of living architecture that separates it from other fields is the changes over time – designers cannot predict exactly the form after several years of growth. Optical methods are used in many engineering projects to check the closeness of single points (e.g. a building's corners) to the original digital plans over the project's lifetime[101]. In living architecture, the workflow must also work in reverse: documenting the structure allows the building of a digital model and the labelling of corners and other key points. As described in Chapter 3, this use of close-range photogrammetry (CRP) and terrestrial laser scanning (TLS) is growing in Historical Building Information Modelling (HBIM). However, the timescale is dramatically different: living structures change significantly each year while historical buildings typically change over decades or centuries, or during singular events such as earthquakes.

Once the point cloud has been constructed, the structure's constituent parts must be meaningfully extracted for analysis. A step must be made from the visible, unconnected point cloud data in 3D space – easily interpreted by the human eye – into connected bodies recognisable in computer vision for structural, mechanical or growth analysis. The fundamental shapes present in the architecture inform the types of objects that can be extracted, and the possible solutions to the computer vision problem. Here, living architecture again contrasts with historical buildings. The abstracted forms that are represented in HBIM are fundamentally different, for example arch or dome components with relatively common or simple parametric forms[102]. In living architecture, the constituent roots and shoots can be seen as 1D linear elements with variable length, direction, shape, and thickness.

As described in Chapter 3, the standard method for 1D skeleton extraction[103] does not lend itself well to LRBs. Based on a range of review papers in the field (particularly Tagliasacchi's extensive 2016 review[18]), we settled on a template-based voxel-thinning method that combines She et al's (2009)[104] efficient template-based method with Lohou and Bertrand's (2004)[17] curve-end preserving method. The skeletons resulting from this process must also preserve some shape data to represent variable root or shoot radii. Voxels provide a good medium for this: discrete connected points to which associated (radius and shape) data can be ascribed. This led to a novel method that uses the thinning iterations needed to reach each skeleton voxel to derive circular and elliptical root cross-sections. In summary, Chapter 3 looks at detailed documentation of the visible surfaces of living architecture and the extraction of curve skeletons that represent a bridge's limbs.

Figure 1.10. Ummonoi bridge with five structurally important roots running the length of the deck and handrails: (a) from downstream, (b) along its length. From Ludwig et al (2019)[74].

1.6.1 Background methods

The photogrammetric surveys of LRBs described in Chapter 3 were conducted first in March 2018, then continued on a second trip in March 2019. March, at the end of Meghalaya's dry season, is suitable for photogrammetry because there is less water in the rivers and streams – making them more accessible and reducing water-reflection problems[105] – and less epiphytic leaf material obscuring the bridge surface. Photogrammetry of the Freiburg Pavilion was conducted in December 2019, when almost all of the leaves had fallen from the trees, allowing access to the structural topology of the stems and branches. Some details of the photogrammetric method are clarified in Middleton et al (2019)[83] and repeated here. In documenting the LRBs, a key limitation to the method was access: rivers, cliffs and trees prevented a full 360° view – downstream perspectives were not accessible for the surveys in Figures 1.11b and 1.11d. While walking on the bridge allowed access to the top surface, the underside was more difficult to view. In some bridges (e.g. Niah Li bridge in Figure 1.11b) good detail of the deck was provided by photos at multiple angles at 20-30cm intervals[83]. Under bridges, light was also often poor and a flash was needed to capture details (Figure 1.11a) – these photos can be less well integrated during photogrammetric reconstruction. In very large bridges, the survey was conducted as if in a room: many photos taken in a sphere from standing positions (e.g. the underside of Niah Li, Figure 1.11b). Smaller bridges were captured like objects, attempting a spherical capture from many angles (compare Figures 1.11b-d, from Middleton et al (2019)[83]). In documenting the Freiburg Pavilion, the combination of handheld DSLR and drone cameras provided many good angles of photography. In the survey we attempted to capture the details (e.g. individual connection points or stems) from inside and outside (Figure 1.11e), essentially piecing together the pavilion from a series of overlapping objects, rather than treating it as a whole room or building with perspectives from many distant angles. The small twigs near the top of the pavilion were poorly captured with both cameras. These twigs did not constitute or obscure the interesting structural topology.

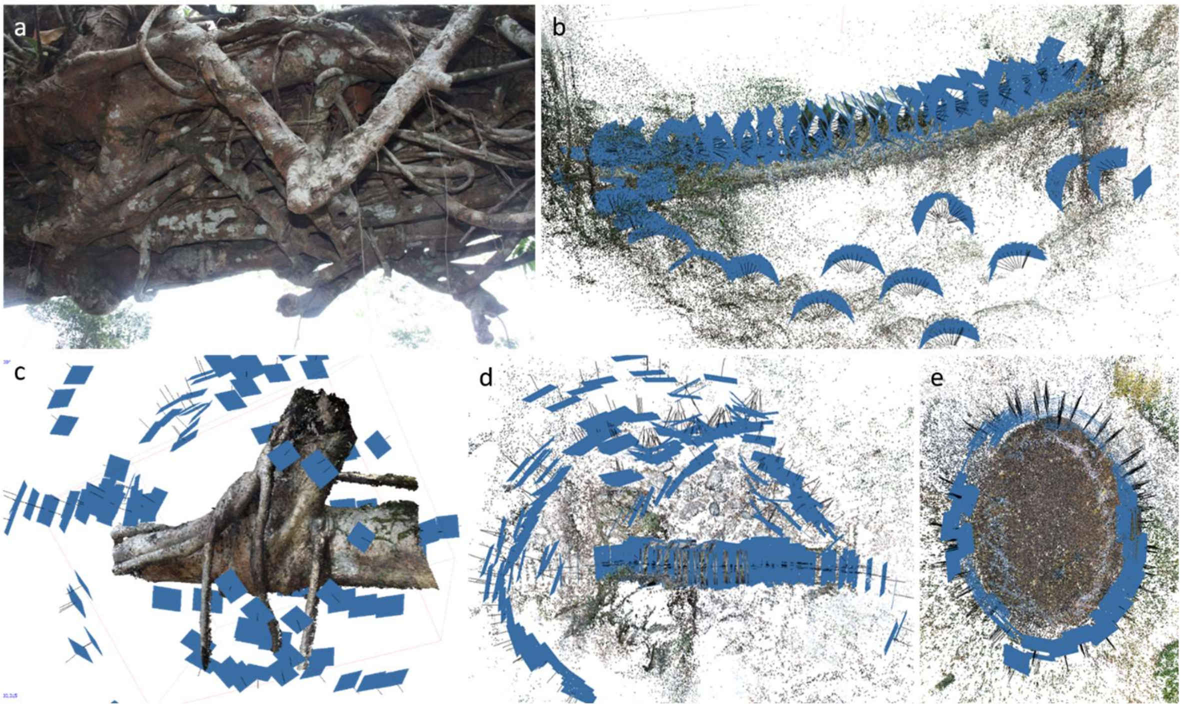

Figure 1.11. Photogrammetric surveys: (a) a flash photo under Nongbareh bridge, (b) Niah Li bridge photographed underneath upstream in the 'room' method, downstream access limited by a cliff, (c) an inosculation in Mawsaw bridge in the photographed in the 'object' method, from Middleton et al (2019)[83], (d) Nongriat Access bridge, photographed from many angles but access limited downstream by the river, from Middleton et al (2019)[83], (e) the drone photo positions outside the Freiburg Pavilion, focusing on details.

1.7 Inosculation Mechanics

Chapter 4 examines the mechanics of inosculations. In this, there are two aims: firstly, to use a mechanical-physiological understanding to inform a model of inosculation mechanics. Secondly, to compare practical models (using finite element analysis) of real inosculations that quantify the relative importance of fibre orientation optimizations and mass allocation optimizations. Inosculations are found in a range of natural settings: common in subterranean roots[106], an essential feature of some climbing plants' growth strategies[107], and uncommon in above-ground branches and stems across a range of species[108]. They are used in many examples of living architecture, from the designed Baubotanik buildings to the artisanal projects by FullGrown and Konstantin Kirsch. They have been used in horticultural ornaments (e.g. espalier), monumental living architecture (e.g. Axel Erlandson's Tree Circus[37]) and landscape architecture (e.g. Labouheyre town square, Figure 1.2b). Inosculations are utilized in European hedges and Meghalaya's living root bridges – traditions seemingly developed independently of one another. Indeed, inosculations are one of the basic building blocks of LRBs.

Sustained contact is needed for two roots or shoots to inosculate. In LRBs, inosculations are formed either by simple contact between roots or by knotting or twisting them together – a common method in LRBs for securing roots in place). When the 'tension' phase of root growth occurs (see section 1.3), the roots are held tightly together. Figure 1.12 adapted from Ludwig et al (2019)[74], shows four different connections, at different stages of growth. Three types of joining technique were trialed by Ludwig (2012)[12] for inducing inosculations in a range of tree pairs: (functionally inelastic) high-strength thread ties, low-stiffness yielding ties, and screws. While the first often caused strangulations, the second did not cause enough pressure to induce inosculation. The direct screwing, while creating a wound that allows infection, forced the two stems together while allowing most of the circumference of the living tree to grow, eventually overgrowing the screw. In this study, I chose to focus on the mechanics of cross-wise inosculations with significant combined growth. There are three reasons for this. Firstly, several inosculations of this kind were available at the Gewächshauslaborzentrum Dürnast (near to Munich), grown in similar conditions and of the same age – the same standardisation would have been difficult with *F. elastica* inosculations. Secondly, these inosculations are very common in living architecture (see Figures 3.4c, 3.5a, and 5.7) and the goal of the study was to examine models of a specific joint type that are applicable to a range of species.

Figure 1.12. Several types and stages of connection of aerial roots, from Ludwig et al (2019)[74]: (a) a knot newly tied before the growing season, (b) a young nodal connection establishing common growth, (c) a fully established complex inosculation within a network, (d) a young root tying together two older ones, both in the short term (fixation) and the long term (inosculation).

Inosculations, like branch junctions[109], may be significantly well adapted to mechanical pressures. While in wooden beams and columns, as in tree trunks, the fibers are aligned with common stresses, this is not the case in engineered timber joints. The change in fibre orientation at timber joints presents an ongoing engineering challenge[110-112]. This problem has been solved by trees in many interesting ways. Various studies[113, 114] show the relative importance of mass addition and fibre orientation in branch junctions. Müller (2006)[115] shows how fibre arrangement results in controlled failure in conifers. Bunk et al (2017 & 2019)[109, 116] identify diverse ‘finger-like’ branch junctions in four species of Araliaceae, the forms and topologies of which are impacted by mechanical pressures and a range of environmental and genetic factors. In a similar vein, Schwager et al (2013)[117] describe a load-adaptation strategy for cacti, given the physiological pressures that result in an outer succulent cortex.

As a subgroup of wood joints, inosculations have received little attention. Similar to other wood joints (such as branch junctions) their adaptations are the result of mechanical and physiological pressures. One key theory for mechanical determination of tree shape is the uniform stress hypothesis[118], which a variety of studies have investigated for stems[119-122]. However, the uniform stress hypothesis is less explored in branching junctions[113] and becomes more complicated when localised stress adaptations are considered[117]. However, recent years have seen an upsurge in investigations into the structure of grown joints[123, 124]. Some projects directly use harvested grown branch junctions, finding their optimal use orientations. Groups in Austria[125], the UK[29] and the USA[30] have developed methods for simultaneous structural form-finding and utilising available joints.

First explored by Millner (1932)[107] in ivy, induced and natural inosculations appear to undergo the same physiological process: a common growth ring forms after the phelloderm and xylem have merged (more detail on inosculation formation is in Ludwig (2012)[12] and Millner(1932)[107]). The common growth ring allows redistribution of water between the tributary and outflowing elements.

In Chapter 4 I draw methods from the investigations of branch and timber joining studies described above: optical methods providing precise external documentation in combination with first-principles mechanical adaptation literature to inform joint mechanics models. In particular, I draw from the mechanical-physiological adaptations seen in naturally occurring tree forks[126]. Deriving a model drawn from these common features of inosculations allows its application to diverse settings.

1.7.1 Background methods

1.7.1.1 LiDAR & photogrammetric point clouds

Unlike the investigations of LRBs in remote rainforest valleys (Chapter 3), a laser scanner was available for these field measurements at TUM's Gewächshauslaborzentrum Dürnast. The LiDAR scanner (Riegl LMS-Z420i), which produces reliably precise point clouds, was used to produce the base data for the finite element analysis. In addition, we performed quick photogrammetric surveys as a backup, following similar methods to Chapter 3. The same 24MP Fuji XT 20 DSLR (APS-C sensor; 18 mm, f/2.8–4 lens) camera was used, taking around 30 photos of each of the four tree pairs described in that study. The photogrammetric reconstruction followed the method in Chapter 3 (using Agisoft Metashape standard edition[127]). The two types of PC were then aligned in Cloudcompare[128]. The mean deviation of the photogrammetric PC from the LiDAR PC was 3.04mm across all points in the four tree pairs (standard deviation 1.9mm). This deviation is similar to that resulting from Poisson meshing at depth level 5 in Chapter 4 from the LiDAR scan (see section 4.3.2). This suggests that photogrammetry would be a valid method for similar models.

1.7.1.2 Finite element model construction

In constructing finite element models for the tree pairs, several options were tested. The model type needed reflects the mostly continuous surface of a tree pair and applies to the diverse geometries of cross-wise inosculations equally. Typically, trees are modelled with cylinders with either variable or constant radii[20, 129]. Moravcik et al (2021)[130] represent junctions with highly conical cylinders near branch bases, but discontinuities remain. Many meshing methods have been used in finite element analysis for such objects. This study does not aim to find the best fundamental mesh type (e.g. topology-first or node-first meshes[131]) but rather to produce a usable modelling method with the tools at hand. These are RiSCAN Pro, free PC manipulation software such as Cloudcompare[128] and Meshlab[132], SpaceClaim[133] and Ansys[134], FEMap 2020[135] and Strand7[136]. Voxel models (of varying voxel size), variable and invariable radius pipe models, non-variable cylinders, and Poisson surface meshes converted to volumes were all trialled. Many models had mesh geometry problems (such as self-intersecting faces and non-manifold edges) that needed to be solved manually. Poisson meshes and non-variable cylinders provide the right balance of detail and robustness for the present study. The chosen workflow is as follows: RiSCAN Pro was used for processing LiDAR data; PC manipulation and mesh-making was done in Cloudcompare; Meshlab was used for correcting errors in the meshes; Spaceclaim was used for conversion of 2D meshed surfaces to 3D meshed volumes; and the FE analysis was performed in Ansys.

Chapter 2

Characterising Regenerative Aspects of Living Root Bridges

This chapter was first published under the same title in *Sustainability* in 2020, with co-authors Amin Habibi, Sanjeev Shankar, and Ferdinand Ludwig. This version includes minor formatting edits. The nine completed Rubrics Worksheets are available online at http://www.mdpi.com/2071-1050/12/8/3267/s1.

2.1 Introduction

Formed without contemporary design tools, Living Root Bridges are an exceptional example of vernacular architecture that uses the manipulation of tree growth as a building technique. By crossing canyons and rivers, the bridges link homes, fields, villages and markets, and provide an alternative to often unsuitable contemporary technologies and materials. They can be seen as a highly specific solution for rural connectivity in Meghalaya's geography and climate – high humidity, heavy rains, torrential rivers and steep, densely forested hillsides. Living Root Bridges (LRBs) can last for centuries, growing stronger with time in a process that combines periodic human maintenance with natural growth processes. They are deeply integrated with their surroundings, providing slope stability and various ecosystem services[137]. In living wood, an LRB produces its own building material on site, absorbing CO_2 over its lifespan.

LRBs can be seen as a form of architecture that goes far beyond the established concept of sustainable design, which aims to satisfy fundamental human needs today without compromising future generations´ prospects[138]. In fact, they seem to be an outstanding example of regenerative design and development. The term "regenerative" describes processes that restore, renew or revitalize their own sources of energy and materials, creating sustainable systems that combine the needs of society with the integrity of nature[139].

In the following sections key background to LRBs and regenerative development and design is given, followed by a formulation of this study's hypothesis. The study's methods are then outlined and results presented and discussed within the wider context of vernacular architectural analysis.

2.1.1 Living Root Bridges – the state of knowledge

Written documentation of LRBs was sparse until recent years[140]. The first published extensive documentation of LRBs is provided by Ludwig et al (2019)[74]. That study maps 75 bridges (shown in Table 2.1), discussing their geographic distribution, dimensions, and some key structural characteristics. Eclectic materials, ranging from simple quantifying data (GPS coordinates, basic bridge dimensions, village populations) to qualitative data such as folk stories, photographs, videos and interviews (e.g. with village headmen and bridge-builders) collected during two research stays in March 2017 and March 2018, contributed to this documentation. The present study draws on the same information and considers the same 75 bridges. Chaudhuri et al (2016)[141] and Shankar (2015)[142] describe the societal setting of the bridges and their construction methods. Middleton et al (2019)[83] present photogrammetry as a documentation technique that captures the geometric complexity of LRBs. A deep well of literature on Khasi history and culture provides useful background. Bareh's *The History and Culture of the Khasi People* provides a well-researched introduction to Khasi culture [143]. An extensive literature review on Khasi philosophy is provided by Malngiang (1991)[144], while Lyngdoh (2015)[145] contrasts traditional Khasi ecological frameworks with contemporary Cartesian dualism. For a deeper understanding of the key interactions between Khasi culture, community structures, and ecology, see Chakraborty's (2018) review of Kynpham Sing Nongkynrih's *The Yearning of Seeds*[146, 147] as well as Shangpliang's description of the traditional position of forests in Khasi society[148]. Tiwari et al (2010)[149] and Cajee et al (2005)[150] discuss Khasi community forest management systems and their social and environmental roles; Tiwari et al (2011)[151] and Ormsby (2013)[152] focus specifically on the Sacred Grove system.

Ficus elastica grows abundantly in the Khasi and Jaintia Hills[77, 151]. To initiate the growth of a Living Root Bridge, a branch of *Ficus elastica* is typically planted on one or both banks of a canyon or river. After the tree reaches an adult stage, aerial roots emerge from the branches. These are trained across a deadwood framework (usually bamboo), and finally implanted in the opposite bank. These roots thicken and produce daughter roots, which are trained similarly. During this process, the bridge builders closely intertwine the roots with each other or with branches, roots or trunks of the same or another *F. elastica* tree in order to initiate inosculations, producing a densely interwoven, and often framework-like structure (Figure 2.1b). The time it takes until the living structure can bear sufficient loads and can be used safely depends on a number of factors, e.g. overall span, exposure to sunlight, soil quality, altitude or regularity of maintenance. Generally speaking, it can be said that the time span from planting a sapling to full usability is in the range of several decades.

From Ludwig et al's (2019) study[74], it is clear that village oral histories and discussions with communities provide key insights into the bridges' positions in society and, in particular, into people's attitudes towards the bridges. That study also notes the LRBs' variety, including a wide range of structural systems, ages, dimensions, and settings. In structural terms the bridges are comparable to compression arches, suspension bridges, and simple beams in single and multiple spans, as well as many other forms. Bridge age estimates are generally poor. Bridges with age information can be sorted into three simple categories: bridges grown by people living today, bridges that were grown by known recent ancestors, and bridges that are known to be very old but with no known histories other than those tied to village histories. Interviews suggest that floods, fires, and landslides destroyed many bridges grown in the past.

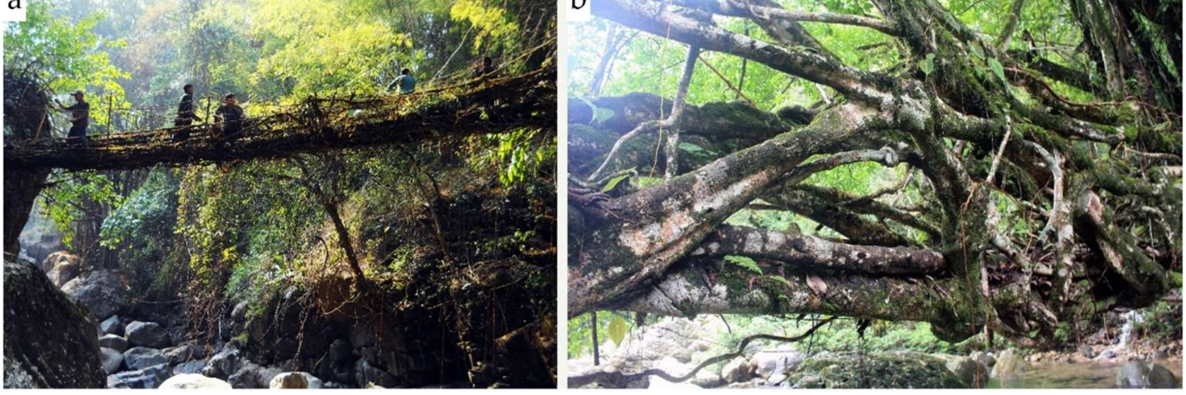

Figure 2.1. (a) A Living Root Bridge during maintenance (photo: Patrick Rogers), (b) detail of the framework-like load bearing structure of another bridge.

A common theme in LRBs is their environmental setting: the vast majority of bridges 68 of 71 geolocated in Ludwig et al (2019)[74] grow on forested valley slopes, while the other three grow on areas of the Shillong Plateau. The bridges generally allow access to farmland for village communities based on the plateau, or access to the plateau for villages in the valleys.

Traditional Use	Minor Tourism Use	Major Tourism Use
Few changes to the bridge or surrounding community or landscape due to tourism. Aside from tourism, changes in land use (to monoculture cropland), building materials (steel and concrete), and other technologies (cell phones) can significantly change perspectives	Some changes due to tourism, particularly reinforcement and maintenance of bridges, maintenance of paths, basic amenities prepared for visitors	Major changes in the bridge can include reinforcement with steel or concrete or damage by overuse. Landscape changes include clearing of nearby forests, new paths and roads built to the bridge, and increased litter. Community change include replacement of traditional incomes by tourism, improved connection to electricity grid and higher incomes.
Arch Bridge Darrang 1 Darrang Broken Diengsiar 1 Halfway Nongbareh Kudeng Rim 5, 8 Laitiam 1,2 Long Ti Uyiang Lyngsteng 1 Mawkliaw 1,2 Mawlam 3 Mawshken 1 Nongbareh 1 Nongpriang 3 Nongthymmai Old Pdei Kongtim 1 Rimai Bridge Rymmai 1 Rynsiet Sohkhmi 1 Suktia 1 Thangkyrta 1,2 Tynrong 1 Tyrngei 1 Wah Kdal Wah Lar Ung Wah Lyngkhen Wah Lynseng Wah Shoh Klea Wah Soh Mad Wah Soh Shiat Wah Spit Wah Surah Wah Tiah Long Wah Tumbai Wah Um Thliem Rangthylliang 1,2,3,10,11,12,13 Nongbah/Mawshuit1 Wah Matieh Lower & Upper	Burma 1 Iar Soh Liang Kongthong 2 Kongthong 3 Kudeng Double Decker Niah Li Bridge Rangthylliang 4 Rangthylliang 5 Rangthylliang 6 Rangthylliang 7 Rangthylliang 8 Ummonoi Wah Amlohmar Wah Koh La 1 Wah Kol La 2	Nongriat Double-Decker Mawkyrnot Long Bridge Mawsaw Hybrid Mawsaw Old Nongriat Access Nongthymmai 1 Nongthymmai 2 Nongthymmai 3 Rangthylliang/Mawkyrnot 2 Siej Wah Thyllong

Table 2.1. The 75 bridges relevant to this survey names provided by Ludwig et al (2019)[74], many of which are debated categorized by extent of use for tourism. Increased use for tourism can result in changes to the bridge and associated community or landscape. Further information about these bridges is provided by Ludwig et al (2019)[74].

Maintenance consists of a variety of techniques: removal of mosses and epiphytes, pruning and tying of roots, laying of material (stones, soil) on the path, or clearing of the associated path (see Figure 2.1a). Through interviews and observation, diverse maintenance regimes are documented: maintenance is conducted by individuals or families, shared amongst a village community, or shared by a consortium of several communities. The extent of maintenance is usually related to use. Bridges that are crossed many times a day receive a large amount of collective attention from users, while those that are left unused are hardly cared for, become overgrown and lose their stability and functionality over the years. Nowadays, with the influx of tourists to the region, some bridges experience more (but not always more adequate) maintenance than others.

To provide a basic understanding of the relative importance of tourism (at the time of writing this paper), the 75 studied bridges are presented in Table 2.1, grouped into three categories according to their traditional or tourist use: bridges that are predominantly used for traditional purposes, bridges with some tourist activity that have seen some changes, and those that have seen major changes. 50 of the 75 documented bridges (66%) are in the first category, 15 (20%) in the intermediate category, and 11 (14%) are significantly changed by tourism (third category). While the regional shift is towards tourism, some traditional use still exists in all bridges. Wah Thyllong bridge, for example, is visited by hundreds of tourists each day, but is still used by farmers, market sellers, and school students. Basic adaptations to tourism are for example preparations within the community to cater for, guide, and accommodate visitors. Alongside this, bridges are reinforced for tourists' safety. In the course of further increasing tourism guesthouses are built, paths to the bridges are adapted or replaced by roads, and farming is scaled down as income is generated from tourism.

2.1.2 Beyond sustainability – regenerative development and design

Sustainable development is typically defined as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs"[138]. This definition from the Brundtland report in 1987 has become the basis for international environmental agreements and laws. In the three decades since, several authors have questioned if sustainability alone is sufficient to ensure a livable future for a rapidly growing human population[153-155]. In fact, the last decades witnessed a radical exploitation of natural resources, a mass extinction of species and a destruction of ecological systems[156]. Sustainability, focusing on resource efficiency and minimizing environmental damage and human health risks may slow down or halt the degradation of the planet's natural systems, but seems unable to solve the pressing problems of an already seriously disturbed planet.

Regenerative design and regenerative development directly address the shortcomings of the sustainability paradigm. Lyle (1996)[14] defines regenerative design as the replacement of linear systems of throughput flows with "cyclical flows at sources, consumption centers, and sinks." Mang and Reed (2012)[86] distinguish regenerative development from design. Regenerative design entails active building of the self-renewing system components. Regenerative development is twofold: identification of phenomena for fruitful regenerative design and cultivation of evolving systems in which users become designers, thus integrating design to the regenerative system. The historical foundations of regenerative design and development are comprehensively covered by Akturk (2016)[92]. As outlined by Mang and Reed in *Regenerative Development and Design*[86] the regenerative approach is directly based on McHarg's book *Design with Nature*[157] which lays the foundation for the ecological view of urban landscape design. Much of the inspiration for regenerative design is drawn from the relationships and adaptations of indigenous peoples to their ecosystems[157]. Mollison and Holmgren developed permaculture as an ecological design system to promote design of human habitats and food production systems based on the relationships found in natural ecological communities see Mollison (1988)[33] for a deeper discussion of permaculture. Although these approaches already contain many regenerative aspects, regenerative design and development did not emerge as an independent discipline until the 1990s. Lyle's *Regenerative Design for Sustainable Development*[14] provided the first comprehensive articulation of, and handbook for regenerative design. It laid out the framework, principles and strategies for a design system aimed at reversing the environmental damage caused by what Lyle called "industrial land use practices". Regenerative systems provide for "continuous replacement, through [their] own functional processes, of the energy and materials used in their operation."

Regenesis Group extend regenerative concepts from design to create the theoretical and technological foundation for regenerative development, forming the distinction stated above. A typical example of regenerative development as articulated by Regenesis and Lyle is the role of humans as influential participants in the health of the earth's web of living systems[86]. As Cole (2012)[158] puts it, this runs anathema to the Cartesian-Newtonian worldview dominant in western-globalized societies, which "implicitly places human enterprise dominant over and essentially independent of nature". Regenerative approaches seek not only to reverse the degeneration of the earth's natural systems, but also to design human systems that can coevolve with natural systems – evolve in a way that generates mutual benefits and greater overall resilience[86].

In recent years, a number of design tools and frameworks were established to support regenerative design and developmental processes. Akturk (2016)[92] gives a summary of five well-established tools: REGEN, Eco-Balance, LENSES, Perkins+Will Framework, and Living Building Challenge. That comparative study concludes that LENSES is the most comprehensive tool in addressing regenerative goals and the only one that is developed as a process-based approach as well as a metrics tool.

The LENSES (Living Environments in Natural, Social, and Economic Systems) Framework was developed by the Institute for Built Environment at Colorado State University and the Rocky Mountain Institute to be "a guidance tool that will lead users to appropriate, contextual, and regenerative decisions and actions"[159]. Currently, it is managed by CLEAR (Center for Living Environments and Regeneration). The intention of this framework is "to shift mind-sets toward regenerative thinking and to inspire positive action throughout the life cycle of a project". It focuses on 'descriptive metrics' instead of 'prescriptive metrics' and can be applied across project types on all scales[86]. Specific solutions are not predetermined; the framework rather assists people through an intentional process of discovery and allows access to a range of tools, as exemplified by the variety of configurations presented in previous studies[159-161].

2.1.3 Main aim of this research

The hypothesis of this study is that LRBs effectively fulfil the above definition of regenerative design and development[86]. It aims to evaluate how far and in which aspects this is the case. With this in mind, LENSES – applied here as a metrics tool using the Rubrics worksheets – was chosen as a methodical basis for the study.

2.2 Materials and Methods

2.2.1 Developing an appropriate metric tool

LENSES is a system made up of three interrelated layers or 'lenses', each acting as a visual aid to help ground concepts. The three lenses – vitality lens, flows lens and foundations lens – perform individual functions. The main aim of the vitality lens is to identify degenerative, sustainable and regenerative (DSR) aspects as well as leverage points within the design process of a project. The flows lens promotes a deep understanding of the context of a project with a focus on key patterns and relationships. Graphically, it shows interrelated aspects of a system that make up the whole. The foundation lens is designed to engage users in creating a shared sense of commitment, to define guiding principles within the context of a project. Two lenses – vitality and foundations lenses – refer more to the planning process, while the flows lens has a greater focus on project assessment. As mentioned above, this study is specifically focused on assessment. Therefore, only the flows lens, and within it the LENSES Rubrics tool is used here.

The flows lens groups focal points into flows. CLEAR [162] provides 11 flows, which are detailed in the Rubrics. It also suggests adding or taking away flows, according to need. In general CLEAR describes the structure of the three lenses less as a fixed system and more as an open source resource.

The flows relevant to LRBs were discovered during the evaluation process. They are described and further explained in section 2.2.2.

The LENSES Rubrics are charts providing a qualitative analysis of focal points within each flow[162]. The main aims of the Rubrics are to evaluate the project's existing state, acknowledge areas for improvement, and continually assess the impact of project decisions. They can be used either in concert with the LENSES process or as a stand-alone resource to establish an understanding of what characteristics and qualities define DSR aspects of a project. They are used here for the latter function, continual assessment of decisions is not a focus of this study (see discussion). Within the Rubrics, statements that range from degenerative to regenerative are provided for each focal point, against which the user evaluates the project. Figure 2.2e shows the Rubric worksheet for the flow 'Beauty' as an example. For each focal point, relevant statements in the Rubrics were highlighted by the authors. From this, a position on the DSR spectrum was identified. Whenever statements from the Rubrics worksheets are directly quoted in the text, they are put in quotation marks without giving further references.

During the evaluation it became clear that the assessment results largely depend on the user perspective. Two key perspectives were identified: the traditional makers and users on the one hand and the globalized viewpoint of researchers or tourists on the other. To provide a basic understanding of the balance of these perspectives, Table 2.1 shows the proportion of bridges impacted by tourism. These contrasting perspectives are useful in analysis, though it must be stated that they are a theoretical assumption. They don't represent a true user experience since this depends upon a complex mix of cultural, social and technological inputs. In Figure 2.2e, examples of sections of text relevant to each of these perspectives are marked in red. For discussion of this perspective with respect to the regenerative paradigm, compare Du Plessis (2012) and Gladwin et al (1997)[85, 163].

The authors chose to include these potentially contrasting perspectives, which led to occasionally contradictory results. To represent the system as a whole whilst preserving the contradictions present within each focal point a new graphic representation was developed. Each focal point is shown as a circle segment which together form a whole circle, similar to the petals in the CLEAR flow lens[97]. The evaluated position is represented with a black line and the range of relevant statements is shaded. Narrow shading represented less ambiguity in the results. For example, Figure 2.10 shows four focal points – Outdoor Comfort & Microclimate is less ambiguously regenerative than Equity & Inclusivity or Physical, Mental and Spiritual Balance, while Healthy Lifestyles is the most ambiguous. The aim of the diagram is to retain detail whilst allowing a summative view. Figure 2.2 shows the aspects of LENSES used in this study and how the system was adapted. The numerical values given in the original Rubrics (-3 for degenerative, 0 for sustainable, +3 for regenerative) were thought to infer a precision that is both unnecessary in this study and misleading.

The basics of the LENSES Rubrics evaluation process in this study are the two aforementioned research expeditions conducted by the first author. The selection of relevant flows as well as the evaluations of the focal points are based on seven semi-structured grounded interviews and on personal observations, as mentioned in Ludwig et al (2019)[74]. Due to the highly specific context, the interviews cannot be published without compromising the interviewees' identities. The evaluation was conducted by a landscape architect specializing in Regenerative Design (Author 2, see Kashkooli et al[164]), an architect specialized in Living Architecture (Author 4, see Ludwig (2016)[165]), and a civil engineer specialized in structural aspects of LRBs (Author 1, see Ludwig et al (2019)[74]) and supported later by an architect and researcher specialized in LRB ecosystem conservation and development (Author 3, see Shankar[142]).

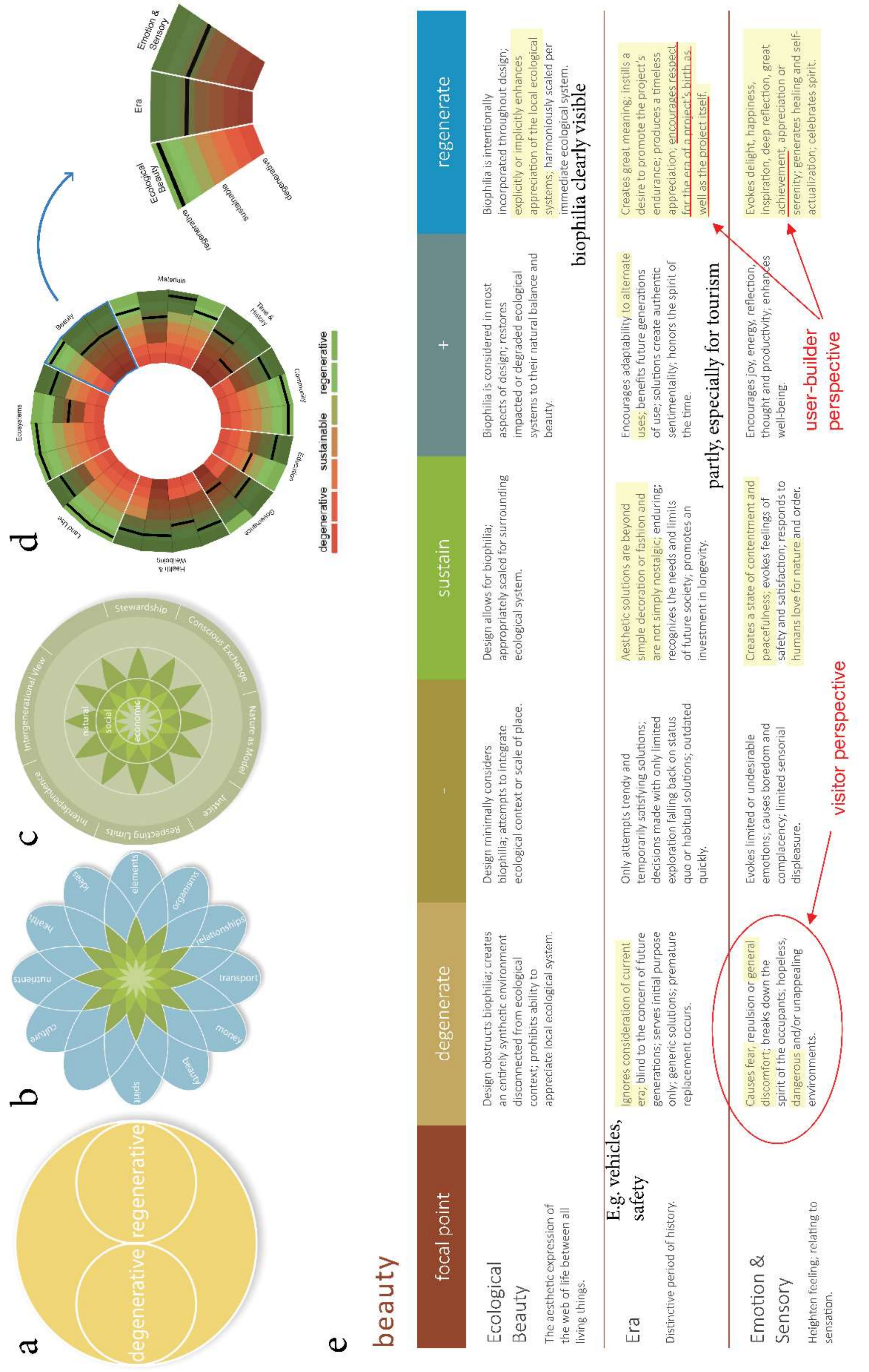

Figure 2.2. Of the three lenses provided, (a) the vitality lens and (c) the foundations lens, were not used, while (b) the flows lens was used in conjunction with (e) the LENSES Rubrics. A new diagram (d) was formed of flow segments to present the results.

2.2.2 Selected flows

Of the 11 flows provided by CLEAR[162] seven were found to be relevant, namely Beauty, Community, Ecosystems, Education, Health and Wellbeing, Land Use and Materials. Each of these flows holds within it between two and four focal points. The four flows Energy, Money, Transportation and Water were excluded. The Rubrics charts approach these flows from a perspective irrelevant to LRBs. Water and Energy are approached from the point of view of a contemporary (e.g. residential) building, assuming a demand for these resources to fulfil the daily needs of the users. A bridge does not consume energy or water in the conventional sense (energy for heating and cooling or water for washing and cooking) Nonetheless water is clearly relevant to LRBs since monsoon rainfall, humidity and soil moisture are important parameters. These aspects are covered in other flows (for example, flooding is addressed in the Ecosystems flow). Transportation is understood in the Rubrics charts from an urban perspective, for example inspecting public transport availability. In a remote forest location with, in many cases, almost no modern forms of transport present these arguments are not applicable. A similar situation occurs in the flow Money. While money from the tourist industry has a major influence on some bridges/communities, the worksheet appears inadequate for a full evaluation of a system that traditionally has no direct financial element.

LENSES encourages users to form new flows, two of which were made here: Governance and Time & History. Time & History is an important aspect of an approach that entails multigenerational efforts and long term growth processes. Governance structures underpin the shared responsibility for communal, long-term projects. Within these new flows, focal points were developed and evaluated, comparable to the standard Rubrics charts. The resulting worksheets are presented in the supplementary information. Within some of the provided flows, some focal points were added or taken away where necessary. This results in a total of nine flows made up of 27 focal points, five of which were added by the authors. Focal point selection is detailed and explained in section 2.3.2.

2.3 Results

2.3.1 Overview of results

Figure 2.3 shows the complete results of the Rubric analysis by focal points, arranged in flows. Flows that seem to have strong interdependences are arranged next to each other (e.g. Ecosystems and Land Use). Of the 27 focal points analyzed, 11 were found to be unambiguous (ten regenerative, one sustainable). 16 were ambiguous (relevant statements were found in more than one Rubric category). Of these, three were generally regenerative, one was regenerative/sustainable and 12 had aspects ranging from regenerative to degenerative. While no entire flow is unambiguously regenerative, Land Use, Ecosystems, and Education show only minor variations. Only Usability in Time (Time & History flow) and Opportunities for Change (Governance flow) are degenerative. Diversity (Ecosystems flow) and Relationships (Education flow) are sustainable. Below is a breakdown of the results by focal point. In section 2.3.2 the assessments of individual flows are detailed for each focal point.

2.3.2 LENSES Rubrics evaluation results

2.3.2.1 Beauty

Three focal points are considered: Ecological Beauty, which refers to the aesthetic expression of coherence within ecosystems (and the associated biophilia); Era, which relates to the balance between modernizing and traditional aesthetics; and Emotional and Sensory Beauty which describes feelings and sensations when using the bridge. The first two focal points are mainly visual judgements, while the third includes considerations of the other senses.

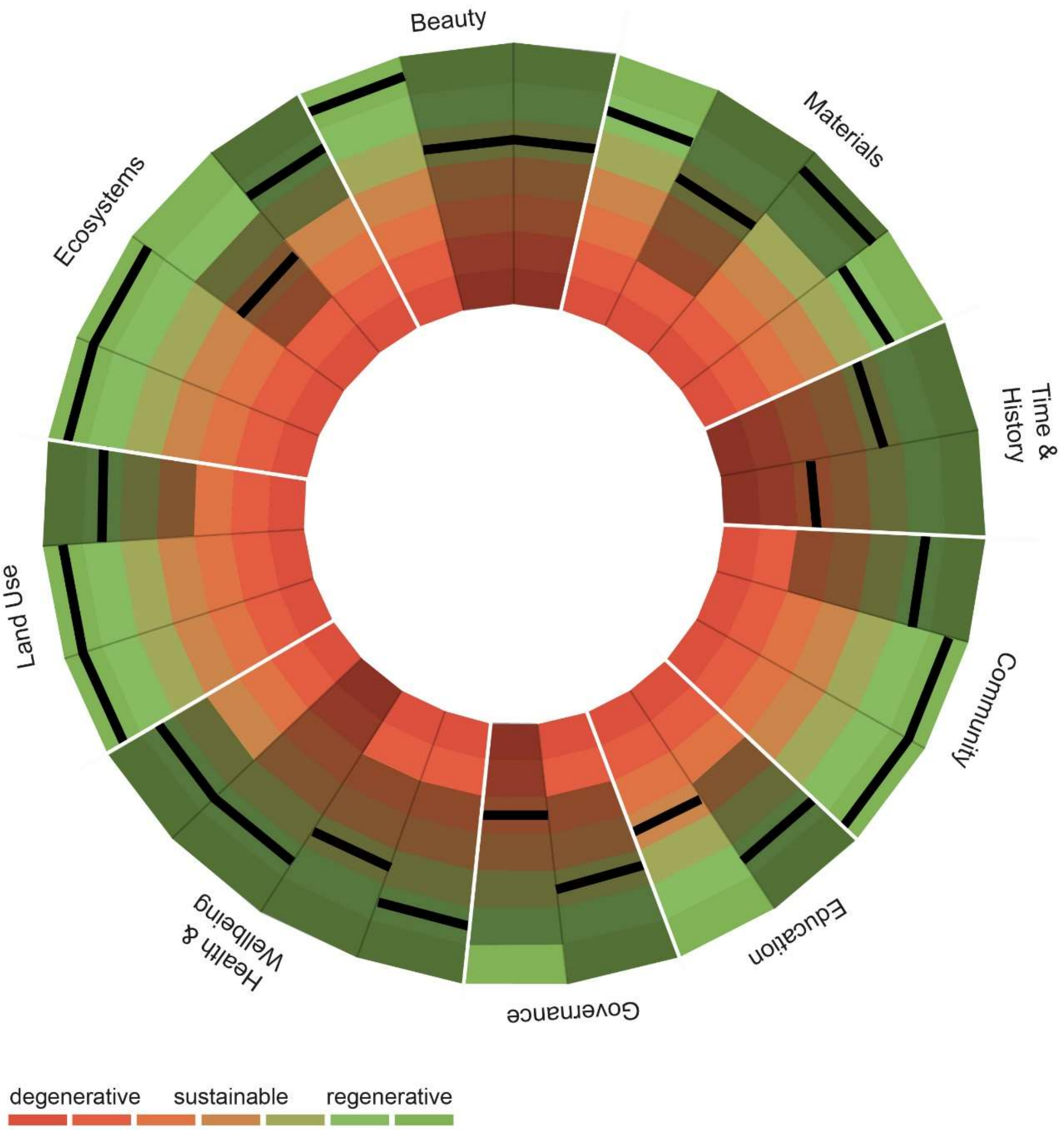

Figure 2.3. Summative circular presentation of the Rubrics evaluation, based on the flows lens.

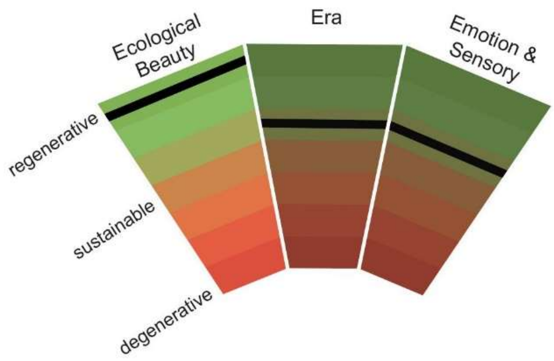

Figure 2.4. Evaluation results of the Beauty flow and its focal points

Ecological Beauty: clearly regenerative

Biophilic characteristics are clearly visible in LRBs. All key LRB building materials arise from the local ecosystem, naturally supporting the growth of epiphytes and other flora and fauna (Figure 2.8a), forming pristine natural sites of ecological beauty. In doing so, LRBs "explicitly or implicitly enhance appreciation of local ecological systems". Three of the bridges documented in Ludwig et al (2019)[74] that have become tourist hotspots rely on imported materials to improve accessibility (mostly concrete and steel). This negatively effects the ecological beauty of the place. Since this use of imported materials relates mainly to access paths and not within the bridges themselves and is an extremely recent phenomenon (in use for not more than 10-20 years), this aspect was not considered in the present evaluation (see Table 2.1 and discussion).

Era: contradictory, regenerative aspects predominate, degenerative aspects are present

LRBs are deeply ingrained in local traditions, which holds an aesthetic value. In the Rubric's terms, this "encourages respect for the era of [the] project's birth" and "produces a timeless appreciation". In Meghalaya, the discourse around environmentalism is developing and embodied by LRBs, a discourse which "promotes the project's endurance". However, the bridges rarely benefit from contemporary materials or technologies and lack "consideration of current era" and do not entirely "honor the spirit of the time", contrasting with the steel bridges built around Meghalaya, which have a grand, modern aesthetic (see Figure 2.5a). An ongoing discussion around sustainability could give LRBs more relevance in the current era. Contemporary materials are occasionally integrated into LRBs – steel wires and concrete sections can support weak bridges, though these are rare – in total the authors have noted eight bridges with concrete or steel parts integrated for accessibility reasons and two for structural reasons. Three of these are due to an influx of tourists (see above), the other seven are to help a young or failing bridge. The technologies of the current era are also not considered, since LRBs are not used by (and have never been designed for) vehicular traffic and are not covered by contemporary building standards.

Figure 2.5. Two contrasting aesthetics: (a) the steel bridge towards Nongriat village can be described as modern, efficient and professional; (b) the traditional Wah Thyllong bridge can be seen as an example of the Ecological Beauty of LRBs. The bank reinforcement and railing made of imported Cherra stone and painted reinforced concrete (imitating bamboo) illustrate a break with this tradition.

Emotion and Sensory: clearly regenerative with minor sustainable and degenerative aspects

There are some clear emotional and sensory drawbacks to LRBs. Especially to tourists and non-locals some bridges can appear as quite unsafe structures (particularly when not well kept or crossing deep canyons), thus LRBs can "cause fear [and] general discomfort" and indeed are sometimes perceived as a "dangerous environment". Regarding this it has to be added that steel and concrete bridges without due maintenance can cause the same fear – in fact many such examples exist in the region. Aside from this, LRBs can "create a state of contentment and peacefulness", "respond to human love for nature", and can evoke senses of "reflection", "achievement" and "serenity".

2.3.2.2 Community

The three focal points of the Community flow are concerned with understanding the impact a project will have on the people who use it.

Defining Community: clearly regenerative with some slightly degenerative aspects

'Defining Community' can be described as a project's capacity to identify and integrate relevant stakeholders and their views. In traditional use, LRBs are often well integrated with their communities (a village, family, or consortium of villages) because of their essential maintenance requirements (typically a "user-upkeep" system, see Figure 2.6b). In fact, embedment in a user community is a precondition for LRBs to develop successfully because of the high time and effort investment in their construction and maintenance. As Shankar[142] puts it, periodic maintenance "ensures a continual relationship between the living bridge and the local community". In some cases, new growth has been seen to reduce as a bridge ages, requiring reduced maintenance in root-guidance. Their construction typically requires no money to buy externally sourced materials or external expertise. Most users have input into the maintenance regime, and thus "stakeholders are … an accurate representation of the community". Though this representation is inherent to the LRBs' construction, it can be undermined by biased community governance structures. The recent exploitation of LRBs by the tourist industry usually involves a small, "self-selected" stakeholder group. Those who speak English or have access to technologies and social connections can benefit, often without generating positive "impact on the [wider] community".

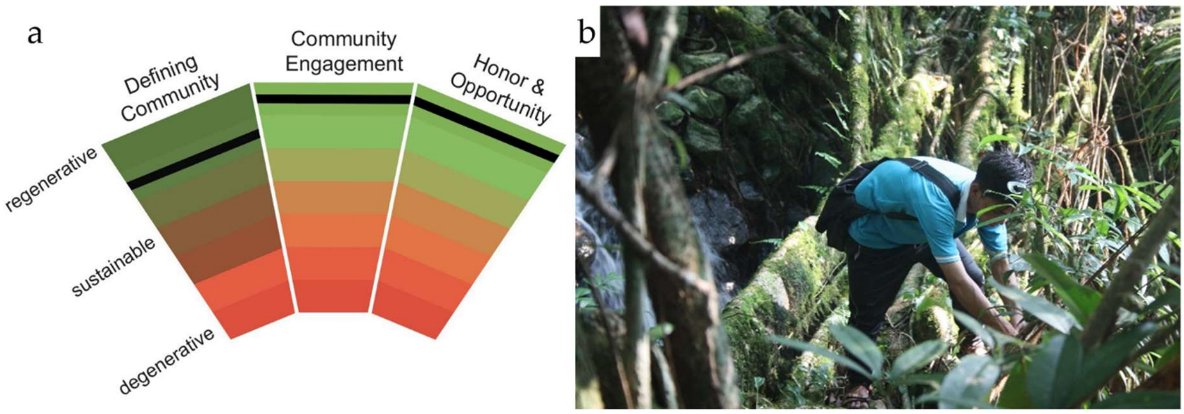

Figure 2.6. (a) Evaluation results of Community and its focal points; (b) a younger resident of Rangthylliang village engaging in LRB maintenance.

Community Engagement: clearly regenerative

LRBs are inherently community projects, requiring good community engagement. The Rubric's rhetoric of bottom-up input does not entirely fit here. However, it is clear that they engage the community well through a variety of systems which depend on local circumstances. As noted in section 2.3.2.8, community participation can suffer when bridge- and landownership are in conflict.

Honor & Opportunity: clearly regenerative

Honor & Opportunity is concerned with an "understanding of local culture" and "creating opportunities through… inclusive decision making". The user-upkeep model engenders "responsibility among community members" and uses an "iterative decision making model".

2.3.2.3 Ecosystems

The four focal points (Figure 2.7) defined by the Ecosystems Rubric apply well to LRBs. These are: Compatibility, through which plant, animal and human communities support and reinforce one another; Productivity, which relates to the renewal of 'natural capital stocks' for ecosystem service provision; Diversity of species and populations; and Adaptability, understood here as the ability of a species, population, community and/or ecosystem to withstand and recover from internally or externally imposed changes or stresses.

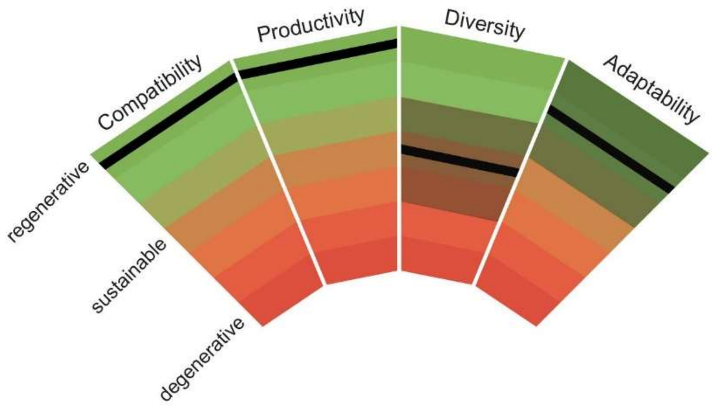

Figure 2.7. Evaluation results of the Ecosystems flow and its focal points

Compatibility: clearly regenerative

The focal point Compatibility describes a regenerative project as allowing "plant, animal and human communities to renew and revitalize their own sources of energy". Energy is not as immediately important in LRBs as in other projects since the only direct energy inputs are through manual labor and sunlight (see materials and methods). By replacing "energy" with "materials" (the end result of energy input in many construction projects), it is clear that the bridges can be described as fully regenerative, especially because they also "enhance the interconnectedness and interdependence of systems, allowing the ecosystem to thrive".

Productivity: clearly regenerative

By providing villagers with access to remote farmland (that other bridge types cannot access) an LRB "actively promotes and manages capital stock". Thereby they also are "catalysts for a healthy society and productive economic system" and therefore can be described as highly regenerative.

Diversity: sustainable with some regenerative and some potentially degenerative aspects

By planting *F. elastica* bridge-builders are using a potentially native tree[74, 79] that is described as a keystone species[166]. From this point of view it can be stated that they "bring new life and vitality to an area" (regenerative). But since this often happens within forests of high biodiversity[167] with many *F. elastica* specimens it can also be stated that LRBs help to "preserve existing diversity" (sustainable). These conflicting perspectives are thus influenced by highly localized conditions. Additionally, the maintenance process can reduce biodiversity through the removal of plants growing on the bridges (See Figure 2.8a). Since this is as a purely manual (not chemical) process and a common practice in a managed forest used for agro-forestry it is not seen as degenerative here. Localized ecological studies are required for a more fundamental understanding of the biodiversity impact of LRBs.

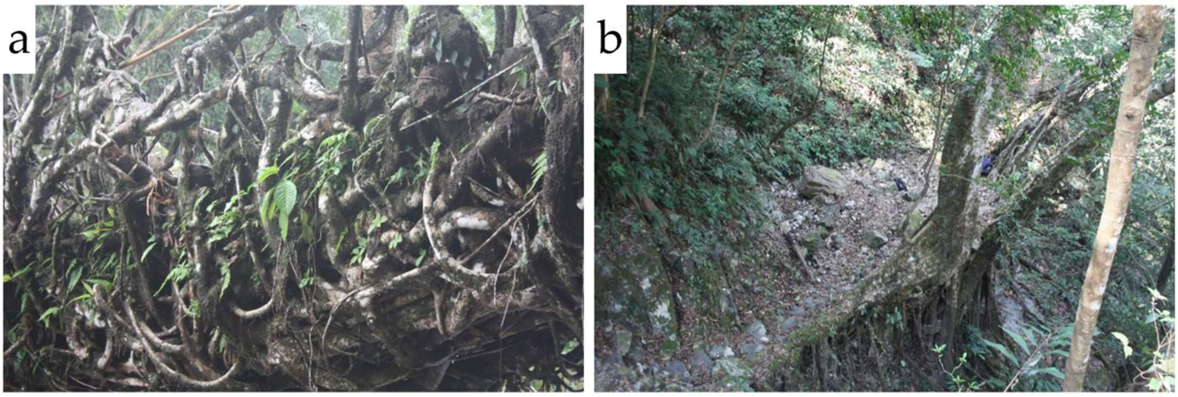

Figure 2.8. (a) Epiphytes are regularly cleaned from Wah Thyllong bridge, possibly inhibiting local ecosystem diversity. However, LRBs can also help ecosystems adapt to changes: (b) the parent tree of a bridge below Mawlam village held back a landslide (possibly caused by deforestation).

Adaptability: mainly regenerative

As integral parts of local ecosystems LRBs express high adaptability especially through their potential to recover after being damaged by, for example, landslides or floods. By stabilizing the soil with their root system they can even protect hillsides from landslides (see Figure 2.8b). In doing so, they "improve ecological resilience, making ecosystems able to adjust to most environmental changes". By providing access to productive forests, LRBs "support the sustainable harvest of a variety of renewable resources". As in all ecosystems their adaptability is limited to a certain degree. Members of bridge-building communities report bridges destroyed by flash floods and by fire – an environmental impact that seems to put them at particular risk especially during the dry season. Altogether it can be stated that LRBs show a high adaptability to some but not all relevant environmental factors.

2.3.2.4 Education

As the bridges are not grown with an explicit educational purpose in mind, two of the Rubric's focal points (Learning Space and Outcomes) were excluded here. Information & Skills Transfer and Relationships are considered (Figure 2.9).

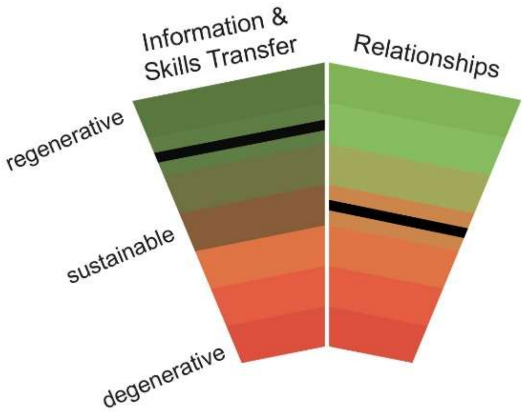

Figure 2.9. Evaluation results for the Education flow and its two considered focal points.

Information and Skills Transfer: regenerative as well as sustainable aspects

LRB growth techniques are passed down over generations within small, rural communities, often directly from parent to child. The transfer of these skills is extremely "hands-on" and "interactive". However, conflicts between villages have resulted in several cases of neighboring villages not sharing techniques. Furthermore, there is no formal system for knowledge transfer, which may be inhibitive.

Relationships: sustainable

Personal, organizational, and community relationships vary between villages. Bridge ownership, maintenance and use structures come in many forms, from village consortia to individual village ownership, to smaller groups, and even private ownership. Within these structures, bridge building and maintenance is a deeply collaborative project, and "trust between players creates opportunities for communication and learning". However, some examples show that this inherent collaboration can quickly break down if a bridge is owned by only some of its users.

2.3.2.5 Health and Wellbeing

The Health and Wellbeing Rubric provides three focal points: Physical, Mental & Spiritual Balance, Equity & Inclusivity, and Healthy Lifestyles. As LRBs are first and foremost outdoor green infrastructures, a fourth focal point was added: Outdoor Comfort & Microclimate (Figure 2.10).

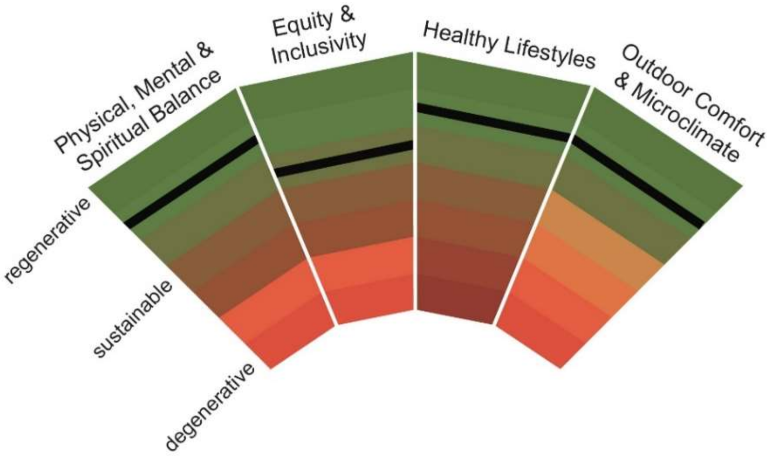

Figure 2.10. Evaluation results for the Health & Wellbeing flow and its focal points.

Physical, Mental & Spiritual Balance: mainly regenerative with some degenerative aspects

While the "interaction with nature" afforded by LRBs "nurtures… spiritual health and well-being", they are inherently "not easily accessible for most populations", especially disabled or elderly. Here in particular the contrast between different perspectives (as mentioned in the methods section) prominently effects the evaluation results. LRBs are inaccessible, for example, by wheelchairs – a technical device not typically used in rural Khasi villages. Elderly Khasi & Jaintia people are well adapted to the steep topography and can access the bridges more easily. Furthermore, Khasi and Jaintia communities use woven bamboo carriages (on display at the Ever Living Museum, Shillong) to carry disabled people through the landscape and over the bridges. Thus the physical, mental and spiritual balance of LRBs is considered regenerative, though disadvantages must be taken into account.

Equity & Inclusivity: contradictory with regenerative and degenerative aspects

LRBs are, on the one hand, inclusive of "all ages… and income levels" and on the other hand, can be exclusive of the disabled and elderly, particularly of tourists. Thereby they "discourage equal access and diversity." Some efforts have been made to make bridges more accessible in tourist hotspots but their very rural locations limit the effectiveness of these measures. Some bridges have become more accessible due to the recent expansion of the rural road network in Meghalaya[168]. "Cultural, intergenerational, and biological diversity" are promoted within certain limits, with little possibility to integrate external influences.

Healthy Lifestyles: contradictory, strongly regenerative, but also highly degenerative aspects

LRBs do "create opportunities to heighten healthy lifestyles" by promoting physical exercise (particularly for visiting tourists) and "provide opportunities for social interaction… natural light and interactions with nature". However, they are not subject to contemporary safety standards and their load-bearing capacity is not proven using contemporary methods. Therefore LRBs in their early growth stages or when fallen into disrepair can be unsafe "space[s] for physical exercise", particularly for non-accustomed users (compare the role of user perspectives in methods section and discussion, also see Table 2.1 for a list of bridges used by tourists).

Outdoor Comfort & Microclimate: somewhat regenerative

Concerning outdoor comfort, some bridges provide shading (from the tree's canopy) in an otherwise exposed area above the river. Unlike, for example, the cables of steel bridges the natural material doesn't heat up in the sun which makes it comfortable to touch. However, they do not provide shelter from rain, which is torrential in the months of May to August (though this is clearly not the main function of a bridge). In total they certainly do not negatively influence the microclimate of the rainforest and in some cases they benefit the microclimate by covering areas of otherwise bare riverbanks.

2.3.2.6 Land Use

LENSES Rubrics suggests three focal points for land use, namely Natural Land, Building Land and Productive Land (Figure 2.11). Due to their multifunctional character and because of being highly embedded in the ecosystem, a clear separation into these sub-categories is difficult here. To cope with these circumstances, the following assessment uses the proposed arguments only partially and argues more freely.

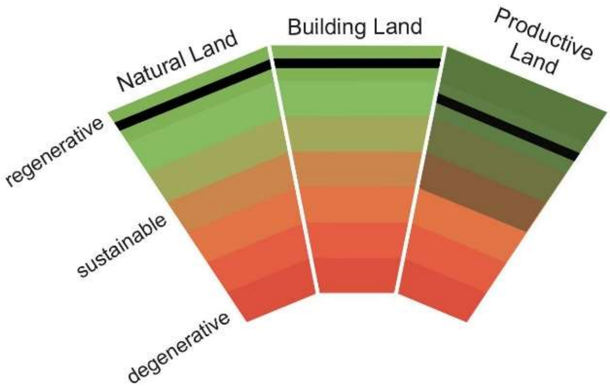

Figure 2.11. Evaluation results for the Land Use flow and its focal points.

Natural Land: highly regenerative

LRBs promote and support the functionality of natural land and provide habitats for native species. They are an integral part of the natural land use and therefore balance natural capital and human land use. Thus, they clearly show a high regenerative potential.

Building Land: highly regenerative

The Rubric focuses here on the interaction of a building with its local environment. As LRBs are grown directly from their environment, they can be considered as clearly regenerative (generating themselves). Traditionally there is no production of waste and they do not release any pollutant on site. Aspects of local history are exhibited through the reliance on several (living and past) generations of builders – indeed, LRBs are testament of a community's long-term presence. As the bridges are entirely grown and maintained by their communities, they "empower local culture with development decisions".

Productive Land: regenerative with some contradictions

LRBs provide access to land that would be unreachable without them (especially during the rainy season). Thereby they enable productive use of land otherwise unused by humans and are integral parts of the agro-forestry system of the Khasi and Jaintia culture. Additionally they offer a supply of latex used for hunting and waterproofing (Figure 2.13b), though over-extraction can kill the tree and destroy the bridge. Today LRBs are becoming "productive" through tourism. This can benefit the communities economically but has clear side effects such as littering and water pollution and unclear long-term socio-economic effects.

2.3.2.7 Materials

The Materials flow is comprised of four focal points: Elegant Simplicity, whereby "no more causes or forces are used beyond being effective"; Health & Wellbeing, understood here as the holistic support of health, comfort, beauty and social responsibility; Environment, considering the multiscalar environmental impact of material selection; and Region, which judges the appropriate use of materials in terms of a place's history, culture, and sense of local identity (Figure 2.12).

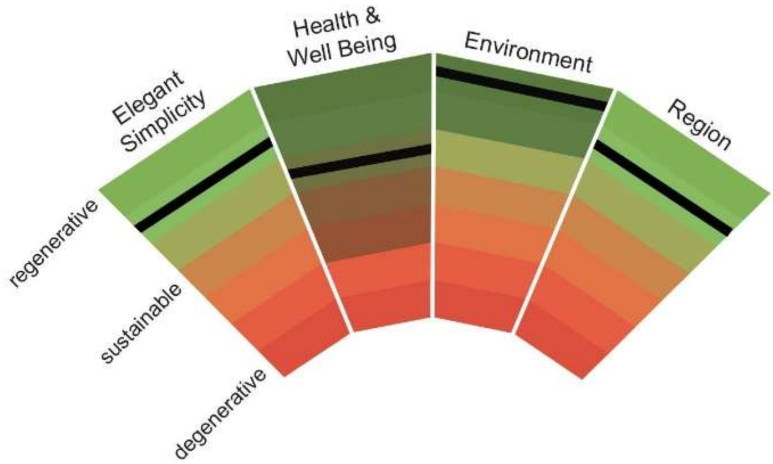

Figure 2.12. Evaluation results for the Materials flow and its focal points

Elegant Simplicity: regenerative

Utilizing just one major material, the living wood of a native species, LRBs "dramatically reduce the use of materials". Bamboo and *Areca catechu* palms, often used in the early stages of growth, are abundant in the surrounding forest (Figure 2.13a and 2.13c). Apart from the flat stones which are sometimes used to form the deck, all building materials are completely biodegradable, directly rejuvenating the local ecosystem. The recent use of steel, concrete, bricks and paint on or nearby some bridges goes against this trend, though this is uncommon and unnecessary in well-maintained bridges.

Health & Wellbeing: contradictory with regenerative and degenerative aspects

LRBs provide, in the words of the Rubric, "inspirational aesthetics, celebrating beauty with a deep connection to nature" – which can clearly be considered regenerative. However, the latex-rich wood of *F. elastica* is prone to fire, and several bridges have burnt down in living memory (Figure 2.13c).

Environment: highly regenerative

The material selection of LRBs is clearly environmentally regenerative, as it "eliminates materials and related processes that contribute to environmental degradation", apart from the recent and uncommon (but increasing) use of steel cables and concrete posts specifically in sites open to tourists. The production, import, use and waste products of these materials can be detrimental to the local and wider environments.

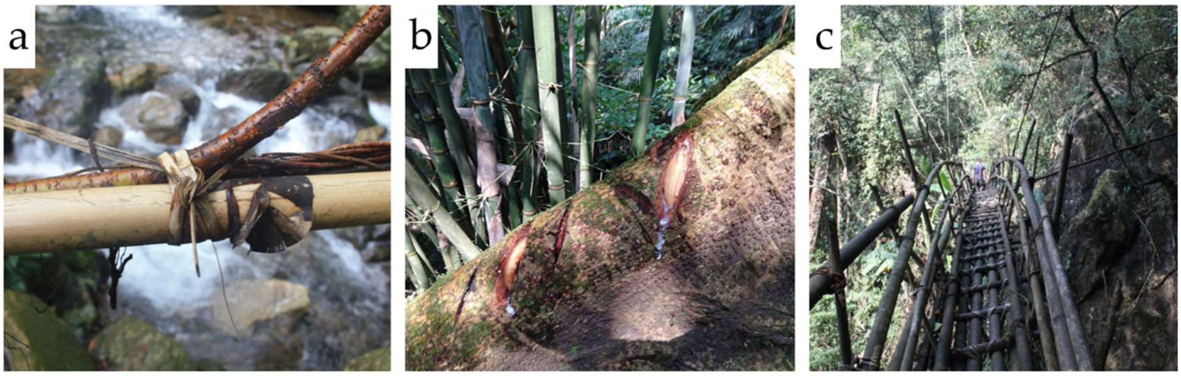

Figure 2.13. LRBs are traditionally made from materials available in the nearby forest: *F. elastica* aerial roots, bamboo and *Areca catechu* palm trunks. (a) shows a root guided along a bamboo scaffold; (b) shows scars from the extraction of latex, used for waterproofing and hunting; (c) is a bridge in Rangthylliang village, which has been rebuilt following its destruction by fire (*F. elastica* is highly flammable).

Region: highly regenerative

The bridges "minimize importation" of materials and "preserve heritage and cultural authenticity" by making use of traditional techniques in bamboo, areca palms and *F. elastica*. This "prompts regional self-sufficiency and long-term economic health" as the farming and tourist industries benefit (from the local community's input) in the long term. The use of *F. elastica* is widespread in Khasi and Jaintia culture, and thus forms part of a wider regional identity. A sense of place is also clear, as the bridges are highly unique.

2.3.2.8 Governance

Governance in LRBs manifests mainly as decision-making in the maintenance process but also includes wider ranging decisions concerning present use and future development. Within governance structures, two focal points were identified: Proportional Voices, concerning the even distribution of decision-making between all stakeholders; and Opportunities for Change, describing the ease with which governance structures can adapt and react to changing conditions and challenges. Over the lifetime of a bridge (up to hundreds of years), relevant governance structures can change dramatically on all levels (e.g. village, municipality, region and state level). Traditionally LRBs mainly had a local economic and societal relevance (providing farm, village, and market access) and therefore have been governed on a local level. Three main systems of bridge ownership and maintenance conventionally dominate: a consortium of villages (*raid*), a single village (*shnong*), and an individual, family or tribe (*kur*)[74, 169]. These do not preclude land ownership – community land (*ri raid*) or private land *ri kynti* - all translations taken from Sarma (2010)[169]. This can lead to conflicts between bridge- and land-owners and thereby can influence community participation. With Meghalaya's special status under the Constitution of India and with the recent onset of tourism, LRBs are gaining wider recognition and regional governance structures are becoming more influential.

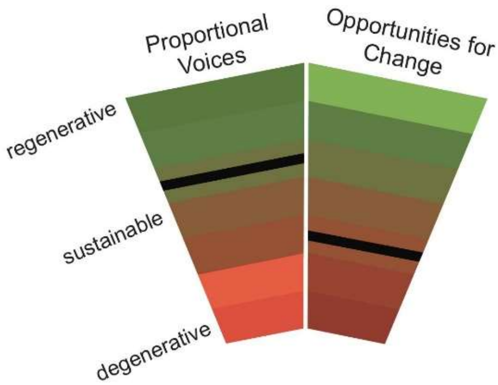

Figure 2.14. Evaluation results for the Governance flow and its focal points.

Proportional Voices: regenerative with degenerative aspects

The majority of maintenance decisions are made on the day-to-day basis, with users contributing to maintenance. Thus, decisions can be said to be built over "rounds of consultation" through the bridge growth process, giving all users the opportunity to contribute. Additionally, there are larger decisions like adding reinforcements, replacing a bridge, changing the accessibility or charging tourists to visit, that are in the end made by the owners or regional authorities, which is not an inherently proportional system. At the village level some representational structures exist such as village committees led by the village headman. The election of the headman varies between villages and the process is not standardized across the region. However, most user communities are small enough to allow shared agreement that represents the majority of stakeholders.

An important issue in regenerative design and development is to take an intergenerational perspective, taking into account the voices of children and descendants, often a minority or even unrepresented voice. With their long growth periods LRBs are inherently aimed at providing a service for future users and thereby provide an excellent example for giving future generations a voice.

Opportunities for Change: contradictory with degenerative aspects dominating

Like a lot of traditional communities around the world, many Khasi and Jaintia communities are witnessing fundamental societal change. In the context of economic development, roads and other technical infrastructures are built throughout the region often by the state or autonomous regional government. Increased formal education and opportunities has led to greater numbers of young people leaving the villages. At the same time well-preserved natural heritage and especially the LRBs have in recent years attracted growing numbers of tourists, which has had a fundamental social and economic impact. The traditional governance structures for LRBs in Meghalaya obviously are not built to cope with these changes.

Community governance structures regarding the bridges differ between villages and are not well coordinated. Therefore, their ability to engage with regional and supra-regional changes is quite limited. In some cases, the literate younger generation clearly sees the opportunities and challenges coming with tourism and may have more adequate skills to deal with them. However, the village headman system very often empowers the elderly (of certain families) who may be less able to deal with tourism due to language and entrepreneurial requirements. In recent years, a number of entrepreneurial groups (some are notably intergenerational) have emerged to overcome these barriers. The focus of these initiatives is on eco-tourism making use of LRBs as local heritage and engaging young people in maintaining and building new LRBs. Such shifts can lead to intergenerational conflicts over ownership.

In summary this shows that there are some opportunities for change in governance but the traditional system in power today has some limitations. At the same time, the new initiatives only represent a minority within concerned communities.

2.3.2.9 Time & History

Two focal points were developed within Time & History: Historical Narrative, which balances the community's traditional and progressive values to form a coherent story, and Usability in Time, which understands the yield of the project over its lifetime (Figure 2.15).

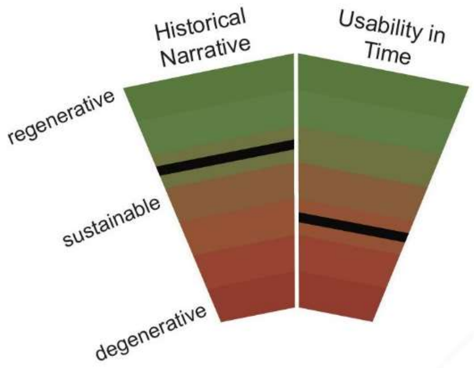

Figure 2.15. Evaluation results for the Time & History flow and its focal points.

Historical Narrative: contradictory with degenerative and regenerative aspects

While LRBs form a major part of traditional village narratives and thus "integrate community history and environment", they make a mixed contribution to a progressive narrative. As described above many remote areas of the Khasi and Jaintia Hills have been recently linked to the outside world and discovered the benefits of contemporary technologies, including steel and concrete bridges which are thought to be strong, safe and easily built. In reality numerous concrete and steel bridges are in poor condition and unmaintained. They can degrade quickly and become unsafe. Nonetheless LRBs are seen as technically outmoded, representing an admirable history but not a future development solution. This causes a strong disruption in the narrative. On the other hand, protecting the environment is valued both traditionally and in contemporary society. In this context LRBs are seen as a form of architecture which sets an example for future development and contributes to a progressive narrative.

Usability in Time: mixed regenerative and degenerative aspects

Since LRBs require many years to grow into a stable structure, they cannot be used in the short- but only in the long-term. Bridge builders traditionally try to overcome this delay by making the temporary bamboo scaffolding accessible (see Figure 2.13c). Despite a very quick construction, maintenance is time consuming as the bamboo rots quickly and has to be replaced every few years. However, once established, LRBs can be extended in use, growing stronger and safer with time. Several older bridges have wider, flatter gangways that can be used by a wider range of people (Figure 2.16a). Others show secondary decks, which have been grown to accommodate additional (pedestrian) traffic or in order to have uninterrupted use of the bridge during floods (Figure 2.16b).

Figure 2.16. (a) Wah Thyllong bridge connecting Nohwet and Riwai villages has a wide and comfortable gangway. (b) A second deck was established on Nongriat Double Decker bridge. According to local residents the upper deck was grown to allow the use of the bridge when the lower deck was flooded (photo: Patrick Rogers).

2.4 Discussion

In the following we discuss the benefits and drawbacks of LENSES as a tool to analyze LRBs on the DSR spectrum. Furthermore we provide the broader context in which this study lies and discuss future research directions.

2.4.1 Suitability of LENSES Rubrics for this study

Qualitative tools such as LENSES Rubrics deliver results based on the subjective assessment of the authors and can therefore only be generalized to a limited extent. Through the intensive discussion of all individual aspects between the authors, who view LRBs from very different cultural and disciplinary contexts, an attempt was made to obtain a holistic assessment. One benefit of this multifaceted focal-point analysis is that the impact of judgement errors (due to potential knowledge gaps) is reduced. The increased detail led to some overlap of specific focal points and flows (e.g. Health and Wellbeing as a flow and also as a focal point in the flow 'Materials'). Some redundancy is caused, but approaching each aspect from multiple angles led to new insights relevant to a complete understanding.

The structure of flows and focal points proposed by CLEAR led to the result that highly relevant aspects, such as safety, only appear as partial aspects of different focal points; integrated throughout the framework, not explicitly expressed. Safety is quite degenerative in LRBs, but the focal points in which it appears are only found to be contradictory overall, which could mislead users. A conflict clearly arises here between contemporary notions of safety as the highest and first priority of built projects and the holism of the LENSES framework. A second round of assessment could integrate a single focal point or flow, named 'Safety and Reliability', which might go some way to solving this.

Another challenge in the application of LENSES Rubrics was that the tool is clearly developed for projects in a more urban context and thus for at least partially degenerated ecological conditions and extremely different social conditions. As shown in the methods section, the authors reacted to this by selecting only the most appropriate flows and introducing new ones. Nevertheless, in the case of Biodiversity, for example, the problem arose that LRBs cannot make a major contribution to increasing biodiversity in a forest area of already high biodiversity and were therefore not classified as clearly regenerative. In a biologically degraded or heavily built-up context, this would be quite different. It is important to reiterate that the traditional worldview of rural Khasi communities includes non-mechanistic, holistic themes, resonating well with the regenerative approach[144, 145].

2.4.2 Discussion of comparable methodological approaches

This study applies a practitioners' tool (LENSES Rubrics) that has arisen from the academic literature of regenerative development and design[159-161]. While regeneration, regrowth, and renewal are the defining features and key terms of the regenerative paradigm, there are many examples of tools within the wider sustainability literature that enable regeneration without explicitly naming it. Regenerative themes (e.g. biophilia, system harmony) are often present. Two such approaches are briefly presented here to discuss the present study in a broader academic context.

Sharma (2015)[170] discusses city greening methods with respect to 'landscape synergism'. They focus on an urban greening technique called "greenways" that utilizes existing (often blue/green) linear areas as multifunctional landscape features. This approach aims to create synergies by minimizing changes to functioning ecosystems while embedding human systems. For example, streams through urban areas form the basis of cycle and pedestrian routes[171, 172]. As synergistic co-existence of social and ecological functions, LRBs are genuine examples of landscape synergism. The systems-oriented framework of landscape synergism provides a strong link between design and analysis. Thus, integration of regenerative and landscape synergism approaches could provide a structure for holistic, design-applicable analysis that helps foresee and avoid potential degenerative side effects.

Ecological land-use complementation (ELC) is a framework through which planners promote biodiversity through land use combinations[173]. In effect, this builds on known regenerative aspects of a landscape, with a focus on ecology. This approach aims to promote resilient systems, a key feature of regenerative design. Design tools such as ELC may be useful in combination with the multi-flow view provided in a LENSES Rubrics analysis in order to integrate multifunctionality in a holistic approach beyond ecology. The conceptual framework developed by Hansen and Pauleit (2014)[176] for multifunctionality in green infrastructure planning points in this direction.

LENSES Rubrics have been used here to describe LRBs as a vernacular form of living architecture in their current context. So far tools for regenerative design and development have not been applied to adapt vernacular systems to a modernizing context. Outside of the regenerative design movement examples of comparable transition processes can be found in the architectural practice. Anna Heringer's DESI training center, for example, demonstrates how vernacular technologies can be adapted to changing pressures by improving their strengths and overcoming their weaknesses. In this project traditional clay building techniques have been further developed to create a modern type of building – a school – based on the knowledge and social networks of all involved stakeholders, underpinned by state of the art design approaches[175, 176]. A comparable approach is conceivable for LRBs.

In addition to such a local adaptation our LENSES analysis can enable LRBs to become concept generators for regenerative design projects as well as modern forms of living architecture in different contexts. An example of such a transfer is permaculture which makes vernacular forms of agriculture applicable in globalized societies[177]. Ferreira et al (2013)[178] describe Sunspaces, a regenerative vernacular microclimatic technology, and discuss its extraction and utilization in contemporary architecture. In order to preserve the regenerative aspects in such transfers a close consideration of the systems between which the technologies are transferred is essential. In this process LENSES Rubrics can also be applied iteratively to assess the transfer's success.

2.5 Conclusion

The evaluation of LRBs with the LENSES Rubrics tool led to a significantly deeper understanding of the technological, ecological and societal conditions under which they arise. The fact that most focal points were assessed as regenerative confirms the initial hypothesis. Nonetheless, degenerative aspects were identified. The partially inadequate safety and limited reliability in early years of growth are particularly clear degenerative aspects which became apparent in a number of focal points. The questions raised in the LENSES Rubrics worksheets contributed significantly to identifying these points. These findings provide a good basis for possible future attempts to overcome current economic, social, and environmental pressures on LRBs. While LRBs have so far been used almost exclusively by the local population to reach fields, markets and neighboring villages, they are currently being used increasingly by tourists or are themselves becoming a tourist attraction. Thus, while they are a potential source of income for the local population, the visit of several hundred tourists per day creates a usage pressure which can significantly damage the bridges and the related ecosystems. Government, private and NGO initiatives are being developed to use and grow LRBs in the context of eco-tourism[142, 179] In this context, the present study reveals that the historically grown social structures face enormous challenges. The passing down of knowledge between generations is an essential traditional social structure for the bridges' future, but new challenges in a changing society require new structures, particularly in negotiating with parties from outside the community such as governments, tourists and businesspeople. Safety and reliability must be improved for tourist use. The potential of contemporary innovative design and engineering tools to improve the safety, stability, ecosystem-services, and longevity of LRBs should be linked as synergistically as possible with traditional approaches see the Baubotanik approach, discussed by Ludwig (2016)[165]. In helping this transformation process, tools such as LENSES offer an adequate base but need to be adapted for specific conditions. With the inventory and assessment of the status quo this study can offer a starting point for such a developmental process. Additionally, this study is a first attempt to analyze vernacular architecture systematically through regenerative design and development thinking, and as such goes some way to establishing a methodological basis for further studies and applications.

Chapter 3

Representing living architecture through skeleton reconstruction from point clouds

This chapter was first published under the same title in *Scientific Reports* in 2022, with co-authors Qiguan Shu and Ferdinand Ludwig. This version includes minor formatting edits. The source code is available at: https://github.com/QiguanShu/skeleton-abstraction-of-point-cloud-by-voxel-thinning and the Freiburg pavilion, Ficus joint and Baubotanik joint PCs are available at: https://mediatum.ub.tum.de/1637267.

3.1 Introduction

Living architecture, created by shaping and merging trees encompasses vernacular and professionally designed structures in temperate, subtropical and tropical settings. It has been adopted in recent decades by architects and designers worldwide to address aspects of urban ecology and climate change adaptation (e.g. by Arbona et al (2003)[65]). Historic examples range from German Tanzlinden[180] and Meghalaya's living root bridges[74], which have recently become famous worldwide, to simple rural practices such as hedge laying (e.g. in the UK)[181]. This study focuses on Meghalaya's living root bridges (LRBs) and contemporary 'Baubotanik' structures. In their pilot study Ludwig et al (2019)[74] describe 75 of Meghalaya's LRBs, as well as ladders, platforms and pathways, which form transport networks and cultural heritage sites for rural and urban communities[182]. LRBs are grown from *Ficus elastica* aerial roots and are mainly situated on steep slopes in deep valleys and dense forests. The bridges are between 2 m and 53 m long, (Figure 3.1a) with details (e.g. inosculations and bark features) at the centimetre scale (Figure 3.1b). Structurally important roots in LRBs have circular, elliptical and 'inverted-T' cross-sections[74], like subterranean roots in other trees[76].

The German neologism Baubotanik describes a contemporary approach that utilises state-of-the-art methods to integrate living tree growth into building design (Figure 3.1c). It is defined as a form of architecture in which structures are created through the interaction of technical and grown elements by manipulating the growth of trees or their parts, joining them with each other and connecting them with non-living components in such a way that they merge into a botanical-technical entity (Figure 3.1d)[12, 183]. Growth manipulation and induced inosculation are central to both Meghalaya's LRBs and contemporary Baubotanik structures, forming anastomotic networks. Through the interaction of different tree species with local environmental conditions, varying manipulation techniques and years or decades of growth processes, diverse and often highly complex topologies emerge.

By using growing organisms as integral parts of functional structures, living architecture holds great potential for environmentally sound and future-oriented building designs. These buildings bring together two distant fields of analysis: mechanics and growth. Both require a structural model that is topologically continuous and accurate and preserves element geometric features such as thickness, curvature and length. Godin et al (1999)[184] describes how geometry and topology inform plant growth, and their documentation provides realistic physiological models of growth and senescence. When considering plant biomechanics, beam theory provides a useful foundation[185]. Tree topology[186] and element shape[113] are vital in determining mechanical properties. But, as described by Jackson et al (2019)[20], the complexity of tree structural forms is addressed in the literature only to a limited extend. This is partly because most authors have focused on conifer stands in the forestry industry and partly due to historical limits to data acquisition, before the recent availability of detailed point clouds (PCs). In particular, anastomoses are not commonly considered in tree skeleton models. The research gap that this reveals is addressed by the present study – the documentation of living architecture (in particular LRBs) in 3D detail and the provision of data structures that allow for structural and physiological analyses of historic and designed living architecture. In pursuit of this, we answer two questions. Firstly, can living architecture be documented in sufficient detail with off-the-shelf (OTS) equipment? Secondly, can a skeleton, with the capacity for volume reconstruction, be developed from PCs of living architecture?

In order to explain our choice of methods, the state of the art of PC data acquisition and skeleton extraction are discussed below with respect to the specific challenges of living architecture. Next, we explain the samples we investigate, the methods we apply and constituent steps of our workflow, and seven criteria on which skeletons of living architecture specimens should be assessed. As results of our study we present selected photogrammetric PCs of LRBs and example skeletons and reconstructed volumes of representative samples resulting from our workflow. We then assess the workflow and resulting skeletons with respect to the seven characteristics, in comparison with two other skeleton extraction algorithms. Finally, the workflow's wider application in and beyond living architecture is discussed.

Figure 3.1. Living architecture exhibits points of interest on a range of scales: (a) a 53m long living root bridge (photo: W. Middleton), (b) details in bridges are at the cm scale (W. Middleton), (c) the Nagold Plane Tree Cube, a contemporary Baubotanik example (F. Ludwig), (d) an inosculation in the Plane Tree Cube (F. Ludwig).

3.1.1 State of the art of PC data acquisition and skeleton extraction

Large datasets are needed to fully describe the complex shapes present in living structures at the range of scales described above. Terrestrial laser scanners (TLS) and close-range photogrammetry (CRP) document the visible surfaces of objects. They are used in the field of architectural heritage, where large buildings are documented, along with small scale details marking unique features, historic techniques and ongoing decay. Fassi et al (2011)[187] show CRP and TLS are useful at scales similar to this study. The use of CRP in combination with other techniques has come a long way: Yilmaz et al (2007)[188] track fire damage of a historic building by combining photogrammetry and basic measurements, while recent studies have focused on TLS integration[189], combined drone- and terrestrial CRP[190] and specific downstream methods such as for construction sites and (H)BIM[189, 191].

CRP and TLS are also compared in forestry and plant science. Many of these studies focus on automating the measurement of diameter at breast height (DBH), a common measure that allows inference of stand make-up. Single-tree surveys[192] show better precision than multi-tree surveys[24]. Surový et al (2016)[192] show that five overlapping cameras are needed for good survey results, while more than eight is unnecessary for documenting forest trees. Forsman et al (2016)[24] show a 5-camera CRP rig produces inferior results to a TLS survey. Liang et al (2014)[193] find that handheld consumer cameras can provide photogrammetric PCs of similar accuracy to those resulting from TLS data in a forest stand of approximately 30x30m. Mokroš et al (2018)[194] find photogrammetry suitable for stem reconstruction within stands. Hanke and Moser (2011)[195] document a Tanzlinde tree using photogrammetry, though the extracted branching structure is significantly less complicated than the topologies of other living architecture mentioned above. Branches and roots are significantly more difficult to document than stems, mainly due to occlusions. Yoshinoa and Okardab (2010)[196] recreate a Melaleuca specimen by informing a simulation model with photogrammetry-derived growth parameters. Changes in living architecture, including growth, senescence, epiphyte presence, and maintenance require more regular documentation than in heritage architecture[182]. Therefore, a tool that can be used regularly by the communities who grow and own living architecture, is easy to transport, is low cost, and requires little training, is preferred. Of the reviewed survey techniques, photogrammetry can provide relatively accurate data at a relatively low cost, with minimal training and lightweight tools. Therefore, CRP was identified as the most suitable method for acquiring the PCs that form the basis of this study.

Generating geometric-topological models of complex structures is a significant challenge. While in simple structures a small number of accurate data points can be collected (e.g. using tacheometry) to represent edges and corners onto which shape primaries are mapped, in complex structures (e.g. an irregular curve in a branch) simple curves and surfaces cannot be easily interpolated and edges and corners are not clear. This challenge is present, for example, in heritage documentation[187, 197]. The shape primaries useful in mechanical and physiological tree models are typically 1D elements connected at branching and joining points. A wide range of studies reconstruct tree stems[198], branches[199] and whole-tree structures[196] from a variety of LiDAR and photogrammetric PCs. Branches and roots that are essentially elliptic or circular in cross-section lend themselves well to skeletonisation, which produces a data-light model. Tagliasacchi et al (2016)[18] discuss the variety of skeletonisation methods available, categorising them by dimensionality and input spatial data. In particular, 1D-curve skeletons provide thin, centred structures that preserve tubular shapes (e.g. branches), well. Cornea et al (2007)[200] compare the main classes of 1D-curve skeletons and Bucksch et al (2009)[201] categorise 1D skeletonisation methods into five groups: geometric, clustering, graph reduction, medial axis, and morphological methods. Geometric methods[202], such as Wang's (2014)[203] minimum spanning tree[204] can process incomplete clouds, producing realistic but potentially false topologies. This causes particular problems for the anastomotic networks common in living architecture. Similarly, clustering methods, such as Xu's (2007)[205] can produce false topologies in detailed parts of PCs. Bucksch and Lindenbergh's (2008) 'graph-reduction' method[206] overlays an octree graph on the PC. It is computationally efficient and can represent topology well when the model's voxels are large enough to cover gaps and noise in the PC but does not guarantee connectedness. Medial axis methods, such as that presented by Huang et al (2013)[103], effectively extract tree skeletons from relatively complete clouds[207, 208]. However, two issues arise in application to network-like structures in living architecture. Firstly, the equal sized local neighbourhoods used throughout the PC require separate elements to be of roughly similar sizes or relatively distant from one another. When a small element is near a large one, the local attraction neighbourhood of points within the large element can engulf the small one. Secondly, by identifying separate elements, the method does not guarantee topology preservation (continuity between elements is only later applied, see bridge points in Huang et al (2013)[103]). Both problems can be avoided using voxel-thinning (classified as a morphological method by Bucksch et al (2009)[201]). Saha et al (2016)[209] describe two kinds of voxel-thinning: parallel thinning[210, 211] and sequential thinning[104, 212], of which the latter group is shown to preserve topology and provide 1-voxel-thick skeletons. As topology preservation is of central importance, sequential voxel-thinning is the most suitable skeletonisation method for living architecture – the method presented here draws on previous findings in this field.

Branches, stems and roots are axial elements with typically approximately circular, elliptical or other simple cross-sections[74]. Element cross-sectional shape and size inform mechanical and physiological models. Therefore, the skeletonisation process should preserve enough information to reconstruct the object's volume accurately. Various methods for this have been documented: comparison of the skeleton with the original voxels[213], cylinder fitting to the original PC[214], and finding the radii and centres of maximum balls (CMB) in the voxel object[215]. Here, we define a new method that reconstructs the object volume based on information captured during the voxel-thinning process, avoiding reliance on reference to the original PC for comparison or fitting.

3.2 Materials and Methods

3.2.1 Photogrammetric surveys

This study is concerned with specimens with generally visible elements. Four representative samples are used to show the skeletonisation workflow below: two small-scale inosculated joints of different complexity and two large-scale structures. The first inosculated joint is a topologically relatively simple specimen, 50 cm long, from a pair of 7-year-old *Platanus* x *hispanica* trees from a Baubotanik test field (hereinafter referred to as the Baubotanik joint). The second inosculated joint is a 1 m long part of a Living Root Ladder near Mawshun village in East Khasi Hills district, of unknown age (hereinafter referred to as the Ficus joint). The large scale structures are the Freiburg pavilion and Wah Koh La bridge. The Freiburg pavilion is a quite young (planted in 2017) and relatively regular structure. The 32 London Plane trees (*Platanus* x *hispanica*) are planted in an oval with 10 m major diameter, 6.5 m minor diameter. The trees are grafted together at two points per tree and connected to a steel ring at the top, which is also supported by six vertical steel poles. A textile roof will be added in due course. Wah Koh La bridge is a two-span bridge across the seasonal Koh La river between Myntheng and Ramdait villages in East Khasi Hills district. The western span, the subject of this study, is 15.4 m long, grows between two trees (on the western bank a river island) and consists of several long roots forming a footway and handrails with many roots intergrown between them, similar to a simple suspension footbridge. It is thought to be 100-200 years old[74], but individual root ages are unknown. Additionally, sections of individual roots from other LRBs are used to assess the volume reconstruction of elements with approximately elliptical cross-sections (hereinafter referred to as elliptical root samples).

In March 2018 and March 2019, 11 photogrammetric surveys were conducted for ten LRBs as well as five surveys of small details of other living architecture, partially described in Middleton et al (2019)[83]. All bridges were scaled by the basic measurements described by Ludwig et al (2019)[74] Additionally, some bridges were scaled with diverse other methods. In November 2019 surveys of three individual Baubotanik inosculated joints and of the Freiburg pavilion were conducted. The surveys were performed using OTS cameras. For each structure only one camera was used. Logistical problems resulted in the use of two different DSLRs: a 12MP Canon EOS 450D DSLR with an APS-C sensor and an EF-S 18 mm f/3.5-5.6 lens for the 11 LRB surveys (including the elliptical root samples) and the five small detail surveys; a 24MP Fuji XT 20 DSLR (APS-C sensor; 18mm, f/2.8-4 lens) for the Baubotanik joints and Ficus joint. A DJI Mavic 2 Pro drone with a 20MP Hasselblad L1D-20C camera (1" sensor; 28mm, f/2.8–f/11 lens) was used for the Freiburg pavilion. The number of photos varied between structures: longer bridges with more accessible angles were captured by more photos. The bridge models ranged from 121 to 1639 photos (mean 701, median 526). The detail and joint surveys used 58 to 150 photos (mean 104, median 97). Agisoft Metashape standard edition[127] was used for all photogrammetric reconstructions using a Lenovo Thinkpad t470s (i5-7200U, 20GB RAM). CloudCompare[128] was used for basic orientation and trimming, as well as the scaling.

A range of scaling methods were used. Six LRBs were scaled to the basic measurements described by Ludwig et al[74]. One LRB, in addition to these basic measurements, was scaled using five 127 mm square markers spaced on the deck. It was surveyed twice (in 2018 and 2019) – the resulting PCs were compared for distortion resulting from photogrammetric reconstruction. The PCs are aligned at eight points, then the distances from the less populated PC (2019) to the nearest points on the more populated PC were measured. For two other bridges and the pavilion, multiple measurement points provided scaling and a measure of distortion. 12 and 15 measurement points were marked with 2cm-wide tape respectively. 21 and 47 measurements between these points were made using a Leica Disto D2 handheld laser. In the pavilion, 16 measurements were made with a tape measure between the bases of eight scaffolding poles. Wah Koh La bridge was measured using 13 element circumference measurements. The Ficus and Baubotanik joints were only measured by one length and one circumference each at an accuracy of 10 mm.

3.2.2 Skeletonisation workflow

The semi-automated process for extracting shape-preserving skeletons from PCs in this study involves nine steps, written in C++ using the Point Cloud Library (PCL)[216]. All steps were developed and run on an Intel i7 (2.8 GHz 16 GB RAM). Steps 1-8 are sequential and perform the basic skeletonisation. Step 9 is the volume reconstruction utilising shape data and is defined for circular (9a) and elliptical (9b) cross-sections. The steps are detailed below.

1. Orientation: eigenvectors are defined for the PC using principal component analysis[217]. This is used to orient the cloud's longest axis in the vertical direction, reducing the void voxel space.

2. Voxelisation: using the PCL[216], an octree is formed, splitting each voxel into 8 sub-voxels at each depth level. Voxels inscribing points are defined as 'object' voxels; all others are 'void' voxels. Voxel length is manually defined, resulting in a specific octree depth. Voxel size is determined in part by the PC density – the gaps between points must be covered by the voxels (i.e. minimum of one point per voxel). Areas of low point density (or small surface holes) can be covered with large voxels; traded for lower precision in areas of high density. Large voxels can also help avoid distortions caused by noise or poor sampling. The octree depths used for the Ficus joint, Baubotanik joint, Freiburg pavilion, and Wah Koh La bridge are seven, eight, nine, and eight respectively.

3. Cartesian coordinate conversion: as steps 4, 6 & 7 involve operations in the cardinal directions, Cartesian coordinates are needed. Functions from the octree module of the PCL library[216] ascribe Cartesian coordinates to each point in the octree[218].

4. Voxel denoising: the noise present in the PC, voxelised in step 2, must be deleted to avoid erroneous topologies. A voxel can be 6-, 18- and 26-connected to other voxels, defined by the neighbourhood shown in Figure 3.2f. This denoising step deletes any object voxels that are not 6-connected to the main object body (the largest connected group of object voxels). A 26-connectedness check was trialled, but was found to leave too many 'loose ends', which were unhelpfully represented in the final skeleton. Palágyi and Kuba (1999)[212] show the impact of such noise on the final skeleton. While a more aggressive 6-connectedness check can lead to holes in the voxel surface (where a surface runs through 18- or 26- but not 6-connected neighbouring voxels), this appears to be relatively manageable (step 5).

5. Surface filling: PCs can exhibit gaps due to self-occlusion or poor sampling. Upon voxelisation, these gaps can translate into one or more voxels missing from an otherwise continuous voxel surface.

Such holes misrepresent the object topology. They are filled manually. For a review of automated hole-filling processes, see Attene et al (2013)[219]. Once occluded positions have been filled, the open ends of the branches that continue beyond the model space are also filled.

6. Internal space filling: the internal spaces are filled. Due to its applicability to complex models (with cavities or intertwining elements), a continuity-check was developed. Void voxels are assumed to be either external, in a single connected group; or internal, in one or more connected groups. Based on this, all voids that are not 6-connected to the external void are filled. This assumption does not allow for voids internal to the main body, though these are not captured by photogrammetric surveys.

7. Voxel thinning: a thin (1-voxel-thick) skeleton is extracted by iterative thinning. During thinning, object voxels are turned to void voxels (herein referred to as deletion). To do this She et al (2009)[104] adapt templates from Palágyi and Kuba (1999)[212], making them more simple (avoiding Palágyi and Kuba's "either/or" points). Four base templates (shown in Figure 3.2a-d) can be rotated to make 6, 12, 8, and 12 unique configurations respectively (compare Figure 3.2a and 3.2e). She et al (2009)[104] combine these 38 configurations with two deletion criteria that preserve topology. However, that method does not preserve curve-end voxels (object voxels with only one 26-adjacent object voxel), which represent branches that do not reach the space boundary. The method presented here combines the templates of She et al (2009)[104] with an adjustment to the P-simple deletion criteria proposed by Lohou and Bertrand (2004)[17]. Each object voxel is compared against the 38 configurations and all fulfilling voxels are checked for adjusted P-simplicity[17] – they are deleted if they meet the four criteria or returned to the set of all object voxels for the next thinning iteration if they don't. An n-connected component consists of voxels linked in a chain by n-adjacency. As described by Palágyi and Kuba (1999)[212], the order of directional thinning impacts the position of the remaining object. In order to provide a well-centred skeleton, we apply all directions of template A, followed by template B, C and D, rather than applying all templates in one direction then moving to the next direction. Figure 3.3 shows the process. The four deletion criteria for an object voxel are as follows:

For an object voxel x that fits at least one of the 38 templates, examining the 3x3x3 neighbourhood of x:

(a) All 26-adjacent object voxels must form a single, 26-connected component

(b) All 18-adjacent void voxels must form a single, 6-connected component

(c) For any 26-adjacent object voxel considered for deletion y, there exists another object voxel z that is 26-adjacent to both y and x. If no y exists, the criterion is satisfied.

(d) For any 6-adjacent object voxels considered for deletion (denoted y), there exist two void voxels (z and t) that form a unit square with x and y – each of x,y,z and t are 6-adjacent to two others. If no y exists, criterion d is satisfied.

As has been discussed elsewhere[209], criteria (a) and (b) ensure that object chains are not broken and cavities are not connected, respectively. Criteria (c) and (d) protect curve ends from deletion. Where curve ends meet the boundary of the modelling space they do not fulfil any templates and are preserved. These criteria are adapted from Lohou and Bertrand (2004)[17]. Criterion (c) was changed to attain 1-voxel-thick skeletons: that study defines z as a non-deletable object voxel whereas here it must simply be an object voxel.

8. 1D curve conversion (segmentation): a 1D curve, fit between voxel centroids, provides the necessary topological connectivity between discrete voxels to form 'branch' elements, rather than the discrete unconnected voxels points[184]. Object voxels with three or more 26-neighbourhood object voxels are considered joint voxels, providing connectivity between elements. Busier junctions exhibit more than one joint voxel. In such cases, the voxel closest to the centroid of the group is chosen as the true joint, and others are described as associated joint voxels.

9. Iteration of exposure volume reconstruction: the 3D volume is reconstructed from the 1D skeleton by counting the iteration on which faces of the skeleton voxels are exposed and building out 2D circular or elliptical cross-sections from each skeleton voxel with radii proportionate to the iteration numbers. In a 1-voxel-thick skeleton, all voxels have a minimum of four exposed faces. The iteration on which the n^{th} face is exposed is referred to as I_n: I_1 to I_4 are recorded.

9a. circular sections: the object is reconstructed assuming approximately circular cross-sections throughout. The method is applied using the iterations of exposure I_1, I_2, I_3 and I_4. In approximately circular cross-sections, as I_2 is after or simultaneous to I_1, volumes reconstructed from I_2 are larger than I_1-based volumes. Accordingly, I_4 volumes replicate almost all of the original voxels and provide many redundant voxels while almost all voxels in I_1 reconstructions are correctly placed, but many original model voxels are missed.

9b. elliptical sections: ratios between iteration-of-exposure of different faces are used to derive the proportions of assumed elliptical cross-sections. Where elliptical ratio (the ratio of major to minor axes) is high, I_2, I_3 and I_4 might be expected to be significantly later than I_1. Therefore, a ratio $I_{n}>1$ to I_1 could replicate the elliptical ratio of the original cross-section. The ratios of $I_n>1$: I_1 and a mean $(I_4 + I_3 + I_2)/3$: I_1 – are compared. The four aforementioned specimens don't exhibit significant elliptical ratios. Instead, 411 skeleton voxels from five LRB root samples with varying elliptical ratios significantly greater than one are examined ("elliptical root samples" as described above)[74]. A linear function is derived from the correlation between elliptical ratio and each I_n:I_1 ratio, and applied to I_1-I_4 reconstructions – in I_1 and I_2 reconstructions, the major axis is enlarged, while the minor axes in I_3 and I_4 reconstructions are reduced.

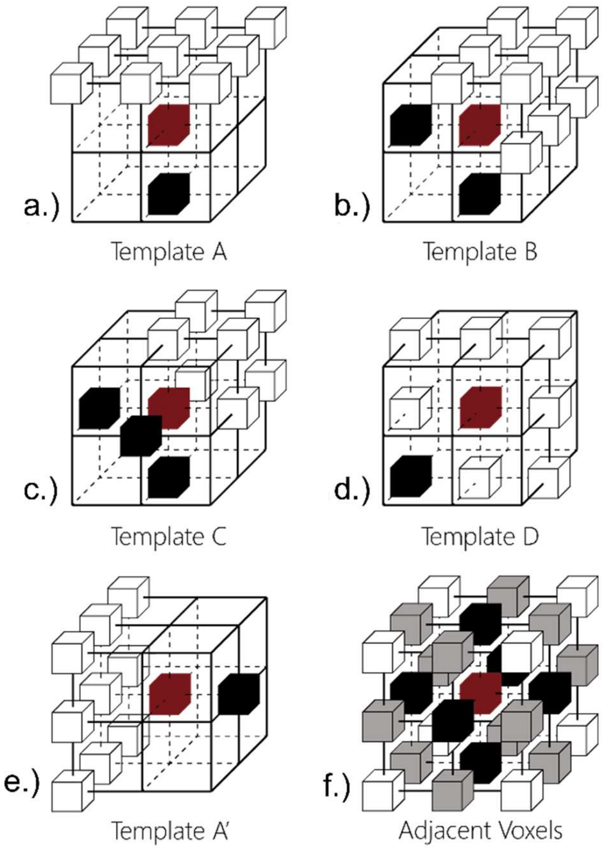

Figure 3.2. (a-d) show the four base template types used in step 7. One variant of template A is shown in (e). Each template assesses the 26 neighbour voxels in a 3x3x3 space around a candidate (red), discriminating between void voxels (white) and object voxels (black). (f) shows the 26-neighbourhood of the red voxel, with face-, edge-, and corner-connected voxels in black, grey and white respectively.

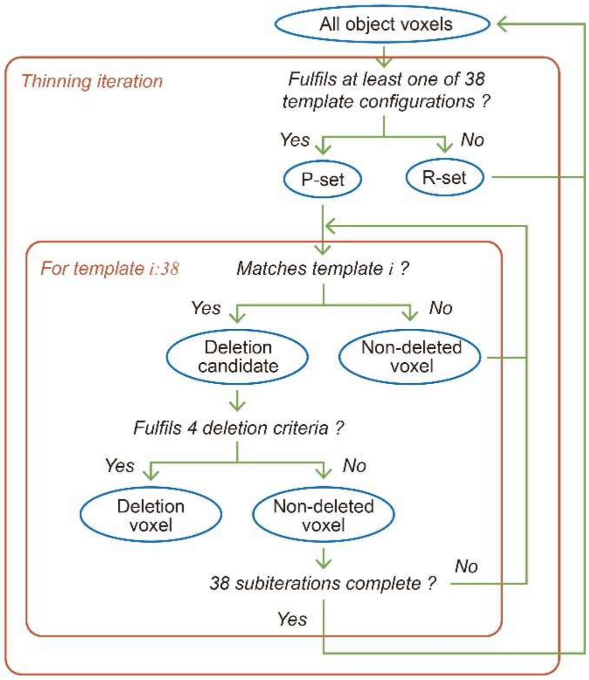

Figure 3.3. The iterative thinning in step 7.

3.2.3 Assessment

Several reviews describe desirable characteristics of skeletonisation workflows[18, 104, 200, 220, 221]. In application to living architecture, some characteristics (centeredness, homotopy) are clearly more useful than others (smoothness, regularisation). In this study we settle on seven characteristics to assess our skeletonisation results: homotopy, skeleton thinness, skeleton centeredness, rotational invariance, volume reconstructibility, scalability (in computing time and data efficiency), and sample robustness (to noise and missing data), each of which is discussed below and covered in Tagliasacchi et al and Cornea et al (2007)[18, 201].

As stated by Arcelli et al (2010)[215], deleting only simple points ensures topology is preserved (**homotopy**). **Thinness** is assessed as containing no voxels that do not preserve topology and can be checked by deleting any non-curve-end voxels. To assess **centeredness,** deviation from the PC centroid is compared between the present method and Huang et al (2013)[103] L1-medial method at through-sectional positions in the four samples. Skeleton points within 0.5 voxel-widths of the PC centroids are called 'correctly' assigned, within 1.5 widths (adjacent voxel) are 'acceptable' and larger deviations are called 'poor'. As in Arcelli et al (2010)[215], **volume reconstructibility** is given by the proportion of voxels in the original model reconstructed from the skeleton. Additionally, the proportion of reconstructed voxels that are correctly assigned is assessed. This is compared for four permutations (I_1-I_4) in assumed circular cross-section elements. The elliptical volumes reconstructed by the method described in step 9b are compared with circular I_1 to I_4 reconstructions.

Scalability is gauged by comparing the computation time and data reduction of samples of different original size[221]. Similar to Arcelli et al (2010)[215], data efficiency is given as a proportion of the source PC. **Sample robustness** of the thinning process (step 7) is assessed by comparing skeletons derived from noisy PCs. Pseudorandom noise in a Gaussian distribution with standard deviation proportional to the voxel size was added to the point coordinates of the four samples. Skeleton homotopy, centeredness, and processing time were inspected at a range of standard deviations. **Rotational invariance** is assessed here by comparing skeletons produced from identical models processed at 90° from one another. The skeleton centeredness and overlap of skeleton voxels are compared.

3.3 Results

3.3.1 Photogrammetric documentation

The photogrammetric surveys in Meghalaya generated 11 PCs of LRBs and five of specific details. The PCs generated vary in quality. Five LRB PCs are generally complete, with some or no details missing. These show the structurally important roots[74] (shown in section in Figure 3.4e) and their interconnections (3.4d, g). Three PCs include all key perspectives, but are missing significant details. Three PCs are missing important perspectives (the bridge in Figure 3.4a,b is complete; 3.4d,e is missing details; and 3.4g,h is missing important perspectives. Wah Koh La bridge is one of the three PCs missing important perspectives. Therefore it was chosen for the skeletonisation study to test the process' robustness to sample quality. Incomplete PCs may be due to a combination of environmental problems (e.g. light dappling or nearby water), computational limits on number of photographs, and limited access to perspectives (e.g. below the deck in a canyon). The five PCs of details capture all key features - Figure 3.4c,f,i. The stems of the Freiburg pavilion PC that resulted from the survey with the drone are generally complete (compare Figure 3.5), with poor quality in the branches above the steel ring. The distortion in the bridge measured in 2018 and 2019 find an average deviation between the 2018 and 2019 surveys of 17 mm (standard deviation 19 mm). In the pavilion and two bridges using measurement points, the on-site and PC measurements match well. Average distortion, including photogrammetric distortions and measurement error, was 0.023% or 7 mm (standard deviation 4.5 mm), 0.52%, 12 mm (10 mm) and 0.12%, 17 mm (13 mm) in the pavilion and two joints respectively. Wah Koh La bridge could not be scaled due to the missing perspectives in the PC.

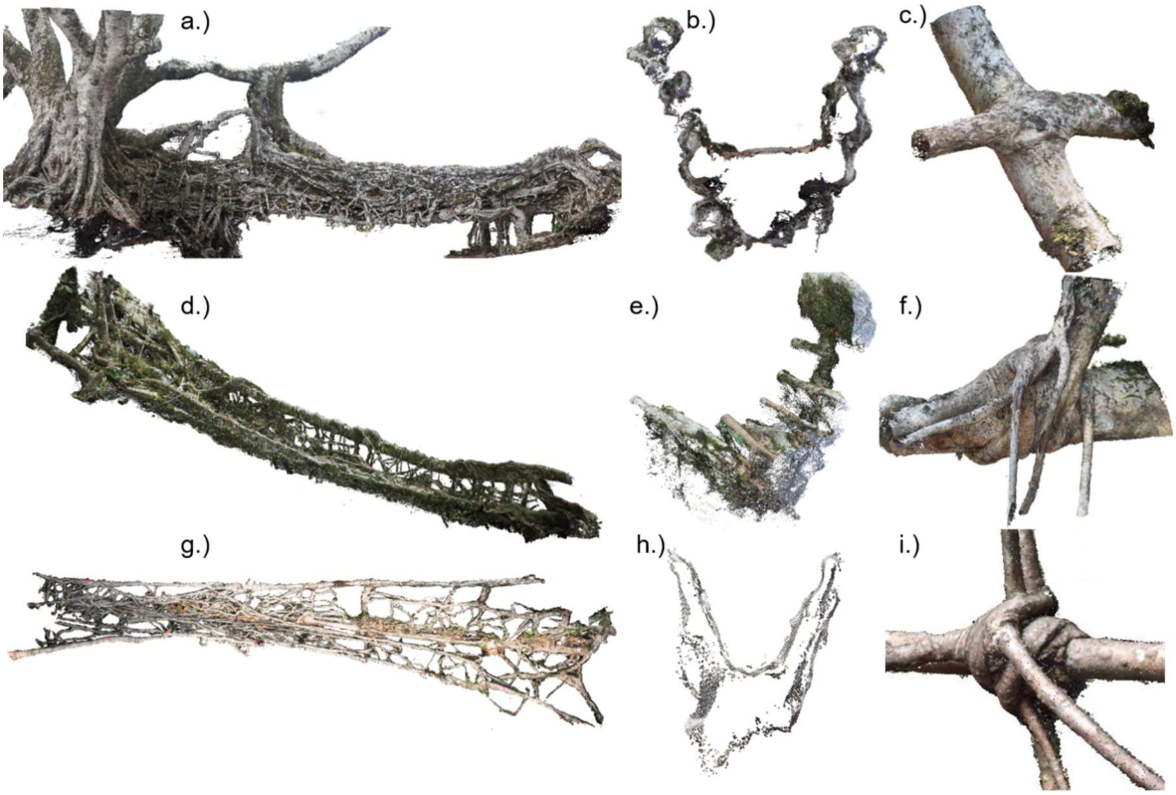

Figure 3.4. The photogrammetric surveys of living root bridges resulted in PCs of differing quality. (a) and (b) show the generally complete Nongbareh bridge; (d) and (e) show Niah Li bridge, relatively complete on the top, missing details on the underside; (g) shows the details captured on the top of Kudeng Rim bridge, missing perspectives from underneath. (c), (f) and (i) are details from other bridges.

3.3.2 Skeletonisation

The outcomes of the workflow's application to four example PCs (the Baubonanik joint, Ficus joint, Freiburg pavilion and Wah Koh La bridge) are presented in Figures 3.5 and 3.6. 3.5a-d shows example photos from the photogrammetric survey; 3.5e-h shows the input PCs; 3.5i-l show the oriented, voxelised model in Cartesian coordinates with noise excluded, surface holes filled and the internal space filled (steps 1 to 6); 5m-p show thin skeletons, segmented into "branches" (steps 7 & 8); 3.5q-t show the reconstructed circular-section volumes produced in step 9a; and Figure 3.6 show cross-sections of elliptical roots, comparing circular and elliptical reconstructions with the original PC (step 9b).

The four samples differ in scale. The voxel size, defined in step 2, reflects the completeness and detail of the PC: more complete and detailed PCs allow for smaller voxels. The Baubotanik joint has 1.1 $\times 10^5$ approximately 7.5 mm object and void voxels, the Ficus joint 2.5 $\times 10^5$ approximately 7.4 mm voxels, the Freiburg pavilion 4.2 $\times 10^6$ 36 mm voxels, and the Wah Koh La bridge 6.2 $\times 10^5$ 58 mm voxels.

The skeleton extraction process is assessed against the seven characteristics described above – the findings are summarised in Table 3.1 and detailed below, in comparison with the L1-medial process[103] applied to the same samples and a different voxel-thinning process, with data provided by Arcelli et al[215].

Characteristic	**Present method**	**L1-medial method, authors' use of Huang's process[103]**	**Distance-driven voxel method, from Arcelli[215]**
Homotopy	Preserved through thinning process	Established after L1-medial	Preserved in distance-driven method
Thinness	1-voxel-thick apart from at busy junctions	busy junctions problem avoided in L1-medial	1-voxel-thick apart from at busy junctions
Centeredness	87% within 1 voxel of centroid	80% within 1 voxel of centroid in L1-medial	Centeredness ensured before thinning
Volume reconstructibility	80-84% of original shape replicated	Established after L1-medial process	69% of original shape replicated
Scalability – computing time; data reduction	Computation time O(n) with n as voxel count; skeletons 0.56-2.7% of input object size	Computation time dependent on diverse variables; skeletons 0.08-1.3% of input object size	Computation time O(n) with n as voxel count; average skeleton 0.81% of input object size
Sample Robustness	Robust to some noise and missing details	L1-medial robust to missing perspectives	Robust to some noise and missing details
Rotational invariance	Minor differences, other characteristics invariant	L1-medial is independent of rotation	Minor differences, other characteristics invariant

Table 3.1. Comparison of the present method, the L1-medial method applied to our PCs; and the findings of a previous study on a different voxel-thinning method.

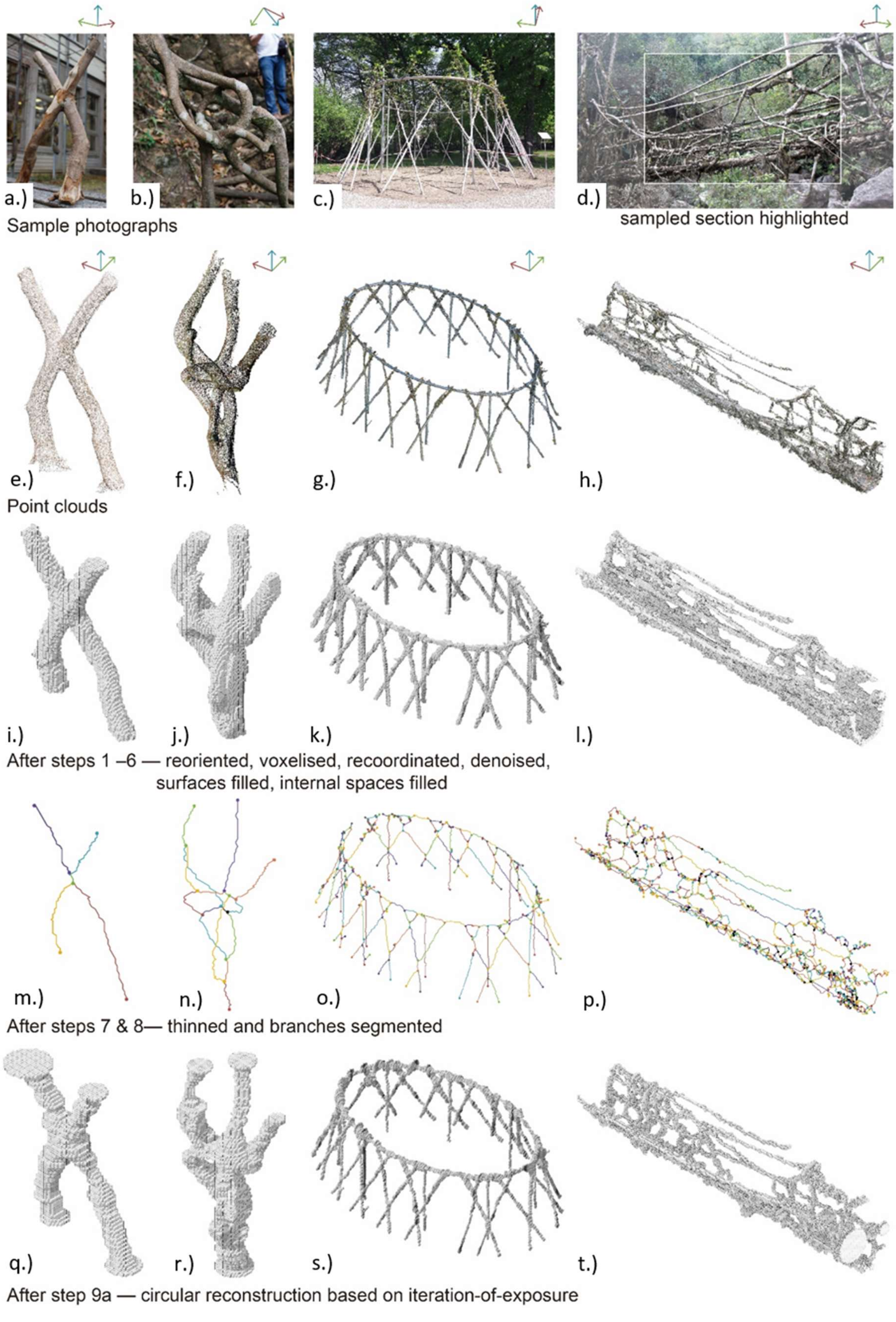

Figure 3.5. The Baubotanik joint, Ficus joint, Freiburg pavilion and Wah Koh La bridge as photographs (a-d) and corresponding point clouds (e-h); reoriented, voxelised model in Cartesian coordinates, denoised with any surface holes filled and the internal space filled (i-l); the resultant 1-voxel-thick skeleton, segmented by joint voxels (m-p); and circular volume reconstruction using iteration-of-exposure counts (q-t);

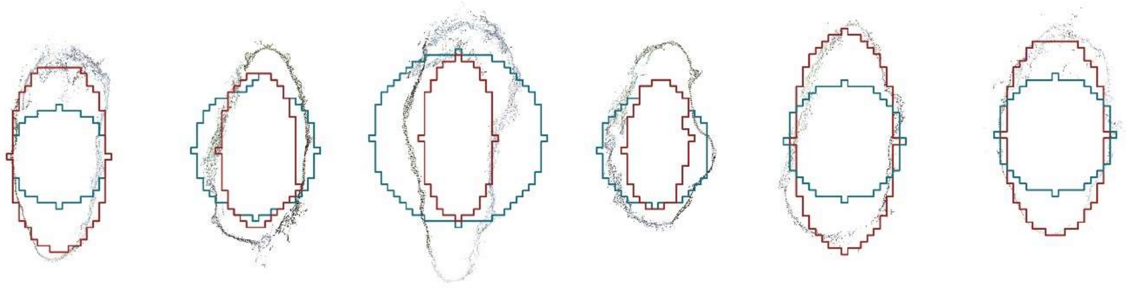

Figure 3.6. Examples of elliptical root sample PCs, reconstructed in step 9a as circles (blue) and 9b ellipses (red).

Homotopy: as described in the methods section, deletion criteria (a) and (b) ensure topology is preserved at every step because 26-connectedness is preserved for object voxels and 6-connectedness for void voxels. Both criteria (c) and (d) preserve many curve-end voxels, though not all possible situations are accounted for.

Thinness: a 1-voxel-thick skeleton is produced at all points apart from busy junctions where connectivity preservation is ensured[220]. In the skeletons shown, no object voxels can be deleted without breaking connectivity.

Centeredness: Figure 3.7a shows the deviations between skeleton voxels and PC centroids. Deviation is counted in voxel-widths for 123 cross-sectional centroids in the Baubotanik joint (35), Ficus joint (53) and pavilion (35) – centroids could not be identified in the Wah Koh La sample. The problems relating to L1-medial methods resulted in five missing centroids (leaving 118 in total). Large deviations exist in both the present method (12.3% of measured points are more than 1.5 voxel widths from the centroid) and the L1-medial method (23%). 39% and 31% of voxels are correctly assigned (within 0.5 voxel widths) in the present and L1-medial methods respectively while 13% and 21% of voxels are more than 1.5 voxel-widths away, respectively.

Volume reconstructibility: comparing I_1 to I_4 reconstructions, results are similar for each of the four samples: I_1 and I_4 reconstructions differ significantly from the original model and I_2 in particular (and I_3 to a lesser extent) reconstructions provide a high proportion of correct allocations and few redundant reconstructed voxels. Using I_2 reconstruction, circular through-sections resulted in 84% replication of the original voxels in both the Baubotanik joint and Ficus joint. I_2 reconstructions resulted in 49% and 41% replication in the pavilion and bridge samples respectively. This compares with 69% achieved in Arcelli's method[215]. 77% and 73% of the reconstructed voxels were correctly allocated in the Baubotanik and Ficus joints respectively (i.e. 27% and 24% were wrongly allocated, respectively). In the pavilion and bridge, 77% and 66% were correctly allocated. Figure 3.7b shows the redundant reconstructed voxels (blue), missing original voxels (red) and common, correctly reproduced voxels (grey) in the Baubotanik and Ficus joints.

For the 411 elliptical cross-sections, a function of the ratio $I_4:I_1$ is found to best predict the true elliptical ratio (ER) of the section: the linear regression $ER = 0.4255*(I_4:I_1) + 1.1235$ has an R^2 value of 0.4832. When applied to reconstructions based on I_1 and I_4, a high proportion of the original model voxels are replicated with few incorrect allocations, compared with I_2 and I_3. The elliptical reconstructions achieve a mean of 80% replication of original voxels and 76% correct voxels for I_1 reconstructions, 33% more replication and just 9% more incorrect voxels than the mean I_1 circular reconstruction.

Scalability: computation time does not significantly increase with sample size for most steps. Steps 6 and 7 are the most computationally intensive. Step 6 took 90-23577 s/Mb of input point cloud data (91-99.6% of total time) and step 7 took 8-109s/Mb (0.5-8.1%) to compute. The major variance in computing time between samples is due to the dependence on the number of void voxels and the number of object voxels in steps 6 and 7 respectively. Huang et al (2013)[103] process takes 19-88s/Mb of input data, depending on a range of variables. Time needed for step 5, the manual hole filling, is defined initially by PC quality (i.e. the presence of holes), then by the sample's complexity (in particular occlusions concealing holes) and voxel size (larger voxels cover holes). Due to these factors, hole filling took up to 10 minutes and 30 minutes in the Baubotanik and Ficus joints, respectively. In both the pavilion and bridge samples, no manual hole filling was needed because large voxels were used. The final skeletons are data light, irrespective of scale – the Baubotanik joint is reduced from 2.6Mb in the original PC to 2.6Kb in the skeleton (0.1% of original size), the Ficus joint from 34Mb to 7Kb (0.021%), the Freiburg pavilion from 80Mb to 70Kb (0.088%) and the LRB from 74Mb to 63Kb (0.085%). In Huang et al (2013)[103], skeletons were reduced to 0.08-1.3% of the original PC size and more complicated structures (with more joints and elements) produced larger skeletons.

Sample robustness: there are two major challenges presented by poor sampling: false topologies and skewed skeleton points. They are caused by PC surface holes and inaccurate (noisy) or imprecise (low resolution) surveys. These are mitigated by voxel size choice (step 2), density (step 4) and hole filling (step 5). Beyond this, step 7 provides some noise robustness. In the noisy PC tests, a robustness threshold was found around a standard deviation of noise at 0.6-0.75 times the voxel size. Below this, little or no false topologies occurred. In this range, the skeletons degraded significantly. Centeredness was generally unaffected apart from around the false topologies. Iteration count and processing time increase with noise. Within PCs, spatial resolution varies between areas: some perspectives are better captured than others. The voxel size is generally defined by low-resolution areas which can open surface holes – changes in resolution in the high- and mid-range areas are less relevant.

Rotational invariance: voxels assigned to the skeleton change when the object is rotated. When rotated through 90°, 76% of the voxels in the Ficus joint are identical, and the maximum deviation between skeletons is 2 voxels, shown in Figure 3.7c. The rotated skeleton is equally preserving of topology, equally thin, equally centred overall, and reconstructs the same proportion of original voxels (84%) with the same proportion of correct allocations (73%).

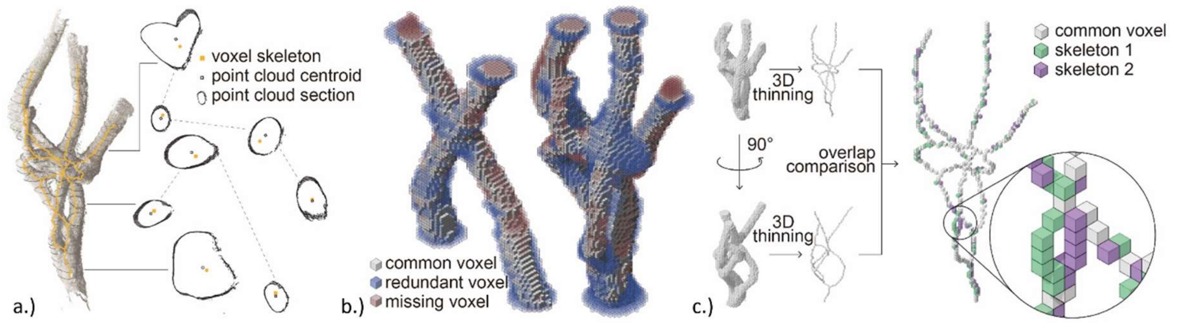

Figure 3.7. Comparison of skeleton centeredness with point cloud centroid at through sections of the Ficus joint (a); comparison of original and reconstructed voxel volumes in Baubotanik and Ficus joints (b); comparison of skeletons processed at different orientations (c).

3.4 Discussion

The results of the photogrammetric surveys show that detailed models of living architecture are achievable with OTS cameras and drones. However, details are more easily captured than whole bridges – complete PCs showing all perspectives of a complex bridge's many details are difficult to achieve due to computing power, access, and lighting conditions. Lighting condition problems may be overcome with LiDAR scanning (with which the skeletonisation method is compatible), though instruments are currently too expensive for widespread use. Portable mobile mapping systems have recently developed significantly, with low-cost[222] and high-accuracy[223] options available. As these two benefits converge, future studies should investigate laser surveys' benefits for living architecture. In comparison with previous documentation of simple length and width data of LRBs[74], PCs provide much more detailed data, showing many of the key structural features of each bridge. In some cases, important sections are not visible due to self-occlusions but nonetheless can be partly inferred from visible parts by the PC viewer. Evaluating the scaling distortions, it is clear that photogrammetry can usually faithfully capture complex living architecture topologies but small distortions are to be expected, such as slightly miss-positioned elements. Such imprecisions could be avoided by integrating a step to compare PCs from different surveys before voxelisation. Comparing the specific details of photogrammetric surveys at different times allows change monitoring[83]. A necessary part of long-term documentation of living architecture is the interchangeability of tools – it should be possible to combine separate surveys. The results of this study and others show that environmental factors and accessibility are generally more significant than the differences between OTS cameras. Detailed models can be used for assessing tree health and growth remotely, for example by adapting the Visual Tree Assessment method[224].

The presented workflow provides novel insight into the potential for iterative voxel-thinning in topological skeletonisation of living architecture specimens. As shown by the four examples, the method dependably reconstructs skeletons from complete or incomplete PCs and can exploit detailed PCs for precise skeletons. This offers an alternative to the L1-medial and distance-driven voxel methods. The proposed method shows better volume reconstruction than the distance-driven voxel method, particularly in smaller scale structures. The skeleton centeredness and homotopy show significant improvements in comparison with the L1-medial method. The results are otherwise comparable, apart from the computation and manual input time (the proposed method is significantly slower). While the method is robust to some noise, the skeleton quality degrades in very noisy PCs. Several aspects of the skeleton are balanced by the voxel size choice in step 2. Larger voxels reduce processing and manual input time and compensate for some noise, surface holes and low spatial resolution in the PC. In cases where these holes determine voxel size, the detail provided by high resolution areas is 'wasted'. Small voxels improve the skeleton centeredness and could, in some cases, help preserve topology and make volume reconstruction more precise. The final skeleton is generally data light - each skeleton voxel contains three dimensional coordinates and three iteration counts: I_1 and I_4 (for elliptical ratios) and I_2 (for circular reconstructions). This allows for flexible use in computer-aided design.

Potential future improvements lie in automation of the manual steps and in optimisation of the iteration-of-exposure reconstruction. Surface filling (step 5) is useful in combination with considered choice of octree depth (step 2). However, step 5 can be laborious. Automation of step 5 could be based on surface-patching[219] if the missing surface is smooth. Step 2 could be automated with a persistent homology approach, in which the optimal voxel size is defined by topology preservation across scales[225]. In the iteration-of-exposure method there are three areas for improvement. Firstly, the reconstruction is in-plane, extrapolating in the x and y directions, forming circles/ellipses along the z axis. This differs from the thinning process, which is three dimensional. Future work could focus on 3D shape primaries. Secondly, voxels at modelling space boundaries and junctions take many iterations to erode, resulting in disproportionately wide reconstructed sections. Where unavoidable, this can be accounted for in the function linking iteration of exposure and elliptical ratio. Thirdly, each element is categorised by cross-section as circular or elliptical, neglecting deviations from these shape primaries (see Figure 3.6). Future investigations could address other shapes such as the 'inverted-T' and 'I' shaped roots, as described by Ludwig et al[74] and Nicoll and Ray[76]. Skeletons with associated shape information can feed easily into the Euler-Bernoulli beam analysis employed by Jackson et al[20] and provides the topology of importance in James' analysis[186]. The directional stiffness caused by elliptical elements can improve beam analyses. The full potential of axial elements in tree mechanics is still to be explored. For example, wood's orthotropic properties are generally not considered[20]. Similar skeleton models are used for analyzing interactions occurring between plant components at different scales during plant growth simulations[184]. Our skeleton model can be translated into L-system languages (e.g. XL language in GroIMP[226]). In this way, it will open up further opportunities for studying resource allocation in relation to branching topology[227, 228] of not just realistic but real plants. Beyond plants, the method could benefit analyses of anastomotic networks in biomedical fields including complex blood vessel maps[229]. By enabling mechanical and physiological analyses, a platform is offered for collaboration between arborists, engineers and architects.

As stated in the introduction, living architecture integrates physiology and mechanics and calls for an iterative design process[230] in which regular documentation, modelling and analysis inform maintenance decisions. The workflow presented here provides a key part of this – structural analyses and growth predictions can be fed by a topologically correct skeleton, and in turn can feed decisions on root and shoot guidance or addition of technical elements. These decisions impact growth, which is once more documented using optical techniques.

3.5 Conclusion

This study presents the first extensive 3D documentation of Meghalaya's unique living root bridges and a method for meaningfully characterising the structure of these and other heritage and designed living architecture. The presented workflow uses low cost, off-the-shelf photogrammetric surveys to produce 1D skeletons via a process that recombines aspects of two previous voxel-thinning algorithms to provide centred, thin, topology-preserving, rotationally invariant skeletons for sections of living architecture. Associated shape information is preserved through a novel technique allowing element reconstruction. The skeletonisation process caters specifically to the challenges common in living architecture: anastomotic networks and diverse neighbouring elements. It includes steps for minimising problems induced by poor sampling. The method is applicable to small and large scale sections of differing complexity. By extracting the key topological features of a complex structure, the method provides a data-light, accurate representation that can be used in mechanical and physiological analyses and simulations of living structures in general. Thereby, the method facilitates design and analysis of growing structures, broadening designers' horizons to complex forms of living architecture in high density urban contexts where precise predictive models are essential.

Chapter 4

Comparing structural models of linear elastical responses to bending moments in inosculated joints

This chapter was first published under the same title in *Trees Structure and Function* in 2023 (DOI: 10.1007/s00468-023-02392-7) with co-authors Halil Ibramhim Erdal, Andreas Detter, Pierluigi D'Acunto, and Ferdinand Ludwig. This version includes minor formatting edits.

4.1 Introduction

4.1.1 Inosculations

Inosculation is the process of intergrowth between two or more plant roots, branches or stems. Inosculations provide essential structural support to naturally grown and manipulated trees. Many examples of living architecture, from living root bridges in Meghalaya (India), Sumatra (Indonesia) and Foshan (China)[182] to the buildings designed with Baubotanik methods in Germany[74] utilise inosculations. A range of species with diverse benefits[231,232] are used in living architecture, including fast-growing species such as willow, birch and poplar[39,41,63,231] and resilient species such as London Plane[165,181,232]. In living architecture, inosculations provide structural support to technical and functional elements, as in the Nagold Plane Tree Cube (Figure 4.1a, b)[12]; link the network of elements that create the structural form; or provide path redundancy in water transport, allowing non-fatal failure of individual elements, as shown by living root bridges surviving landslides or cuts by humans[182]. In particular, inosculations are a central structural feature of naturally-growing strangler figs, many of which are high-value trees in tropical and subtropical cities such as Mumbai[234], Hong Kong[235], and Singapore[79]. In deciduous trees[108], inosculations occur from time to time (6.6% of bifurcations of similar-sized branches surveyed by Slater[236] have inosculations) above ground and are common in roots[106].

Inosculations allow, through their common growth, distribution of both water and mechanical loads between otherwise separate elements. At the inosculation, the living cambium of two or more shoots or roots conjoin and generate one common growth ring (Figure 4.1c), as described by Slater (2018)[108]. From then on, tissue links the roots and crowns of both trees, allowing the cross-flow of water and nutrients and the reorientation of fibres for mechanical support. Comparing Slater (2018)[236] and Ludwig (2012)[12], it is clear that the inosculation's mechanical and physiological functions depend on how and when the tissues merge during the inosculation process. This depends largely on the way the constituent trunks are initially joined. As well as providing new pathways for water transport between roots and crowns, the inosculation can perform a structural function – long elements brace one another along their length (Figure 4.1a, b), reducing their slenderness ratios and thus the bending stresses. Slater (2018) finds that naturally-growing trees with inosculations above branch bifurcations invest less in support at the bifurcation[108], indicating the mechanical role of the inosculation in resisting cleavage of the bifurcating branches. In some species, such as *Ficus elastica*, many inosculated aerial roots can form a network with both physiological and mechanical functions, distributing and reducing mechanical stresses, providing multiple water or nutrient pathways, and building redundancy into the tree. These combined functions underpin the development of Meghalaya's living root bridges[74] and Baubotanik design[12, 61, 182, 237]. In living architecture, loading regimes are designed according to growth predictions. As the tree grows and elements take form, load distribution can be calculated more precisely. In this iterative process loading is re-evaluated as the structure grows and is pruned and guided into shape. Numerical models are needed for detailed analysis of inosculations, which change as the structure grows. In contrast to this, in non-grown structures, simple mechanical models inform the broad design and precise numerical models are used in the final stages before construction. Lessons from these models can inform a general understanding of inosculation mechanics, which feeds into future designs.

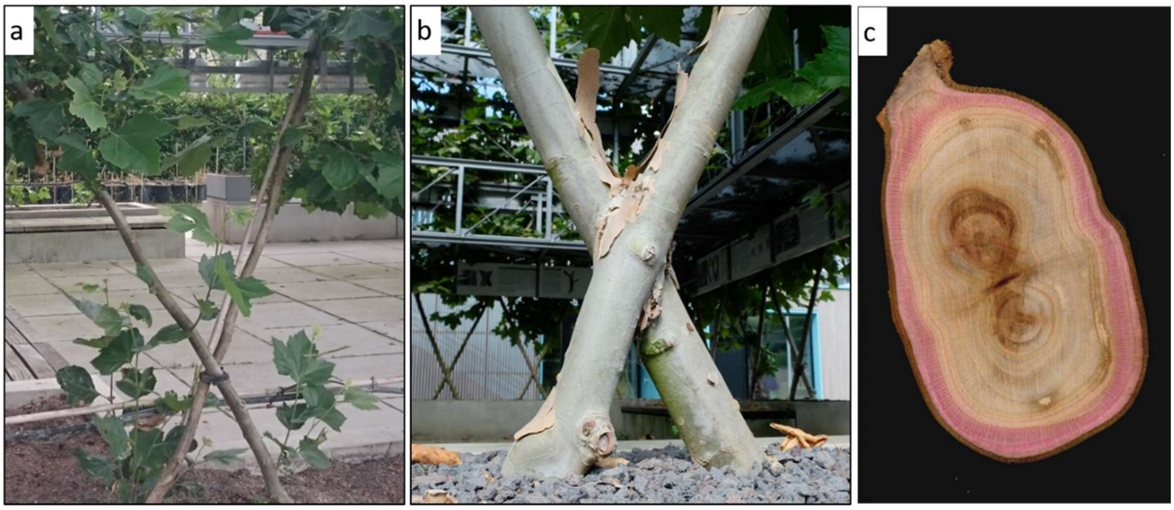

Figure 4.1. Induced inosculations in *Platanus* x *hispanica*. In the Nagold Plane Tree Cube before inosculation (a) and 7 years after inosculation (b). A horizontal slice through a pair of inosculated stems of *Platanus* x *hispanica* (with the water-conducting xylem dyed pink) – photo produced by Christoph Fleckenstein.

4.1.2 Mechanical features of inosculations

Typically, mechanical stiffness and strength in tree joint optimisation comes from two macroscopic features: mass growth and fibre orientation. By adding mass, the tree distributes stresses over a wider area. Mattheck describes the uniform stress hypothesis in which trees can allocate mass to reduce stress gradients, thereby efficiently avoiding potentially dangerous stress concentrations. For more detail compare Mattheck and Bethge (1998)[238] and Slater[239]. The fibre orientation defines the direction of relative strength and stiffness of the wood and the direction of water transport. Across a range of species, Young's modulus parallel to the fibres of clear dry wood is around 10 to 30 times higher than across it within the growth ring (the tangential direction); and compressive strength is typically 6 to 13 times larger parallel to the fibres than perpendicular to it, for the same species[36].

These sources can simultaneously contribute to mechanical optimisation, particularly in branch junctions[113], where stresses are high and where adaptations serve to level out longitudinal fibre deformations, resulting in constant strains instead of constant stresses. Some authors have investigated specific optimisations at branch junctions[240-242] or the specific fracture strength of branch junctions[243-245] while others provide a general understanding of structural attachment[246].

Of naturally occurring branch junctions, inosculated branch or stem pairs of similar size, like those designed in Baubotanik (Figure 4.1), mostly resemble tree forks. As described by many authors[240, 247, 248], a fork typically resists compressive forces in the outer edge of each branch and, more importantly, tensile forces in the middle section between the two branches. In Baubotanik-designed inosculations, elements growing at diagonals and supporting dead and live loads (Figure 4.1a-b) create tension forces in the inosculation between the branches. Throughout this study, in analogy to forked trees, the parts of the tree pairs above an inosculation (leading to the canopy) are called branches while those below the inosculation (leading to the roots) are called trunks. After the formation of a common growth ring the top-side of an inosculation can be seen as similar to a tree fork: two branches rising from a common joint[12]. As described in Slater et al (2014)[126], the wood fibre in forks must combine mechanical function (Figure 4.2a) with the physiological function of water transport from roots to stem (Figure 4.2b). These functions converge in the compressive area, with forces running along the fork from base to top. In the tension area, the forces run from branch to branch, which is not a viable water transport path. Slater's (2014)[126] anatomical investigations show that in this tension zone, fibres passing from the upper side of the branch down to the stem interweave (Figure 4.2c-d). This provides a pathway for water transport while allowing transmission of forces along the fibres, stretching instead of cleaving them. This is a combination of mass addition and fibre orientation.

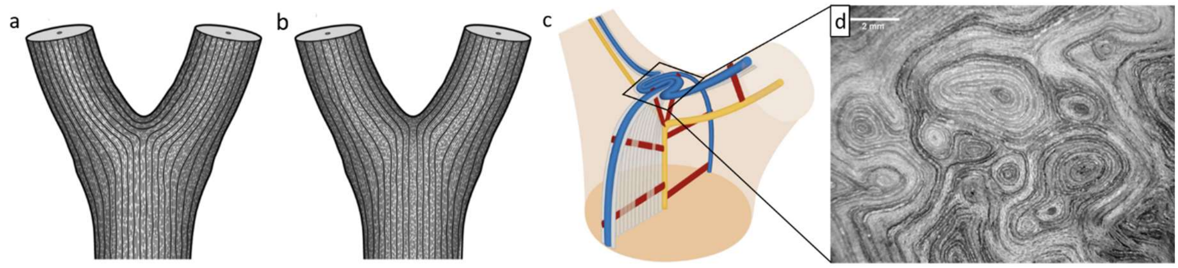

Figure 4.2. From Slater et al (2014)[126]: a fork with idealised fibril orientation for tension-zone mechanics (a) and for water transport from branches to roots (b). A model of the tension zone (interwoven vessels in blue, piths in yellow, fibres in white and rays in red), compromising mechanics and water transport (c). Interwoven fibres are visible by simply debarking a fork of common ash – (d) shows the interwoven zone, photographed from above.

4.1.3 A mechanical model of inosculations

A mechanical model of inosculations should include realistic material characterisation, be geometrically precise, and involve a construction that reflects the basic features of fibre orientation optimisation.

Over the last few years, the 3D-capture of complex shapes and representation of them in mechanical models has made significant progress. Recent improvements in cameras and LiDAR scanners have increased capacity for precise documentation[20, 83]. The resulting point clouds allow detailed maps of tree geometry, previously typically modelled as cylinders informed by diameters at key points. Software for comparing and manipulating point clouds is widely available. Steps have been made in utilising the detail provided by the resulting point clouds[317]. Photogrammetry is now affordable to many, while the cost of the most precise LiDAR scanners remains high. Additionally, constructing suitable meshes for FEA is still a time-consuming task that is generally not yet automated. Designers must find a balance between geometric detail and resource investment.

Recent detailed structural studies of trees recommend the use of orthotropic properties in future research[20, 249]. While Young's modulus in clear, straight-grained green timber is generally well mechanically characterised along the fibre[250], the equivalent data is generally missing in the across-fibre directions and in wood with abnormalities or natural optimisations for branching[251-253]. As a result, mechanical models of living trees rarely include orthotropic mechanical properties. Vojackova models orthotropy in a single branch[129], though other studies avoid orthotropy due to the paucity of material property data[20, 130, 249, 254].

The aim of this study is to develop a model for the mechanical behaviour of inosculations in the elastic range that adequately includes geometry, material properties and fibre orientation. Therefore, the central research question is: what are the relative benefits of including geometric detail and orthotropic material optimisations in mechanical models that can be used during living architecture's iterative process of design and maintenance? The models should be simple enough to be applied to diverse inosculations and should result in a deeper understanding of the key mechanical optimisations at play in inosculations.

In this paper, different model features are compared to understand their relative contributions to an inosculation's mechanical behaviour by replicating an experimental bending test in finite element analysis (FEA). Firstly, isotropic and orthotropic material properties are compared. Then, three levels of geometric detail are compared. Finally, a model of the tension zone suggested by Slater is compared with a model of local elemental orthotropy, a combination of these two, and the global isotropic and orthotropic models. In addition, we present qualitative results of bending tests beyond the elastic limits to stimulate future research on the failure modes of inosculations.

2.2 Materials and Methods

2.2.1 Bending tests

Four pairs of white willow Salix alba trees (labelled and referred to herein as A12, A14, A24 and B13) at 14 years of age were chosen from a field of 62 inosculated tree pairs to conduct force measurements under bending in May 2021. The four pairs were selected for the clear alignment of the bases of the two trunks, inosculation (also referred to herein as the 'joint'), and branches in a single plane so that the out-of-plane bending caused by pulling would be limited. In A12, the trunk widths differed significantly and the smaller branch was pulled. In A14, A24, and B13, the branch with a suitable attachment point for the pulling cable that was best aligned with the bending plane was chosen for winching. This also determined the position of the force point on the branch, which was 27cm, 30cm, 35cm and 56cm from the top of the inosculation in B13, B24, A12 and A14 respectively. Each tree was pulled with a 7.8kN winch from an anchor point 3-10m away, connected to the tree by a forcemeter. The winch position was chosen to allow a close to 90° angle between the force direction and the pulled branch, maximising the component of the force that acts in bending and minimising unwanted axial forces along the branch. The tree pairs were bent with steadily increasing force and released six times within the elastic range. Several days later, each tree was then pulled a seventh time to failure, ignoring these limits.

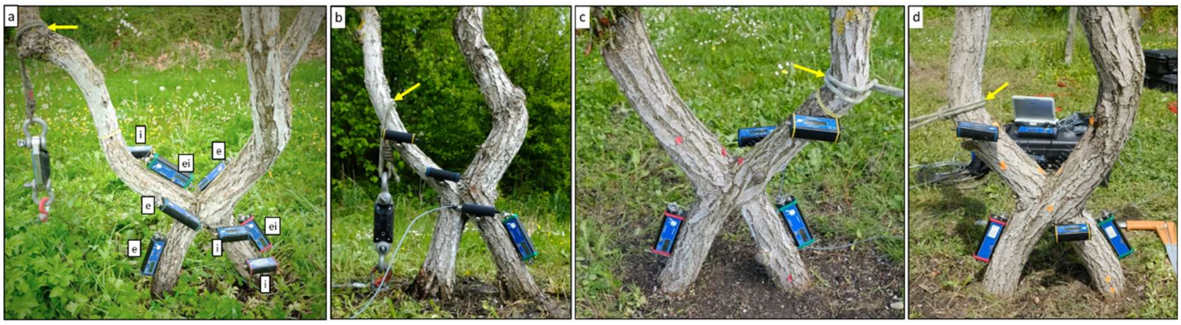

Figure 4.3. Winching setup for each tree pair. A14 is set up for the elastic pulls (a) and A12, A24 and B13 for the pull to failure (b,c,d). Labelled in (a) inclinometers, i, and elastometers with in-built inclinometers, ei, provide the rotation data used in this study. Elastometers, e in (a), ensure the elastic limits of the trees are not reached. Yellow arrows mark each force point.

Standalone biaxial inclinometers and triaxial inclinometers (built into elastometers) were used to measure the rotation of the tree pair at several points, as shown in Figure 4.3. Additionally, non-inclinometric elastometers were used during the six pulling experiments within the elastic range, to ensure the elastic limit was not reached: no more than 0.1% strain was allowed in any elastometer[248]. No more than 0.20° of rotation was allowed at the base, a limit for damage to the root base[255]. Apart from this gauge of maximum strain in the pulling experiments below the elastic limit, the elastometric data is not used in the present study. All devices were standard TreeQinetic devices, run with the PiCUS TreeQinetic software[256].

Different setups were used in the initial six pulls and the seventh pull. In the first six pulls, four biaxial inclinometers and two triaxial inclinometers were used. Biaxial inclinometers were placed below the force point (yellow arrows in Figure 4.3) and above and below the inosculation for all six pulls, and at the back and front foot for three pulls each. Triaxial inclinometers were placed on the back leg and the pulled branch, providing seven rotation measurement points in total. Additionally, three standalone elastometers without built-in inclinometers were placed around the tree pair (labelled 'e' in Figure 4.3a) to check elastic limits were not exceeded. In the seventh pull, three biaxial inclinometers (below the force point, above and below the inosculation) and two triaxial inclinometers (one on each leg) were used – totalling five rotation measurement points (no standalone elastometers were used). All instruments were aligned to the bending plane. While the biaxial inclinometers measure in-plane and out-of-plane rotations separately (allowing direct comparison with in-plane rotation in the FEA model), the triaxial inclinometers do not separate these rotations, but provide a resultant value of the vector sum of the three directions they measure.

4.2.2 Material Characterisation

Orthotropic material properties of *S. alba* wood are sparsely documented. Some databases provide isotropic stiffness and strength data[257, 258] while several studies, some of which are summarised by Leclercq[259], describe dry orthotropic strength properties. No study of orthotropic green *S. alba* properties was found. Van Casteren[260] finds the Young's modulus of green *S. alba* branches to be around 5 GPa, Kretschmann's detailed catalogue of the mechanical properties of green and dry wood includes species similar to *S. alba*: yellow poplar and black willow[36]. Leclercq describes several mechanical properties (such as compressive strength) along and perpendicular to the fibre (i.e. not differentiating between radial and tangential directions), five of which are also presented by Kretschmann (2010)[36] for dry wood of 30 other species. Considering the relationship between green and dry wood, few studies have been made that compare orthotropic mechanical properties[251, 261], and none that considers *S. alba* or similar species. Only the Young's modulus measured along the fibre direction (E_L) is well documented in green and dry wood – it is catalogued for 30 species (not including *S. alba*) by Kretschmann (2010). From this data, it can be seen that $E_{L,dry}$ is a good indicator of $E_{L,green}$: a linear regression of $E_{L,green} = 0.73*E_{L,dry} + 775\text{MPa}$ has an R^2 value of 0.915. While Kretschmann (2010) notes an increase in stiffness properties with a decrease in moisture content, little other relevant data is available.

This study draws primarily on two sources: Kretschmann's (2010) orthotropic properties for dry wood of 30 species (not including *S. alba*); and the five aforementioned mechanical properties in Leclercq's (1997) study of *S. alba* and the corresponding properties in Kretschmann's (2010) catalogue of 30 other species. These five properties, and Leclercq's (1997) values for *S. alba* are shown in Table 4.1, in columns 1 and 2 respectively. In order to derive orthotropic mechanical properties of green *S. alba* wood from literature data, this study follows four steps (shown in Figure 4.4)

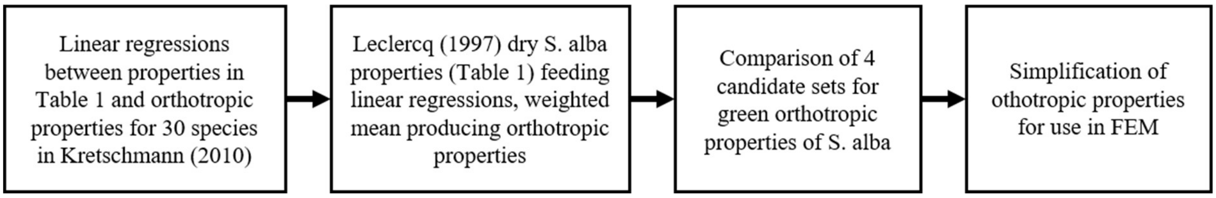

Figure 4.4. Flow chart of derivation of orthotropic material properties of green *S. alba* wood.

		For E_R					
Property	Leclercq (1997), LQ	m	C	$E_{R,LQ} = m*LQ + C$	R^2	R^2 weighting $R^2_{LQ} \div \Sigma R^2$	$E_{R,LQ}$ contribution
Specific gravity, ρ	0.382	2474	49	995	0.393	0.243	242
Young's modulus parallel to fibre, E_L	5290 MPa	0.0748	393	794	0.139	0.086	68
Shear strength, τ	6.31 MPa	119	110	861	0.572	0.353	304
Compressive strength parallel to fibre, $\sigma_{c,L}$	27 MPa	0.0204	326	875	0.212	0.131	115
Tensile strength perpendicular to fibre, $\sigma_{t,\perp}$	2.145 MPa	0.161	67	1017	0.303	0.187	190

Table 4.1. Calculation of E_R using weighted linear regressions, derived from Kretschmann (2010) and fed with Leclercq's (1997) properties for *S. alba*.

In the first step, a linear regression between each of the properties in column 1 of Table 4.1 (e.g. shear strength, τ) and each of the dry orthotropic properties (e.g. radial Young's modulus E_R) is found for the 30 species in Kretschmann's (2010) dataset (for example, $E_R = 0.119*\tau + 110$). The R^2 regression coefficient is noted in each case (for the given example, $R^2_{ER,\tau} = 0.572$). Five regressions inform each of the nine dry orthotropic properties.

In the second step, Leclercq's (1997) values for *S. alba* (the values in column 2 of Table 4.1) are fed into these regressions, predicting the orthotropic properties of dry *S. alba*. For the given example, $E_R = 119*6.31 + 110 = 861$ MPa (columns 3-5, Table 4.1). A weighted mean of the five linear regressions informs each of the nine dry orthotropic properties. The weights (column 7 of Table 4.1) are proportionate to the regression coefficients (column 6 of Table 4.1), with the contributions (column 8 of Table 4.1) summing to produce properties for dry orthotropic *S. alba*. Table 4.1 shows this calculation for E_R (the final column sums to 919 MPa).

In the third step, due to the paucity of data on *S. alba* green wood, four candidate sets of orthotropic properties are compared for replication of the experimental results for tree pair A14. One of these sets is then taken forward as the 'green' *S. alba* properties. The sets are: set 1, the 'dry' properties calculated above; set 2, the dry properties calculated above, with E_L modified by the linear regression between $E_{L,green}$ and $E_{L,dry}$ stated in the opening paragraph of this section; set 3, the modification in set 2 applied to all Young's moduli and shear moduli, not only to E_L; and set 4, using the properties of set 2 with all other properties (other than E_L) modified by the ratios to E_L described by Davies et al (2016)[251] for Monterey pine. Each set was compared with the experimental data from tree pair A14, in the 'Slater' and 'isotropic' models (described in section 2.4), on P5 meshes (described in section 2.3). Sets 1, 2 and 3 were similarly accurate (R^2 = 0.67, 0.66 and 0.64 respectively) and better than set 4 (R^2 = 0.56) in the Slater model. In the isotropic model, all four sets were similar (R^2 = 0.375, 0.371, 0.367, and 0.371, respectively). Given the similar accuracy of sets 1, 2 and 3, the relative accuracy (R^2 = 0.915) of the linear regression between green and dry wood ($E_{L,green} = 0.73*E_{L,dry} + 775$MPa), and the lack of data for other green-dry property relations, property set 2 was used. This results in a significant assumption that the differences between green and dry wood in each property apart from E_L are negligible. This may limit the accuracy of the models.

Finally, the radial and tangential directions are simplified into one direction 'perpendicular to the fibre' due to the convoluted growth rings within the joint (see Figure 4.2d). The growth rings, and the radial and tangential directions along and across them, are unclear without destructive microscopy. Therefore, from the derived orthotropic values, a mean of the tangential and radial directions is taken as the perpendicular direction to the fibre orientation, resulting in simplified orthotropic properties. In the finite element models, these are compared with isotropic properties (see Table 4.2). In line with previous studies[20, 130], the longitudinal Young's modulus and shear modulus are applied in isotropy, while the Poisson's ratio used is the mean of the two Poisson's ratios derived from longitudinal pressure (resulting in radial deformation, υ_{lr}; and resulting in tangential deformation, υ_{lt}).

	Specific Gravity ρ	Young's modulus E_L, MPa	Young's modulus $E_{R,T}$, MPa	Shear modulus $G_{LR,LT}$, MPa	Shear modulus G_{RT}, MPa	Poisson ratio $\upsilon_{LR,LT}$	Poisson ratio υ_{RT}
Isotropic	0.357	4639	4639	426	426	0.355	0.355
Orthotropic	0.357	4639	715	426	9.26	0.348	0.361

Table 4.2. Inferred isotropic and orthotropic mechanical properties for green *S. alba* used in the finite element analysis.

4.2.3 Geometric detail

Three levels of geometric detail are compared: a cylinder model and two Poisson surface meshes. A simple cylinder model that replicates a basic tree mechanical model and the typical level of detail used in growth prediction models (element length and radius). A LiDAR point cloud is used to generate Poisson surface meshes at two levels of detail. This is performed in CloudCompare (v2.11.3)[128], which uses an octree to determine relative precision. An octree divides the model volume into 8 sub-volumes with each increasing level of 'depth'. A mesh of octree depth 5 ('P5' mesh) is a relatively precise reconstruction that requires minimal work in preparing the mesh for analysis. A mesh of octree depth 6 ('P6' mesh) requires significant mesh preparation and has a higher level of precision. The average distance between the mesh and the LiDAR point cloud is 21mm, 2.7mm and 1.7mm in the cylinder, P5 and P6 models respectively. All LiDAR point clouds were generated from two to four scans of the trees with a Riegl LMS-Z420i at 3-4m scan distance. Kersten [262] finds the LMS-z420i has 2-4mm accuracy at up to 205m distance to the target. A 5mm voxel point cloud was produced using RiSCAN Pro[263].

4.2.4 Structural model configurations

The meshes were pre-processed in Meshlab[132], creating closed-surface 2D meshes with triangular elements. They were then imported into SpaceClaim[133] where they were converted to tetrahedral volumetric meshes. The cylindrical meshes consist of around 30,000 elements, while the P5 and P6 meshes consist of 10,000-15,000 and 40,000-45,000 elements, respectively. Ansys Mechanical[134] was used for static finite element analysis.

The material properties were applied to the P5 mesh in five different model configurations, shown in Figure 4.5. The first configuration is an isotropic material (Figure 4.5a). The second (Figure 4.5b) is an orthotropic material applied with a global orientation (the fibres running vertically from the ground to the top of the model). The third (Figure 4.5c) is a local element orthotropic model with four parts (one for each branch and trunk), segmenting the joint into four. The fourth is a global orthotropic model (as in the second) with the upper middle part of the joint oriented so the fibres are in the plane of bending, reflecting Slater's proposal of this area utilising the fibres' longitudinal stiffness (Figure 4.5d). The fifth combines the local orthotropy of the third configuration and the middle section proposed by Slater (Figure 4.5e). To compare isotropic and global orthotropic models, the first (Figure 4.5a) and second (Figure 4.5b) configurations were applied to the cylindrical (2 models) and P6 models (2 models), as well as the aforementioned P5 models. Table 4.3 lists the models and the comparison groups.

Model	Isotropic cylinder	Orthotropic cylinder	Iso P5	Ortho P5	Iso P6	Ortho P6	Elemental ortho P5	Slater P5	Combined P5
Isotropy vs orthotropy	✓	✓	✓	✓	✓	✓			
Geometric detail	✓	✓	✓	✓	✓	✓			
Localised features (P5)			✓	✓			✓	✓	✓

Table 4.3. All nine models built for each tree pair and the three lines of comparison relevant to each. 'Iso' and 'ortho' stand for isotropic and orthotropic respectively.

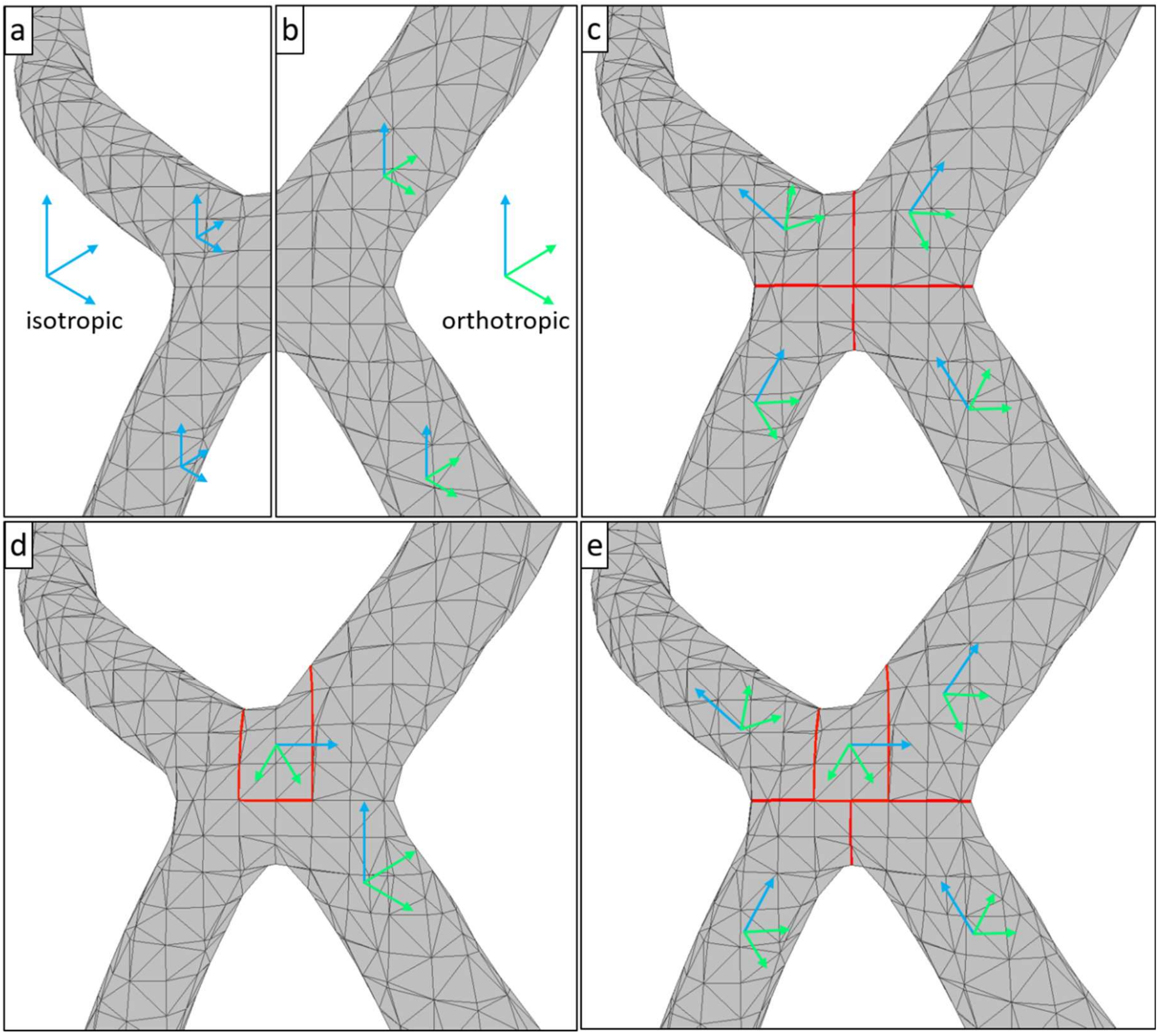

Figure 4.5. The P5 Poisson mesh of A14 split into parts for the five model configurations: the isotropic (a) and orthotropic (b) global models, the elemental orthotropic model (c), the Slater model (d), and the combined model (e). (a) and (b) are also constructed in P6 and cylindrical models, totalling 9 models.

In each model, winching loads were applied to a node corresponding to the force points marked in Figure 4.3, in the direction of the winch, guided by the LiDAR point cloud. As the core experiments were of elastic-range bending, all model parts only used elastic material properties. All model constituent parts (e.g. the five parts shown in Figure 4.5e) were connected at nodes, such that no displacement could occur between the nodes in each part. Characterising complex soil-root interactions is a major field of study[264]. In the present finite element model, a range of soil stiffness modulus values (between 0.005N/mm^3 and 2N/mm^3) were tested. A rotation spring stiffness of 1N/mm^3, applied to all underground faces, was found to replicate the trunk base rotations most effectively and was used in all models. This meant no displacements or rotations were fixed at any point as boundary conditions. While this is significantly higher than typical soil stiffness values[265], it accounts for the otherwise unknown root system stiffness.

Each inclinometer is attached to the tree at two points of contact. Corresponding points were located in the FEA-generated meshes. A line was drawn between these points in the models. The in-plane rotations of the FEA model at these points were compared with the in-plane rotations measured by the inclinometers in the field. The quality of fit of the rotations in each model to the experimental data was assessed by R^2 values.

4.3 Results

R2 values are used as a measure of accuracy throughout. As these differ between measurement points, to compare them (between geometric detail, material characterisation, or structural models) they are normalised to the mean of R2 values considered at each measurement point. All results described below refer to the in-plane rotations as measured by the inclinometers, compared between the FEA models and experimental results.

Each tree pair reached its elastic limit at a different load. In A12, A14 and A24 the elastic range limit (0.1% strain) was reached in the pulled branch at 0.1kN, 0.2kN and 0.6kN respectively. In B13, the elastic limit was reached at the base (0.20° of rotation) at 1.4kN. Failure occurred first in the pulled branch in trees A12 and A14, in the tension zone of the joint in A24 (in the tension zone) and by base-overturning in B13. Photographs of each tree pair before testing and after failure are shown in Appendix E1.

The models captured the behaviour of A14, A24 and B13 (average R2 = 0.53 across all models) better than A12 (R2 = 0.38). Within each tree pair, model accuracy varies significantly between measurement points, pointing to the significance of localised mechanical features. As the models compared in this study are of the inosculation mechanics, the results around the inosculation are compared below. Graphs of experimental data and models for each measurement point of each tree are in Appendix E2. Rotations in the biaxial inclinometers were predominantly in-plane – average out-of-plane rotation in the inclinometer nearest the force point is 20% of the in-plane rotation. Out-of-plane rotations are higher near to the force point. Near the ground, both in-plane and out-of-plane rotations are considerably smaller and more impacted by random error, reflected by larger out-of-plane rotations relative to in-plane rotations.

4.3.1 Material characterisation

Isotropic and orthotropic models were compared. Each group includes 24 measurement points (four tree pairs at three geometric detail levels, above and below the joint). At 15 of 24 points, the orthotropic models are more accurate. As shown in Figure 4.6a, the orthotropic models have a higher median accuracy and higher interquartile values than the isotropic models. The cylindrical models were mostly unaffected by orthotropic characterisation (R^2 increased on average by 0.026) while the P5 and P6 were more affected (R^2 increased on average 0.071 and 0.070 respectively). Figure 4.7 shows the models and data for A14, below (4.7a) and above (4.7b) the inosculation (also in in Supplementary Material B). The orthotropic Poisson mesh models generally predict more rotation (i.e. less stiffness) than occurred in the experiment, while the isotropic and all cylindrical models generally predicted higher stiffness than the real tree.

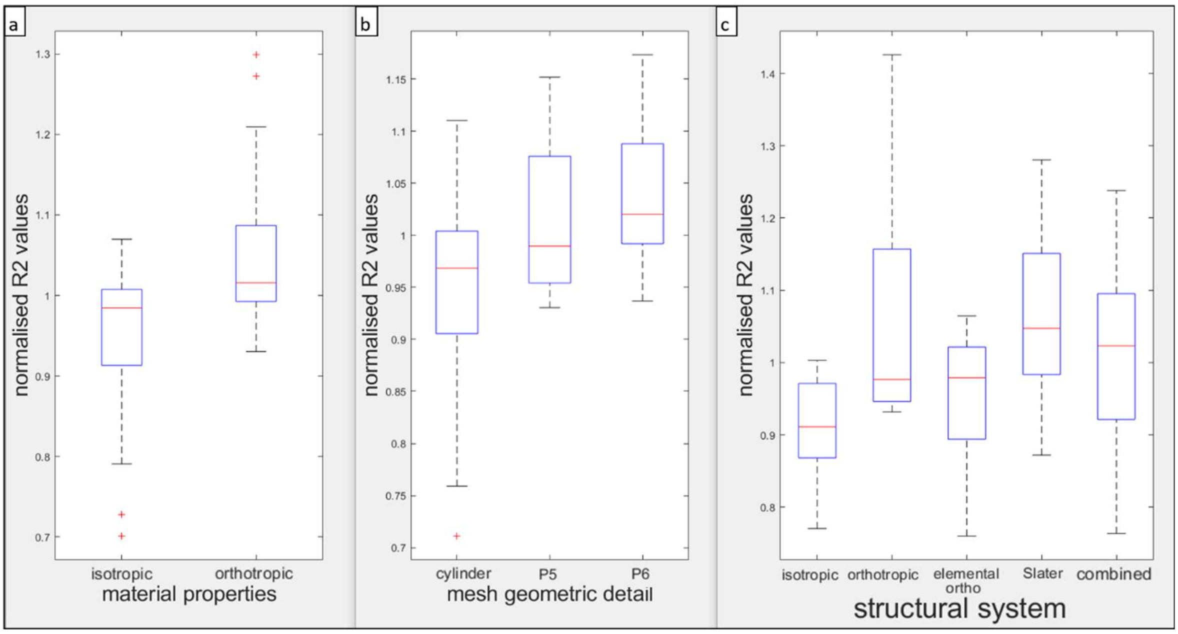

Figure 4.6. Model R^2 values (normalised to the measurement point mean) in predicting in-plane rotation above and below the joint: in isotropic and global orthotropic material characterisations (a) at three levels of geometric detail (b) and five structural model configurations using a P5 mesh (c).

4.3.2 Geometric detail

Geometric detail is compared for isotropic and (global) orthotropic models above and below the joint in four tree pairs (totalling 16 measurement points). The P5 mesh models are more accurate than the cylinder models at 11 of 16 points. The P6 mesh is more accurate than the P5 mesh at 6 of 16 points. As shown in Figure 4.6b, the median normalised P6 R^2 value is slightly higher than the P5 median and significantly higher than the cylinder model median.

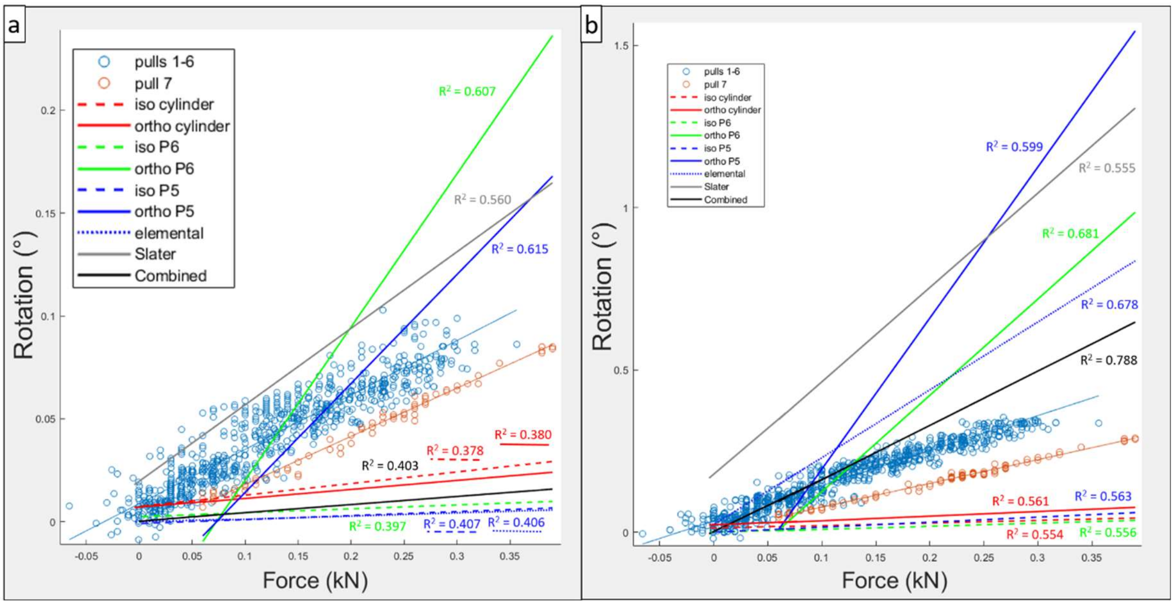

Figure 4.7. Experimental and model data below (a) and above (b) the inosculation in A14.

4.3.3 Structural model configurations

The five structural model configurations (Figure 4.5) are compared in a P5 mesh, above and below the inosculation for all four tree pairs (totalling 8 measurement points). The isotropic model is the least accurate, followed by the global and elemental orthotropic models respectively. The Slater model is the most accurate, followed by the combined model. As shown in Figure 4.6c, there is significant variation within structural models, particularly in the orthotropic model. R^2 values vary between tree pairs: A12 R^2 values range from 0.279 to 0.463, while R^2 ranges from 0.403 to 0.788 in A14.

4.4 Discussion

This study finds that improvements in elastic model accuracy arise from both higher geometric precision and detailed structural models (based on changes in the representation of localised fibre direction), independently and in combination with one another. While the improvements in cylindrical models caused by moving from isotropic to orthotropic materials are small, the equivalent improvements in the Poisson meshes are larger. The P6 models are not consistently more accurate than the P5 models. This points to the benefits of combining moderate geometric detail and orthotropic material property characterisation. While the local orthotropic model was an improvement over the isotropic model, it was not as accurate as the (less complicated) global orthotropic model. In contrast, the Slater-style tension zone significantly improves accuracy. This leads to the key result of the study: that, more than high geometric detail or precise material characterisation, the correct identification of specific optimisations should inform living architecture mechanics models. Documenting and meshing highly detailed geometry can be expensive and time-consuming with diminishing marginal returns in accuracy, compared with the benefits of moderate geometric detail and meshes that characterise mechanical optimisations such as Slater's tension zone.

In the iterative design process, the required level of geometric detail can come from two sources: direct documentation and growth prediction. Direct documentation can come from periodic photogrammetric or LiDAR surveys. Two directions for application of the present findings are recommended. Firstly, studies building predictive models of inosculation mass growth (combined with pruning plans, based on initial and environmental conditions) can incorporate the changing mechanics of the inosculation. Secondly, visual methods for assessing inosculations for mechanical strengths/defects can be developed that consider the Slater tension-zone, incorporating the present study's findings into growth design and guidance practice without the need for detailed numerical models.

Further development of the models presented here should reflect the developmental features common to a broad range of inosculations. A sister study to this one (in review) compares the structure of inosculations with tree forks, describing similar mechanical-physiological trade-offs. Anatomical investigations would provide the botanical perspective related to the present mechanical investigations. Improved orthotropic mechanical characterisation of green wood is needed in most species, including *S. alba*. This includes characterisation of wood in the inosculation, and specifically tension wood in hardwood species. This would shed light on the relevance of the material properties used (and the underpinning assumptions relating the properties of dry and green wood). This would allow application of a range of mechanical properties to the models, testing for accuracy in replicating the experimental results. Characterisation of inelastic behaviour may shed light on the failure modes presented here, which remain a point of interest and not a key result of this study (given the limited number of failure mode data points). The basic level of geometric precision achieved by the P5 meshes requires neither high computation nor human time investment while the P6 meshes require significantly more human hours to prepare. More detailed meshes demand more computation time. When utilising these techniques, practitioners must find a balance between mechanical precision and time input. Mesh precision also informs the necessary documentation precision, with photogrammetry, mobile LiDAR and terrestrial LiDAR offering different levels of detail.

The Slater-style tension zone may be found in many Baubotanik joints, living root bridges, and naturally-growing inosculations (as well as tree forks). Given the common growth ring forms around the entire inosculation[107], this zone is likely to occur regardless of the inosculation type – crossed (as in this study) or parallel trunks[12], or knots (as in the living root bridges)[74]. While this provides a broad scope for the present research, the diversity of forms makes it difficult to run studies like the present one, comparing across trees. Future studies should aim to make direct comparisons with the present results. This study does not differentiate between the pre-existing independent trees and the common growth that forms the interwoven zone because the *S. alba* saplings that the studied pairs originated from were so small that their mechanical effects were considered negligible. Models of inosculations with little common growth in comparison with pre-existing growth should incorporate this[266]. Such a model would require documentation of the trees before inosculation. Given the importance of even a basic geometric characterisation, this documentation is also essential for predictive structural analysis. These should be aggregated with growth models and pruning plans.

4.5 Conclusion

This study shows that models of elastic behaviour in inosculations benefit from a combination of moderate geometric precision and a structural model that reflects local optimisations, such as the tension zone adaptation proposed by Slater (2014)[126]. Drawing on the optimisations of naturally-growing tree forks subject to similar physiological and mechanical pressures has yielded a fruitful model of inosculation mechanics. Finite element analysis of point cloud-derived meshes has yielded a method for analysing existing and predicted inosculations – an essential part of the iterative process of designing living architecture. If practitioners can capture and model the basic form of tree elements and joints, major improvements in structural models can be realised. Future studies should replicate the present models in new settings, investigating different species and inosculation forms. Deeper research into the failure modes of inosculations would give designers key insight into their practical use in structural engineering.

Chapter 5

Application of the methods and workflows in living architecture design

An important goal of this research was to develop methods that can be applied in practical Baubotanik projects. This was done in the context of teaching courses. The Masters' studio series: Design – Build – Grow! was run in the winter semesters 2020/21 and 2021/22 in collaboration with Qiguan Shu and Ferdinand Ludwig. The goal of the studio series was to utilise our research in LRBs and the associated methods in design, as well as pushing the research further – applying the work to different settings. The studios resulted in the design of two buildings. Arbor Kitchen was constructed in March 2021 and March 2022 at Neue Kunst am Ried Sculpture Park, Baden-Württemberg; and the Living Root Pavilion is planned for construction at the North Eastern Hill University (NEHU) campus in Shillong, Meghalaya. In section 5.1.1 and 5.1.2, the methods and workflows from Chapters 2 and 3 are applied to Arbor Kitchen. In sections 5.1.3, potential application of the method from Chapter 4 is discussed. In section 5.2, application of the methods and workflows to the Living Root Pavilion is discussed.

5.1 Arbor Kitchen

The first Design – Build – Grow! studio (2020/21) involved 11 architecture and landscape architecture students from TUM. It challenged students to design a roof for a grove of 32 London Plane trees (planted in 2012) surrounding stone tables and an oven, under which the visitors and artists at Neue Kunst am Ried Sculpture Park can gather, eat, cook, and discuss, while the trees continue to grow. The client wanted the structure to interact with the landscape and to preserve the play of light through the canopy by minimizing the use of technical elements. The resulting pavilion, Arbor Kitchen, encourages the trees to grow up through a space truss roof under translucent shingles, intergrowing with the truss to stabilise it. The design began with 2D trusses running between major branches on opposite sides of the grove, linked together by lateral rebar rings (the design system is shown in Figure 5.1b). The space truss was built in a workshop in Munich, coated with anti-corrosion paint, and transported to the site in 14 parts, weighing a total of 800kg and covering a footprint of $57m^2$. The truss reaches from around 2.5m at its outer edge, where it is supported near the first major branching points in the trees to around 4m in the centre, where an opening in the ridge allows branches to grow out. In March 2022, one year after the truss was installed (March 2021), translucent fibre-reinforced polymer shingles were added. The result is shown in Figure 5.1c.

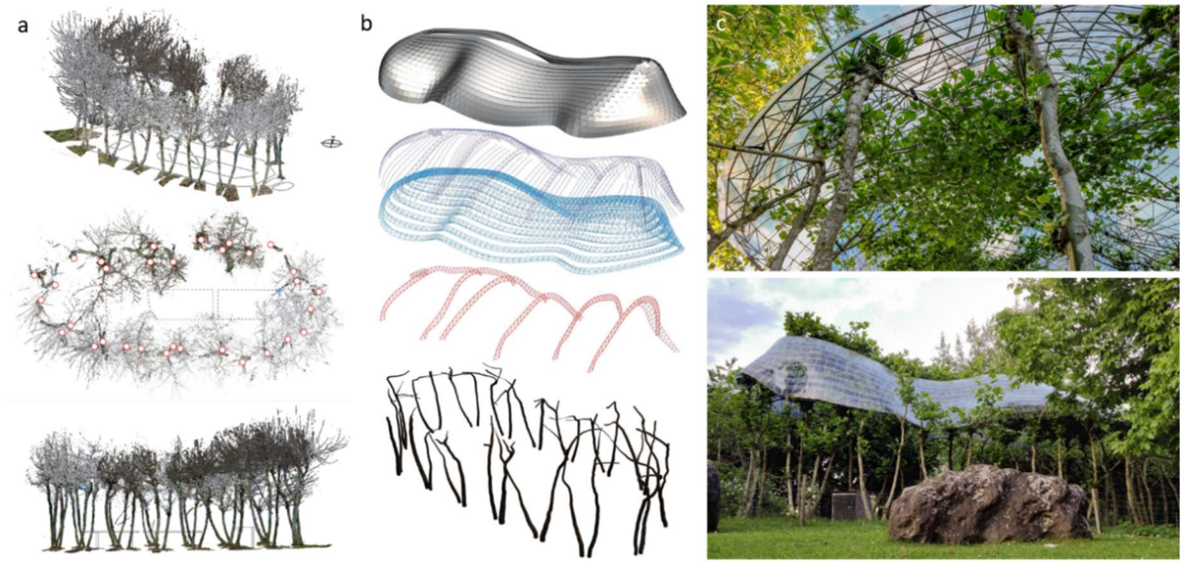

Figure 5.1. Arbor Kitchen: (a) perspectives of the photogrammetry of the tree grove, (b) design of the roof as 2D trusses fit to main branches with looped trusses to form a space truss, and shingles on top, (c) perspectives of the built structure in 2022 (photos by Kristina Pujkilovic).

5.1.1 Characterizing Regenerative Aspects of Arbor Kitchen

Here, an initial assessment of Arbor Kitchen with the LENSES Rubrics is presented. The assessment was done by the author alone, who was also a designer and constructor on the project. This is not meant to be a complete and final assessment, but rather an initial look into Arbor Kitchen's benefits and short-comings from a regenerative perspective. Ideally, the assessment would be repeated throughout Arbor Kitchen's lifetime by independent parties. The results are presented in Figure 5.2 and the full highlighted Rubrics are attached in Appendix C. Three main findings spring from this initial assessment, discussed below.

Firstly, the impact of the project on ecosystems is highly variable. As a grove of trees, Arbor Kitchen can be home to a range of ecological activity. *P. hispanica* is a hardy species[267] that helps create a stable and specific microclimate[268, 269], improves soil water levels and variability, and increases soil carbon storage and nutrient turnover[270]. This can result in lichen and fungi growth[271, 272] as well as potentially damaging pests[267, 273]. Fibre-reinforced polymer shingles may have a further greenhouse effect, increasing biomass productivity[270]. However, ecosystem diversity is low (and was not greatly considered in design), largely due to the use of a single non-native tree species. Low diversity can lead to low resilience. This points to the need for deeper work with ecologists in the design process.

Secondly, the small scale of the project had a major impact on what could be achieved. Arbor Kitchen was able to fulfil the central goals of the project well. The project began as a teaching and learning project, and will continue as a research project for students in years to come. As a small project, this could be put at the centre of planning, and each step of design and construction had space for students to learn. In considering the 'Beauty' flow, a design brief limited to a roof allowed the consideration of several significantly differing designs, while the shingle design was allowed a long time for ideation. A larger or more complex project may not have had this flexibility. The design brief asked for a structure that interacts with the landscape. As seen through the 'Land' flow, the enriched function of the site, as a tree grove and a shelter for meeting, discussion, learning and cooking is highly regenerative. A project that demanded walls or building services may not have allowed such multifunctionality in a small space. Other aspects that were not well achieved relate predominantly to the project scale. The major shortfall is in access to the site, which is very difficult to reach by public transport. A larger project could, for example, encourage a bus route to the site (though this is unrelated to the design or use of living architecture). This could intersect with encouraging a wider community of stakeholders (see 'defining community' focal point) from the project's start.

Finally, transparency of supply chains and working process is essential to regenerative construction, materials sourcing and funding. Only by understanding the sources of materials, their production processes, embodied carbon, water and other resources, the details of any offsetting schemes employed, and the destinations of any profits, can designers fully understand the impacts of a project. The two main technical materials used in Arbor Kitchen contrast this. The 'green steel' used[274] involves a relatively high level of transparency, whereby the supplier states their participation in a nationwide scheme for development and climate change mitigation. While some details are missing (e.g. exact numbers on investment in international vs local carbon offsetting), the material's embodied resources are, to a large extent, visible. In contrast, the fibre-reinforced polymer shingles were bought from an supplier that does not publish carbon footprint data. The designer must rely on generally available information about manufacture and disposal processes, which can be highly variable[275, 276]. Transparency intersects with project scale – transparency of working process (fabrication, site preparation, installation) can be well documented at a small scale (compared with the living root bridges, grown by thousands of people across Meghalaya), while demanding transparency from suppliers is easier for large scale designed projects.

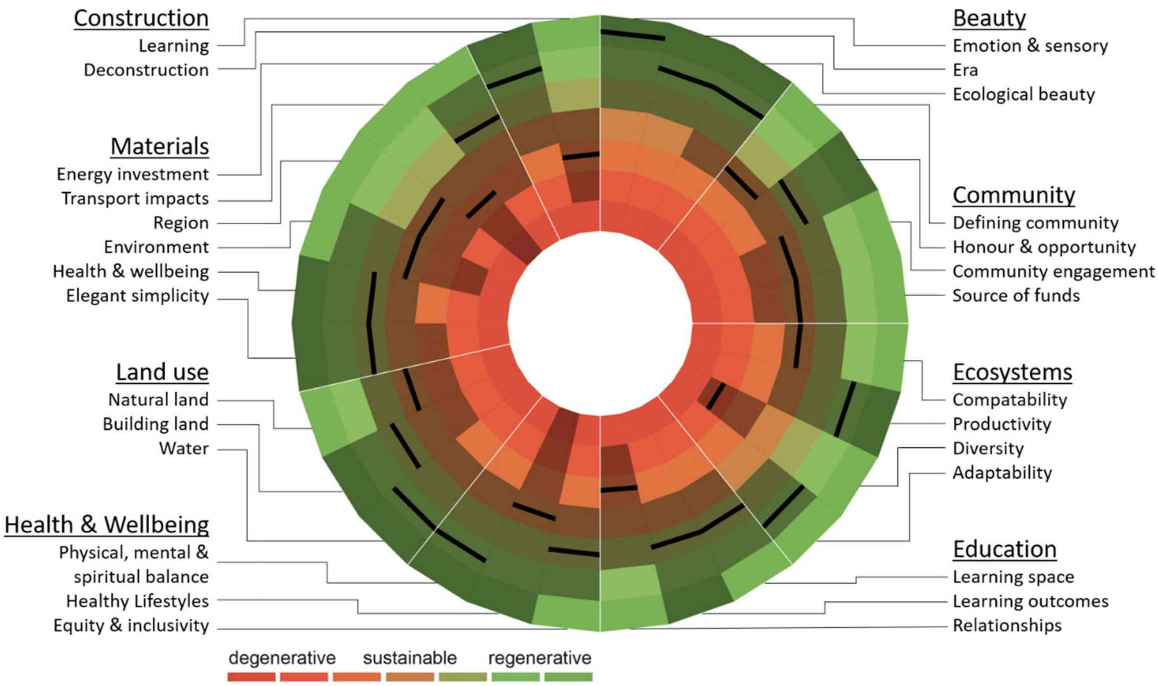

Figure 5.2. Preliminary LENSES Rubrics analysis of Arbor Kitchen. The relevant rings are greyed over (e.g. 'learning' in 'Construction' flow is sustainable and somewhat degenerative). The Energy, Money, Water, and Transportation flows were removed and the Construction flow added.

5.1.2 Documentation and Representation

After input lectures and practice with photogrammetry, the students documented the plane tree grove at Neue Kunst am Ried. Two different groups went to the site in October 2020 and December 2020. The latter took place after a snowfall in December 2020: the white snow clearly delineated the dark branches and trunks, producing a high quality photogrammetric point cloud of the trunks and undersides of the branches (Figure 5.1a). From this, skeletons of the trees were extracted, which were used as guides for 2D span trusses that underpinned the space truss. The digital plans then comprised of skeletons of the truss and trees, supplemented by a point cloud of the tree volumes and minor branches. Based on this, the truss was prefabricated in a workshop and lowered onto the trees with a crane, where the trunks and branches were bent into shape to make the best connections with the truss.

Once the roof was installed, it was LiDAR-scanned in May 2021. Figure 5.3a compares the October 2020 photogrammetric PC (from before roof installation) with the May 2021 LiDAR PC (from after installation and a single growth season). The photogrammetric survey used a 24MP Fuji XT 20 DSLR (APS-C sensor; 18 mm, f/2.8–4 lens) and has around 200,000 points per tree. The LiDAR PC was captured with a Riegl LMS-Z420i at 3-10m distance and has around 60,000 points per tree. Comparing visible marks near the bases of the tree trunks (where real deformation is minimal) that could be identified in both PCs, 12 measurement distances were drawn, shown in red in Figure 5.3a. These distances were compared between the two PCs. The mean differences in these distances is 0.39% (equivalent to 46mm in the 12m roof). This indicates the two methods produce little distortion on the scale of the whole scene and are (on that scale) somewhat interchangeable (though errors in individual smaller elements may still occur). The visible discrepancies between the PCs in Figure 5.3a are due to two main factors. Firstly, the manipulation of trunks and branches to make good connections with the truss. Due to the low weight of the roof and the minimal growth time between surveys (six winter months), this is likely to be the main real-world difference. Secondly, the photogrammetric PC is visibly more fragmented than the LiDAR PC around the upper trunks and branches, due to the interference of small twigs. Solutions to this fragmentation, and ways of extracting the 'true' objects, are well discussed elsewhere[207-210]. A skeleton was abstracted from the LiDAR PC using the method described in Chapter 3 (Figure 5.3b). Repeating this documentation and abstraction annually can allow updated mechanical and physiological analyses of Arbor Kitchen's status and its redesign (through new connections, pruning and manipulation).

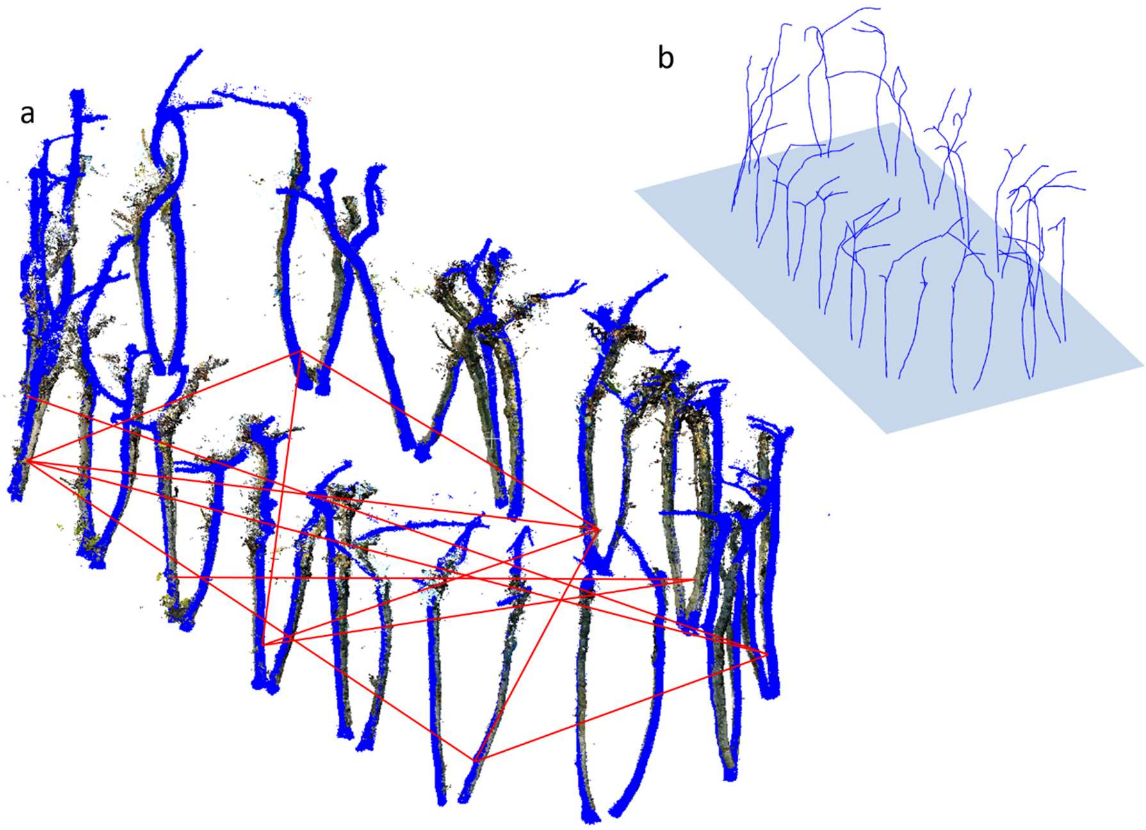

Figure 5.3. Digitization of Arbor Kitchen. (a) Point clouds: the October 2020 photogrammetric point cloud before the installation of the roof in photo-colours and the LiDAR point cloud from May 2021 after roof installation in blue. Red lines refer to measurements comparing PCs for deviation. (b) A skeleton model abstracted using the method described in Chapter 3.

5.1.3 Junction Mechanics

In its current state, Arbor Kitchen does not exhibit structural cross-wise inosculations (though several branches have been connected and the structure will exhibit many cross-wise inosculations in years to come). Many connections between the trees and truss in Arbor Kitchen are currently based around branching points in the trees. Many of these are connections to both branches above co-dominant bifurcations[277, 278] (or 'forks'). An example is shown in Figure 5.4: 5.4a shows a photo of the fork, 5.4b shows a LiDAR PC, and 5.4c shows a Poisson mesh based on the PC. In a simple gravity load scenario, the top half of a fork weighted on both branches resembles the top half of the cross-wise inosculation used structurally in many Baubotanik buildings – this resemblance is described in more detail in section 4.1. The forks are also similar to the forks examined by Slater (2014)[126] discussed in section 4.1. The method for finite element modelling (including meshing from the PC and model construction) described in Chapter 4 may be useful here. In particular, models including the Slater tension-zone that informs the most accurate models in Chapter 4 may prove particularly fruitful as the tension-zone was described by Slater in forks (the general area circled in red in Figure 5.4c). Models of these forks should be based on well characterised material properties and could be usefully informed by anatomical investigations of *P. hispanica* forks. In addition to the tension-zone, compression-zones on the undersides of the branches are analysed by Slater (2013). Models of the Arbor Kitchen's forks should investigate these zones (blue circles in Figure 5.4c).

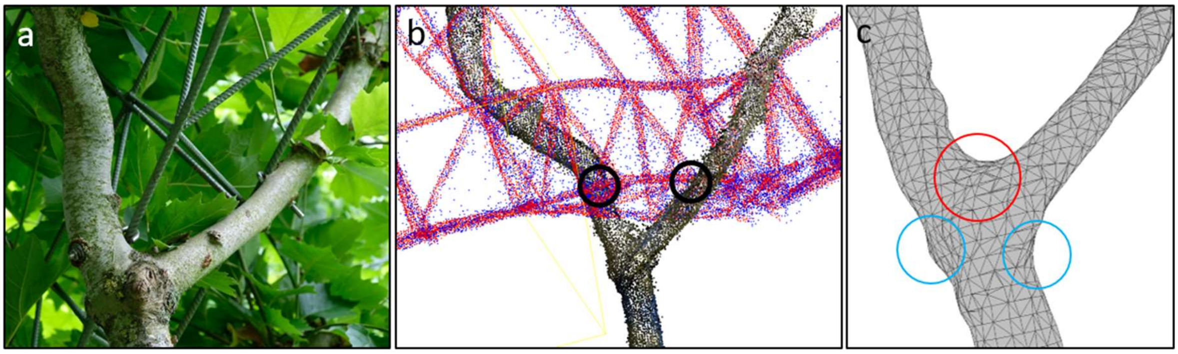

Figure 5.4. Connection of the Arbor Kitchen truss to branches above a codominant bifurcation: (a) a photo taken a few months after installation (photo: Ferdinand Ludwig), (b) a LiDAR PC representation of the junction and truss, (c) a Poisson mesh based on the PC with potential tension-zone (red) and compression-zones (blue) marked.

5.2 Living Root Pavilion

The second Design – Build – Grow! studio (2021/22) involved 12 architecture, landscape architecture and materials science students from TUM and North Eastern Hill University (NEHU). It was run as part of the 50th anniversary of Meghalaya's statehood in 2022, celebrating, exhibiting and exploring the region's traditional architecture. The design brief was a short-term structure made using traditional regional construction and weaving techniques to be grown over, in the long-term, by a living root structure that will be celebrated in Meghalaya's 100th anniversary. Traditional techniques include preparation of construction bamboo[279], weaving of bamboo, rattan and cane for lattices and walls[280], and construction (of scaffolding and buildings) with bamboo, areca palm trunks and other local timber[74, 281]. A group of students from TUM and NEHU worked with the Living Bridge Foundation and A+ Atelier Architects, based in Meghalaya. The resulting design is shown in Figure 5.5. The short-term design (Figure 5.5a) is of a grid-work of bamboos forming an undulating structure that is both shelter and platform, embodying two of Meghalaya's celebrated landscapes: mountains and caves. Saplings are planted in woven containers at the top of the structure. The long-term design involves the growth of the roots down through the bamboo grid over time. The bamboo will be regularly checked and decaying poles will be replaced or roots allowed to grow in their places. The roots will be guided to match the form of the original structure, eventually replacing it entirely (Figure 5.5b). The bamboo construction and woven sapling containers were prototyped in March 2022.

Figure 5.5. The Living Root Pavilion design: (a) in the short-term installation on NEHU campus in Shillong as a bamboo grid structure, and (b) in the long term grown structure (aerial roots of *F. elastica* replacing the bamboo over time).

5.2.1 Transfer of regenerative design from LRBs

The assessment of the living root bridges in Chapter 2 details the regenerative, sustainable and degenerative aspects of LRBs in their current settings. A core goal of the design of the Living Root Pavilion is to bring the cultural and ecological features of LRBs to the city. With this in mind, it is useful to look at the regenerative and degenerative aspects of LRBs. With reference to the Living Root Pavilion, the potential for transfer of regenerative aspects and avoidance of degenerative aspects is examined, based on the LENSES Rubrics analysis results from Chapter 2. The regenerative and degenerative remarks highlighted in the Worksheets (presented in Appendix C) were evaluated for potential transfer and avoidance respectively, allowing an understanding of the potentially regenerative and degenerative aspects of the Living Bridge Pavilion.

The results are presented in Appendix D and some key themes are outlined here. Certain regenerative aspects are well transferred. While the original function of the LRBs (as a transport network) does not transfer to the pavilion, their function as a visitor site does transfer. With this, the regenerative cultural aspects of the LRBs are accentuated. One aspect of the design is the integration of Meghalaya's weaving tradition, employed for baskets, building walls, stools, and many other household items[148, 280, 281]. By working with the same materials (*F. elastica*, bamboo, rattan, cane, Areca palm), the ecosystem, material and beauty elements are transferred. On the other hand, a completely different community is served. The pavilion should be much more accessible to diverse users who are unused to or simply cannot access the forest's difficult terrain. It is also tended by different groups of users and growers, and the educational and governance structures must be reconfigured. While very high ecosystem function of the LRBs in managed forests clearly cannot be directly transferred to Shillong, the pavilion may bring greater biodiversity to the campus[282].

5.2.2 Documentation and Representation

During the Living Root Pavilion's design, photogrammetric surveys of scale models and potential sites were conducted to allow exchange of ideas between students in Germany and India. After construction, both the complex growth of the living root structure and the highly complicated short-term bamboo structure will benefit from detailed documentation. Regularly documenting this with photogrammetry has two uses: assessment of the decay (and need for replacement) of the bamboo, rattan and cane elements; and capturing and planning the growth of roots as the ficus saplings overgrow the structure. One unknown is the necessary regularity of documentation, which depends on the useable lifespan of the bamboo (typically 2-5 years untreated[283] with a range of treatments available[279, 284]) and the growth speed of the *F. elastica* aerial roots. As the variable longevity of bamboo is one of the main barriers to its wider structural use[285], this research, which allows for that variability through regular documentation and a replacement plan, could pave the way for advances in bamboo building engineering[285]. The skeletonisation method proposed in Chapter 3 is built for elements in purely living structures, and is more easily adaptable to structures with few non-living elements than structures that have many. One solution may be the automated pre-separation of living and non-living elements by, for example, pixel colour[286] or cylindrical surface identification[287].

5.2.3 Inosculation Mechanics

The Living Root Pavilion will grow into a complex network of roots and inosculations. Essential to the mechanical investigations of the pavilion is a deeper understanding of inosculations formed by *F. elastica* aerial roots in various formations. The potential mechanical optimisations discussed in Chapter 4 should be investigated in aerial roots. For this, a wide survey of inosculations is needed, as well as mechanical testing and anatomical documentation, adapting the methods described in Chapter 4 and Slater et al (2014)[126]. In other mechanical investigations, regular documentation of the pavilion could shed light on the role of growth density and redundancy in structural stability. One potentially fruitful line of inquiry is through dynamic analysis[288, 289], which could allow the extraction of key structural properties such as dominant natural frequencies and mechanical stiffness. Optical methods are showing promising potential for measurement of dynamic responses[290].

5.3 Outlook

5.3.1 Urban Living Architecture

As these methods in living architecture progress, are supplemented by other useful methods, and are used in new structures, the horizons of application broaden. In particular, urban environments could benefit greatly from living architecture. Architects in dense tropical and subtropical megacities, where space is limited and the few trees are highly valued[10], should draw on banyan trees growing in dense urban environments (such as the Hong Kong Ficus walls, Tongliang temple in Taipei, and street trees in India, China and elsewhere[291]), as well as on the range of architectural projects that create conditions for trees to grow (in biomass)[292, 293]. Design of urban living architecture is an ongoing exploration with students at TUM. In 2022, I co-supervised groups of students who designed growth for buildings on a hypothetical megacity street, teaching them the foundations of *F. elastica* growth. Each group was provided with a building façade, and encouraged to imagine a building-tree topology after 100 years of growth. The results are shown in Figure 5.6. These trees could be structurally separate from buildings, or deeply structurally integrated. Their growth can be highly precisely guided, or they can be allowed to grow naturally over the building's surface. The students developed wide-ranging design ideas, with potential functions of the grown elements across the building, from shading facades and balconies to multi-storey structural staircases.

Figure 5.6. Student designs for building-tree topologies with *F. elastica* in a city street, inspired by the living root bridges (photo: Qiguan Shu).

5.3.2 Directions of future research

The creation of these methods and workflows opens many doors for future research: improvements to their process through enmeshing with other tools or data; application to other projects; and combination with adjacent fields of research. Some areas of future research work that interact with the present studies are discussed here.

The regenerative analysis method can be expanded to encompass translation between projects. As stated in section 2.4.2 (and shown in a preliminary study in section 5.2.1), projects that adapt vernacular technologies to modern contexts can benefit from this transfer analysis. Combining the present method with others can allow designers to draw on established work or develop new methods. For example, the results presented in sections 2.3 and 5.1.1 show that a regenerative assessment can benefit from deeper dives into ecology, for which a range of tools are available[87, 173]. In living architecture in general there is broad application potential for regenerative methods, particularly with regards to rethinking the interacting needs of many stakeholders based on trees' ecosystem functions and widespread public benefits.

The benefits of point clouds and their derivative representations are clear in grown structures, and therefore may be useful for a wide range of other projects. Point clouds are useful when documenting the complex shapes and the distributed changes caused by growth and decay. Some light has been shed on the comparative benefits of photogrammetric and LiDAR point clouds in living architecture in sections 1.7.1.1 and 5.1.2 showing that, for the mechanical analysis of inosculations and the tree trunks in Arbor Kitchen, the differences between the two methods are negligible. More research is needed in this direction. The utility of different optical may differ depending on the structure and its setting. In particular, the relevance of underperformance by photogrammetry in the presence of small leaves and twigs should be examined.

The skeletons presented in Chapter 3 provide the basis for mechanical and physiological investigations of whole living structures. In this area, there may be more to learn from living root bridges. LRBs appear to be remarkably resilient in two interesting ways. Firstly, landslides, rockfalls and floods occur each monsoon in Meghalaya, often taking place in streams and rivers, and directly hitting the bridges. Many bridges have survived major damage. A significant part of this resilience to damage may be due to the structural and physiological redundancy of root networks, and their potential for regrowth. Given the regularity of landslide, rockfall or flood damage, research into LRB resilience and regrowth after damage is necessary. Secondly, Meghalaya is in a region of very high earthquake risk. In 1897, an earthquake flattened much of Shillong[294], while at least some living root bridges survived it (according to the age estimates by bridge-builders and users[74]). In modern seismic engineering, ductile materials[295] and cross-bracing[296] are two key tools in minimising damage. A network of living roots embodies both of these adaptations. The structural topologies of LRBs and the ductility of their constituent roots should be examined, as well as their dynamic resonance features[297]. This may shed light on key structural topologies when designing with *F. elastica* growth.

In developing finite element models of inosculations (or other structures), material mechanical properties are needed that relate to the orthotropic nature of wood. In the calibration of the models presented in Chapter 4, the required elastic properties are calculated from the literature. There were two reasons for this: the inosculations in question were part of ongoing field experiments and samples could not be extracted; and no in-situ tests had been developed for precise documentation of inosculations (or other living wood joints). Future studies should investigate the use of μCT scanning[27] or tomography[298] for in-situ characterisation of inosculation wood. While the comparison of four sets of material properties presented in section 4.2 go some way to showing the relative importance of precise characterisation, future mechanical models could be informed by direct investigations, particularly of inosculation wood. These investigations should comprise of two parts: inference from anatomical examination and mechanical testing. Anatomical examinations (such as conducted on inosculations in a paper by colleagues at TUM, in review) can help identify differences in mechanical properties via differences in biological structures, and thus the relevant mechanical tests for quantifying them. The tortuous interwoven fibres captured by Slater's (2014)[126] anatomical investigations of hazel forks led to compression and tensile tests comparing stiffness between this region and others within the fork[299]. Rüggeberg et al (2008)[300] are inspired by the microstructural changes across vascular bundles of palm trees (*Washingtonia robusta*) to investigate cell wall area fraction. To examine adaptations at this scale, microtensile stiffness tests were used, and cell wall area fraction was found to correlate with tissue stiffness.

The models of inosculation mechanics presented in Chapter 4 can be improved by application to a range of inosculations (of different species, geometries and loading scenarios) and by understanding better the origins of the tension-resistant zone (whether this is Slater-style interwoven fibres or other optimisations[299]). These can be studied in Baubotanik buildings that utilise cross-wise inosculations, such as the Baubotanik Tower, Plant Tree Cube (both detailed in section 1.2), and Freiburg Pavilion (detailed in section 3.2.1). Given there are many cross-wise inosculations present in these structures (Figures 3.5a and 4.1b), in similar formations and under comparable loads, they could provide a useful dataset for understanding common mechanical features. This comparison may shed light on the environmental or genetic origins of such features, a question relating many plant biomechanics phenomena, including the adaptations of buttress roots in tropical trees[301-303] and aerial roots in LRBs[74]. Such investigations would require a combination of regular documentation using LiDAR or photogrammetry as well as anatomical investigations. One mechanical feature of branches and trunks that was not been modelled in Chapter 4 is radial variation of stiffness, seen in green[261] and dry[303] wood. For this, different meshing methods may be useful, such as voxel and pipe models based on a central skeleton that allow easy allocation of radially varying properties. In exploring the wider application of the presented foundational research, we can turn to biomimetics. Researchers transfer the optimisations to organic joints in technical joints, such as braided junctions with a range of angles[304] and pull-out resistant T-joints[305] including for specific uses, such as aeroplanes[306]. The fibre orientation and mass addition of inosculations may be of interest in this field.

A pressing area of research adjacent to the current project is the growth conditions of *F. elastica* aerial roots. In general, it is not known what conditions, processes or hormones stimulate *F. elastica* shoot or aerial root growth. Anecdotal evidence that LRBs grow more quickly in higher temperatures is supported by the literature[307, 308]. Increased lighting period up to 20 hours per day and increased light intensity were found to increase growth[204], while no clear effect was found from increased relative humidity (from 60 to 85%)[309]. The addition of biochar or Nitrogen also has been found to promote root and shoot growth, and biochar reduces chromium-induced phytotoxicity[310, 311]. One study found root growth stimulated by two growth hormones in moderated concentrations[312]. *F. elastica* aerial roots are still poorly understood. Settle and Cernusak demonstrate the range of growth media for ficus saplings. LRB-growers often use moss, soil and enclosed palm trunks to initiate, encourage or guide aerial root growth[313]. Moles et al (2019)[291] found PVC pipes filled with potting mix, sphagnum moss, and a mix of both encourages aerial root growth in *Ficus rubiginosa*. Zhang et al (1995)[314] discuss the hormones present in aerial root tips. Further research on *F. elastica* aerial roots is needed.

5.4 Concluding remarks

In this thesis, methods and workflows for three aspects of living architecture design are developed. In Chapter 2, the regenerative, sustainable and degenerative aspects of living root bridges are assessed, allowing structured transfer of regenerative aspects to new projects, such as the celebration of Khasi cultural heritage in the Living Root Pavilion. The presented method also allows an understanding of the areas for improvement as a project develops, whether that is accommodating diverse ecosystems in Arbor Kitchen or improving access to living root bridges. Chapter 3 examines documentation and representation of living architecture, developing a low-cost workflow. Given their capacity to capture fine details, PCs are ideal for documenting the complex, unpredictable shapes arising in living architecture. The skeletonisation method built upon the foundation of PC data allows accurate representation of geometry and topology, and scales with PC quality, meaning improvements in technology can result in improvements in mechanical and physiological analyses. In Chapter 4, mechanical investigations are made of one of living architecture's key building blocks, the cross-wise inosculation. A method for modelling inosculations is provided, showing that a certain level of geometric detail is needed, alongside consideration of localised mechanical features. The mechanics of trees, and junctions in particular, are relatively poorly understood when compared with other building materials (sawn and glued timber, concrete, steel). The mechanical investigations of inosculation presented in Chapter 4 provide the basis for a mechanical model. With the improved characterisation of mechanical properties, such models will improve precision in design of loads.

The contribution of each line of research stands alone, but they come together in the dynamic approach that is fundamental to designed living architecture. Monitoring, analysis and design must be cyclical. In this way, engineering questions are central to design. As trees grow, their changing shapes must be documented, which allows precise mechanical analysis. Their structural loads can then be redesigned by including or removing technical or grown elements or changing use regimes. These loading changes should be understood in the wider regenerative design context. Another aspect of redesign is manipulation and pruning of trees for future grown states. As the trees grow stronger, more weight can be shifted onto the grown elements. Decay or death of trees can require weight shifted back onto technical elements or redistributed between the grown parts. As living architecture is taken up around the world, different practitioners can learn from one another by analysing, redesigning and discussing their work, back and forth between vernacular and professional architects.

This approach, accommodating time and uncertainty, has broad application also beyond living architecture. Time has an essential role in design and urban planning, from seasonal leaf litter clearance to old trees treasured as heritage landscape architecture or the growth and change of ecosystems as they adapt to a changing climate. Changes to non-living buildings may also be understood through this approach. The Eurocodes requires risk minimisation during a building's lifespan at the outset of design (see Eurocode 0 – Basis for structural design, Partial Factor Design[315]). This static approach, in which buildings are designed once results in 'over-strength' structures that (theoretically) do not change during their operational life and are too often demolished and too rarely monitored[316]. Designs and design methods that allow for monitoring and refurbishment could ensure safety while reducing waste and deepening public appreciation of cultural heritage buildings. In an unpredictably changing climate, the predicted risk approach is particularly susceptible to failure.

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Appendix A.

List of Living Root Bridges in Meghalaya (reproduced from Table S1 in Supplementary materials of Ludwig et al (2019)[1] reported in 2017/18

ID	Bridge Name	Degrees North (WGS84)	Degrees East (WGS84)	Altitude (m a.m.s.l.)	Main Village	River	Maintenance Group	Length (m)	Comment	Age estimates* (years)
1	Arch Bridge	25.337047	91.869545	727	Nongblai	-	v	2		
2	Burma 1	25.22155	91.98137	582	Burma	Wah Rbain	v	8.8	span 1 (2 parallel spans)	ca. 70 +
2	Burma 1							9.1	span 2 (2 parallel spans)	Ca. 40
3	Darrang 1	25.20516	92.01889	57	Darrang	Wah Sheng Pnar	ut	10.4		
4	Darrang Broken	25.199893	92.02186		Darrang	-	ut			
5	Diengsiar 1	25.21874	91.82688	757	Diengsiar	Wah Juki	uk	16.9		
6	Double-Decker	25.25135	91.67159	394	Nongriat	Mawsaw	v	24.6	span 1 (double-decker)	ca. 200
6	Double-Decker							18.4	span 2 (double decker)	
7	Halfway Nongbareh	25.231476	92.02035	599	Nongbareh & Kudeng Rim	Amchrai	uk	16.2		
8	Iar Soh Liang	-	-	-	Rangthylliang	-	i			
9	Kongthong 2	25.34485	91.82443	562	Kongthong	Wah Langta	uk	10		
10	Kongthong 3	25.34468	91.82458	555	Kongthong	Wah Langta	uk	16.3		
11	Kudeng Double Decker	25.22949	92.03191	542	Kudeng Rim & Kudeng Thymai	Amlohmar	i	29		
12	Kudeng Rim 5	25.22664	92.03979	520	Kudeng Rim	Wah Amkshar	v	30.7		
13	Kudeng Rim 8	25.23319	92.02389	673	Kudeng Rim	Am Sohlashan	ut	19.2		
14	Laitiam 1	25.23336	91.76718	332	Laitiam	Ustem	v	19.4		
15	Laitiam 2	25.2327	91.76888	307	Laitiam	Ustem	v	11.8		
16	Long Ti Uyiang	25.340448	91.86933	723	Nongblai	-	v	12		ca. 70
17	Lyngsteng 1	25.29853	91.80371	800	Lyngsteng	Wah Ulkhit	uk	14.9		
18	Mawkliaw 1	25.22774	91.81338	835	Mawkliaw	Wah Shari	ut	12.8		
19	Mawkliaw 2	25.23001	91.81118	862	Mawkliaw	Wah Umlwai	ut	16.7		
20	Mawkyrnot Long Bridge	25.29576	91.88293	1070	Rangthylliang/ Mawkyrnot	Wah Niur	c	52		
21	Mawlam 3	25.2627	91.84249	458	Rangthylliang/ Mawkyrnot	Wah Mynsaw	i	13	span 1 (double-decker)	
21	Mawlam 3							12.5	span 2 (double-decker)	
22	Mawsaw Hybrid	25.25766	91.67554		Nongriat	Umshiang	v			ca. 100
23	Mawsaw Old	25.2475	91.6745	334	Nongriat	Umshiang	ut	14.6		ca. 200

ID	Bridge Name	Degrees North (WGS84)	Degrees East (WGS84)	Altitude (m a.m.s.l.)	Main Village	River	Maintenance Group	Length (m)	Comment	Age estimates* (years)
24	Mawshken 1	25.28552	91.77377	739	Mawshken	Wah Mdon	uk	16.9		
25	Niah Li Bridge	-	-	-	Rangthylliang		uk	-		
26	Nongbah/ Mawshuit 1	25.30576	91.78537	555	Nongbah/ Mawshuit	Wah Myor	ut	15		
27	Nongbareh 1 (village Link)	25.22826	92.00876	607	Nongbareh	Wah Amlayee/ Ammusai	v	14.1		ca. 400+
28	Nongpriang 3	25.27781	91.74971	495	Nongpriang	Wah Umshet	ut	10		
29	Nongriat Access	25.25095	91.67219	376	Nongriat	Mawsaw	v	11.3		ca. 200
30	Nongthymmai 1	25.2491	91.67966	407	Nongthymmai	Simtung	v	25		
31	Nongthymmai 3	25.24915	91.67992	410	Nongthymmai	Simtung	v	36.1		
32	Nongthymmai Old	25.25344	91.68758	528	Nongthymmai	Simtung	v	34.1		
33	Pdei Kongtim 1	25.34547	91.81026	726	Pdei/ Kongtim	Umrew (unconfirmed)	v	33.8		
34	Rangthylliang 1	25.29647	91.88554	1211	Rangthylliang	Wah Kumpa	v	13.4		
35	Rangthylliang 10	25.30519	91.88525	881	Rangthylliang	Wah Risam	ut	9.8		
36	Rangthylliang 11	25.30512	91.88543	890	Rangthylliang	Wah Risam	ut	12.5		
37	Rangthylliang 12	25.30359	91.87199	421	Rangthylliang	Wah Pynursla	uk	52.7		
38	Rangthylliang 13	25.30211	91.87254	447	Rangthylliang	Pung Stait	uk	17.5		
39	Rangthylliang 2	25.29565	91.88302	1073	Rangthylliang	Wah Kumpa	c	9.8		
40	Rangthylliang 3	25.29692	91.88203	1053	Rangthylliang	Yiar Shit Kjat	i	4.8		
41	Rangthylliang 4	25.30001	91.88274	1023	Rangthylliang	Wah Mawlong	i	35.7		
42	Rangthylliang 5	25.30183	91.88492	1073	Rangthylliang	Wah Sohshiat	ut	13.3		
43	Rangthylliang 6	25.30676	91.88983	1149	Rangthylliang	Wah Pynursla	i	12.3		ca. 70
44	Rangthylliang 7	25.30684	91.88773	1029	Rangthylliang	Wah Pynursla	v	18.8		
45	Rangthylliang 8	25.30638	91.88557	891	Rangthylliang	Wah Pynursla	i	18.3		
46	Rangthylliang/ Mawkyrnot 2	25.29566	91.8829	1068	Rangthylliang	Wah Niur	c	40.7		
47	Rimai Bridge	25.19	91.92	280	Rimai	Wah Kwang	v	31.8		
48	Rymmai 1	25.29749	91.77993	483	Rymmai	Wah Umlwai	uk	18.5		
49	Rynsiet	25.2779	91.62988	354	Nongsteng and Nongbah	Rynsiet	v	35.6		
50	Siej	25.213028	91.6768	664	Siej	Umkar	i	25.2		66
51	Sohkhmi 1	25.25058	91.78358	418	Sohkhmi	-	uk	11.2		
52	Suktia 1	25.22289	91.79153	177	Suktia	Wah Pohwer	ut	9.2		
53	Thangkyrta 1	25.30708	91.80974	706	Thangkyrta	-	ut	6.4		
54	Thangkyrta 2	25.30624	91.80693	774	Thangkyrta	Wah Umsong (unconfirmed)	uk	20.4		
55	Tynrong 1	25.24808	91.63512	443	Tynrong	-	uk	14		
56	Tyrngei 1	25.2383	91.79356	331	Tyrngei	Wah Umsha	uk	11.4		
57	Ummonoi	25.20834	91.67049	689	Soh Sarat	Ummonoi	c	7		
58	Wah Amlohmar	25.23757	92.03035	706	Kudeng Rim	Amlohmar	ut	20.2		

ID	Bridge Name	Degrees North (WGS84)	Degrees East (WGS84)	Altitude (m a.m.s.l.)	Main Village	River	Maintenance Group	Length (m)	Comment	Age estimates* (years)
59	Wah Kdal	25.33484	91.86614	678	Nongblai	Wah Kdal	i	8		ca. 35
60	Wah Koh La 1	25.24098	91.66119	278	Myntheng	Koh La	c	19.3		ca. 60
61	Wah Koh La 2	25.24095	91.66093	277	Myntheng	Koh La	c	15.4		ca. 200
62	Wah Lar Ung	25.345118	91.87331	762	Nongblai	Lar Ung	i	18.3		ca. 700
63	Wah Lyngkhen Hybrid	25.340519	91.87037	732	Nongblai	Lyngkhen	v	10		
64	Wah Lynseng	25.34301	91.86846	780	Nongblai	Lynseng	v	34.1		
65	Wah Matieh Lower	25.339943	91.87265	788	Nongblai	Matieh	v	6.3		
66	Wah Matieh Upper	25.339943	91.87268	790	Nongblai	Matieh	v	10		
67	Wah Shoh Klea	25.19	91.89	350	Lyngkhong	Shoh Klea	uk	16.3		
68	Wah Soh Mad	-	-	-	Rangthylliang	Wah Soh Mad	i	-		
69	Wah Soh Shiat	-	-	-	Rangthylliang	Wah Soh Shiat	uk	-		
70	Wah Spit	25.33619	91.86714	718	Nongblai	Spit	v	14.6		
71	Wah Surah	25.344595	91.874176	756	Nongblai	Surah	v	6.5		
72	Wah Thyllong	25.20688	91.89737	541	Mawlynnong/ Nowhet/ Riwai	Thyllong	c	13		ca. 200+
73	Wah Tiah Long	25.33727	91.87263	830	Nongblai	Tieh Long	i	6.2		ca. 15
74	Wah Tumbai	25.339113	91.869484	721	Nongblai	Tumbai	v	10.08		
75	Wah Um Thliem	25.340513	91.8721	737	Nongblai	Um Thliem	v	8		
76	Nongthymmai 2	25.24914	91.67968	407	Nongthymmai	Simtung	v	4	new attempt, tourism interest	

Appendix B.

Interviews with bridge-builders and members of users described in Ludwig et al (2019)[1] and Chapter 2

Each of the seven interviews given here were conducted by Wilfrid Middleton, with the explicit intention of understanding more clearly the Living Root Bridges in the context of their age, use and maintenance.

Where necessary, explanatory information is given in [square brackets], based on observations made by the interviewer either during, shortly after, or shortly before the interview. Otherwise, the bullet-pointed information is a simplified transcription of information provided during the interview. Short introductions to the interview settings are provided.

Names have been omitted to protect the interviewees' identities.

Interview 1, June 2017, Kudeng Rim Village, West Jaintia Hills, Meghalaya

Conducted between Wilfrid Middleton and Interviewee 1 in Kudeng Rim village over the course of one hour, shortly after meeting for the first time in June 2017. As Interviewee 1 speaks English, no translator was needed. Notes were taken during the interview. The following write up summarizes the main information given by Interviewee 1 during the interview:

- Interviewee 1 reports that his family is from Kudeng Rim. He lives in Kudeng Rim, selling fish around the Jaintia region. Interviewee 1 is 23 years old.
- He claims that he is one of the few people in the village who speaks English.
- With a friend of his, Interviewee 1 worked on a bridge between Kudeng Rim and Kudeng Thymmai in 2016, forming a second deck out of bamboo, training large bundles of roots over the structure. [This bridge is #11 in Appendix A, Kudeng Double Decker].
- He began working on the bridge for two reasons: to restore a piece of village cultural heritage and because he had heard tourists were interested in the bridge. In the year since then he has guided one tourist around the bridges in the area.
- He cannot recall either having seen work done on the bridge or hearing of anybody from the area working on it.
- According to Interviewee 1 Nongbareh is a very old village, perhaps seven hundred years old. He cannot recall any origin stories that might help make this more precise, but knows that some of the older people in the village know some such stories.
- Interviewee 1 says that the bridge linking the two sides of the village [#27, Nongbareh 1 (village link)] is probably as old as the village, at least 400 years old. The bridge is vital to crossing between the two sides, as the river can become very flooded. [A steel bridge currently crosses the river circa 100m upstream].

Interview 2 with Interviewee 2 and others from Nongblai, May 2017, Nongblai Village, East Khasi Hills, Meghalaya

A meeting organised by a guide, conducted between Wilfrid Middleton and Interviewee 2 at his home in Nongblai village over the course of two hours in May 2017. Around fifteen members of the village community were present. As the sole Khasi and English speaker present, all translation was done by the guide. Notes were taken immediately and written up in the present form at a later date. The topics discussed fall into four main areas.

On Interviewee 2:

- Interviewee 2 is around 85 years old and is a well-respected village elder in Nongblai.
- In 2001 he was presented with an award for his traditional drum-making.
- Interviewee 2 has been given responsibility for tending to many of the bridges in Nongblai as he farms each day in a large area of land in the north end of the valley.

On the subject of Nongblai village:

- 60 families in Nongblai, with around 400 residents in total.
- All land around the village is each area is privately owned and cultivated by separate families.
- Nearby villages are Wahlyngkhat, Rngain, Wah Ken and Shuthim. Only Wahlyngkhat requires no living bridge to reach via the shortest route. [Wahlyngkhat is also the main market and access to (regional town) Pynursla and (state capital) Shillong.]
- The walk to Wahlyngkhat is around 1.5 hours. This would be greatly eased by a road, which the villagers would like, but it is not the most important investment from most people's perspectives. Walks to other villages are similar distances.
- The village mainly cultivates cash crops such as medicinal black pepper, bay leaves, broomsticks, and betel nuts. They also cultivate a wide range of fruit as well as black pepper for consumption in the village.

On the subject of bridges in Nongblai:

- 18 bridges in the village area. 6 more were destroyed by floods a long time ago: the last flood was 40 years ago. None were destroyed by landslides. There are several perennial rivers and streams in the valley. Most years, the river level reaches near the bottom of most of the bridges but only rarely floods through the bridge.
- The youngest bridge [Wah Tiah Long, #73] is 15 years old. It is on a route from farmland to Wahlyngkhat. The other young bridge [Wah Kdal, #59] is maintained by the village headman and is 35 years old, drawn from a very old tree.
- Long Ti Uyiang bridge [#16] is probably about 70 years old. [This estimate originally came from another man in the village, agreed upon by Interviewee 2.]
- The oldest bridge in Nongblai is Wah Lar Ung [#62], thought to be as old as the village.
- Bamboo is always used as a framework before a bridge is grown to full strength. Interviewee 2 believes this takes about 10 years.

Interview 2 continued

- Interviewee 2 is [in his own words] generally respected in the village for his work on the bridges. Several of the people that he goes to the forest with help him in the maintenance work. This is mostly small work: cutting, tying, pruning, or planting young roots, laying rocks and soil, clearing epiphytes, and replacing bamboo. Some major works are needed occasionally. One such work is the wrapping of a cracked or decayed root with smaller roots. This supports the old root as it decays or heals while growing the young roots in old root’s place as soon as possible.
- None of the bridges have grown weaker during his lifetime. In general, they grow stronger or have reached a mature, stable state.

On the origins of Nongblai:

- Shallem Khonglam, a Jaintia woman came to Shuthim, and rented a patch of land in the valley from them.
- For a long time, the land had just been for cultivation by the Shuthim people, now Shallem lived down here, cultivating and trading, somewhat ostracised by Shuthim village.
- A famine came, which killed many of the people in Shuthim. Some fled to Shallem's area down in the valley. The famine did not reach there – it is thought because it is protected from weather and the lower level provides hotter climate for cultivation. It may have been some other biological island factor – cultural or natural segregation may have protected her from a crop disease of some sort.
- The village grew from Shallem’s family and others – Khonglam became the dominant clan.
- The village retains a strong Khonglam section.
- The village has not grown much in the last 70 years. Mostly, when people get rich or educated they leave – the village elders hope that people will come back – tourism might help bring them back.
- “Eco-challenge” marathons in 2015 and 2016 brought 500 and 600 people to the village respectively. The challenge used the bridges as a running route. This is the biggest tourism the village has seen, as well as a small and steady flow of individuals from India and Europe, who heard about Nongblai primarily through Interviewee 2's drumming.
- Interviewee 2 believes that the story is 700 years old and that some of the bridges are as old as the village.

On the origins of Rangthylliang:

- A war between Khyrim people and Jaintia Pur people, won by the Khyrim.
- A man named Snipator came from Jaintia Pur with a seed of ficus elastica.
- Snipator made the first bridge, but it was destroyed. The place is now sacred – nobody is allowed to tamper with it.

Interview 3, April 2017, Nongriat Village, East Khasi Hills, Meghalaya

This interview was conducted between Wilfrid Middleton and Interviewee 3 over the course of one hour in his house in Nongriat village in April 2017. His daughter organised the meeting and acted as translator. Notes were taken during the interview and written into the present form later at a later date.

- Interviewee 3 was born in Nongriat and has lived his entire life there. He is now quite old. [Estimates of his age by members of the village community range between 70 and over 100 years old, most people guessing he is 90 years old. There are no clear records.]
- Interviewee 3's grandfather was involved in build of double decker, upper deck only. Interviewee 3 was told that the lower deck was occasionally over-flown in a flood, so the upper deck was built. More floods in past that flooded through the lower deck, none lately – hard to say when last one was. A 16 -year-old boy from the village said [in English, during the conversation with Interviewee 3] that it flooded when he was a young boy.
- Good bridges [Double decker #6, Nongriat Access #29] are not maintained by anyone, nobody has to work on them. Both may be around 200 years old, but he is unsure.
- The nearest bridge at Wah Koh La [#60, Wah Koh La 1], which may be 200 years old, was washed out around 60 years ago by a landslide, so is much smaller than the further bridge [#61, Wah Koh La 2].
- These bridges [#60,61] are still used by people of both villages to get into forest to pick bay leaves and black pepper and by the people of Ram Dait to get to Sohra. These, as well as broomsticks, are the main exports. Broomsticks require forest clearing while other crops do not.
- Mawsaw Hybrid bridge [#22] may be 100 years old [this refers only to the section that reaches between the eastern bank and the large rock in the centre of the river]. The tree on the rock was never large enough to string roots across the gap to the western bank, so roots were never able to replace the temporary bamboo. It was eventually replaced with the metal bridge that exists today. 20 years ago a landslide at caused people to place bamboos across the bridge. These were integrated with the old root bridge and small roots were used to tie them in. [Other than this, no explanation was given for how the metal components were integrated into the bridge].
- When he was a boy, he used the Mawsaw Hybrid bridge [#22] to get to Sohra [Cherrapunji] as there was no good route through Tyrna, as today.
- The Umshiang bridge between Nongriat and Nongthymmai [#23] may be 200 years old. About 35 years ago (when Interviewee 3's daughter was a child) a big landslide destroyed two of the three spans in the main Mawsaw [Old, #23] bridge that leads to Nongthymmai village. Two roots were left. Two roots still remain today in these spans. Interviewee 3's daughter joked about the people carrying bags to market across them. In the short term bamboo was used to span the gap, until a steel bridge was built. It is now renewed every ten years or so.
- New steel bridge decisions are made by the Member of Legislative Assembly [Regional Government] responsible for the area. However, takes at least 1-2 years to get anything built, so new bridges are started (or replacements made) in meantime.
- The people of Nongriat are originally from the next valley over [now the village of Thied Dieng]. Interviewee 3 believes that the tradition of growing root bridges comes from there. There was a feud between the two tribes and they fled to this valley. Bad relations between the people of the two valleys still exist: marriage between the tribes is not accepted by either group.

Interview 4, April 2017, near Rangthylliang Village, East Khasi Hills, Meghalaya

This interview was conducted between Wilfrid Middleton and Interviewee 4 over the course of three hours during a tour of Rangthylliang village in April 2017. Interviewee 4 speaks some English, but most of the interview was translated by a guide. Notes were taken during the interview and written up at a later date.

- Interviewee 4 is 25 years old, and is from a farming family in Rangthylliang.
- He farms a patch of land to the south of the village and helps his three uncles farm the majority of the north-west face of the hill on which Rangthylliang sits.
- Interviewee 4 reconstructed a bridge lately that was just a single large root [#43, Rangthylliang 6]. He added the small roots. The bridge is 70 years old, begun when his grandmother was born. Several bridges were not repaired for a long time, but Interviewee 4 and several other young men in the village have put a lot of effort into restoration.
- Nobody taught him the tradition, though he does much of it with his uncles.
- He thinks his bridge would grow faster if it was in a hotter place – it is at quite a high altitude, where it is cold.
- Interviewee 4 says the bridges at lower altitudes grow more quickly.
- There is quite a lot of trouble with latex plucking in the village. Some cutting is done for latex while other cuts are made to attempt to direct growth of the tree in particular directions.
- Interviewee 4 is building a new bridge with his uncle by trailing large, stiff roots across a gap. The bridge is in an area that is hard to access during the summer rains.
- There was another (now deserted) village further down the hill [the remains of which are still visible, mainly vegetable patch terracing]. There are lots of bridges and F. elastica specimens in this area. The bridges used to be a means of accessing the market for the village, but the growth of Rangthylliang, as well as the creation of easy tarmac roads has meant that nobody lives down below the bridges anymore, and they are only used when farmers harvest crops.

Interview 5, May 2017, Near Riwai Village, East Khasi Hills, Meghalaya

This interview was conducted between Wilfrid Middleton and Interviewee 5 over the course of an hour in May 2017 at Wah Thyllong bridge [#72] near Riwai village. Interviewee 5 speaks some English, and translations were helped with by two boys from the school.

- Interviewee 5 is a cleaner at a school in the secondary Nowhet and farms a piece of land to the south of the village, near to Rimai village.
- Interviewee 5 says that the bridge at Wah Thyllong [#72] is at least 200 years old, perhaps older.
- In the past, the bridge featured in the local religious practices. A large rock in the river remains from this practice.
- Bridge ownership is contested between the three villages and rotates every few years.

Interview 6, June 2017, Siej Village, East Khasi Hills, Meghalaya

This interview was conducted between Wilfrid Middleton and Interviewee 6 over the course of an hour at the Umkar bridge in Siej village in June 2017. Interviewee 6's grandson, translated between Khasi and English.

- Interviewee 6 is around 80 years old and has been working on the living root bridge in Siej [#50] all of his life.
- He is the village headman [a role recognised by the Meghalaya government for each village in the state] and, in this position, knows exactly how much (tourist and local) attention the bridge receives.
- When he was a boy, Interviewee 6 planted the tree with his father and grandfather in 1951 with the explicit intention of building a bridge.
- The tree was already mature and producing aerial roots when planted. Interviewee 6 is unsure whether the aerial roots were trained that year or in the years following.
- Interviewee 6 cannot remember when the deadwood scaffolding [probably made from bamboo and areca nut palms] was removed.
- [The bridge links the villages of Siej and Mot. There is a large boulder halfway across the river that cuts the bridge into two sections.] The tree was planted on the Mot side, and was grown across to the Siej side. A flood washed away the bamboo bridge that existed on the Siej end in the 1960´s.
- The bridge on the Mot side grew stronger and the Siej-side bamboo bridge was rebuilt.
- 19 years ago (1998) Interviewee 6, then around 50 or 60 years old, began to grow the Siej side of the bridge. The majority of the roots in the deck were trained a year later (18 years ago)
- Between 2001 and 2002 a concrete bridge was built a few metres upstream, and the bamboo/root hybrid was no longer used as the main concourse.
- In 2006, a BBC documentary that drew international attention to the bridges was shot here. In 2015-17, Chinese and French film crews came to Siej.
- As we examined the bridge, Interviewee 6 told me the ages of several sections, generally divided into the original section, up to 66 years old, the newer section at (mostly) 18 or (occasionally) 19 years old, and some younger work done 7 years ago.
- The youngest part of the bridge is blocked off from use [by a bamboo protective frame], as Interviewee 6 would like to let it grow before it is used. He trained most of the roots in this section 7 years ago, while some roots are younger. [No age estimate was obtained for the protective frame].
- The three new sections: an overhead platform, and a supporting section, were started 4, 3, and 1 year ago respectively. [These are visibly separate to the main deck, formed of aerial roots from different parts of the tree.]
- Interviewee 6 thought that any individual section would need 30 years to grow to full strength.
- Interviewee 6 believes that roots that have space to grow around them are able to grow faster.
- There is no current plan on how to grow the bridge – Interviewee 6 has never planned at a large scale, he works day-to-day. Each day he spends 2 or 3 hours working on the bridge, particularly during the summer. Recently Interviewee 6 has worked more with younger members of his family and the village on the bridge.

Appendix C.

Completed LENSES Rubrics Worksheets for Living Root Bridges, reproduced from Supplementary Materisal from Characterising Regenerative Aspects of Living Root Bridges in *Sustainability* **2020**, 12, 3267, doi:10.3390/su12083267

First worksheet overleaf

beauty

focal point	degenerative	degenerative-sustainable	sustainable	sustainable-regenerative	regenerative
Ecological Beauty The aesthetic expression of the web of life between all living things.	Design obstructs biophilia; creates an entirely synthetic environment disconnected from ecological context; prohibits ability to appreciate local ecological system.	Design minimally considers biophilia; attempts to integrate ecological context or scale of place.	Design allows for biophilia; appropriately scaled for surrounding ecological system.	Biophilia is considered in most aspects of design; restores impacted or degraded ecological systems to their natural balance and beauty.	Biophilia is intentionally incorporated throughout design; explicitly or implicitly enhances appreciation of the local ecological systems; harmoniously scaled per immediate ecological system. ***biophilia clearly visible***
Era Distinctive period of history.	Ignores consideration of current era; blind to the concern of future generations; serves initial purpose only; generic solutions; premature replacement occurs. ***E.g. vehicles, safety***	Only attemps trendy and temporarily satisfying solutions; decisions made with only limited exploration falling back on status quo or habitual solutions; outdated quickly.	Aesthetic solutions are beyond simple decoration or fashion and are not simply nostalgic; enduring; recognizes the needs and limits of future society; promotes an investment in longevity.	Encourages adaptability to alternate uses, especially for tourism, benefits future generations of use, solutions create authentic sentimentality, honors the spirit of the time. ***partly, especially for tourism***	Creates great meaning; instills a desire to promote the project‘s endurance; produces a timeless appreciations; encourages respect for the era of a project‘s birth as well as the project itself.
Emotion & Sensory Heighten feeling; relating to sensation.	Causes fear, repulsion or general discomfort; breaks down the spirit of the occupants; hopeless, dangerous and/or unappealing environments.	Evokes limited or undesirable emotions; causes boredom and complacency; limited sensorial displeasure.	Creates a state of contentment and peacefulness; evokes feelings of safety and satisfaction; responds to humans love for nature and order.	Encourages joy, energy, reflection, thougth and productivity; enhances well-being.	Evokes delight, hapiness, inspiration, deep reflection, great achievement, appreciation or serenity; generates healing and self-actualization; celebrates spirit.

time + history

From a historical perspective, how social, economic and environmental progress are combined in the project to fit a local narrative

focal point	degenerative	degenerative-sustainable	sustainable	sustainable-regenerative	regenerative
Historical Narrative Does a story run from the past to the future?	Antithetical to local historical narrative (as embodied by folk stories, residents' worldviews, residents' self-perceptions); opposes view of progress in localised narrative.	Limited adherence to local traditional construction or maintenance; project's embodied progress not specific to place or people.	Project is not placed clearly in continuum of local history, rather only fits well with traditional, future, or current sense of place; does not show involvement of variety of voices, from traditional, to current, to future-focused.	Integration of local traditional values with social, economic and environmental goals only by-product of project's functionality; both traditional and progressive attitudes are accommodated.	Enhance the integration of community history and environment for local narrative; both traditional and progressive attitudes towards place strengthened; these attitudes integrated into building, maintenance and use.
Usability in Time Is use within a particular timeframe?	Use limited to specific time frames in either long or short term; detrimental to use of other infrastructure or projects during build and take-down; no reusability after immediate functional life.	Usable only in long or short term but flexible within these limits; minimal disruption to surrounding community.	Materials useful after take-down; minimal upkeep required to continue usefulness beyond planned lifespan, minimal functionality during build and take-down.	Use adaptable to a range of possible expected future functions; useful throughout life-cycle (during build, maintenance, take-down) and beyond (materials reused).	Useful throughout life cycle, from building phase to take-down; use adaptable to unexpected functions; usefulness improves above needed level with time: creation of new uses and improved accessibility of use.

governance

How is the balance of stakeholder power enacted, what forms of governance are , how social, economic and environmental progress are combined in the project to fit a local narrative

focal point	degenerative	degenerative-sustainable	sustainable	sustainable-regenerative	regenerative
Proportional Voices Distribution of decision-making throughout society	Project does not account for variety of voices; minimum stakeholders respected; runs against views voiced in community groups.	Minority of powerful stakeholders allow majority a voice; powerless minorities unrepresented.	Inclusive of current voices; agreed representation of minorities coherent with status quo; no efforts made to improve representation.	Minorities given voice but not built into governance structure; future voices acknowledged, discussed, but not built into planning.	Respect for and efforts to represent future voices (children, descendants, immigrants); several rounds of consultation with current voices; progressive inclusion of minority voices in governance structure.
Opportunities Inertia of governance structures and corresponding decision-making	Does not allow changes to be made by any stakeholders; governance structure fixed for entire length of project.	Minimal changes possible by small number of stakeholders requiring major efforts; single governance structure quite inert and powerful.	Established governance structure is malleable but change not encouraged; all project decisions made through this governance structure; capacity for course-change of project built in to plans.	Planned consultation on turnover of governing body, no turnover explicitly planned; changes can be discussed and induced through one or two channels; some reactive changes of project planned.	Regular turnover of members of governing body; governing body actively reviewed and changes considered; project changes can be brought about through a variety of structures; most likely changes of project course planned for with changes to governance integrated.

community

focal point	degenerative	degenerative-sustainable	sustainable	sustainable-regenerative	regenerative
Defining Community Identifying stakeholders and community impacts.	No attempt to identify stakeholders and/or stakeholders are ignored; accepts pre-defined groups and pre-existing boundaries; no recognition of the scope and scale of impact to those being affected by the project; does not consider impacts of adding or removing services.	Minimal effort to identify key stakeholders; Self-selected participation; insignificant amount of research conducted on project's impact to surrounding community. ***In tourism context***	Key project team members and some community members are identified as stakeholders; existing and future community (e.g. aging community) is defined; minimal effort conducted to recognize project's impact on local social structures, economic situation, and environmental conditions.	Stakeholders include a diverse representation of community members; consideration for who and what is directly and indirectly affected serves as decision-making factor.	Stakeholders are intentionally chosen based on an accurate representation of the community; results in opportunities for those typically excluded from decision-making process; In-depth research on project's impact to natural, social, and economic systems serves as decision-making factor.
Community Engagement Create communal ownership and responsibility for the project by actively engaging and infroming community members in a manner in which they feel safe and represented.	Community intentionally or unintentionally ignored in decision making process; does not inform stakeholders of process or decisions; community does not feel represented due to discrimination, isolation, and lack of involvement.	Assumptions made to compensate for a minimal community engagement process; engagement only accessible to small, select groups; minimal outreach to inform stakeholders of process or decisions; artificial creation of safety and tolerance for community input.	Conventional public engagement processes (formal and legislated);Moderate amount of community participation and empowerment; Some effort made to inform stakeholders of process and decisions; limited or conventional populations feel safe in participating in the process; authoritative figures ask limited questions with limited sharing and listening.	Intentional and comprehensive community engagement process; diverse stakeholder representation; continual outreach to inform stakeholders of process and decisions; relationships are built between project team and community members; accessible and responsive avenues for community input.	Authentically seeks engagement and accurate community representation; creates opportunities for expanding representation and methods for involvement; continually informs and educates stakeholders using an established common vocabulary; actively creates safe and genuine avenues for stakeholder input; honors input with deep listening and responsive decision-making.

Inherently grass-roots, due tu embededment in community for all aspects of instigation/use/maintenance

community

focal point	degenerative	degenerative-sustainable	sustainable	sustainable-regenerative	regenerative
Honor & Opportunity Understanding and honoring local culture, and creating opportunities through an inclusive decision making process.	Intentionally ignores local knowledge, resources, and cultural characteristics; violates or disrespects cultural values; Top down decision-making; decisions result in reduced opportunities for community members; implements one-time use functions; inflexible plans.	Unintentionally disregards local knowledge, resources, and cultural characteristics; makes assumptions about cultural values; top-down decision making; decisions driven by convenience and short-term needs; political will and business interests drive decisions over community voice; adapts only to keep things as they are.	Recognition of local knowledge, resources, and cultural characteristics; generic approach to honoring local community; decisions preserve options and opportunities; responds to change with new opportunities; mostly top-down decision making.	Promotes understanding, appreciation, and expression of local culture; implements measures to account for future growth and generations; adaptive design; resource sharing; bi-directional decision-making between project team and community members; increased opportunities for community members.	***Based on*** ~~Celebrates~~ and authentically incorporates local knowledge, resources, and cultural characteristics; iterative decision making model; seeks informed responses to grass-roots needs; shared understanding, pride, accountability, ownership, involvement, and responsibility among community members; provides and inspires opportunities for education and employment of community members.

ecosystems

focal point	degenerative	degenerative-sustainable	sustainable	sustainable-regenerative	regenerative
Compatibility The reinforcing relationships of plants, animals, and human communities within an ecosystem to support one another.	Creates conflict between communities within the ecosystem; increases competition for limited resources; significantly degrades systems within the ecosystem or within upstream and/or downstream communities.	Jeopardizes the interconnectedness and interdependence of systems; results in a decline of ecosystem function; causes detrimental impacts to upstream or downstream communities.	Communities positively support one another within the ecosystem; results in no degradation of upstream or downstream communities.	Enhances the interconnectedness and interdependence of systems, allowing the ecosystem to thrive; contributes to the restoration of upstream or downstream communities.	Plant, animal, and human communities within the ecosystem renew and revitalize their own sources of energy, as well as the life supporting capacity of upstream and downstream communities.
Productivity The capacity for natural capita stocks to be renewed and to produce ecosystem services.	Destroys natural capital stocks, completely stopping regenerative capacity; degrades the health of society and productivity of the economy; places great stress on both human and manufactured capital to compensate for natural capital losses; results in doubtful future provision of ecosystem services.	Degrades natural capital stocks and reduces the capacity to regenerate and produce ecosystem services; results in negative impacts on the health of society and the productivity of the economy; makes inefficient use of human and manufactured capital; uncertain future provision of ecosystem services.	Meets minimum requirements to regenerate and produce ecosystem services; maintains sufficient stocks for a healthy society and productive economy; balances production from natural capital with the use of human and manufactured capital; positive indications of the future provision of ecosystem services.	Removes threats to natural capital stocks; ensures regenerative and productive capacity of these stocks; promotes a healthy society and a productive economic system; future provision of ecosystem services is certain. ***Through access to fields etc.***	Actively promotes and manages natural capital stocks; enhances regenerative capacity and productivity of ecosystem services; enhanced flows of ecosystem services are catalysts for a healthy society and productive economic system; guaranteed future provision of ecosystem services.

ecosystems

focal point	degenerative	degenerative-sustainable	sustainable	sustainable-regenerative	regenerative
Diversity The genetic and/or ecological variations in species, populations, communities or ecosystems that occur over time and/or space.	Ignores and/or significantly damages the existing diversity; degrades ecosystem structure and function in the near future.	Minimally recognizes and maintains the existing diversity; value of diversity not understood and/or not considered in decision making process.	Preserves the existing diversity; recognizes additional ecosystem components that should be incorporated to maintain existing diversity.	Restores diversity to reflect natural ecosystems; adopts preventative measures to ensure diversity is maintained; increases the diversity of nearby stressed ecosystems.	Creates ecosystems that bring new life and vitality to area; diverse ecosystems serve as a fundamental component of project; serves as an important regional center of diversity and resilience; positively impacts surrounding social, economic, and natural systems.
			High diversity already present		***Some plants removed in maintenance***
Adaptability The ability of a species, population, community and/or ecosystem to withstand and recover from internally or externally imposed changes or stresses.	Reduces ecological resilience and redundancy in time and/or space, making ecosystems highly vulnerable to environmental stresses; degrades very easily and cannot tolerate any harvest of natural resources because they lack the capacity to be renewed.	Limits ecological resilience or redundancy in time and/or space, making ecosystems able to adjust to only a limited number of environmental changes; tolerates a very limited harvest of natural resources due to reduced resiliency.	Maintains ecological resilience and redundancy, making ecosystems able to adjust to many internally or externally imposed environmental changes; allows the sustainable harvest of renewable natural resources.	Improves ecological resilience or redundancy, making ecosystems able to adjust to most environmental changes; supports the sustainable harvest of a variety of renewable resources; serves, on a limited basis, as a support system for nearby stressed ecosystems.	Shows abundant ecological resilience and redundancy in time and space, allowing ecosystems to adjust to many environmental changes; serves as regional genetic and/or ecological reservoir to replenish nearby stressed ecosystems.
				e.g. soil protection	***within natural limits***

education

focal point	degenerative	degenerative-sustainable	sustainable	sustainable-regenerative	regenerative
Learning Space The physical, built environment, technology and other material elements within a space.	Inadequate and non-operational resources; poor quality space with potential health risks; inflexible space; unwelcoming and uninspiring; inappropriate use of space.	Insufficient and inefficient use of resources; outdated but operational resources; poor quality space yet potential for improvement; inadaptable yet usable; dull.	Adequate amount and quality of resources; healthy space yet not engaging; appropriate for single purpose use.	Up-to-date resources; ample access to resources; healthy and welcoming space; slight adaptability; appropriate for a couple of different uses.	Access to unlimited resources; healthy, engaging and inspiring space; interactive space that contributes to teaching; adaptable and changeable space; appropriate for a multitude of uses.
		No intentional school element beyong direct bridge construction skills			
Information & Skills Transfer The content, delivery, and reception of skills and information.	Lack of creativity; stale, unchanging information; segmented disciplines; new skills neither taught nor attained; absence of encouragement; obstinate learning; lack of engagement.	Restrictive parameters; discourages new ideas or concepts; resistant to change; not motivated to seek resources that facilitate change; mediocrity encouraged.	Integration of disciplines available if sought out; change is neither encouraged nor discouraged; information content and delivery are slow to change, yet practical; interest and exploration is present.	Integrated disciplines and hands-on transfer of traditional knowledge from one generation to the next; exploring various teaching methods and learning; challenging typical thought.	Multidisciplinary and interconnected content; continuous acceptance and exploration of new ideas; understanding and challenging paradigms; engaged in rethinking and reflective thoughts.
		Hands-on transfer of traditional knowledge from one generation to the next			

focal point	degenerative	degenerative-sustainable	sustainable	sustainable-regenerative	regenerative
Relationships Relationships between people, organizations, and communities. ***Strong relation to Khasi culture and its conflicts with outside social systems, e.g. state governments.***	Mistrust between players creates fear that limits communication; hierarchical relationships dominate; suppression from above; disinterest in collaboration; relationships restricted by friction and latency; no values; stagnant culture.	Segmented trust between players; hierarchy dominates though allows some input from lower levels; minimal interest in or ability to expand collaborative relationships; Lack of support for team building, sharing of ideas and exploring new ideologies; lackluster values; outdated culture.	Trust between players creates opportunities for communication and learning in some contexts and within some communities; practical hierarchy with collaboration amongst players; full transparency yet to exist; positive values and culture yet no true enforcement.	Trust between players and communities exist in most contexts; active engagement and collaboration amongst players; partnerships between players create a transparent and effective line of communication; shift towards positive role models in leadership positions; positive values and culture are pre¬valent.	Trust between players exists in all contexts and communities; decisions, common goals and direction are clearly understood by all players; authority is distributed to players and communities to implement plans with minimal friction or latency; an environment of collaboration, mentoring, and peer to peer learning is solidly in place; inspiring and encouraging culture and values.

health & wellbeing

focal point	degenerative	degenerative-sustainable	sustainable	sustainable-regenerative	regenerative
Physical, Mental & Spiritual Balance The opportunities for relaxation, rejuvenation, culture, creative expression, interactions with nature, personal development and spiritual growth that can create balance.	Prevents or destroys physical, mental and spiritual balance; inequity; lack of access to healthy options; disconnected; poor environmental health conditions.	Diminishes physical, mental and spiritual balance; lack of access to conditions that promote health and well-being.	Limited options exist to achieve physical, mental and spiritual balance and are not easily accessible for most populations. ***lack of access e.g. for disabled and elderly***	Encourages or increases physical, mental and spiritual balance; multiple options that promote health and well-being.	Nurtures a heightened sense of physical, mental and spiritual health and well-being; equal access to options; promotes equity and inclusivity, healthy lifestyles, connectivity and environmental health and well-being.
Equity & Inclusivity Ensure service integration, inclusivity and empowerment of all living things.	Creates disparity for current and future generations; lack of respect for cultural, intergenerational and biological diversity; denies access for all abilities and income levels; segregates populations on social, economic and environmental factors.	Minimally considers future generations; hinders social, economic and environmental equity; discourages equal access and diversity.	Acknowledges and integrates some level of social, economic and environmental equity; recognizes cultural and intergenerational diversity; provides limited opportunities for equal access and diversity.	Increases social, economic and environmental equity; various opportunities that encourage inclusivity and diversity across ages, cultures, income levels, religions, and backgrounds.	Generates and honors current and future social, economic and environmental equity and inclusivity; promotes cultural, intergenerational and biological diversity; provides abundant access for all ages, abilities and income levels. ***Generally built for next generation to use***

health & wellbeing

focal point	degenerative	degenerative-sustainable	sustainable	sustainable-regenerative	regenerative
Healthy Lifestyles Providing convenient access to physical exercise, affordable and healthy food options, natural light, fresh air, and safe environments that are well maintained. ***+ outdoor comfort and microclimate***	Destroys or prevents opportunities to increase healthy lifestyles; lack of access to safe spaces for physical exercise, privacy, introspection and social interaction; lack of nutritious food and ability to interact with nature; perpetuates toxic health conditions for current and future generations.	Impedes opportunities to increase healthy lifestyles; discourages access to healthy conditions such as fresh air, clean water, natural light and nutrition; introduces toxic substances.	Provides exposure to opportunities that increase healthy lifestyles; promotes and provides access to healthy conditions such as fresh indoor and outdoor air, clean water, natural light and balanced nutrition; minimally toxic conditions. ***No shelter, apart from sometimes shading from associated tree***	Promotes opportunities to increase healthy lifestyles; encourages physical exercise, nutrition, interactions with nature, and spaces that support occupant needs and activities; abundance of fresh indoor and outdoor air. ***No unusually material properties (e.g. metal as heat sink)***	Creates opportunities to heighten healthy lifestyles; provides safe spaces for physical exercise, privacy and introspection; provides opportunities for social interaction, fresh and nutritious food, clean water, natural light and interactions with nature; indoor and outdoor air quality results in rejuvenation.

land use

focal point	degenerative	degenerative-sustainable	sustainable	sustainable-regenerative	regenerative
Natural Land Land uses that preserve, protect, and regenerate ecosystems.	Not valued or respected other than for monetary value; natural light works against/degrades habitat, native species, ecosystem due to human alterations; no site assessment conducted; no ecological foot-printing assessment considered; lack of funding for maintenance programs; no value identified for environmental services.	Promotes and reinforces conservation practices; documents inventory of site boundaries; conducts site assessment; applies ecological foot-printing technique and notes results.	Prioritizes preservation practices; creates systems that pay for themselves; balances natural resource supply and sink functions; results of site assessment and ecological foot-printing lead to mitigation on/off-site.	Implements land protection practices; utilizes natural light to enhance habitat, native species, ecosystem; ecological foot-printing and site assessment leads to rectification of problems on/off-site	Restores functionality of land; utilizes natural light to restore habitat, native species, ecosystem; balances natural capital and human land use on/off-site; intrinsic value of environmental services assigned a monetary value for return on investment (ROI) calculations.

land use

focal point	degenerative	degenerative-sustainable	sustainable	sustainable-regenerative	regenerative
Building Land Actual development of land, including building, facilities and infrastructure.	Uncontrolled production; discharges pollutant and waste release on/off-site; homogenous; horizontal development; maximize traditional, impervious, mono-use infrastructure; no consideration of microclimate or energy sources; no consideration of human-produced heat or land temperature increase; lack of local influence in development; destroys historical aspects of site.	Awareness for production; discharges pollutant and waste release on/off-site; minimizes sprawl; encourages multi-use development; incorporates impervious, multi-use, mass-transit infrastructure; awareness of microclimate, energy sources, and land temperature increase.	Mitigates production's release of pollutants and waste on/off-site; heterogeneous, vertical and low-impact development; multi-use, long-lasting and non-traditional infrastructure; mitigates microclimate; mitigates land temperature increase; produces nutrient-rich soil; preserves historical aspects; acknowledges carrying capacity to reduce congestion.	Rectifies and/or repurposes production's pollutant and waste release on/off site; low/no waste; maintains microclimate; maintains land temperature.	Eliminates production's pollutant and waste release on/off site; maximizes reuse; smart-growth; restores microclimate; restores temperature of land; showcases historical aspects; empowers local culture with development decisions; diverse decision makers.

Clear multifunctionality, combining Building Land and Natural Land

materials

focal point	degenerative	degenerative-sustainable	sustainable	sustainable-regenerative	regenerative
Elegant Simplicity The principle that no more causes or forces are used beyond being effective.	No consideration of quantity, quality, durability or appropriateness; extravagant, wasteful or trendy solutions; results in premature failure or replacement; exploitative.	Limited consideration is given to reuse and reduction of materials as well as the appropriateness; wasteful and lack of care; appropriate selections ruled out due to extra effort involved.	Selects only materials that are needed or make significant positive contributions; materials are used in appropriate quantity, quality and character; durable and stand the test of time.	Through creative exploration, discovers solutions that eliminate or reduce the need for some materials; considers reusing existing materials first; durable and stand the test of time.	Inspires solutions that creatively eliminate or dramatically reduce the use of materials; elegantly simple answers unearthed; extensive and inclusive processes used for all selections; promotes complete biodegradation or direct rejuvenation of ecosystems.
Health & Wellbeing The use of a holistic ~~research and selection~~ process to support health, comfort, beauty and social responsibility. ***long-term experience***	Intentional or inadvertent disregard for the tangible/intangible negative effects on a place; generic design with lack of concern for aesthetics; exploitation of people with a primary focus on profit. ***fire-prone***	Lack of knowledge of material production processes, composition, and associated impacts on health, safety and well-being; conventional design with minimal attention given to aesthetics and social responsibility. ***entirely trial-and-error knowledge production***	Full understanding and use of third party product verifications; avoids toxic chemicals and materials; balances sustainability with timeless design; connects to nature; fair labor practices.	Enhances place; restores the health of people; uses materials and systems that embody full life-cycle assessment with transparency of benefits/ risks; uplifting design that connects with nature; fosters participation of diverse stakeholders; decreases social inequalities.	Stimulates well-being and encourages health through material selection; nurtures happiness; inspirational aesthetics celebrating beauty with a deep connection to nature; creates social equity throughout project design and implementation.

materials

focal point	degenerative	degenerative-sustainable	sustainable	sustainable-regenerative	regenerative
Environment Material selection that eliminates use of limited resources, utilizes low impact production and delivery processes, and matures natural habits.	Oblivious to the degradation of environment; intentional or inadvertent exploitation of natural habitats; excessive use of fossil fuel based energy; indiscriminate use of limited resources.	Cognizance of the detrimental impacts of all inputs and outputs related to energy, limited resources, and native habitats; only activates standard compliant methods and selections from	Exceeds compliance-driven inclusiveness to consider some environmental aspects of the product and related processes; initiates steps for material selection process that considers life-cycle analysis	Stimulates restorative results inclusive to all processes in material creation, selection, distribution, and installation; assists in restoring resources and habitat to levels that existed before adverse human im-	All-encompassing approach to material selection; completely eliminates materials and related processes that contribute to environmental degradation, including the use of limited natural resources; creates no waste; stimulates healthy, thriving natural habitats.
Region Consideration of place.	Intentional or inadvertent disregard for local needs and resources; no community involvement or opportunities; disconnected resource providers; careless importation; disregards ecological, social, and cultural context.	Limited response to community identified interests and needs; provides some opportunities within the locale; some regard for utilizing locally available resources; limited or “token” response to context, local history, culture, and natural systems.	Utilizes people and resources from the local community; assists in gaining broader community support; decisions assist in filling gaps in the local or regional economy; responds to community input, context, local history, culture, and natural systems.	Supports and values locally based businesses, talent and resources; inspires new local economic enterprises; minimizes importation; supports long-term economic, ecological and social viability; invokes previously nonexistent community partnerships; preserves heritage and cultural authenticity.	Fosters regional resources creating local jobs and opportunities; prompts regional self-sufficiency and long-term economic health; nourishes and self-sustains previously nonexistent community partnerships; deep inclusion and expression of context and culture; fosters dignified solutions promoting sense of place.

Appendix D.

Evaluation of potential for transfer/avoidance of regenerative/degenerative aspects of Living Root Bridges to the Living Root Pavilion: Remarks from LENSES Rubrics analysis of Living Root Bridges.

Table D1: regenerative aspects from Appendix C, marked with potential for transfer. High transferability is marked in green, complicated transferability is marked in yellow, low or zero transferability is marked in red.

Comments are given regarding transfer of each remark.

Table D2: degenerative remarks from Appendix C, marked with potential for avoidance. Aspects that can be avoided easily are marked in green, aspects where avoidance is complicated are marked in yellow, aspects with low or zero capacity for avoidance are marked in red.

Table D1. Transferability of regenerative aspects

Focal point	Key statements	Comments
Ecological Beauty	"explicitly… enhance appreciation of local ecological systems"	Shillong is, geographically, within the natural habitat of ficus elastica and the other species used as temporary materials. However, the suitability of the urban ecosystem is debatable.
Community Engagement	"LRBs are inherently community projects" and "they engage the community well through a variety of systems"	In an urban setting, a community is still needed to tend root growth Community engagement systems must be more explicitly defined
Honor and Opportunity	"understanding of local culture" and "opportunities through… inclusive decision making". The user-upkeep model engenders "responsibility among community members"	A user-upkeep model is more difficult in an urban setting and requires explicit interventions.
Ecosystem compatability	"plant, animal and human communities to renew and revitalize their own sources of [materials]"	Through growth, materials are renewed. However, other materials must be brought from around the state.
Ecosystem productivity	"actively promotes and manages capital stock" by access to farmland	New land is not accessed through the Shillong Living Pavilion
Ecosystem adaptability	"improve ecological resilience, making ecosystems able to adjust to most environmental change"	The environmental challenges in urban and rural situations are different. Soil stability may be transferable, while other aspects must be rethought.
Outdoor comfort	Bridges "provide shading" and are "comfortable to touch"	The benefits seen in rural settings are intensified in urban heat islands.
Natural Land	"promote and support… natural land and provide habitats for native species"	Shillong's green spaces may benefit from the pioneer species f. elastica
Building land	"grown directly from their environment" with "no production of waste". "Aspects of local history are exhibited through the reliance on… generations of builders"	The urban green space is a constructed environment. Local history and minimisation of waste are key features of living root architecture on exhibition in the Pavilion
Elegant simplicity	"LRBs dramatically reduce the use of materials" and "all building materials are completely biodegradable"	The pavilion would take space in otherwise tree-covered ground. The same biodegradable materials are used in the Pavilion
Environment	"eliminates materials and related processes that contribute to environmental degradation apart from the recent and uncommon… use of steel cables and concrete posts"	The Pavilion is designed with the same low-impact materials, also with occasional possible use of steel.
Region	"minimize importation of materials and preserve heritage and cultural" aspects	Two core goals of the Shillong Living Pavilion

Table D2. Potential avoidance of degenerative aspects

Focal point	Key statement	Comments
Beauty: Era	Traditional methods are contrary to the "current era" and without modern materials, do not "honour the spirit of the time"	In the urban setting, there is less call for modern materials to honour the spirit of the time, with potentially greater demand for historical beauty.
Emotion & Sensory	LRBs "can cause fear [and] general discomfort and indeed are sometimes perceived as a dangerous environment"	The discomfort arises from the canyon landscape and from the heterogenous surface of living root architecture. The former is changed in the urban setting, the latter requires design adaptations.
Defining Community	The recent exploitation of LRBs by the tourist industry usually involves a small, "self-selected" stakeholder group.	The urban setting involves a much larger stakeholder group who, through appropriate governance systems, can be represented fairly.
Ecosystem diversity	"the maintenance process can reduce biodiversity through the removal of plants growing on the bridges"	Explicit ecosystem goals and plans are needed to counter this problem in the Pavilion
Information & Skills transfer	"conflicts between villages have results in… villages not sharing techniques [and] there is no formal system for knowledge transfer"	The LBF, whose key goals are inducing cooperation between villages and setting up a formal knowledge transfer forum, are leading the project.
Education relationships	"examples show that… collaboration can quickly break down if a bridge is owned by only some of its users"	Governance systems must be used that allow collaboration, with voices for experts, users and maintainers.
Physical, Mental & Spiritual Balance	LRBs are "not easily accessible for most populations, especially disabled or elderly" such as by wheelchairs	Given the unpredictability of living root growth, access for wheelchairs is inherently difficult, though access for the elderly can be built in.

Table D2. Potential avoidance of degenerative aspects, continued

Focal point	Key statement	Comments
Equity & Inclusivity	LRBs "discourage equal access and diversity."	The Pavilion siting allows access by more people than the rural LRBs
Healthy Lifestyles	"not subject to contemporary safety standards and… not proven using contemporary methods"	The Pavilion can be checked more regularly and safety measures can be added more easily
Productive Land	Over-extraction of latex from the tree can kill the bridge	No current need for raw latex in the urban environment
Materials: Health & Wellbeing	"the latex-rich wood of F. elastica is prone to fire–several bridges have burnt down in living memory"	The latex-rich wood is a necessary part of the construction. Fire-monitoring can be much higher in urban spaces.
Proportional voices	Governance structures can be poorly set up to cater to diverse voices within the village	Urban governance structures may run into similar problems but can be arranged to avoid them
Opportunities for change	Governance structures are not well adapted to regional (e.g. infrastructure) and wider (e.g. climate) changes.	In Shillong governance systems are better adapted to regional changes. Wider changes are difficult worldwide.
Historical narrative	"LRBs are seen as technically outmoded, representing… history but not a future development solution"	New design with living architecture can counter this, particularly when coupled with research
Usability in time	LRBs "cannot be used in the short-term… only in the long-term"	The Pavilion confronts this problem with a short-term structure

Appendix E1. Tree pair failure photos

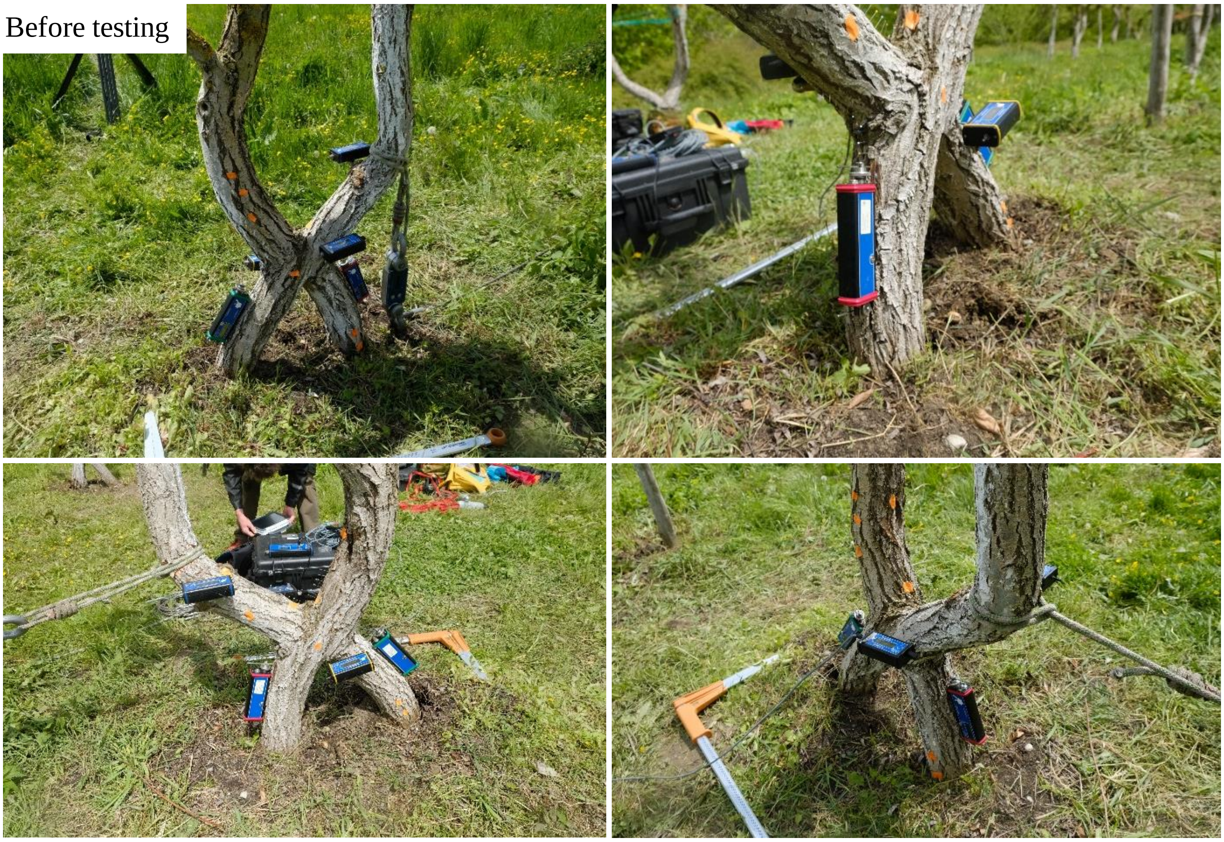
Tree pair failure photos A12

Tree pair failure photos A14

Tree pair failure photos A24

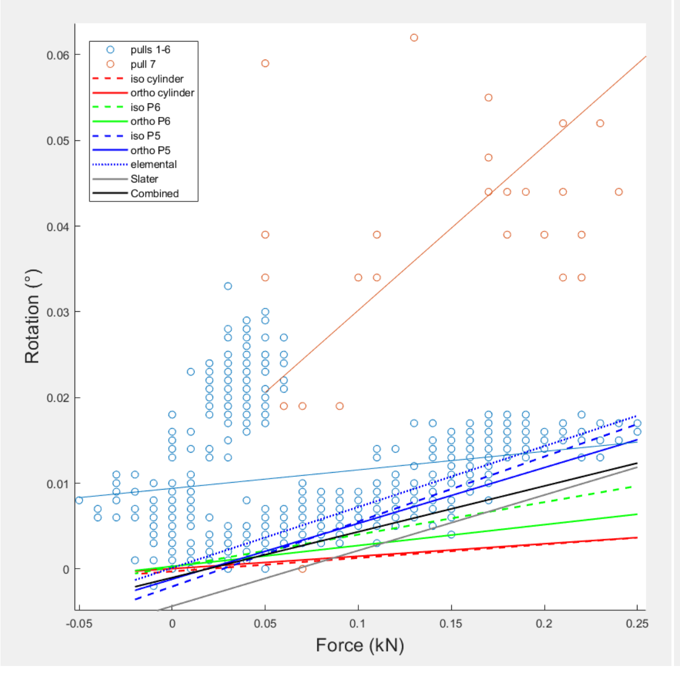

Before testing

Tree pair failure photos B13


Before testing

Appendix E2. Graphs of experimental and model results

back foot



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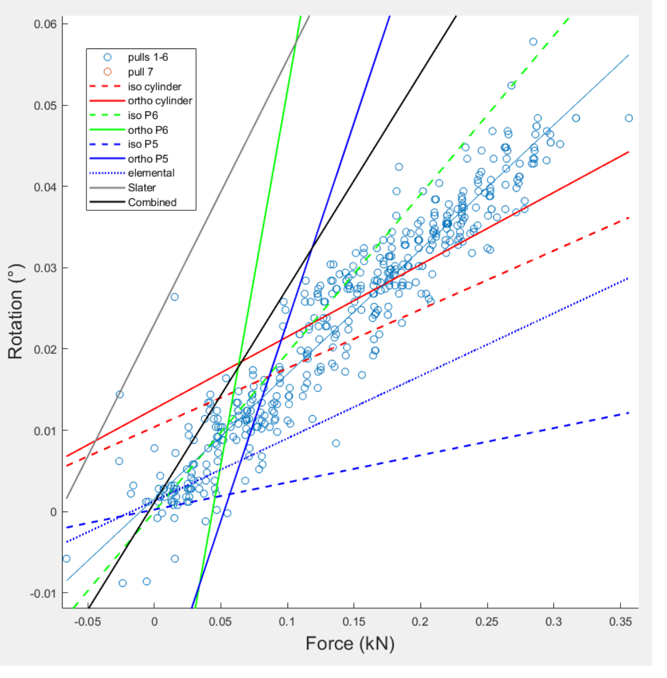

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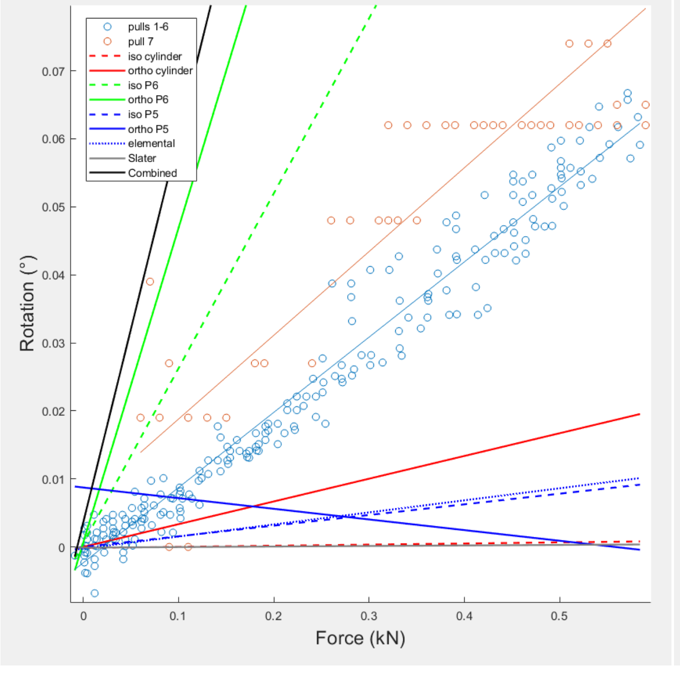

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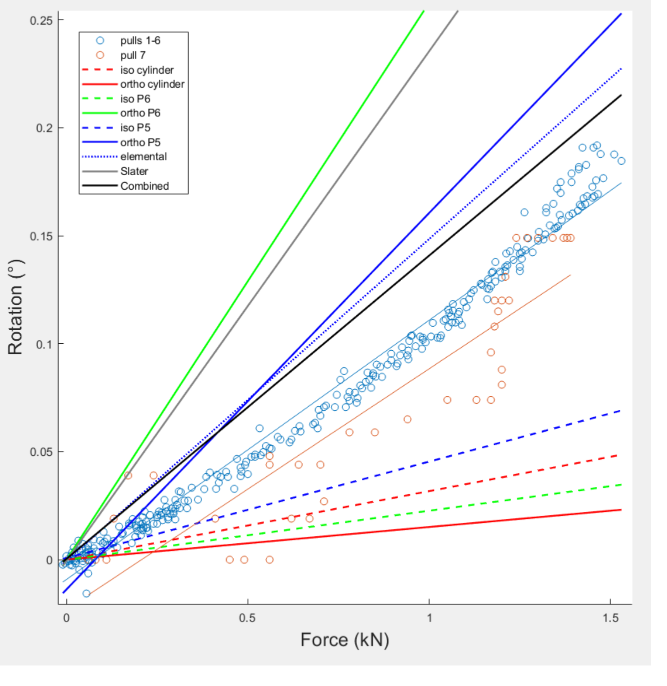

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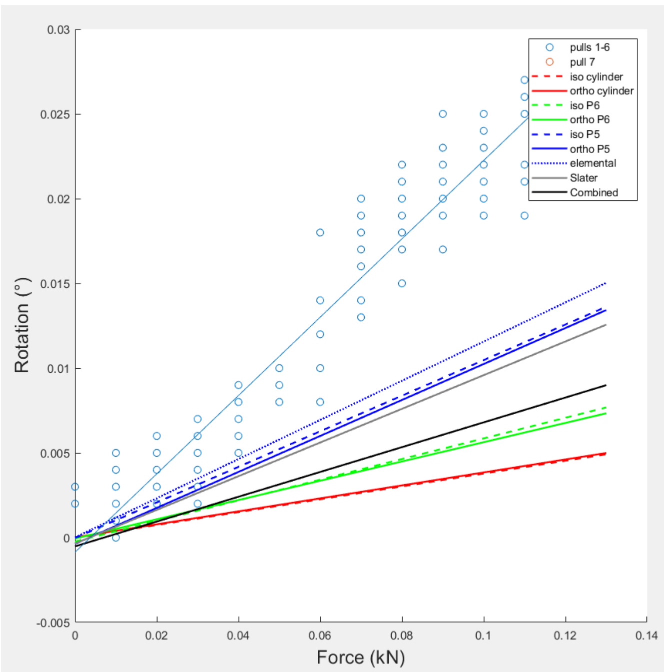
front foot



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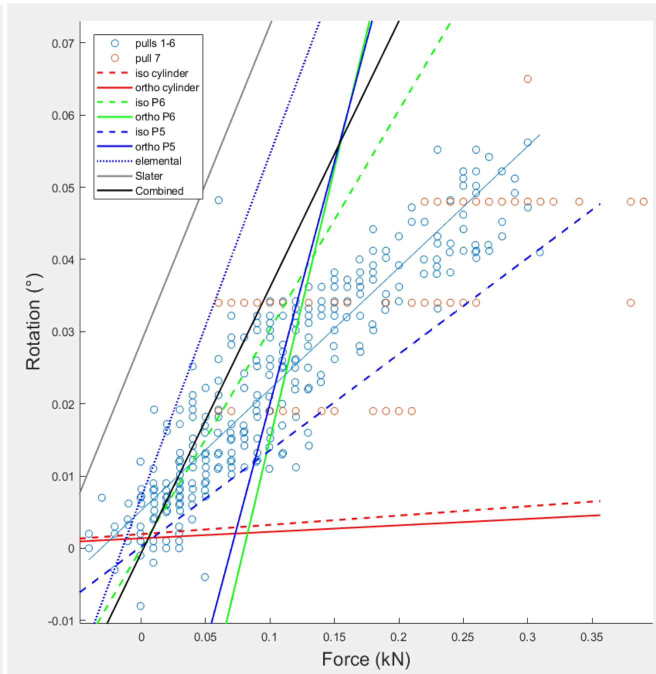

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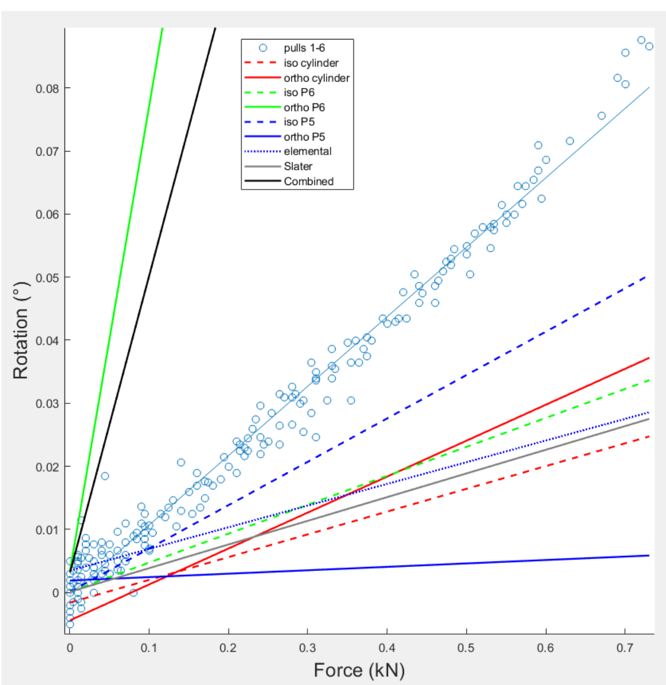

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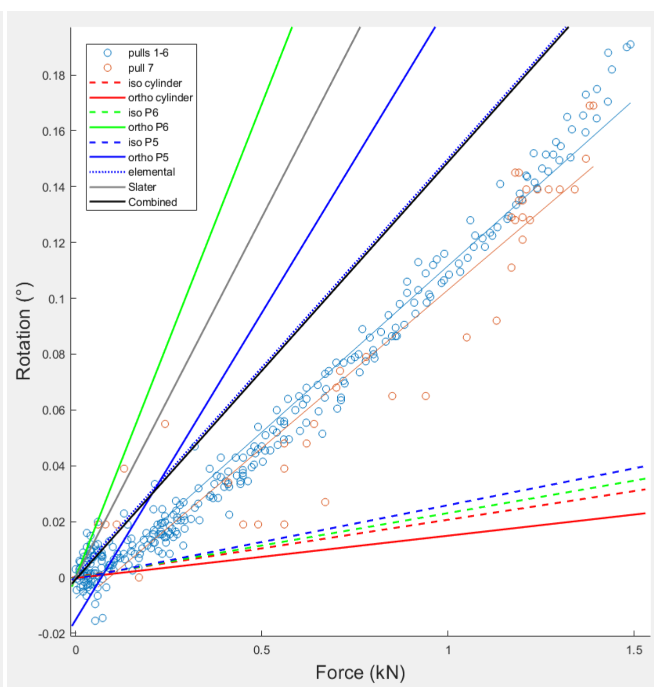

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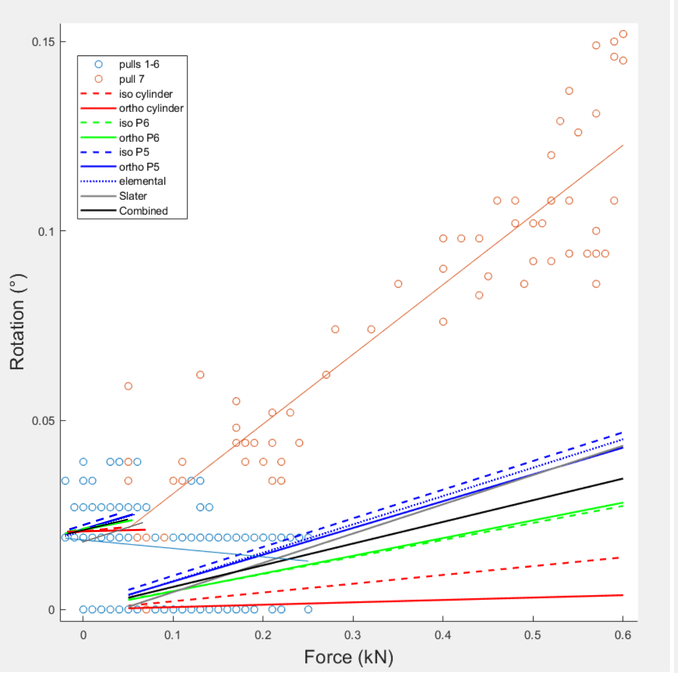
Back leg



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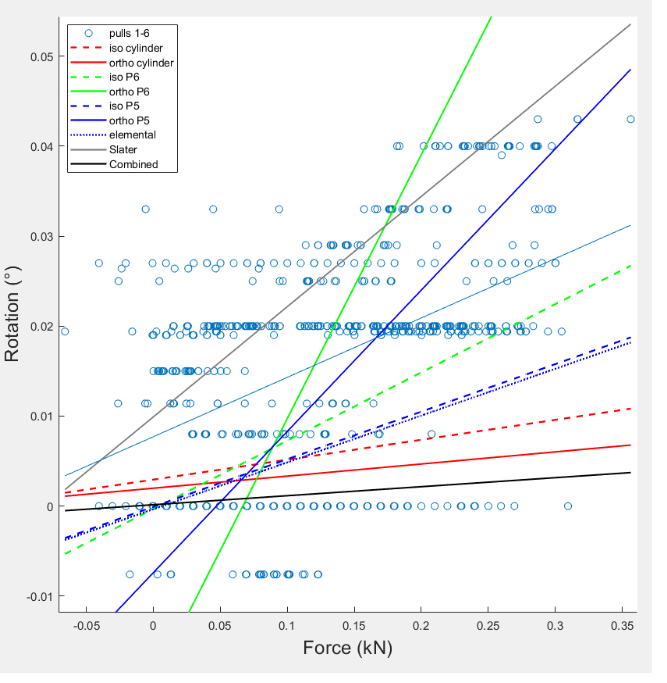

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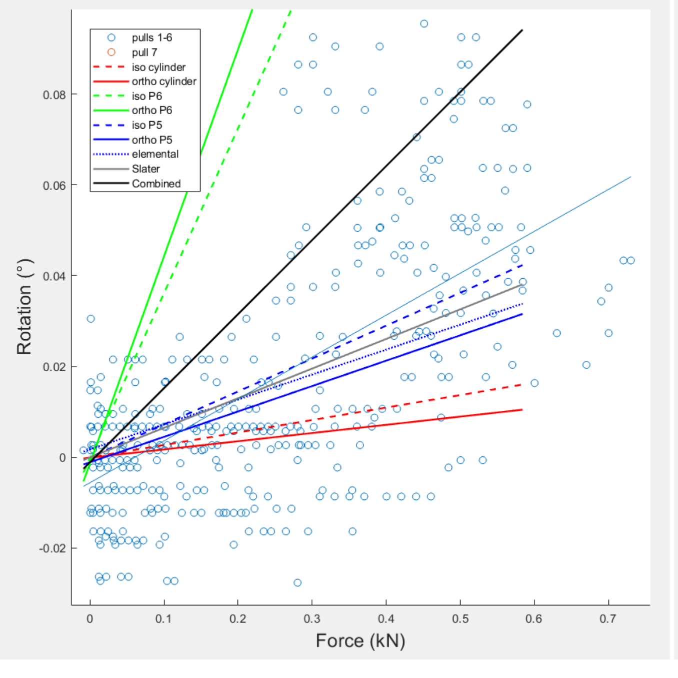

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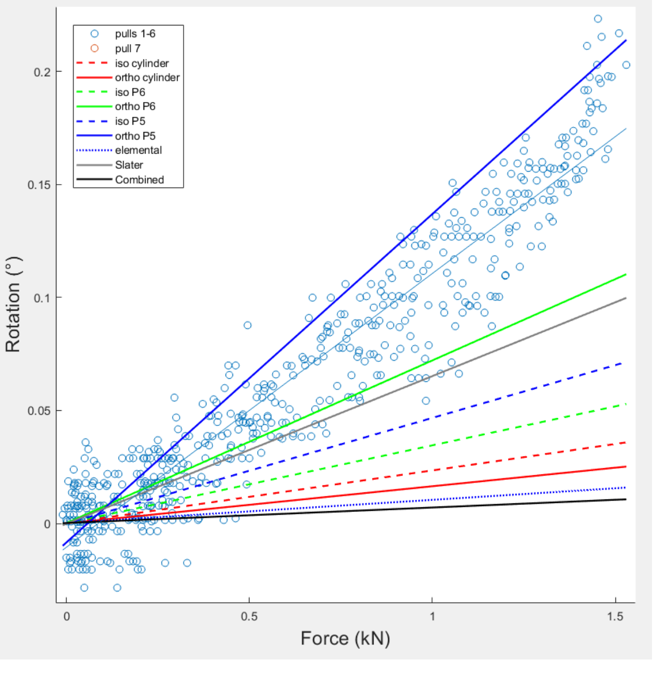

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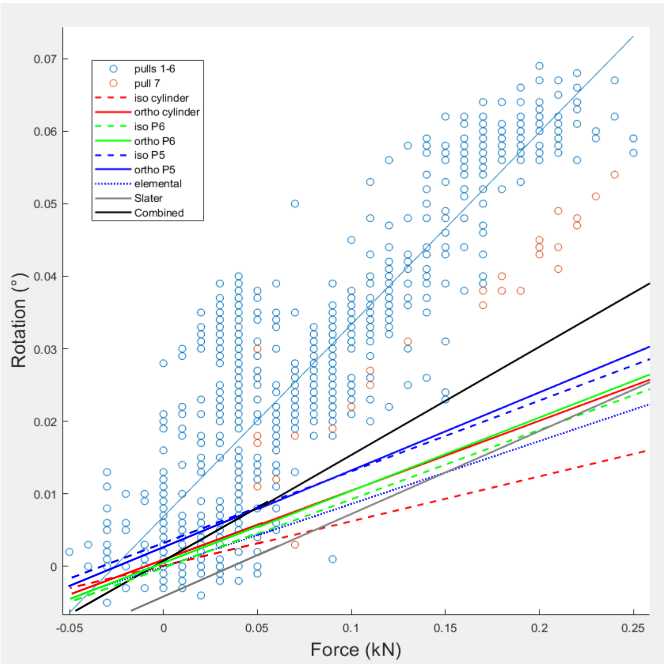
Below joint



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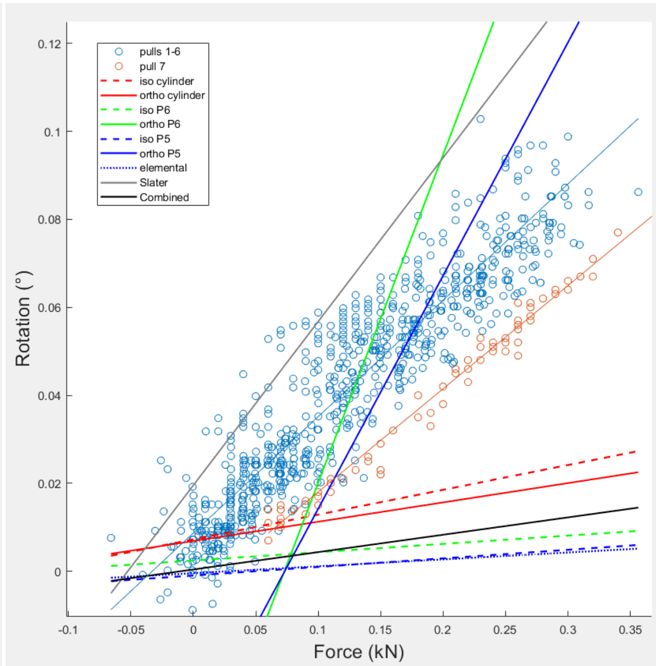

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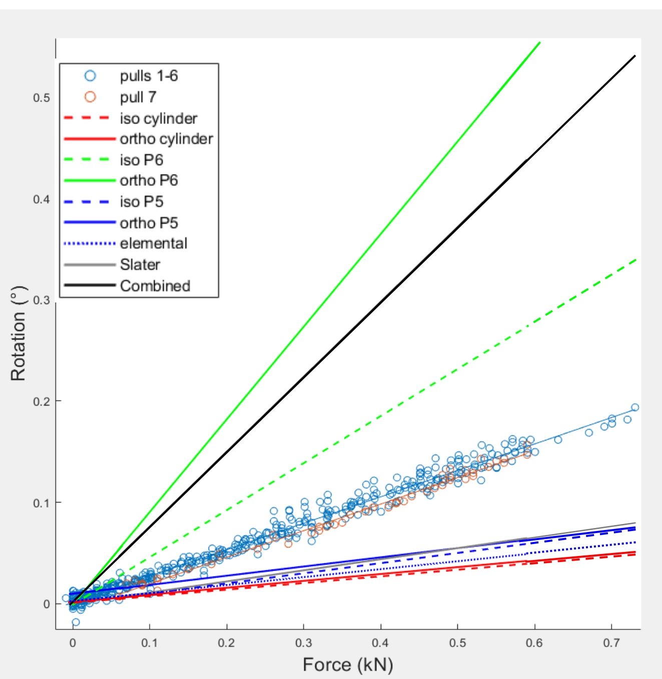

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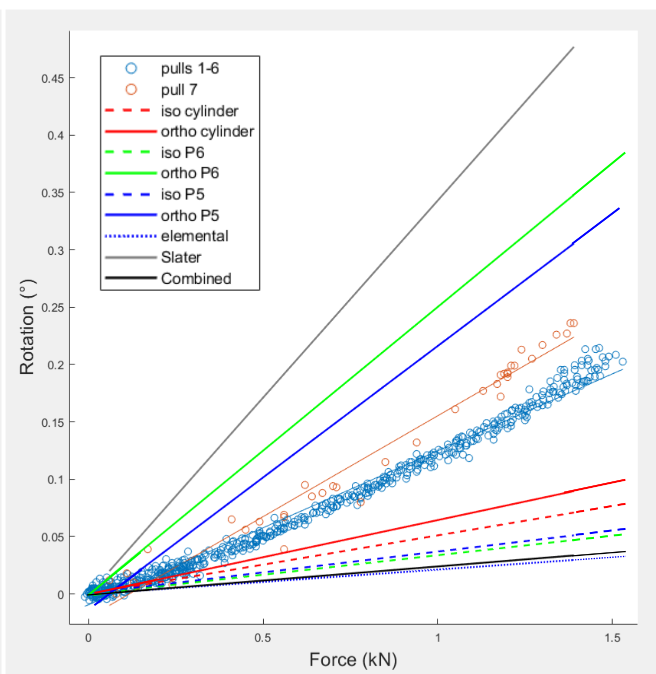

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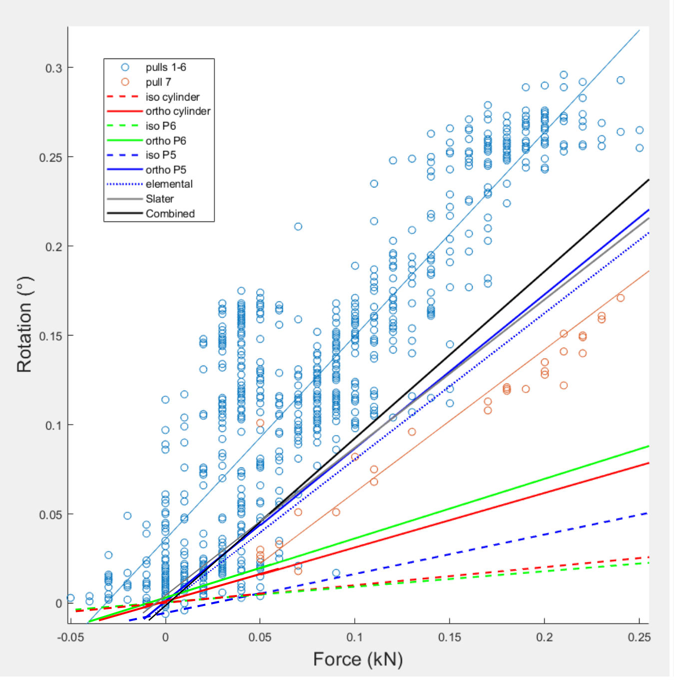
Above joint



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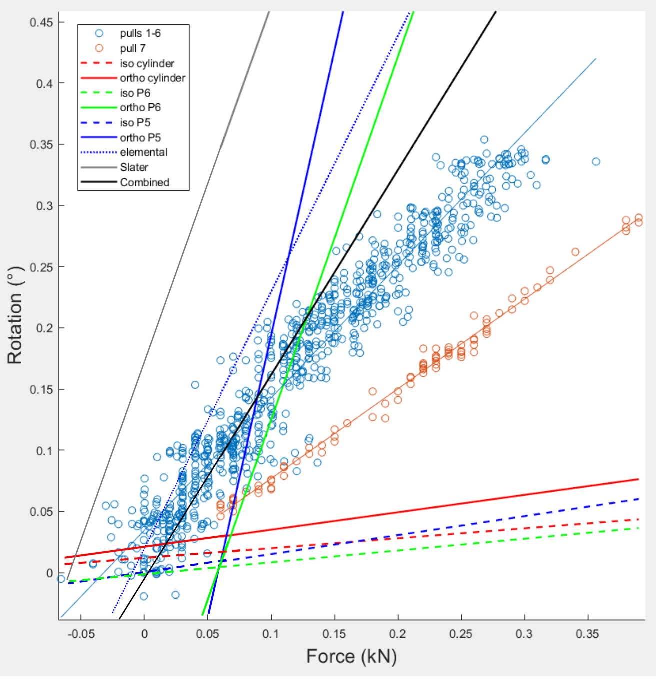

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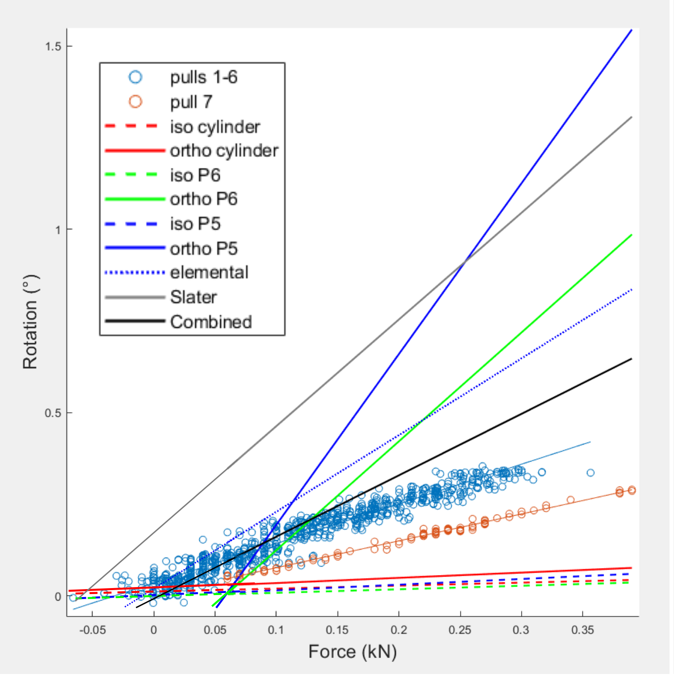

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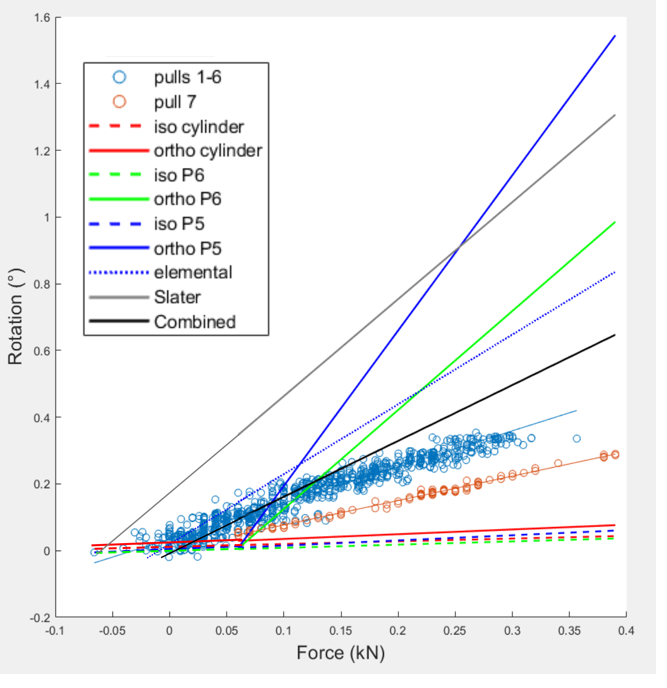

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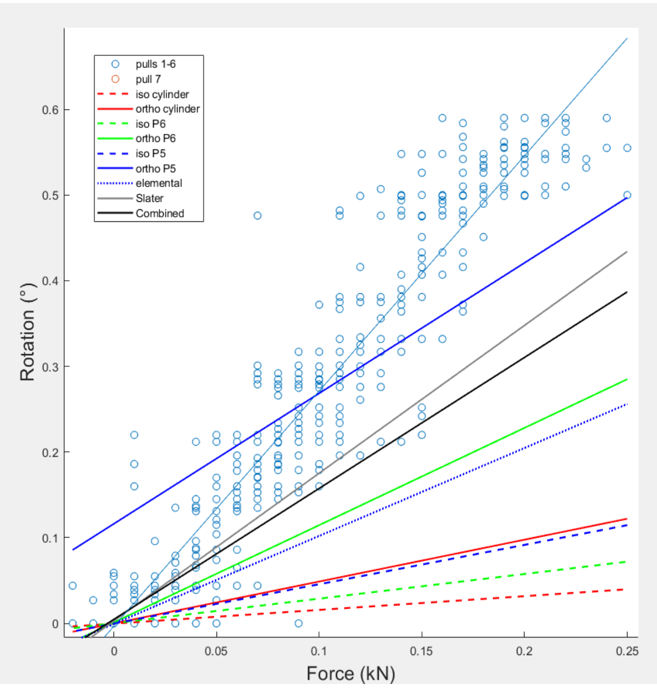
Mid-winched limb



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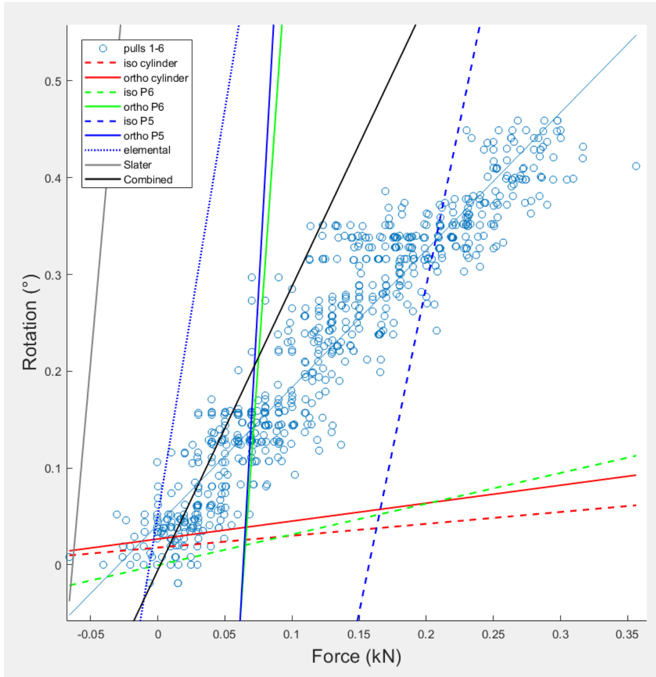

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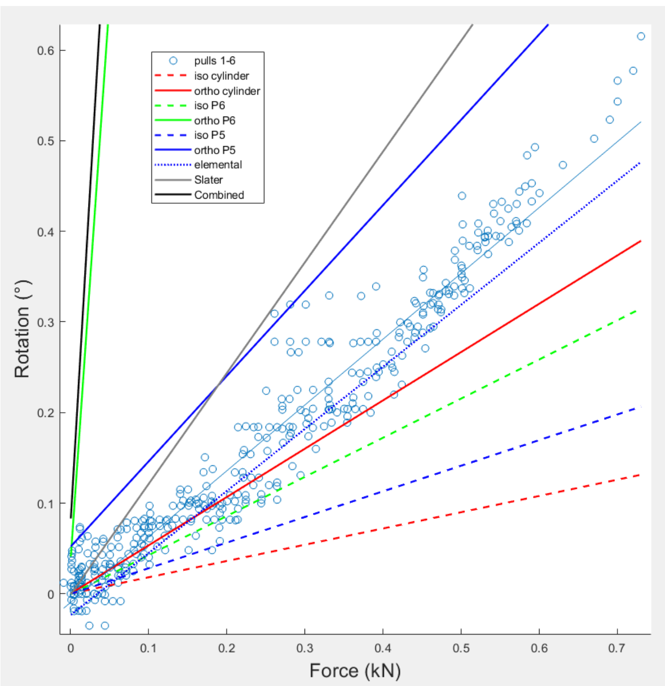

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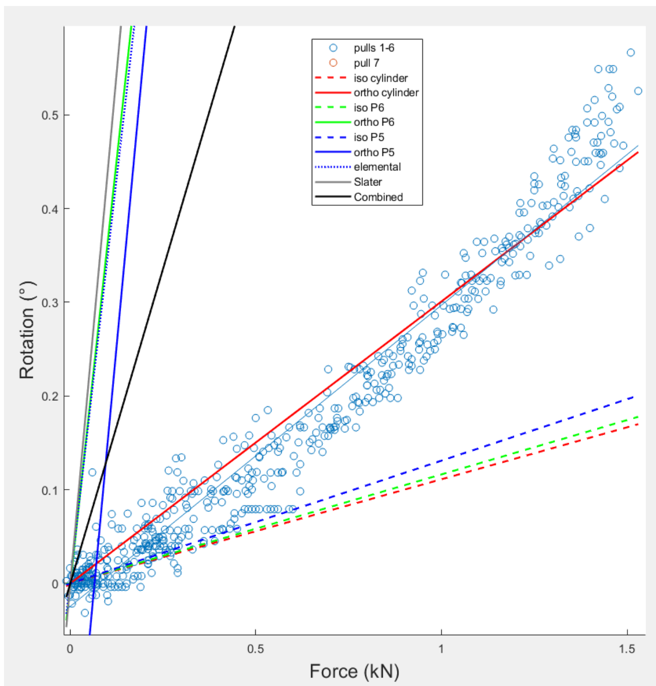

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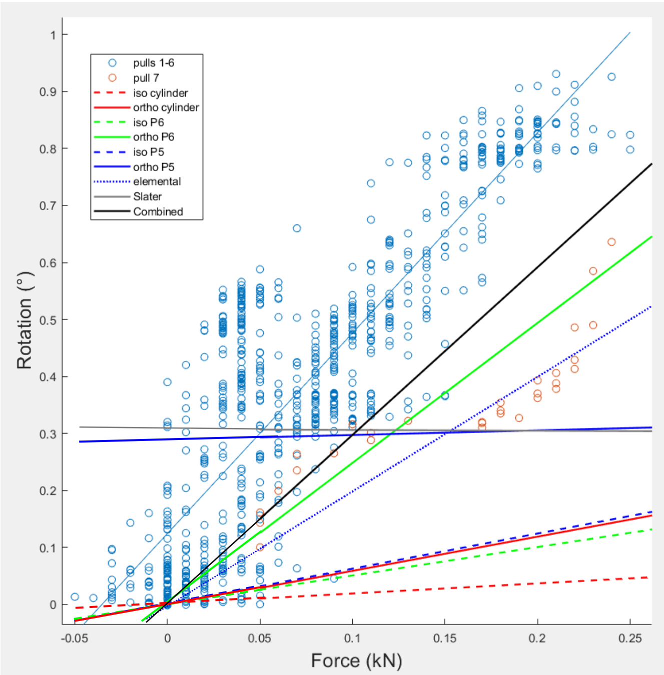
Mid-winched limb



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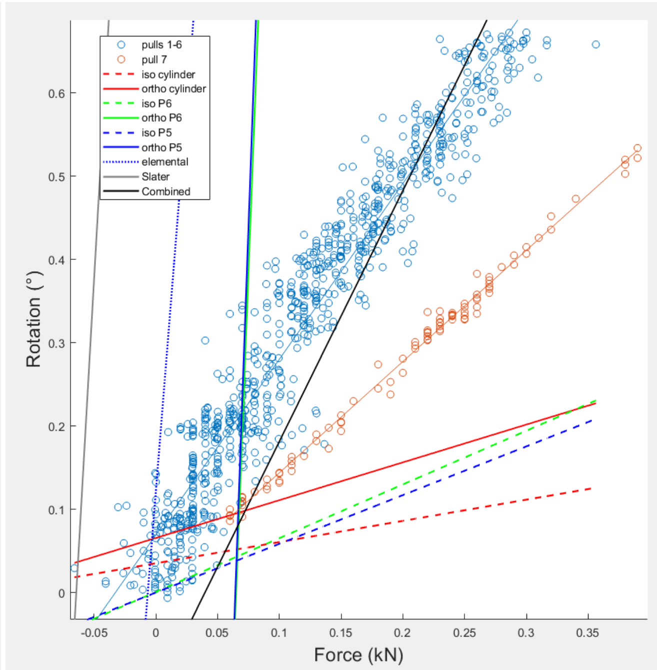

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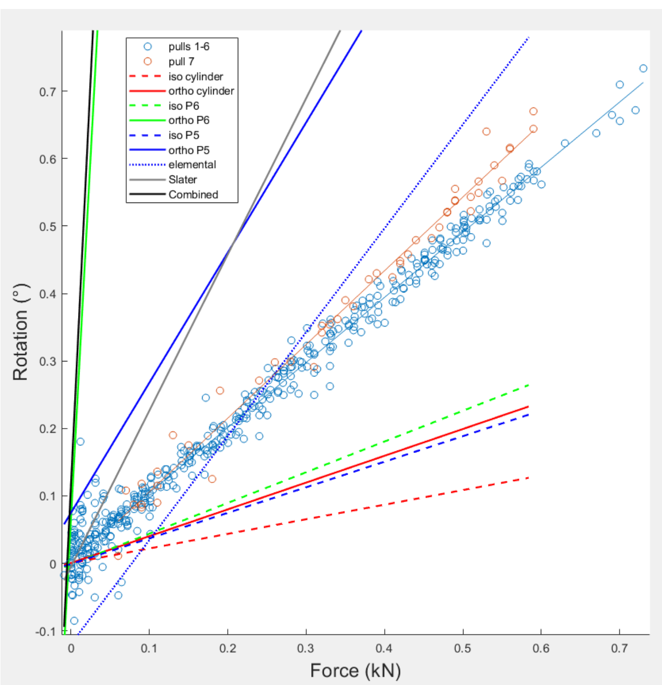

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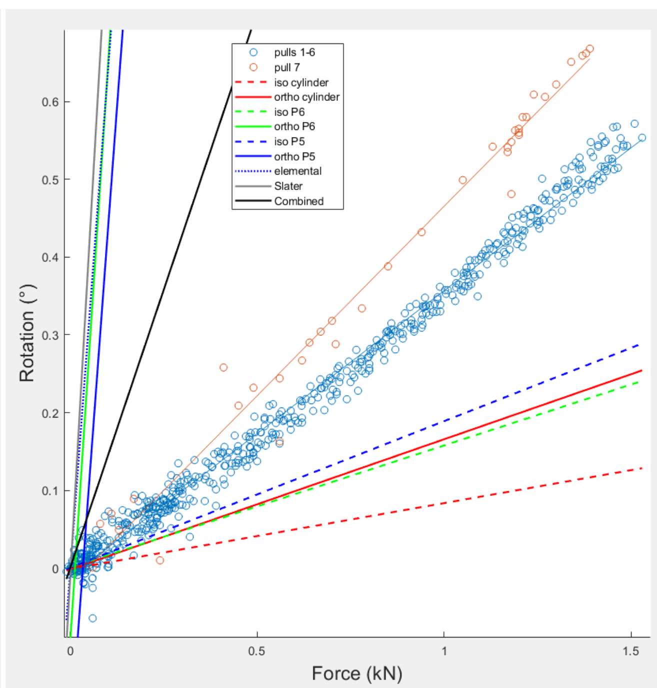

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